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Watts Bar 1 – Uncertainty quantification for Start of Life, Hot Zero Power

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- WIMS® model of Watts Bar Unit 1

- Benchmark results

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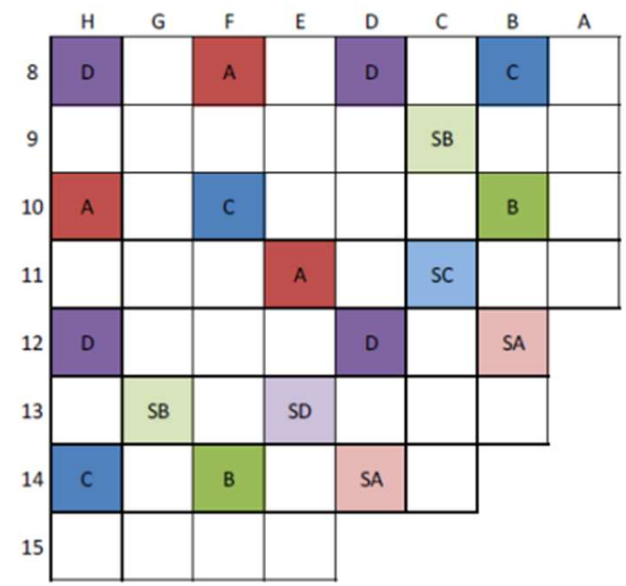
Introduction

Introduction

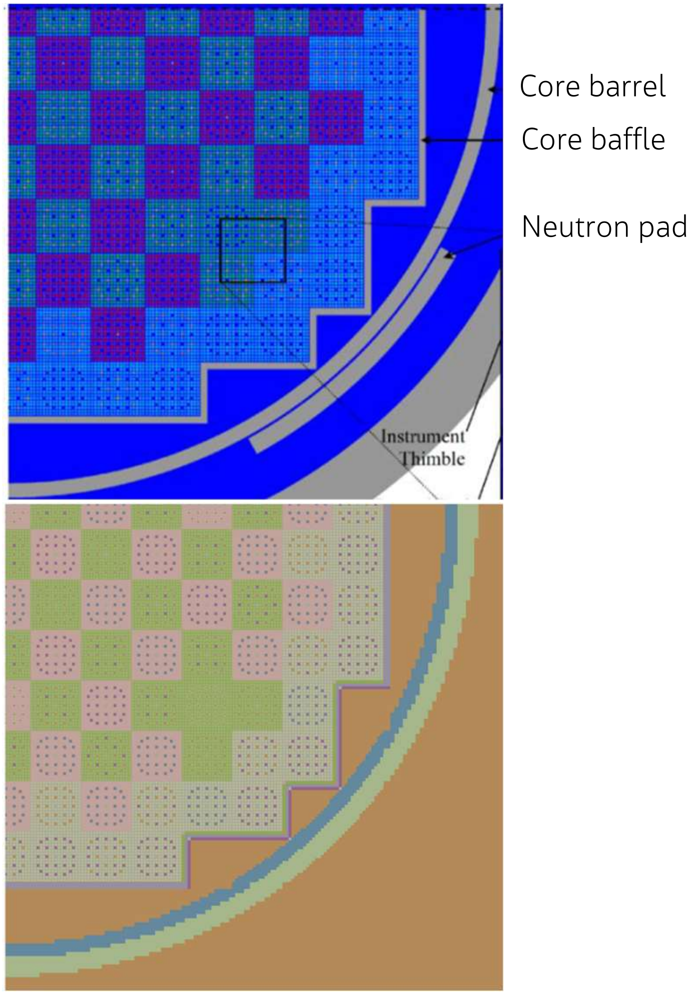
- TVA Watts Bar Unit 1 benchmark
- Proposed by NEA's Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems (WPRS)
- This is a PWR with:
  - 193 17x17 fuel assemblies
  - 3411 MWth
  - 8 control rod banks



