

Preliminary SCALE Results for the OECD/NEA Benchmark for Uncertainty Analysis in Modeling of SFRs

Friederike Bostelmann, Bradley T. Rearden

Reactor and Nuclear Systems Division Oak Ridge National Laboratory

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

2nd SCALE Users' Group Workshop, August 27-29, 2018, ORNL



Introduction

- In the United States, interest is growing in advancing modeling and simulation capabilities for advanced reactor systems
- The SCALE 6.2.3 code package offers a number of transport sequences and different methods for uncertainty and sensitivity analyses
- SCALE is part of the US Nuclear Regulatory Commission (NRC) licensing
 path that will soon be confronted with advanced reactor systems
- As part of ongoing activities for advanced reactor systems, calculations for the sub-exercises of the UAM-SFR are performed using a variety of SCALE modules



Introduction

- With SCALE 6.2, only multigroup libraries optimized for thermal systems are shipped
- Preparation of sodium-cooled fast reactor (SFR) calculations using AMPX (shipped with SCALE 6.2)* include:
 - Generation of a new 302-group cross section with appropriate weighting spectrum and a group structure optimized for fast spectrum systems
 - Corresponding 302-group covariance library



(LWR) pin cell and SFR assemblies [1]

[1] F. Bostelmann, W. Zwermann, A. Pautz, "SCALE Covariance Libraries For Sodium-Cooled Fast Reactor Systems," Proc. PHYSOR 2018, Cancun, Mexico, April 22-26, 2018

Applied SCALE modules

TSUNAMI-2D

- Linear perturbation theory
- Transport solver NEWT
- 302g ENDF 7.1 XS data
- 302g SCALE 6.2 covariance data (mainly ENDF 7.1)

CE TSUNAMI

- Linear perturbation theory
- Transport solver KENO-VI
- CE ENDF 7.1 XS data
- 302g SCALE 6.2 covariance data (mainly ENDF 7.1)
- Eigenvalue uncertainties -CLUTCH
- GPT responses GEAR (CLUTCH+IFP)

SAMPLER

- Random sampling approach
- Monte Carlo code KENO-VI
- 302g ENDF 7.1 XS data
- XS samples based on 302g SCALE 6.2 covariance data (mainly ENDF 7.1)



Ex. I-1: Pin cells

CAK RIDGE

Eigenvalues and uncertainties

| | ME | T1000 | MOX3600 | | |
|------------|------------------|------------------------------------|-----------|-------------------------------------|--|
| | k _{inf} | k_{inf} $\Delta k_{inf}/k_{inf}$ | | ∆k _{inf} /k _{inf} | |
| TSUNAMI-2D | 1.3585 | 1.52% | 1.1924 | 1.69% | |
| CE TSUNAMI | 1.3588(2) | 1.52(2)% | 1.1920(3) | 1.71(1)% | |



CE TSUNAMI: Top 3 contributors

| | MET1000 | MOX3 | 600 |
|-------------|-------------------------------------|-------------|-------------------------------------|
| | ∆k _{inf} /k _{inf} | | ∆k _{inf} /k _{inf} |
| U-238 inel. | 1.35% | U-238 inel. | 1.56% |
| Na-23 el. | 0.28% | U-238 cap. | 0.31% |
| U-238 cap. | 0.23% | Pu-239 cap. | 0.25% |



Ex. I-1: Pin cells

k-inf and 1-group xs uncertainties



fuel

cladding

cladding

coolant

National Laboratory

Ex. I-2: Fuel assemblies

CE TSUNAMI: nominal values and uncertainties

| | М | ET1000 | MOX3600 | | |
|------------|----------------------|---------|--------------|-------------|--|
| | nominal uncertainty | | nominal | uncertainty | |
| Eigenvalue | 1.2800(1) 1.41(1)% | | 1.1467(1) | 1.52(1)% | |
| Doppler | -338(13) pcm | 6.3(5)% | -781(21) pcm | 5.2(3)% | |
| Na-void | 5895(9) pcm 5.47(1)% | | 2945(10) pcm | 5.57(1)% | |

