ARE SCALE LATTICE PHYSICS CODES PERFECT ENOUGH?

Ugur Mertyurek

Matthew A. Jessee

Benjamin R. Betlzer

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

Oak Ridge National Laboratory

Objectives

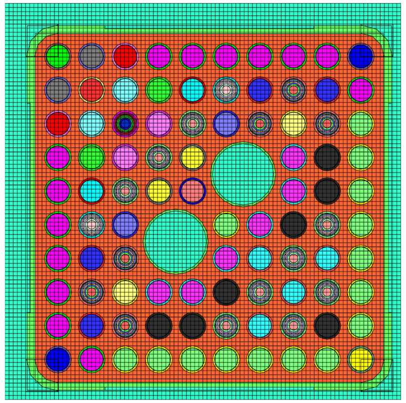
- Complete a comprehensive LWR lattice physics code performance assessment for SCALE 6.2
- Document a set of PWR and BWR benchmarks to be modeled with both TRITON/NEWT and Polaris, as well as continuous-energy TRITON/(CE) KENO for reference solutions

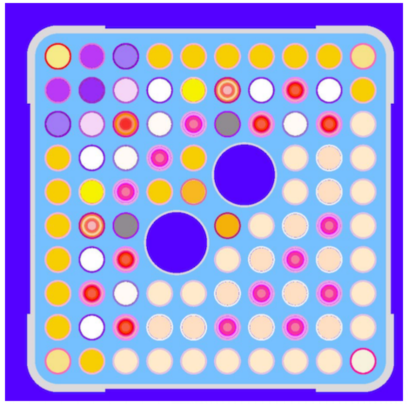
- LWR assemblies beginning of life (BOL) baseline
- Control elements
- Mixed oxide (MOX) fuel
- Reactivity worth of depleted fuel
- Depletion calculations
- Boron injection
- Enrichment
- Fuel temperature

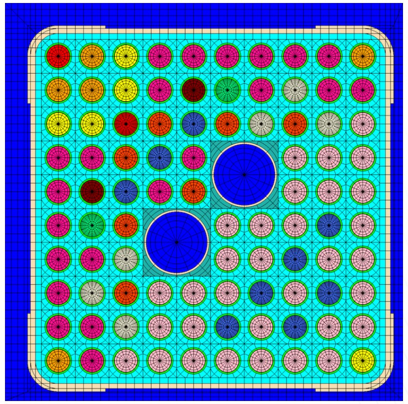
- Burnable poison (BP) loading
- BP spatial variations
- PARCS quantities of interest (QOI) parameters
- Fuel reflector models
- International numerical benchmarks
- BWR vanished zone patterns
- RCA measurement comparisons

SCALE Lattice Physics Capabilities

- NEWT Sequence
  - CENTRM (2D MoC) based cross section processing with user specified Dancoff factors
  - Slice balance transport method
  - Generalized geometry
- MG Keno Sequence
  - CENTRM (2D MoC) based cross section processing with user specified Dancoff factors
  - Monte Carlo transport method
  - Generalized geometry
- CE Keno Sequence
  - Continuous Energy cross section processing
  - Monte Carlo transport method
  - Generalized geometry
- Polaris Sequence
  - ESSM (Embedded Self Shielding) based cross section process
  - MoC transport method
  - Flexible geometry with LWR applications in mind







OAK RIDGE National Laboratory

SCALE Lattice Physics V&V Strategy

Assess accuracy of CE KENO calculations

- Compare k-eff for Evaluated Criticality Safety Benchmark Experiments (ICSBEP) and the International Reactor Physics Experiments (IRPhE)
- Compare predicted isotopic distributions of depleted fuel with RCA measurements

↓

Asses accuracy of TRITON and Polaris calculations

- Compare k-eff and pin powers with reference CE KENO values for a set of numerical benchmarks covering common lattice types for a wide range of state points
- Model international benchmarks and compare k-eff and isotopic distributions.
- Compare predicted isotopic distributions of depleted fuel with RCA measurements