Watts Bar 1 – Quarter core with control rod banks

Introduction

- Whole core model using GEOM-WIMS
  - 22 energy groups
  - Homogenized Cross-Sections at the pincell level using Method of Characteristics and SPH
  - Whole core solve in MERLIN using SP3
  - Thermal hydraulics feedback using 1D subchannel module ARTHUR
  - Dynamic Reshielding
- Key assumptions
  - End plugs and thimble plugs omitted
  - Gaps in fuel rod and Pyrex omitted
  - Core baffle, core barrel and neutron pad modelled semi-explicitly
  - Spacer grids modelled as additional outer ring on fuel clad (at grid heights)



Watts Bar 1 – GEOM Model (bottom) v KENO (top)

Benchmark

Watts Bar 1 – Benchmark

- Exercise 1 – Start up Hot Zero Power tests
  - 32 cases modelled
  - Critical boron concentration
  - Bank reactivity worth
  - Differential soluble boron worth
  - Rod worth as a function of insertion

- In GEOM-WIMS, library ENDF7.1 and JEFF3.1.2 used for Best estimate calculation, Latin Hypercube Sampled libraries of JEFF 3.1.2 used for uncertainty quantification

Case	Boron (ppm)	Temp (K)	A	B	C	D	SA	SB	SC	SD	Description
1	1285	565	-	-	-	167	-	-	-	-	Initial
2	1291	↓	-	-	-	-	-	-	-	-	ARO
3	1170	↓	0	-	-	97	-	-	-	-	Bank A
4	↓	↓	-	0	-	113	-	-	-	-	Bank B
5	↓	↓	-	-	0	119	-	-	-	-	Bank C
6	↓	↓	-	-	-	18	-	-	-	-	Bank D
7	↓	↓	-	-	-	69	0	-	-	-	Bank SA
8	↓	↓	-	-	-	134	-	0	-	-	Bank SB
9	↓	↓	-	-	-	71	-	-	0	-	Bank SC
10	↓	↓	-	-	-	71	-	-	-	0	Bank SD
11	↓	↓	-	-	-	-	-	-	-	-	ARO
12	↓	↓	0	-	-	-	-	-	-	-	Bank A
13	↓	↓	-	0	-	-	-	-	-	-	Bank B
14	↓	↓	-	-	0	-	-	-	-	-	Bank C
15	↓	↓	-	-	-	0	-	-	-	-	Bank D
16	↓	↓	-	-	-	-	0	-	-	-	Bank SA
17	↓	↓	-	-	-	-	-	0	-	-	Bank SB
18	↓	↓	-	-	-	-	-	-	0	-	Bank SC
19	↓	↓	-	-	-	-	-	-	-	0	Bank SD
20	1291	560	-	-	-	-	-	-	-	-	Low temp
21	↓	570	-	-	-	-	-	-	-	-	High temp
22	1230	565	-	-	-	0	-	-	-	-	D @ 0%
23	↓	↓	-	-	-	23	-	-	-	-	D @ 10%
24	↓	↓	-	-	-	46	-	-	-	-	D @ 20%
25	↓	↓	-	-	-	69	-	-	-	-	D @ 30%
26	↓	↓	-	-	-	92	-	-	-	-	D @ 40%
27	↓	↓	-	-	-	115	-	-	-	-	D @ 50%
28	↓	↓	-	-	-	138	-	-	-	-	D @ 60%
29	↓	↓	-	-	-	161	-	-	-	-	D @ 70%
30	↓	↓	-	-	-	184	-	-	-	-	D @ 80%
31	↓	↓	-	-	-	207	-	-	-	-	D @ 90%
32	↓	↓	-	-	-	-	-	-	-	-	D @ 100%