CE TSUNAMI: Top 3 contributors

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| MET1000 | | | | MOX3600 | |
|-------------|--------------|-------------|-------------|-------------|-------------|
| Eigenvalue | Doppler | Navoid | Eigenvalue | Doppler | Na-void |
| U-238 inel. | U-238 inel. | Na-23 el. | U-238 inel. | U-238 inel. | Na-23 el. |
| Na-23 el. | Na-23 el. | Na-23 inel. | U-238 cap. | O-16 el. | Na-23 inel. |
| Fe-56 el. | Pu-239 inel. | U-238 inel. | Pu-239 cap. | Pu-239 cap. | U-238 inel. |



MET1000



MOX3600

Ex. I-2: Fuel assemblies

k-inf and 4-group macro xs uncertainties



cladding

fue

coolant

duct

Ex. I-3: Super-cells

CE TSUNAMI: nominal values and uncertainties

| | ME | T1000 | MOX3600 | |
|------------|---------------|-------------|--------------|-------------|
| | nominal | uncertainty | nominal | uncertainty |
| Eigenvalue | 1.0841(1) | 1.49(1)% | 1.0771(1) | 1.52(1)% |
| CR worth | 12081(11) pcm | 2.81(1)% | 4973(11) pcm | 2.67(1)% |

CE TSUNAMI: Top 3 contributors

| MET | 1000 | MOX3600 | | |
|-------------|-------------|-------------|-------------|--|
| Eigenvalue | CR worth | Eigenvalue | CR worth | |
| U-238 inel. | U-238 inel. | U-238 inel. | U-238 inel. | |
| Fe-56 inel. | Fe-56 inel. | U-238 cap. | Na-23 el. | |
| Na-23 el. | Na-23 el. | Pu-239 cap. | U-238 chi | |



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Ex. I-3: Super-cells

k-inf and 4-group macro xs uncertainties of central absorber assembly



fuel assemblies

primary -control

assembly



Ex.I-4: MET1000 full core

- Step 1: Criticality calculations using KENO-VI
 - Model of only $1/_6$ core
 - Reach convergence of assembly-averaged power
 - > 4×10^8 neutron histories in CE calculation
 - > 1×10^9 neutron histories for 302g calculation
 - Comparison of multigroup (MG) to continuous energy (CE) calculation to assure that effects due to 1D self-shielding in infinite lattice are negligible





Ex.I-4: MET1000 full core



| ENO-VI 302 | g assembly | power map |
|------------|------------|-----------|
|------------|------------|-----------|

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| Code | k _{eff} | | | |
|-------------------------------------|------------------|--|--|--|
| KENO-CE | 1.01652(4) | | | |
| KENO-MG | 1.02175(2) | | | |
| ∆ k _{eff} = 523 pcm | | | | |



Ex.I-4: MET1000 full core

- Step 2: Uncertainty analysis
 - SAMPLER/KENO-VI calculations
 - i. Generate cross section perturbations based on the 302g covariance library
 - ii. Run KENO-VI model using perturbed 302g XS data; sample size 102 (planned: 350)
 - iii. Determine mean values and standard deviations
 - CE TSUNAMI calculations for comparison of at least eigenvalue uncertainties
 - Challenge: Find correct settings (number of latent generations, grid for weighting function)
 - Direct perturbation calculations to confirm settings





Ex.I-4: MET1000 full core



SAMPLER/KENO-VI 302g assembly power map: relative uncertainties due to nuclear data

Eigenvalue of full core

| Code | k _{eff} | Uncertainty |
|-----------------|------------------|-------------|
| CE TSUNAMI | 1.01652(4) | 1.149(1)% |
| KENO-MG | 1.02175(3) | |
| SAMPLER/KENO-MG | 1.02204 | 1.158% |

Axial power distribution of Assembly 6

| Layer | Power | Uncertainty |
|-------|-------|-------------|
| 5 | 0.769 | 1.601% |
| 4 | 1.031 | 1.645% |
| 3 | 1.155 | 1.594% |
| 2 | 1.107 | 1.598% |
| 1 | 0.938 | 1.506% |

This is the first set of results for the fuel assembly power distribution with a limited sample size.
→ Analysis to be completed.