SCALE Lattice Physics V&V Strategy

- CE KENO Validation (Criticals)
- NEWT, Polaris Numerical Validation (14 Test Suites)
- RCA Measurements (UOX, MOX)

Geometry

BWR
- 8×8 General Electric (GE)
  - Two small water rods (GE5)
- 9×9 GE
  - Two water rods (GE11)
  - Large water rod
  - Off-centered water box (Atrium9)
- 10×10
  - Two water rods (GE12, GE14, GNF1)
  - Off-centered water box (Atrium10)
  - Water diamond and wings (SVEA96-optima)

PWR
- 14×14 Westinghouse (WE) (small guide tubes)
- 15×15 WE
- 16×16 Combustion Engineering (CE) (large GT)
- 17×17
  - Standard WE
  - Optimized Fuel Assembly (OFA) WE
- 18×18 WE

Burnable Poisons

- **Gadolinia (Gd_2O_3):**
  - 0 wt % to 10 wt % natural gadolinia
  - 4 and 12 rod patterns
- **Wet Annular Burnable Absorber (WABA):**
  - 14.0 wt % B_4C content in an Al_2O_3-B_4C mixture
- **Burnable Poison Rod Assembly (BPRA):**
  - 1 g/cm3, 2 g/cm3 and 4 g/cm3 B_4C densities
  - 4, 12, and 24 rod patterns
- **Borosilicate Glass (PYREX):**
  - 12.5 wt % B_2O_3 content
  - 4, 12, and 24 rod patterns
- **Integral Fuel Absorber (IFBA):**
  - 1.5 and 4 mg ^{10}B/inch boron loadings with 3.1 wt % ^{235}U
  - 80, 104, and 120 rod patterns with 3.1 wt % ^{235}U enrichment

Control Rod/Control Blade Types:

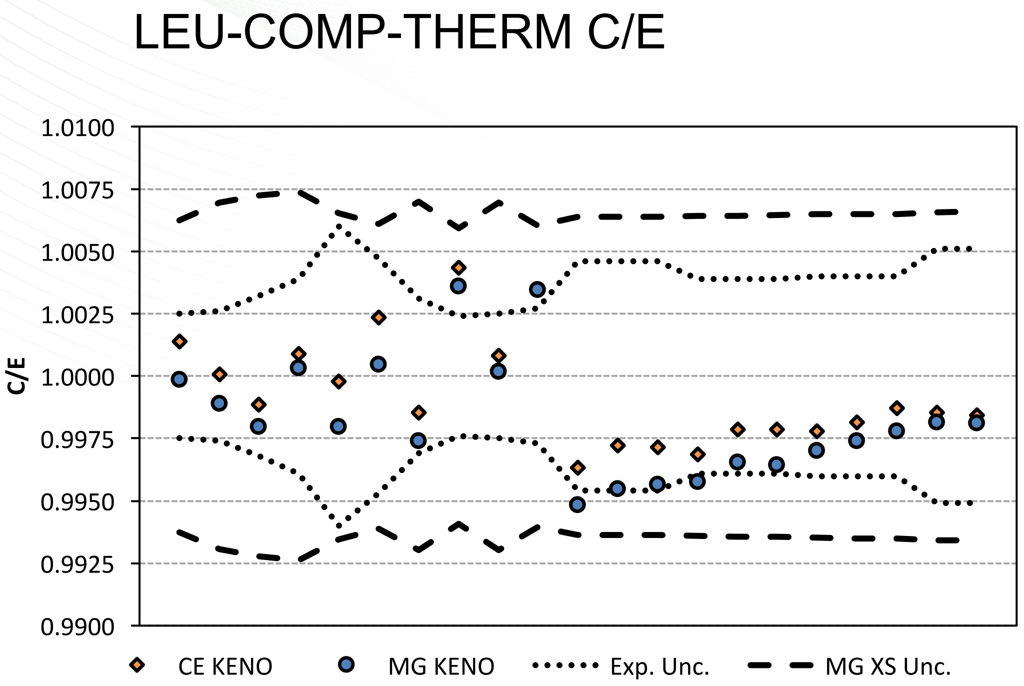
PWR
- Ag-In-Cd (AIC),
- B_4C, and
- Inconel absorber.