Watts Bar 1 Exercise 1 - 32 cases

Best-Estimate Results

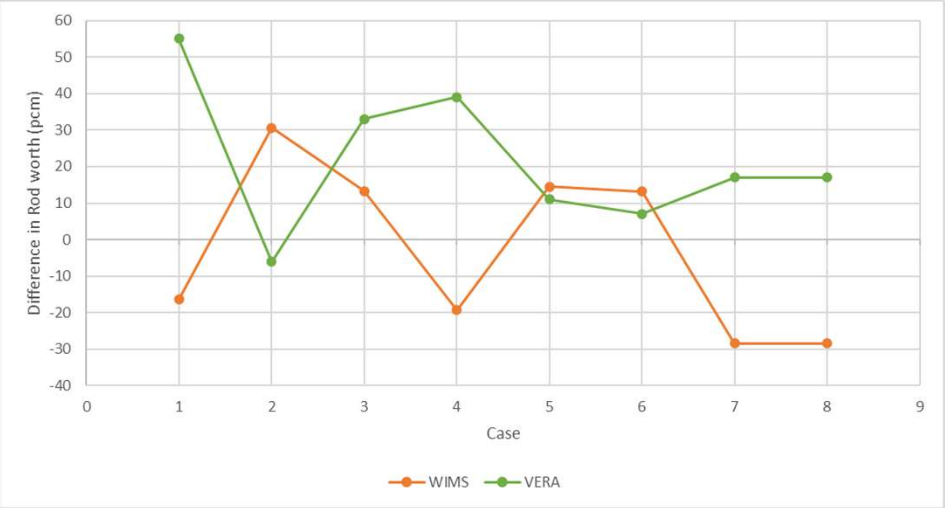
- Critical Bank Positions

Case	Boron Concentration (ppm)	Fully inserted control rod bank	Bank D position (steps)	WIMS K-eff (ENDF7.1)	Measured K-eff	Delta (pcm)	VERA K-eff	Delta (pcm)
1	1285	-	167	0.997737	1.00000	-226	1.000345	35
2	1291	-	230	0.997979	1.00000	-202	1.000779	78
3	1170	A	97	0.997130	1.00000	-287	0.999182	-82
4	1170	B	113	0.996668	1.00000	-334	0.999723	-28
5	1170	C	119	0.997513	1.00000	-249	0.999433	-57
6	1170	-	18	0.997128	1.00000	-288	0.999543	-46
7	1170	SA	69	0.997885	1.00001	-212	0.999385	-62
8	1170	SB	134	0.997314	1.00000	-269	0.999769	-23
9	1170	SC	71	0.998484	1.00000	-152	0.999399	-60
10	1170	SD	71	0.998484	1.00000	-152	0.999403	-60

Best-Estimate Results

- Control bank reactivity worth: $\rho = \left(\frac{1}{k_i} - \frac{1}{k_{ARO}}\right) \times 10^5$

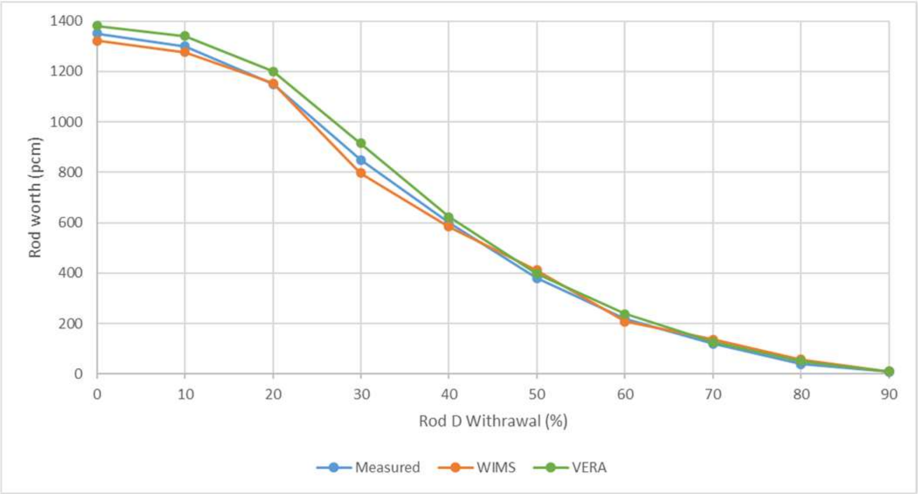
Case	Control bank	WIMS	Measured	Delta (pcm)	VERA	Delta (pcm)
12	A	827	843	-16	898	55
13	B	910	879	31	873	-6
14	C	964	951	13	984	33
15	D	1323	1342	-19	1381	39
16	SA	450	435	15	446	11
17	SB	1069	1056	13	1063	7
18	SC	452	480	-28	497	17
19	SD	452	480	-28	497	17



