# TVA Watts Bar Unit 1 Modeling with Serpent 2.1.31

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# Outline

- Use of Serpent in the Reactor Dynamics and Fuel Modeling Group (RDFMG), Nuclear Engineering Department (NED) at NC State University (NCSU)
- Use of Serpent for multi-group cross-section and other parameters' generation
- Use of Serpent for whole reactor core Modeling and Simulation (M&S) with example of TVA Watts Bar 1 PWR core M&S

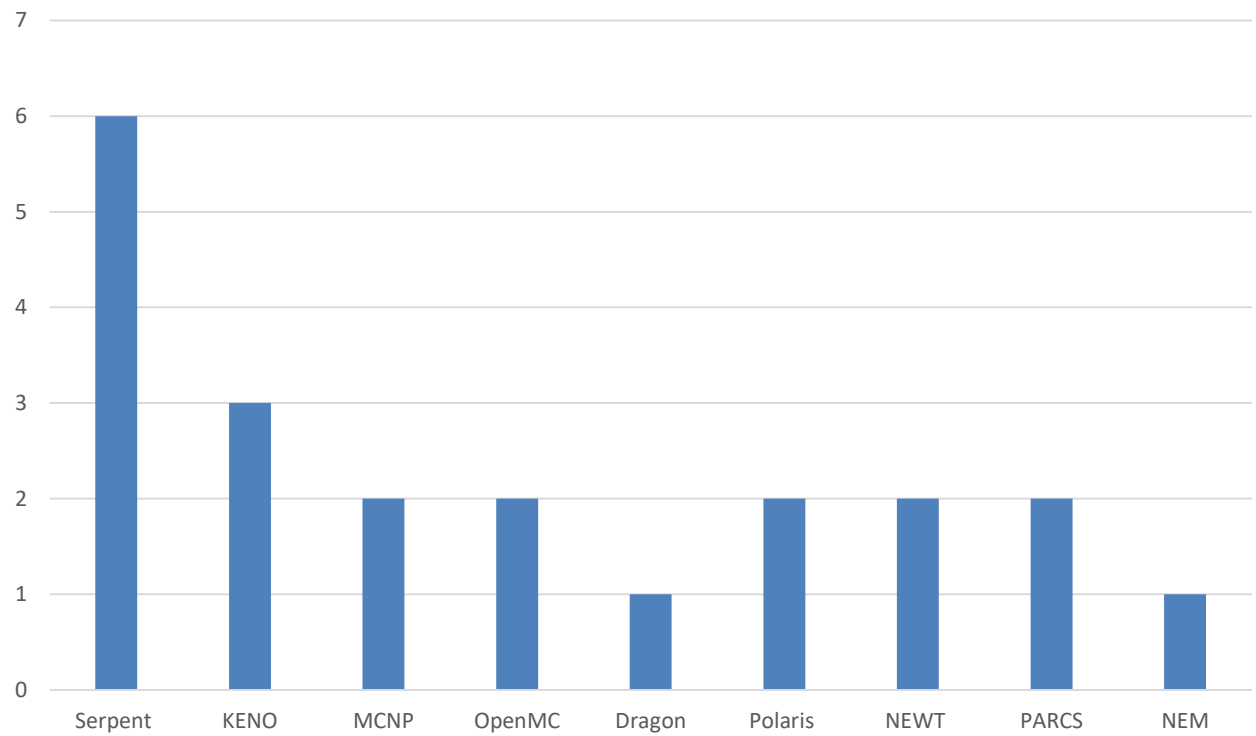
# RDFMG group at NED, NCSU

- RDFMG: research group within the NED at NCSU
  - 25 graduate students
  - 3 post docs
  - 4 faculty

- Fields of interest:
  - Core neutronics
  - Core and System Thermal Hydraulics (TH)
  - Fuel Performance (FP)
  - Multi-physics and multi-scale simulations
  - Coupled neutronics/TH/FP M&S
  - Verification, Validation and Uncertainty Quantification (VVUQ)
  - High-to-Low (Hi2Lo) model information, data analytics coupled with artificial intelligence