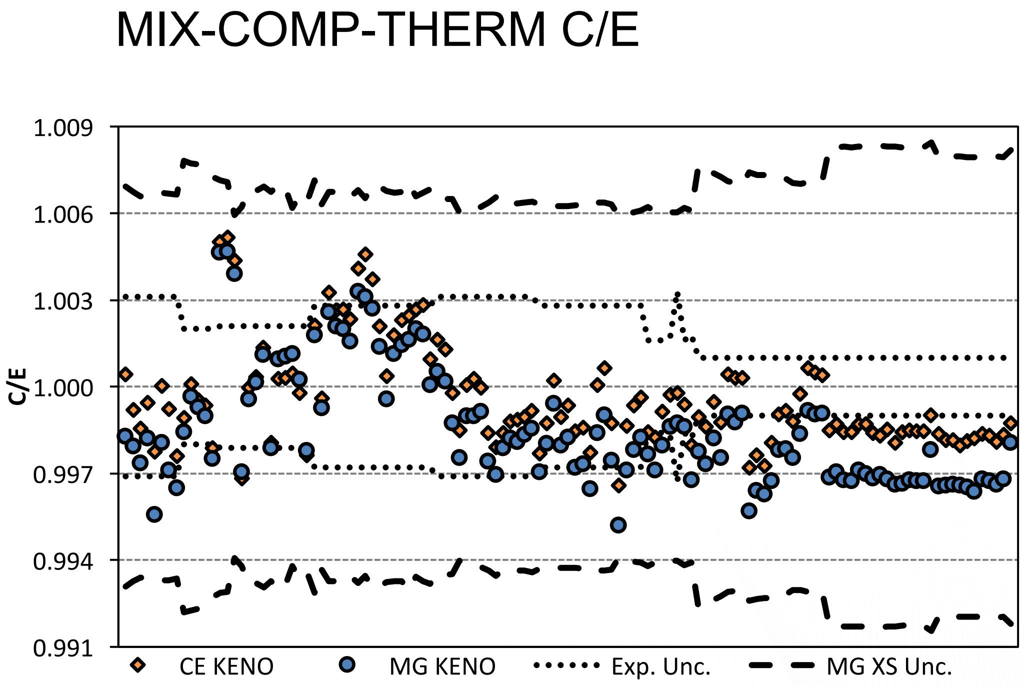
BWR:
- Standard OEM (B_4C),
- Marathon, and
- Standard OEM (hafnium).

Terminology

- Bias: Systematic difference between two sets of data.
- Trend: A pattern of gradual change in difference between two sets of data.
- Acceptance Accuracy: Minimum acceptable accuracy in the test results before further methodology and modeling improvements are considered necessary (e.g., 400 pcm k_{inf}, 1.5% RMS)
- Target Accuracy: Intended long-term accuracy in the test results; test results that do not satisfy this accuracy will be considered for future methodology improvements (e.g., 200 pcm k_{inf}, 1/0.5% RMS)
- Significant: Differences that are greater than or equal to the target accuracy