Best-Estimate Results

- Bank D Integral Worth: $\rho = \left(\frac{1}{k_i} - \frac{1}{k_{Dout}}\right) \times 10^5$

Withdrawal (%)	WIMS	Measured	Delta (pcm)	VERA	Delta (pcm)
0	1322	1350	-28	1381	31
10	1277	1300	-23	1340	40
20	1153	1150	3	1200	50
30	796	850	-54	916	66
40	585	600	-15	623	23
50	412	380	32	399	19
60	208	220	-12	238	18
70	137	120	17	128	8



Best-Estimate Results

- Differential Soluble Boron Worth (DBW):

$$DBW = \left(\frac{\frac{1}{k_{C1}} - \frac{1}{k_{C2}}}{(C_2 - C_1)} \right) \times 10^5$$

	DBW (pcm/ppm)	Delta (pcm/ppm)
Measured	-10.77	-
VERA	-10.15	0.62
WIMS	-10.22	0.55

Latin-Hypercube Sampling

Uncertainty Quantification methods in ANSWERS codes

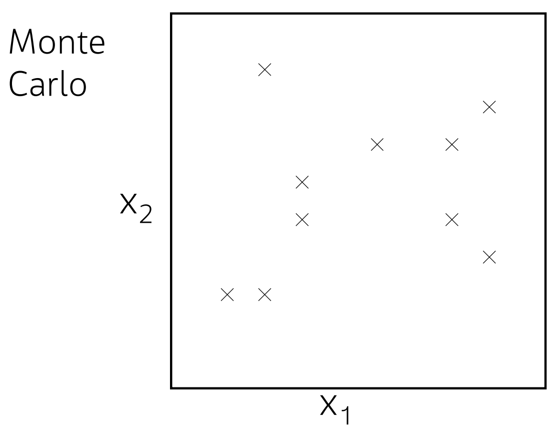
- Sensitivity and perturbation methods
  - Combine sensitivities and nuclear data uncertainties to estimate contribution to uncertainty for a give system
  - Breakdown of uncertainty contributions by nuclides and reaction
  - Intrusive and code-specific; few runs needed

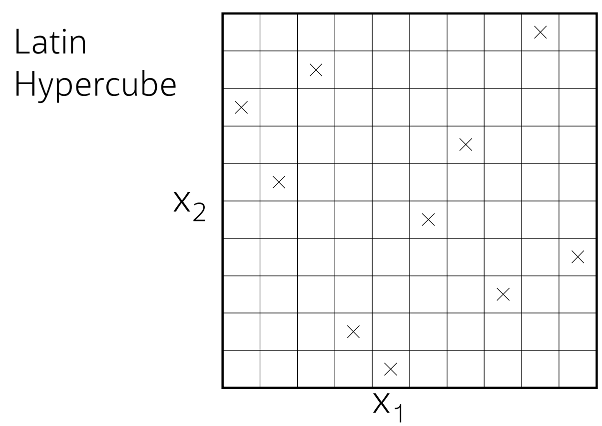
- Sampling method
  - Involves sampling in the nuclear data uncertainties to generate sets of randomly perturbed data sets
  - Simultaneous treatment of all uncertainties to get total response
  - Non-intrusive and generic
  - Only total uncertainty; lots of runs needed