# Serpent use in the RDFMG

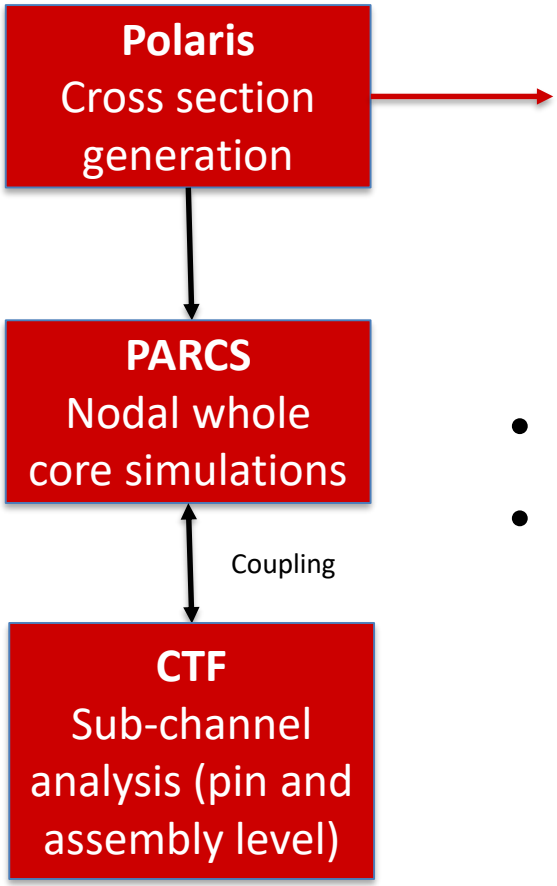
- Active users (past year) of a sample of neutronics codes in the group



# Serpent use in the RDFMG

- Serpent is used for M&S and VVUQ of Light Water Reactors (LWRs) and advanced reactors including Small Modular Reactors (SMRs) and micro-reactors:
  - Group constant generation
  - Code-to-code comparison
    - Lattice level
    - Core level
  - High-fidelity reactor physics whole-core modeling
  - Multi-physics M&S (near term future)

# Koeberg NPP Cycle 23 modeling




Branches, histories, burnup on lattice level

Reflector XS (top/bottom/side/corner)

Currently, perturbed cross-sections (XS) are generated with SAMPLER

- Koeberg: PWR in South Africa (970 MW)
- Eskom released operational data to NCSU

# Koeberg NPP Cycle 23 modeling

RMS between operational data and PARCS predictions using Polaris libraries

Uncertainties: modeling, experimental measurements, discretization …

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 0.322 | 0.388 | 0.32 | | | | | | |
| | | | | 0.375 | 0.758 | 1.183 | 1.236 | 1.168 | 0.743 | 0.357 | | | | |
| | | | 0.479 | 1.177 | 1.269 | 1.149 | 1.196 | 1.12 | 1.247 | 1.156 | 0.469 | | | |
| | | 0.47 | 1.233 | 1.237 | 1 | 1.23 | 0.903 | 1.219 | 0.99 | 1.224 | 1.229 | 0.477 | | |
| | 0.357 | 1.158 | 1.228 | 1.261 | 1.264 | 1.129 | 1.061 | 1.125 | 1.254 | 1.255 | 1.232 | 1.173 | 0.374 | |
| | 0.743 | 1.248 | 0.99 | 1.257 | 1.181 | 1.112 | 1.257 | 1.112 | 1.178 | 1.26 | 0.986 | 1.265 | 0.757 | |
| 0.319 | 1.167 | 1.119 | 1.218 | 1.125 | 1.113 | 1.184 | 1.041 | 1.183 | 1.109 | 1.125 | 1.226 | 1.145 | 1.18 | 0.321 |
| 0.387 | 1.234 | 1.193 | 0.901 | 1.058 | 1.257 | 1.041 | 0.789 | 1.04 | 1.255 | 1.057 | 0.899 | 1.193 | 1.233 | 0.387 |
| 0.321 | 1.18 | 1.144 | 1.228 | 1.126 | 1.11 | 1.183 | 1.039 | 1.182 | 1.11 | 1.122 | 1.216 | 1.117 | 1.165 | 0.319 |
| | 0.757 | 1.266 | 0.999 | 1.26 | 1.178 | 1.11 | 1.254 | 1.108 | 1.177 | 1.252 | 0.986 | 1.245 | 0.742 | |
| | 0.374 | 1.174 | 1.232 | 1.255 | 1.253 | 1.122 | 1.056 | 1.124 | 1.258 | 1.253 | 1.221 | 1.154 | 0.357 | |
| | | 0.477 | 1.229 | 1.222 | 0.987 | 1.215 | 0.899 | 1.224 | 0.994 | 1.23 | 1.227 | 0.468 | | |
| | | | 0.469 | 1.154 | 1.244 | 1.116 | 1.191 | 1.141 | 1.263 | 1.171 | 0.476 | | | |
| | | | | 0.356 | 0.741 | 1.164 | 1.232 | 1.177 | 0.755 | 0.373 | | | | |
| | | | | | | 0.319 | 0.387 | 0.321 | | | | | | |