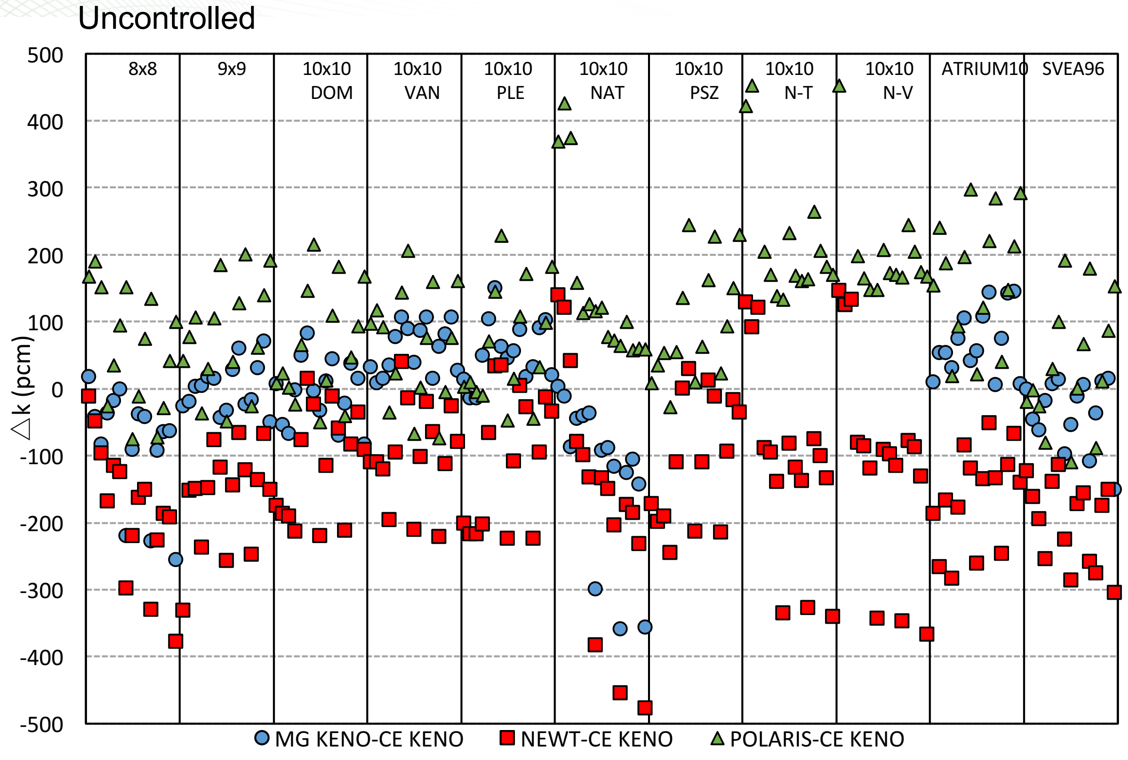
CE KENO CRITICALITY BENCHMARK ASSESSMENT