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Next steps

- Completion of full core analyses
- Investigation of validation exercises for the neutronics exercises
- Long term: coupled neutronics/TH calculations



Backup



Ex.I-4: MET1000 full core - SAMPLER relative uncertainties due to nuclear data

(A) Run simulation with same settings, determine average of output:



(B): Normalize power of each sample calculation to mean value, then determine average:



0.6

0.54 0

0.45 0.73

0.60 0

0.54 0

0.6

0.40

18

0.45 0.73

Backup: Ex.I-4: MOX3600 full core

Code

KENO-CE

KENO-MG

 $\Delta k_{eff} = 387 \text{ pcm}$

k_{eff}

1.01131(2)

1.01518(3)

| | | | 0.46 0.49 0 | 0.49 0.46 | | | |
|--------------|---------------|----------------|----------------|----------------|------------------|----------------|------------------|
| | 0 | 0.45 0.54 0.61 | 0.67 0.71 0.7 | 2 0.71 0.67 0 | .61 0.54 0.45 | | |
| | 0.45 0.6 | 1 0.74 0.82 0. | 87 0.90 0.92 0 | 0.92 0.90 0.87 | 7 0.82 0.74 0.6 | 1 0.45 | |
| | 0.54 0.73 0 | .89 0.98 1.02 | 1.04 1.04 | 1.04 1.04 1 | .02 0.98 0.89 0 | .73 0.54 | |
| C | .61 0.81 0.9 | 8 1.08 1.12 | 1.07 1.07 1 | 1.07 1.07 | 1.12 1.08 0.9 | 8 0.81 0.61 | |
| 0.46 0.6 | 6 0.86 1.02 1 | .11 1.11 1.13 | 1.14 1.16 1.1 | 6 1.16 1.14 1 | .13 1.11 1.11 1 | .02 0.86 0.66 | 0.46 |
| 0.48 0.71 0 | .90 1.03 | 1.12 1.17 1. | 20 1.22 1.21 1 | 1.21 1.22 1.20 | 1.17 1.12 | 1.03 0.90 0. | 71 0.48 |
| 48 0.72 0.9 | 1 1.04 1.07 1 | .12 1.18 1.22 | 1.25 1.25 | 1.25 1.25 1 | .22 1.18 1.12 1 | .07 1.04 0.91 | 0.72 0.48 |
| 0.71 0.91 | 1.07 1.1 | 6 1.20 1. | 25 1.27 1.27 1 | 1.27 1.27 1.25 | 1.20 1.10 | 6 1.07 0. | 91 0.71 0.46 |
| 66 0.90 1.04 | 4 1.07 1.17 1 | .24 1.26 1.27 | 1.28 1.29 1.3 | 0 1.29 1.28 1 | .27 1.26 1.24 1 | .17 1.07 1.04 | 0.90 0.66 |