- Both methods use the same covariance library

Latin-Hypercube Sampling (LHS)

- Nuclear data is sampled over normal distributions defined by the covariance data
- Sampling methodologies include Monte Carlo and Latin Hypercube
- This work uses Latin Hypercube Sampling to ensure adequate coverage of the sample space (without excessive samples)
  - 25 samples – 90/90 confidence
  - 60 samples – 95/95 confidence





Latin-Hypercube Sampling (LHS)

- Base nuclear data is JEFF-3.1.2 (for vast majority of nuclides)
- Best available covariance data
- Two sets of sampled libraries
  - LHS25 – 90/90 confidence
  - LHS60 – 95/95 confidence
- WIMS and BINGO libraries produced based on same data and uncertainties
- Perturbed cross sections for all ~300 nuclides
  - Informed by covariance data for 177 nuclides
- Perturbed thermal scattering for bound nuclides
- Perturbed nubar and fission spectra for major actinides
- Perturbed burnup data (half-lives, fission yields, branching ratios)
- General parameters (e.g. Temperatures, shielded nuclides, etc.) as standard libraries

Uncertainty quantification results

Uncertainty quantification

- 60 Latin Hypercube Sampling libraries used with JEFF-3.1.2

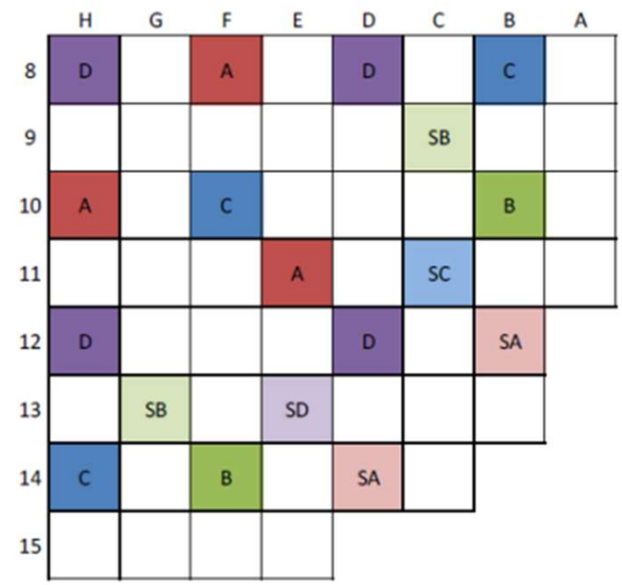
- Reduced scope compared to best-estimate work
  - K-eff, power profile uncertainties for critical case - Case 1
  - Bank worths – Cases 11-19

- For each case:
  - Calculation run with Best-Estimate library first,
  - Flux solution saved,
  - Same calculation run with each sampled library, using best estimate flux solution as first guess to save computational time (from ~8.6 to ~2.6 cpu hours)