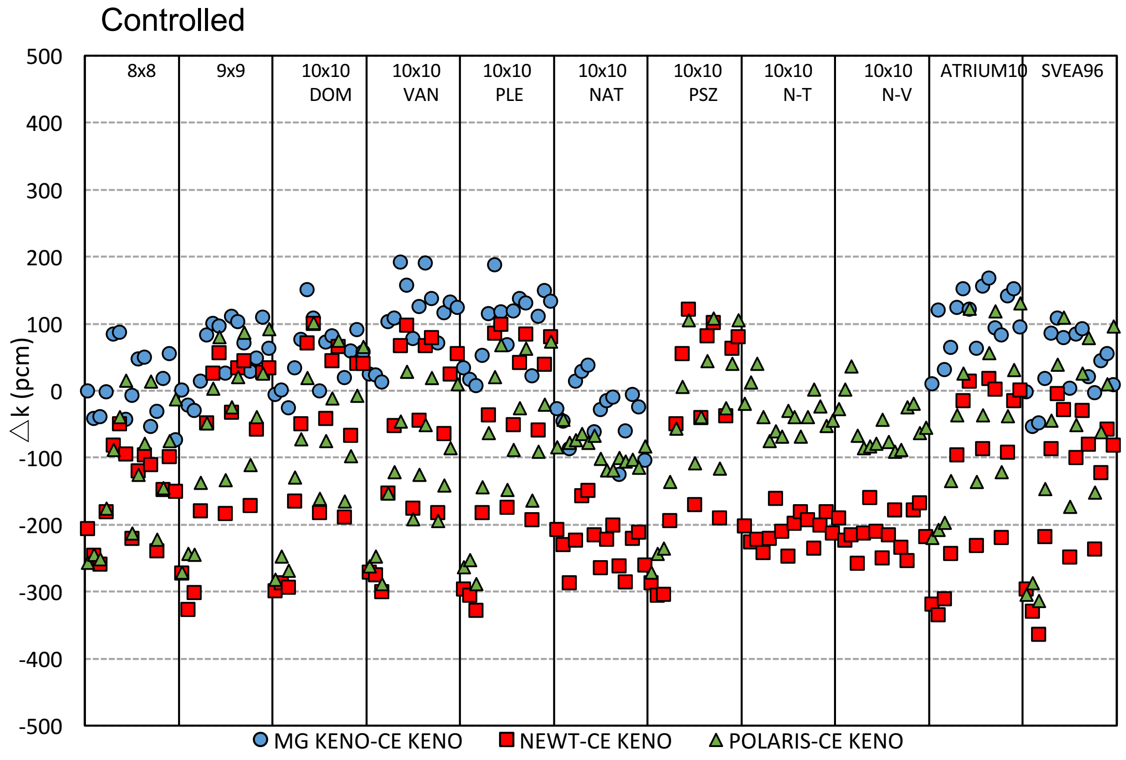


- ✓ A set of critical experiments applicable to LWRs, flux spectra, and fuel materials are used to validate 3D CE KENO for LWR fuel.
- ✓ The k_{eff} biases from these experiments provide a basis for the accuracy of the CE KENO results
- ✓ A detailed explanation of uncertainties and discussion on individual experimental sets can be found in a recent paper by Marshall et al., "Validation of SCALE 6.2 Criticality Calculations Using KENO V.a and KENO-VI," *ICNC 2015*, Charlotte, North Carolina, 13–17 Sep (2015).

Trends in Lattice Geometry (BWR)