Modeling uncertainties coming from Polaris/PARCS?



Point of contact: Agustin Abarca (*aabarca@ncsu.edu*)

# Comparison of cross section libraries between Polaris and Serpent

**Polaris**
Cross section generation
↓
**PARCS**
Nodal whole core simulations

**Serpent**
Cross section generation
↓
**PARCS**
Nodal whole core simulations

**Step 1**: generating the same set of lattice models with Serpent

- 8 assemblies
- 22 BU steps
- 8 histories
- 36 branches

**Step 2:** Verification of model equivalency between Polaris and Serpent (isotopic inventory, geometry etc.) Current status

**Step 3:** Cross section parameterization/functionalization (GenPMAXS) and PARCS simulations

# Comparison of cross section libraries between Polaris and Serpent

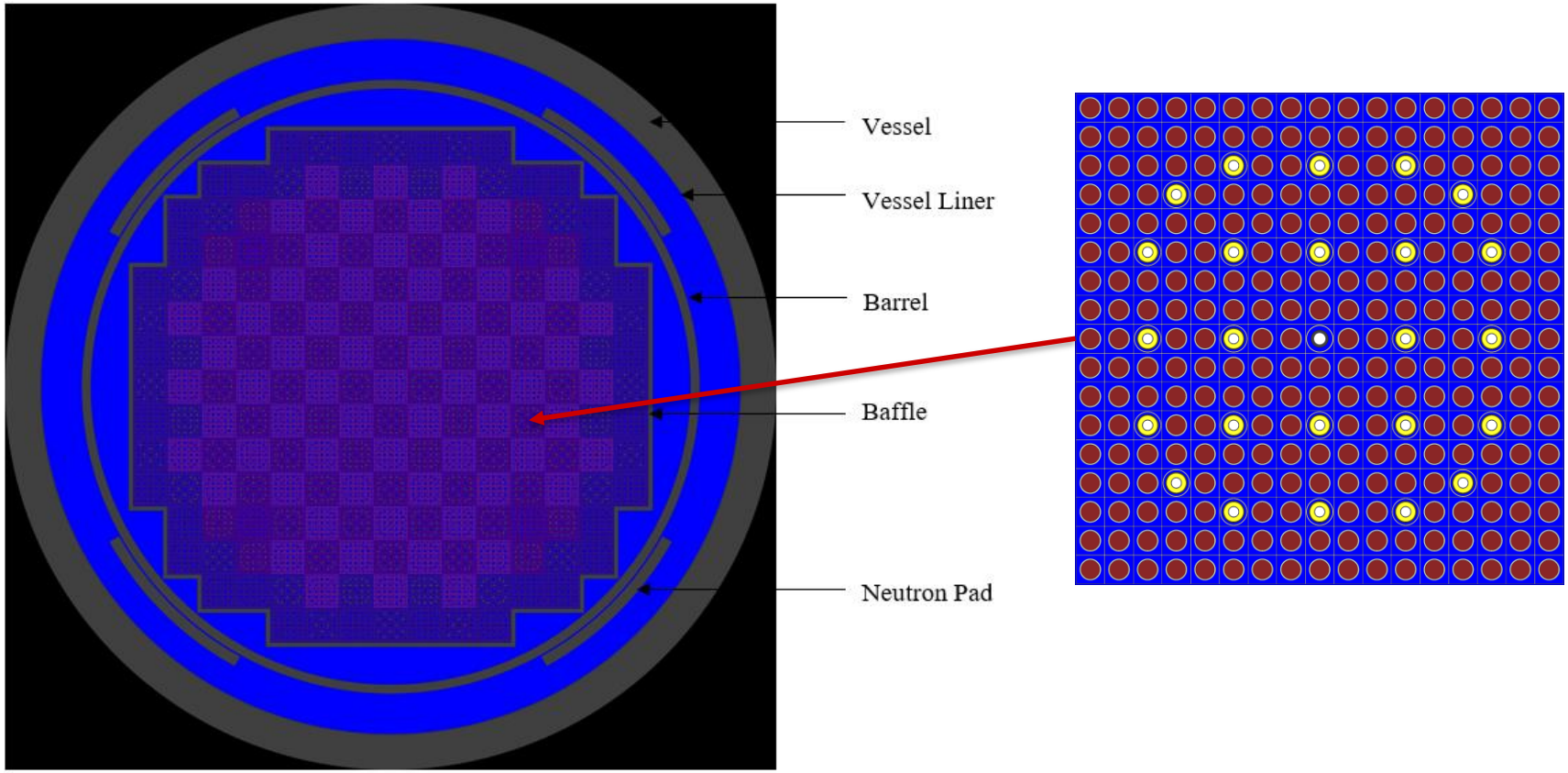
- Other parameter compared:
  - Performance of CMM
  - DBRC mode