| 0.86 1.03 1 | .07 1.16 1.2 | 3 1.29 1.31 1. | 31 1.31 1 | 1.31 1.31 | 1.31 1.29 1.2 | 3 1.16 1.07 1. | 03 0.86 0.61 |
| 81 1.01 | 1.12 1.20 1 | .26 1.30 1.32 | 1.32 1.32 1.3 | 3 1.32 1.32 1 | .32 1.30 1.26 1 | .20 1.12 | 1.01 0.81 0.54 |
| 0.97 1.11 1 | .11 1.18 | 1.27 1.30 1. | 32 1.33 1.33 1 | 1.33 1.33 1.32 | 2 1.30 1.27 | 1.18 1.11 1. | 11 0.97 0.73 0.4 |
| 89 1.08 1.1 | 1 1.17 1.22 1 | .25 1.28 | 1.32 1.33 | 1.33 1.32 | 1.28 1.25 1 | .22 1.17 1.11 | 1.08 0.89 0.60 |
| 0.98 1.12 1 | .13 1.20 1.2 | 5 1.27 1.29 1. | 31 1.33 1.33 1 | 1.33 1.33 1.31 | 1 1.29 1.27 1.2 | 5 1.20 1.13 1. | 12 0.98 0.73 0.4 |
| 81 1.02 | 1.14 1.21 1 | .25 1.27 1.29 | 1.31 1.32 1.3 | 3 1.32 1.31 1 | .29 1.27 1.25 1 | .21 1.14 | 1.02 0.81 0.54 |
| 0.87 1.04 1 | .07 1.15 1.2 | 1 1.27 1. | 29 1.32 1 | 1.32 1.29 | 1.27 1.2 | 1 1.15 1.07 1. | 04 0.87 0.61 |
| 67 0.90 1.04 | 4 1.07 1.16 1 | .21 1.25 1.27 | 1.28 1.30 1.3 | 2 1.30 1.28 1 | .27 1.25 1.21 1 | .16 1.07 1.04 | 0.90 0.67 |
| 0.71 0.91 | 1.07 1.10 | 6 1.22 1.25 1. | 25 1.26 1.30 1 | 1.30 1.26 1.25 | 5 1.25 1.22 1.10 | 6 1.07 0. | 91 0.71 0.46 |
| 48 0.72 0.9 | 1 1.04 1.07 1 | .14 1.20 1.22 | 1.26 1.2 | 8 1.26 1 | .22 1.20 1.14 1 | .07 1.04 0.91 | 0.72 0.48 |
| 0.48 0.71 0 | .90 1.04 | 1.13 1.17 1. | 17 1.20 1.23 1 | 1.23 1.20 1.17 | 1.17 1.13 | 1.04 0.90 0. | 71 0.48 |
| 0.46 0.6 | 7 0.87 1.02 1 | .12 1.11 1.11 | 1.12 1.15 1.1 | 7 1.15 1.12 1 | .11 1.11 1.12 1 | .02 0.87 0.67 | 0.46 |
| 0 | .61 0.82 0.9 | 8 1.08 1.11 | 1.06 1.07 1 | 1.07 1.06 | 1.11 1.08 0.9 | 8 0.82 0.61 | |
| | 0.54 0.73 0 | 89 0.97 1.01 | 1.03 1.04 | 1.04 1.03 1 | .01 0.97 0.89 0 | 73 0.54 | |
| | 0.45 0.6 | 0 0.73 0.81 0 | 86 0.90 0.91 0 | 0.91 0.90 0.86 | 5 0.81 0.73 0.6 | 0 0.45 | |
| | | 45 0.54 0 61 | 0.66 0.70 0 7 | 2 0.70 0.66 0 | 61 0.54 0.45 | | |
| | | | | | | | |