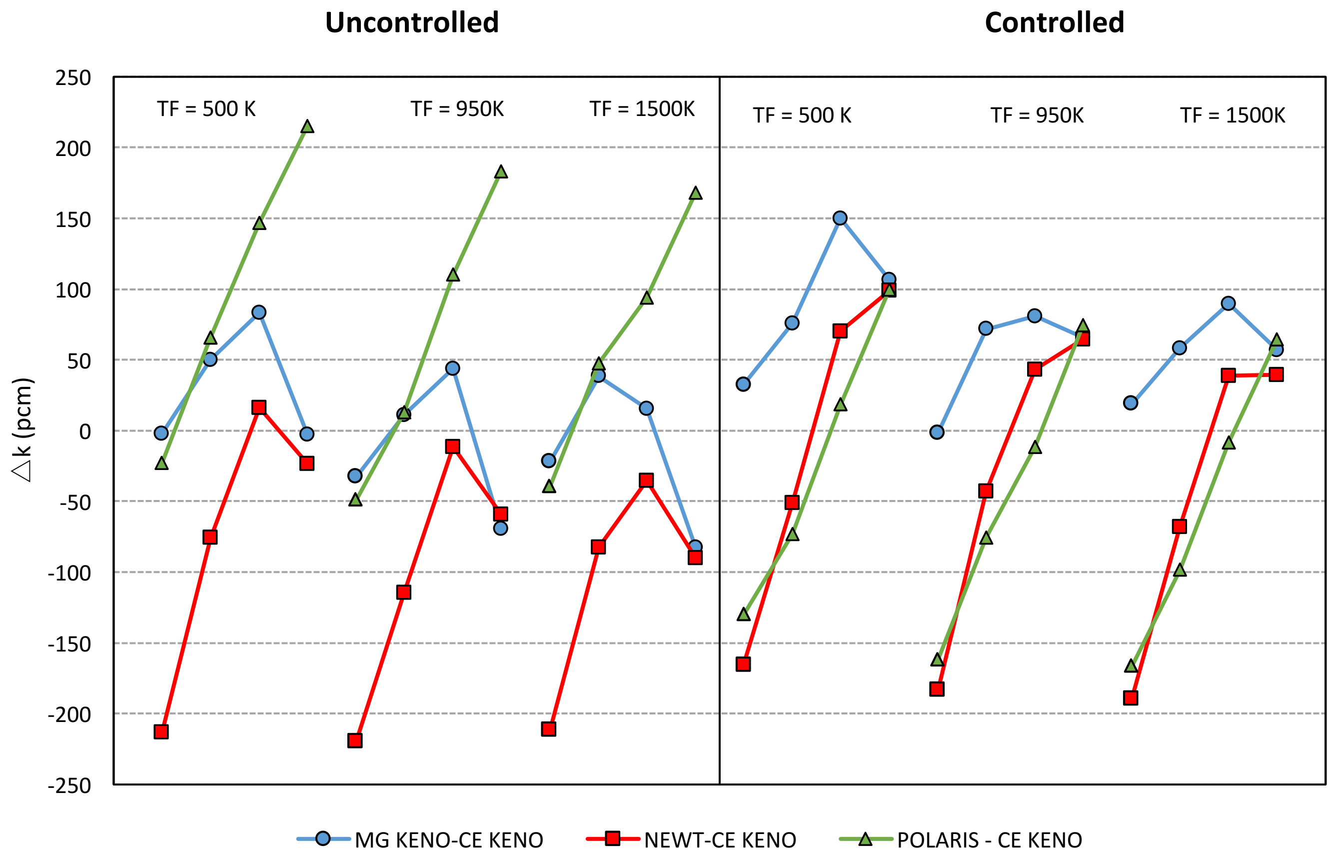


- ✓ NEWT differences are generally lower than the MG KENO differences
- ✓ NEWT results can be improved further by increasing quadrature set (not practical in the current implementation)



- ✓ The largest differences are observed for natural enrichment zones
- ✓ No significant bias for rodded configurations except Polaris
  - ✓ Polaris uncontrolled: △k average +150 pcm
  - ✓ Polaris controlled: △k average -100 pcm

Trends in Void Fraction and Fuel Temperature (GE14)



- ✓ Consistent void trends in Polaris and NEWT results (0% through 70% void fraction)
- ✓ No significant trend with increasing fuel temperature
- ✓ Control blades introduce bias for Polaris
  - ✓ Polaris: Controlled △k – Uncontrolled △k ~ -200 pcm
  - ✓ NEWT: Controlled △k – Uncontrolled △k ~ 40 pcm
- ✓ NEWT 90% void case show more bias than other void fractions for controlled cases

Uncontrolled Pin Powers (GE14 BWR)

NEWT 0% Void (RMS=0.40%, MAX=0.98%)

0.95%	0.83%	0.55%	0.36%	0.47%	0.20%	0.55%	0.32%	0.65%	0.98%
0.83%	0.16%	-0.30%	0.03%	-0.18%	-0.12%	-0.47%	-0.04%	-0.36%	0.30%
0.55%	-0.30%	-0.20%	-0.85%	-0.16%	-0.41%	-0.10%	-0.74%	-0.11%	-0.05%
0.36%	0.03%	-0.85%	-0.02%	-0.22%	N/A	N/A	-0.07%	-0.39%	0.07%
0.47%	-0.18%	-0.16%	-0.22%	0.61%	N/A	N/A	-0.16%	-0.27%	0.01%
0.20%	-0.12%	-0.41%	N/A	N/A	0.43%	-0.08%	-0.51%	-0.13%	0.02%
0.55%	-0.47%	-0.10%	N/A	N/A	-0.08%	-0.31%	-0.14%	-0.53%	-0.04%
0.32%	-0.04%	-0.74%	-0.07%	-0.16%	-0.51%	-0.14%	-0.62%	-0.07%	0.07%
0.65%	-0.36%	-0.11%	-0.39%	-0.27%	-0.13%	-0.53%	-0.07%	-0.17%	0.33%
0.98%	0.30%	-0.05%	0.07%	0.01%	0.02%	-0.04%	0.07%	0.33%	0.62%

NEWT 90% Void (RMS=0.54%, MAX=1.15%)