Uncertainty quantification - Results

- k-effective and rod worth

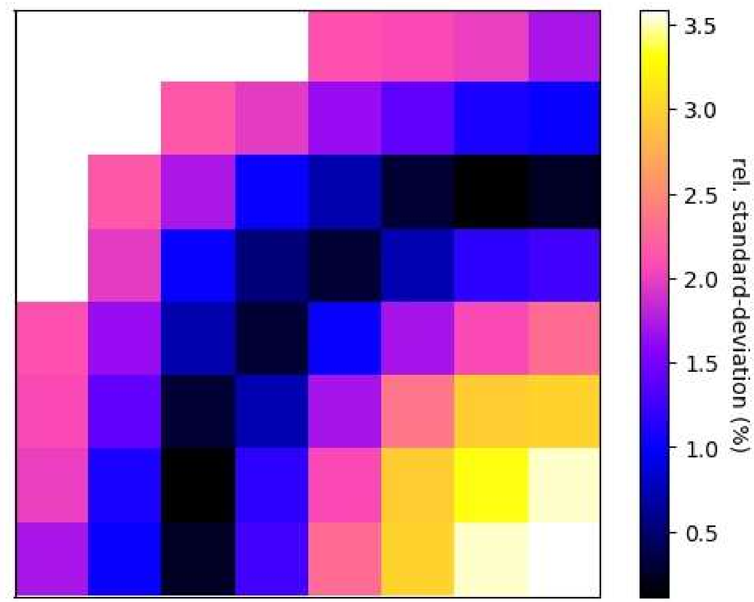
Case	Measured	WIMS ENDF7.1	Delta (pcm)	WIMS JEFF 3.1.2	Delta (pcm)	Standard deviation (pcm)
k-effective	1.00000	0.997737	-226	0.9978449	-216	565
Bank A worth	843	827	-16	820	-23	36
Bank B worth	879	910	31	917	38	22
Bank C worth	951	964	13	963	22	20
Bank D worth	1342	1323	-19	1320	-22	26
Bank SA worth	435	450	15	452	17	13
Bank SB worth	1056	1069	13	1071	15	7
Bank SC worth	480	452	-28	452	-28	3
Bank SD worth	480	452	-28	452	-28	3



Watts Bar 1 – Quarter core with control rod banks

Assembly and Axial power profile

- Very small impact of nuclear data uncertainties on axial power (~0.01-0.5%)
- Larger impact on assembly powers: 3.6% for the central assembly, ~2% for the edge assemblies
- Assembly power standard-dev RMS: 1.86%



Assembly power uncertainties

Comparison to SCALE/PARCS - Xu et al., *M&C, 2017 [2]*

- 200 samples of few group XSs using Sampler/Polaris

	WIMS – 60 LHS libs	SCALE/PARCS – 200 samples
k-effective std-dev	560 pcm	565 pcm
RMS assy powers	1.86%	2.06%
Max std-dev assy	3.59%	3.69%

- Also found very small impact on axial power profile

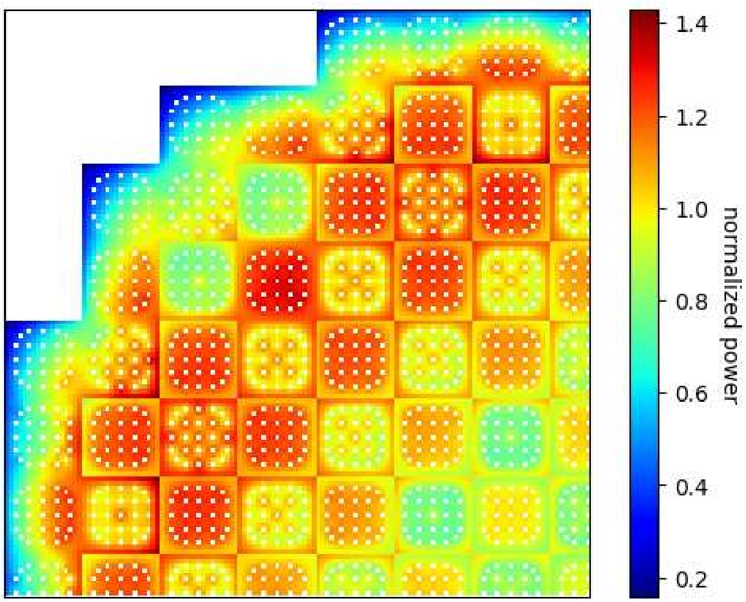
- Similar radial uncertainties to WIMS

3.69					
3.65	3.42				
3.10	3.10	2.45			
2.43	2.16	1.79	1.02		
1.37	1.29	0.76	0.29	0.69	
0.35	0.12	0.28	0.80	1.20	2.12
0.98	1.06	1.46	1.84	2.38	2.70
1.84	2.17	2.29	2.46		