# Modeling of TVA WB1 with Serpent

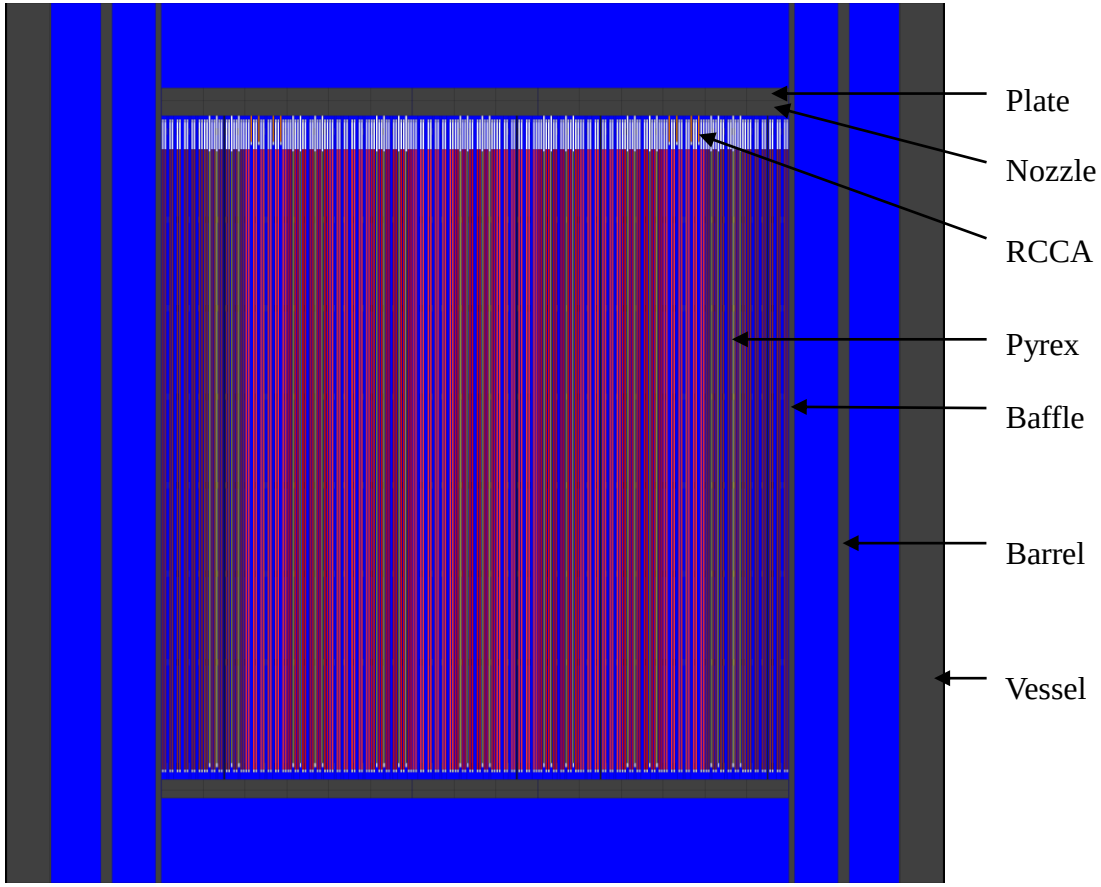
- Whole-core simulation of Tennessee Valley Authority (TVA) Watts Bar Unit 1 (WB1) PWR
  - Cycle 1 operational data
  - Zero Power Physics Test (ZPPT) conditions (single physics – neutronics with fixed thermal-hydraulics feedback)
- Objective: including the ZPPT results in the International Reactor Physics Experiment Evaluation Project (IRPhEP) handbook
  - Requires nominal modeling of core with a Monte Carlo (MC) code
  - Requires uncertainty quantification