1.09%	1.15%	0.95%	0.36%	0.56%	-0.13%	0.32%	0.37%	0.95%	0.71%
1.15%	0.82%	0.34%	0.37%	-0.06%	-0.09%	-0.01%	0.10%	0.79%	0.96%
0.95%	0.34%	-0.07%	-0.14%	0.05%	-0.47%	-0.06%	-0.29%	0.07%	0.25%
0.36%	0.37%	-0.14%	-0.20%	-1.10%	N/A	N/A	-0.62%	-0.28%	-0.22%
0.56%	-0.06%	0.05%	-1.10%	-0.50%	N/A	N/A	-1.04%	-0.07%	-0.64%
-0.13%	-0.09%	-0.47%	N/A	N/A	-1.01%	-0.63%	-0.68%	-0.15%	-0.50%
0.32%	-0.01%	-0.06%	N/A	N/A	-0.63%	-0.73%	-0.25%	-0.35%	-0.35%
0.37%	0.10%	-0.29%	-0.62%	-1.04%	-0.68%	-0.25%	-0.40%	-0.10%	-0.25%
0.95%	0.79%	0.07%	-0.28%	-0.07%	-0.15%	-0.35%	-0.10%	0.22%	0.42%
0.71%	0.96%	0.25%	-0.22%	-0.64%	-0.50%	-0.35%	-0.25%	0.42%	0.36%

2.0% 1.8% 1.6% 1.4% 1.2% 1.0% 0.8% 0.6% 0.4% 0.2% 0.0% -0.2% -0.4% -0.6% -0.8% -1.0% -1.2% -1.4% -1.6% -1.8% -2.0%

Polaris 0% Void (RMS=0.32%, MAX=1.07%)

1.07%	0.71%	0.14%	-0.25%	-0.31%	-0.48%	-0.15%	-0.10%	0.36%	1.00%
0.71%	0.39%	-0.01%	0.13%	0.00%	-0.11%	-0.29%	-0.02%	-0.06%	0.11%
0.14%	-0.01%	-0.12%	-0.38%	-0.16%	-0.21%	-0.11%	-0.49%	-0.07%	-0.15%
-0.25%	0.13%	-0.38%	0.01%	0.03%	N/A	N/A	0.10%	-0.12%	-0.10%
-0.31%	0.00%	-0.16%	0.03%	0.70%	N/A	N/A	0.04%	-0.08%	-0.16%
-0.48%	-0.11%	-0.21%	N/A	N/A	0.70%	0.11%	-0.27%	-0.11%	-0.12%
-0.14%	-0.29%	-0.11%	N/A	N/A	0.11%	0.10%	-0.10%	-0.21%	-0.19%
-0.10%	-0.02%	-0.49%	0.10%	0.04%	-0.27%	-0.10%	-0.24%	-0.05%	0.01%
0.36%	-0.06%	-0.06%	-0.11%	-0.08%	-0.11%	-0.21%	-0.05%	0.24%	0.32%
1.00%	0.11%	-0.14%	-0.10%	-0.16%	-0.12%	-0.19%	0.01%	0.32%	0.77%

Polaris 90% Void (RMS=0.19%, MAX=0.57%)

0.57%	0.42%	0.12%	-0.05%	-0.09%	-0.26%	-0.29%	0.06%	0.24%	0.37%
0.42%	0.35%	0.22%	0.13%	0.03%	-0.18%	-0.07%	-0.15%	0.41%	0.37%
0.12%	0.22%	-0.21%	0.16%	-0.08%	0.05%	-0.14%	-0.04%	-0.09%	0.11%
-0.05%	0.13%	0.16%	-0.22%	-0.02%	N/A	N/A	-0.13%	0.02%	-0.01%
-0.09%	0.03%	-0.09%	-0.02%	0.12%	N/A	N/A	-0.17%	-0.04%	-0.07%
-0.26%	-0.18%	0.05%	N/A	N/A	-0.09%	-0.08%	-0.16%	-0.23%	-0.04%
-0.29%	-0.07%	-0.14%	N/A	N/A	-0.08%	-0.09%	-0.25%	-0.08%	-0.13%
0.06%	-0.15%	-0.04%	-0.14%	-0.17%	-0.16%	-0.25%	-0.14%	-0.22%	-0.08%
0.23%	0.40%	-0.10%	0.02%	-0.04%	-0.23%	-0.08%	-0.22%	0.06%	0.17%
0.37%	0.36%	0.10%	-0.02%	-0.07%	-0.04%	-0.13%	-0.08%	0.17%	0.32%