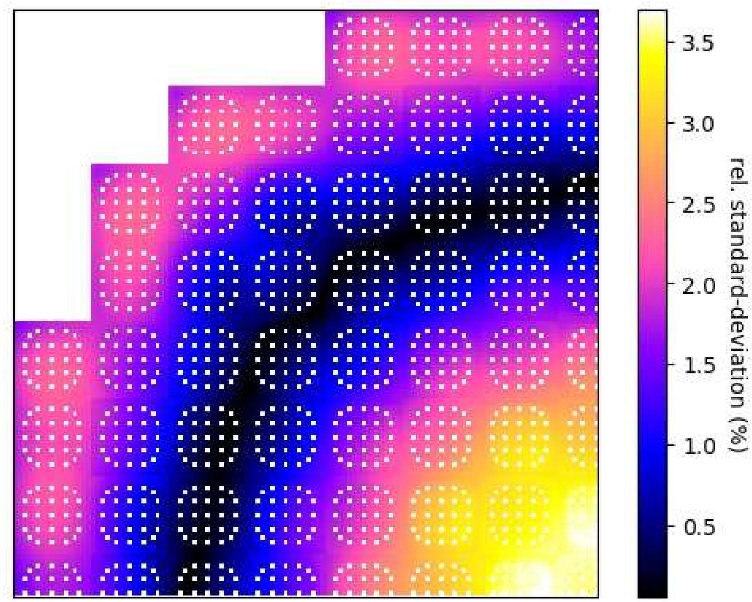
Assembly power uncertainties in SCALE/PARCS

Uncertainty quantification – Pin power & uncertainties

- Highest uncertainties in the centre (max 3.7%) and near edge (~2.5%)
- Low uncertainties in between… why?



Normalized pin power



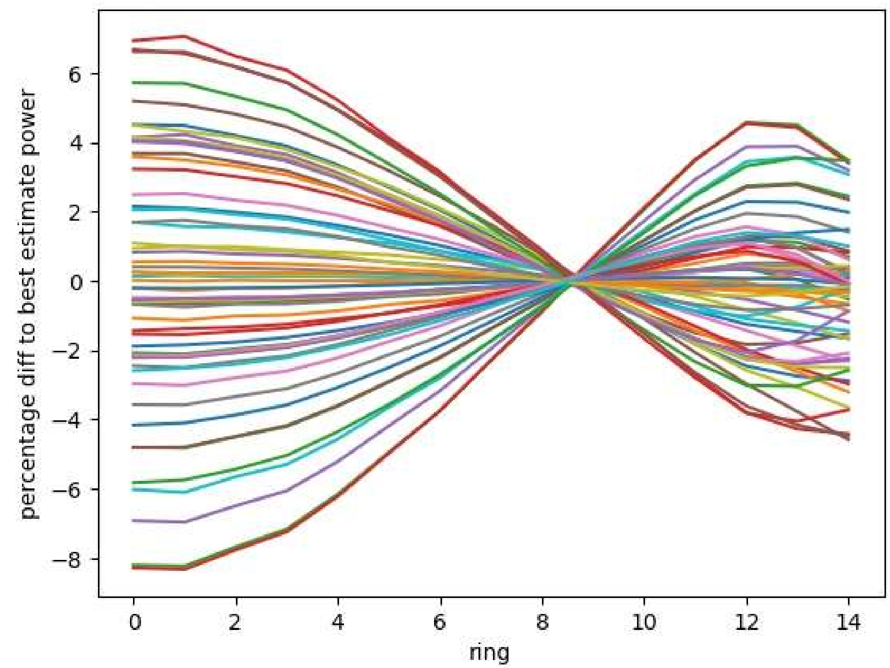
Relative standard-deviation for pin powers

Uncertainty quantification – Pin power & uncertainties

- It helps to look at pin powers at different distances from the centre

- Comparing each sampled library against best estimate we see:
  - Higher power in the centre along lower power at the edge
  - Or: lower power in the centre, along higher power at the edge
  - Power very close to best estimate in between