KENO-VI 302g assembly power map

0.46 0.48 0.48 0.46

3.9% 3.1% 3.1% 3.9 9% 2.8% 2.6% 1.7% 1.2% 1.1% 1.2% 1.7% 2.6% 2.8% 3.9 0.8% 1.0% 1.8% 3.8 2.7% 0.9% 0.6% 0.4% 0.4% 0.4% 0.5% 2.2% 0.7% 0.3% 0.2% 0.2% 0.2% 0.1% 0.1% 0.2% 0.2% 0.2% 0.3% 0.7% 2.29 0.4% 0.2% -0.1% -0.0% -0.1% -0.2% -0.2% -0.1% -0.0% -0.1% 0.2% 0.4% 0.6% 1.4% 3.5 2.4% 0.9% 0.4% 0.3% 0.4% 0.9% 2.4% 0.1% -0.2% -0.3% -0.3% -0.1% -0.1% -0.3% -0.3% -0.2% -0.1% 2.4% 0.6% 0.5% 0.2% 0.0% -0.1% -0.2% -0.3% -0.5% -0.3% 0.3% -0.5% -0.3% -0.2% -0.1% 0.0% 0.2% 0.5% 0.6% 2.4% .4% -0.6% -0.5% -0.5% -0.6% -0.4% 3 3% 0 7% 0 4 0 1% -0 4% -0 3 0 3%-0 4%-0 1 4% 0 7% 3 3 0.9% 0.3% 0.1 % -0.5% -0.6% -0.4% -0.4% -0.4% -0.6% -0.6% -0.6% -0.4% -0.4% -0.4% -0.6% -0.5% -0.1% 0.1% 0.3% 0.9% 1.9% 0.1% 0.0% 0.6%-0.69 -0.8%-0.8%-0.6%-0.1% 0.0% 0.1% 1.9% 2.1% 0.3% -0.0% 0.5% -0.8% -0.8% -0.8% -0.7% -0.6% -0.5% -0.5% -0.5% -0.6% -0.7% -0.8% -0.8% -0.8% -0.5% .1% 0.4% -0.1% -0.3% -0.5% -0.7 0.7% -0.5% -0.5% -0.6% -0.1% -0.1% -0.6% -0.5% -0.5% -0.7% 0 7% -0.5% -0.3% -0.1% 0.4% 3.1 -0.1%-0.4% 1.1% 0.0% -0.4% -0.7% -1.0% -0.9% -0.9% -0.69 -0.4% -0.1% 0.6% -0.9% -0.9% -1.0% -0.7% -0.4% 0.0% 1.1% -0.6% -0.5% -0.6% -0.1% -0.1% -0.6% -0.5% -0.6% -1.0% -1.1% 2.1% 0.1% -0.2 7% -1.0% -0.9% -0.7% -0.7% -0.6% -0.5% -0.6% -0.5% -0.6% -0.7% -0.7% -0.9% -1.0% -0.7 -0.2% 0.1% 2.19 7%-0.7%-0.5%-0.2%-0.0% 1.89 18% -0.0% -0.2% -0.5% -0.7% -0.7% 7% 07 8%-07 7% -0.8% -0.8% -0.8% -0.8% -0.8% -0.8% -0.8% -0.9% -0.8% -0.7% -0.7% -0.4% -0.1% 0.1% 1.2% 3.4% 0.7% 0.2% 0.3% -0.6% -0.8% -1.0% -0.8% -0.8% -0.9% -0.9% -0.8% -0.8% -1.0% -0.8% -0.6% -0.3% 0.2% 0.7% 3.49 .5% 0.6% 0.4% 0.1% -0.2% -0.5% -0.9% -0.7 0.7%-0.8%-0.7 7% -0.9% -0.5% -0.2% 0.1% 0.4% 0.6% 2.5% 2.7% 0.9% 0.4% 0.2 .4% -0.6% -0.6% -0.6% -0.8% -0.8% -0.6% -0.6% -0.6% -0.4% 0.1% -0.3% -0.3% -0.4% -0.6% -0.6% -0.6% -0.4% -0.3% -0.3% 0.1% 0.3% 0.6% 1.6% 3 1 6% 0 6% 0 3% 2.3% 0.8% 0.5% 0.2% -0.0% 0.1% -0.3% -0.3% -0.1% 0.0% 0.2% 0.5% 0.8% 2.3% 2.7% 1.0% 0.6% 0.3% 0.4% 0.3% 0.1% 0.1% 0.3% 0.4% 0.3% 0.6% 1.0% 2.7% 1.7% 1.0% 0.8% 0.7% 0.5% 0.4% 0.4% 0.5% 0.7% 0.8% 1.0% 1.7% 3.9% 3.7% 2.8% 2.4% 1.5% 1.0% 0.9% 1.0% 1.5% 2.4% 2.8% 3.7%

> Relative difference between CE and 302g calculation

3.7% 2.7% 2.7% 3.7%