Point of contact: Thamer Albagami (*talbaga@ncsu.edu*)

# WB1 model in Serpent (radial view)



# WB1 model in Serpent (axial view)



# Criticality configurations

| Case | Boron (ppm) | Bank D Position (steps) | Fully Inserted Bank | $K_{efffective}$ | | Difference (pcm) |
|---|---|---|---|---|---|---|
| | | | | Serpent 2.1.31 | CE-KENO-VI | |
| **1** | 1285 | 167 | - | 0.99937 ± 3.8E-05 | 0.99990 ± 1.0E-05 | -53 |
| **2** | 1291 | 230 | - | 0.99978 ± 3.8E-05 | 1.00032 ± 1.3E-05 | -54 |
| **3** | 1170 | 97 | A | 0.99846 ± 4.0E-05 | 0.99880 ± 1.0E-05 | -34 |
| **4** | 1170 | 113 | B | 0.99881 ± 3.8E-05 | 0.99937 ± 1.3E-05 | -56 |
| **5** | 1170 | 119 | C | 0.99864 ± 4.0E-05 | 0.99904 ± 1.3E-05 | -40 |
| **6** | 1170 | 18 | D | 0.99864 ± 4.0E-05 | 0.99908 ± 1.3E-05 | -45 |
| **7** | 1170 | 69 | SA | 0.99851 ± 3.9E-05 | 0.99902 ± 1.2E-05 | -51 |
| **8** | 1170 | 134 | SB | 0.99891 ± 3.9E-05 | 0.99932 ± 1.2E-05 | -41 |
| **9** | 1170 | 71 | SC | 0.99906 ± 3.9E-05 | 0.99898 ± 1.3E-05 | 8 |
| **10** | 1170 | 71 | SD | 0.99900 ± 3.9E-05 | 0.99898 ± 1.3E-05 | -2 |