- This explains the dip in standard deviation between centre and edge



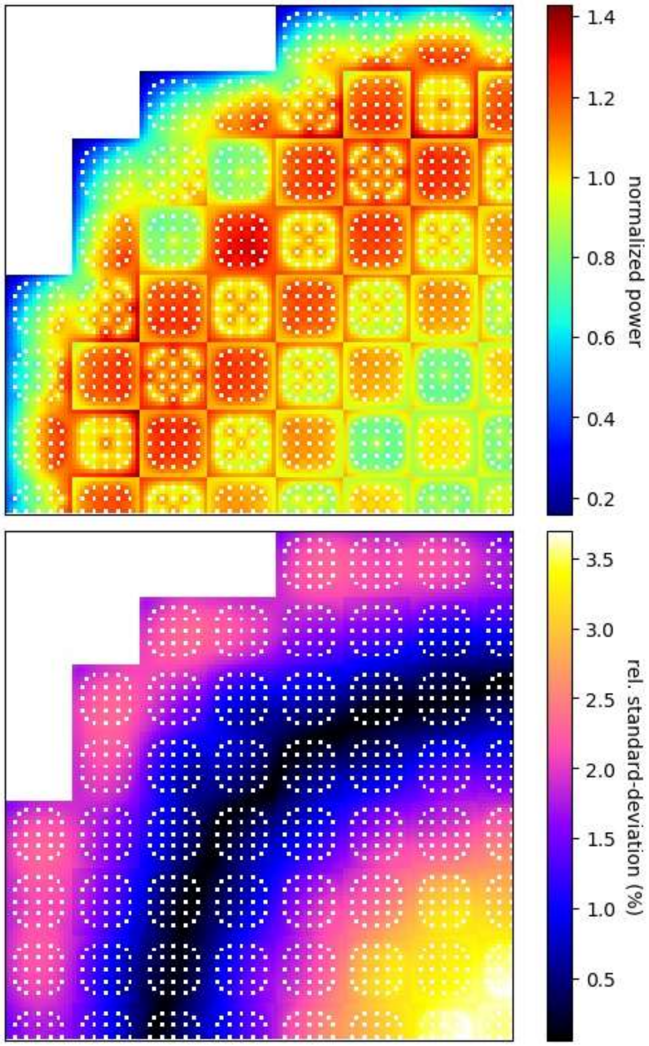
Difference in pin power for all 60 sampled libraries at different distances from the centre

Pin power & uncertainties

- For safety, we care about the hottest pin, highest nodal power – even at zero power
- Luckily here, hottest pins tend to be in between the centre and the edge

	Hottest pin	Highest nodal power
Best estimate	1.429	3.082
Rel. std-dev (%)	0.88	0.54

- Uncertainties for hottest pin/highest nodal power much lower than max 2D pin uncertainties (~3.7%)



Conclusion

- Updated results for HZP at Start of Life for Watts Bar 1 are in very good agreement with measured data
- Uncertainty quantification done using the Latin Hypercube sampled libraries which reduces number of runs necessary significantly while producing results in line with MC sampling
- Nuclear data uncertainties
  - Has large impact on k-effective (560 pcm)
  - Lead to a max. 3.7% standard deviation for 2D pin power, but only 0.5% for the hottest node, and 0.9% on hottest pin
  - Has a small impact on rod worth (10-30 pcm) and axial power (~0.01-0.5%)
- Work starting on Hot Full Power

Reference

- [1]: Benchmark specifications – *VERA Core Physics Benchmark Progression Problem Specifications, Rev. 4, 2014, A. T. Godfrey, Oak Ridge National Lab* https://corephysics.com/docs/CASL-U-2012-0131-004.pdf
- [2]: Uncertainty quantification for Watts Bar 1, Cycle 1 in SCALE/PARCS - *Two-Step Uncertainty Analysis of Watts Bar Nuclear 1 Cycle 1 with SCALE/PARCS, Xu et al. M&C 2017*

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