# Criticality configurations

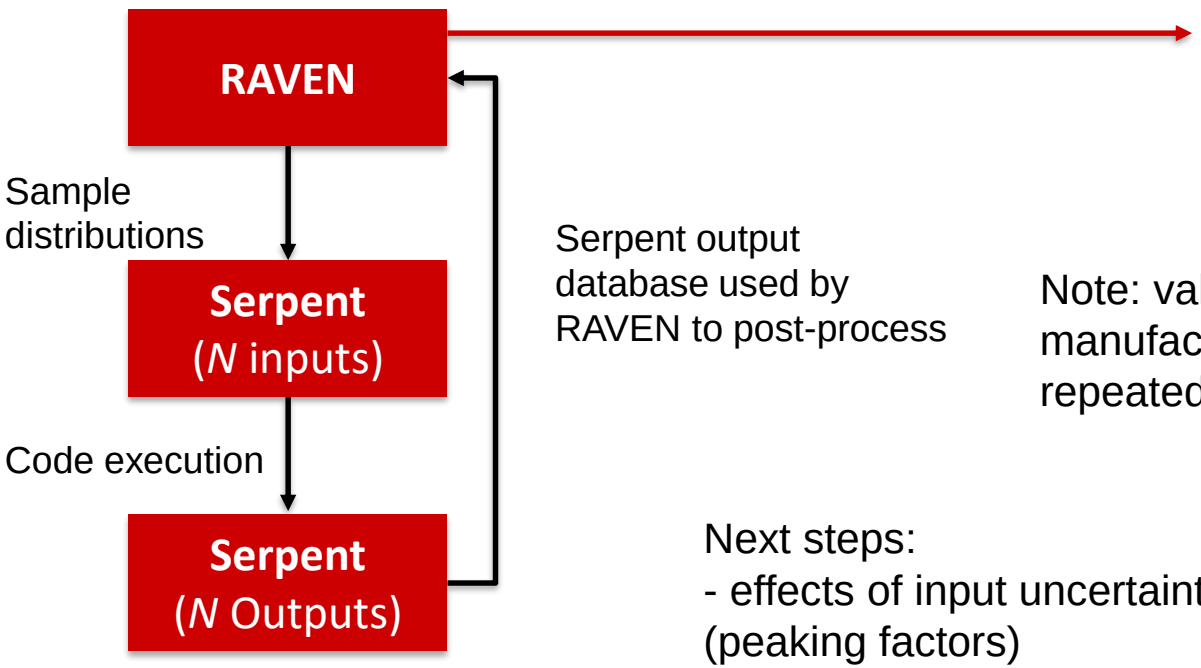
| Critical Cases Results with Two Cross Section Libraries | | | | | | |
|---|---|---|---|---|---|---|
| | | | | $K_{efffective}$ | | |
| **Case** | Boron (ppm) | Bank D Position (steps) | Fully Inserted Bank | Serpent 2.1.31 and ENDF/B VII.0 | Serpent and ENDF/B VII.1 | Difference (pcm) |
| **1** | 1285 | 167 | - | 0.99937 ± 3.8E-05 | 0.99964 ± 3.8E-05 | -27 |
| **2** | 1291 | 230 | - | 0.99978 ± 3.8E-05 | 1.00000 ± 3.8E-05 | -22 |
| **3** | 1170 | 97 | A | 0.99846 ± 4.0E-05 | 0.99858 ± 4.0E-05 | -12 |
| **4** | 1170 | 113 | B | 0.99881 ± 3.8E-05 | 0.99923 ± 3.8E-05 | -42 |
| **5** | 1170 | 119 | C | 0.99864 ± 4.0E-05 | 0.99873 ± 4.0E-05 | -9 |
| **6** | 1170 | 18 | D | 0.99864 ± 4.0E-05 | 0.99889 ± 4.0E-05 | -25 |
| **7** | 1170 | 69 | SA | 0.99851 ± 3.9E-05 | 0.99872 ± 3.9E-05 | -21 |
| **8** | 1170 | 134 | SB | 0.99891 ± 3.9E-05 | 0.99911 ± 3.9E-05 | -20 |
| **9** | 1170 | 71 | SC | 0.99906 ± 3.9E-05 | 0.99920 ± 4.0E-05 | -14 |
| **10** | 1170 | 71 | SD | 0.99900 ± 3.9E-05 | 0.99930 ± 4.0E-05 | -30 |

# Uncertainty quantifications

- Serpent was coupled to RAVEN to be able to evaluate output uncertainties of quantities of interest with respect to uncertain input parameters
- RAVEN
  - Developed by Idaho National Laboratory
  - Uncertainty quantification code using random sampling
  - Post-processing capabilities: reduced order models, data mining

# RAVEN/Serpent coupling

| Parameter | Distribution (1σ, normal) | Unit |
|---|---|---|
| Fuel Density | ±0.1700 | $g/cm^3$ |
| Fuel Pellet Diameter | ±0.0130 | mm |
| Gap Thickness | ±0.0240 | mm |
| Clad Thickness | ±0.0250 | mm |
| $^{235}U$ Concentration | ±0.0024 | w/o |




Serpent output database used by RAVEN to post-process

$\sigma_{keff}$ = 0.00167

95% Confidence interval: 0.00150 – 0.00201

Note: values of uncertain manufacturing parameters were repeated over lattice elements

Next steps:
- effects of input uncertainties on local metrics (peaking factors)

- Implementing independent uncertain values over lattice elements

# Summary and future steps

- Use of Serpent in RDFMG group at NCSU:
  - Group constant generation (Koeberg NPP)
  - High-fidelity neutronics (WB1 NPP)
- Serpent was coupled to RAVEN for uncertainty quantification
- Development of Serpent / CTF coupling for multi-physics multi-cycle TVA WB1 M&S and VVUQ as part of the OECD/NEA PWR Multi-Physics Multi-Cycle Depletion benchmark