- ✓ The largest differences are observed at wide-wide gap and around water rods (NEWT only)
- ✓ Polaris pin power results show better agreement with increasing void

Controlled Pin Powers (GE14 BWR)

NEWT 40% Void (RMS=0.37%, MAX=0.90%)

0.84%	0.90%	0.64%	0.51%	0.45%	0.30%	0.37%	0.21%	0.87%	0.78%
0.90%	0.30%	-0.05%	-0.02%	-0.31%	-0.08%	-0.23%	-0.02%	0.01%	0.35%
0.64%	-0.05%	-0.13%	-0.49%	-0.14%	-0.40%	-0.08%	-0.59%	-0.12%	0.06%
0.51%	-0.02%	-0.49%	-0.13%	-0.35%	N/A	N/A	-0.19%	-0.43%	0.08%
0.45%	-0.31%	-0.14%	-0.35%	0.04%	N/A	N/A	-0.37%	-0.22%	-0.12%
0.30%	-0.08%	-0.40%	N/A	N/A	-0.01%	-0.03%	-0.36%	-0.14%	-0.19%
0.37%	-0.23%	-0.08%	N/A	N/A	-0.03%	-0.44%	-0.20%	-0.43%	-0.23%
0.21%	-0.02%	-0.59%	-0.19%	-0.37%	-0.36%	-0.20%	-0.60%	-0.05%	0.03%
0.87%	0.01%	-0.12%	-0.43%	-0.22%	-0.14%	-0.43%	-0.05%	-0.26%	0.19%
0.78%	0.35%	0.06%	0.08%	-0.12%	-0.19%	-0.23%	0.03%	0.19%	0.52%

NEWT 40% Void Controlled (RMS=0.37%, MAX=0.99%)

-0.08%	-0.22%	-0.42%	-0.40%	-0.24%	-0.36%	-0.14%	-0.18%	0.73%	0.76%
-0.22%	-0.35%	-0.35%	-0.15%	-0.41%	-0.11%	-0.41%	-0.04%	0.05%	0.59%
-0.42%	-0.35%	-0.26%	-0.46%	-0.08%	-0.27%	-0.03%	-0.24%	0.02%	0.66%
-0.40%	-0.15%	-0.46%	-0.24%	-0.25%	N/A	N/A	-0.10%	-0.16%	0.33%
-0.24%	-0.41%	-0.08%	-0.25%	-0.07%	N/A	N/A	-0.13%	0.11%	0.50%
-0.36%	-0.11%	-0.27%	N/A	N/A	0.50%	0.00%	-0.19%	0.06%	-0.01%
-0.14%	-0.41%	-0.03%	N/A	N/A	0.00%	-0.51%	-0.09%	-0.31%	0.44%
-0.18%	-0.04%	-0.24%	-0.10%	-0.13%	-0.19%	-0.09%	-0.27%	-0.01%	0.62%
0.73%	0.05%	0.02%	-0.16%	0.11%	0.06%	-0.31%	-0.01%	0.16%	0.99%
0.76%	0.59%	0.66%	0.33%	0.50%	-0.01%	0.44%	0.62%	0.99%	0.90%

2.0% 1.8% 1.6% 1.4% 1.2% 1.0% 0.8% 0.6% 0.4% 0.2% 0.0% -0.2% -0.4% -0.6% -0.8% -1.0% -1.2% -1.4% -1.6% -1.8% -2.0%

Polaris 40% Void (RMS=0.26 %, MAX=0.84%)

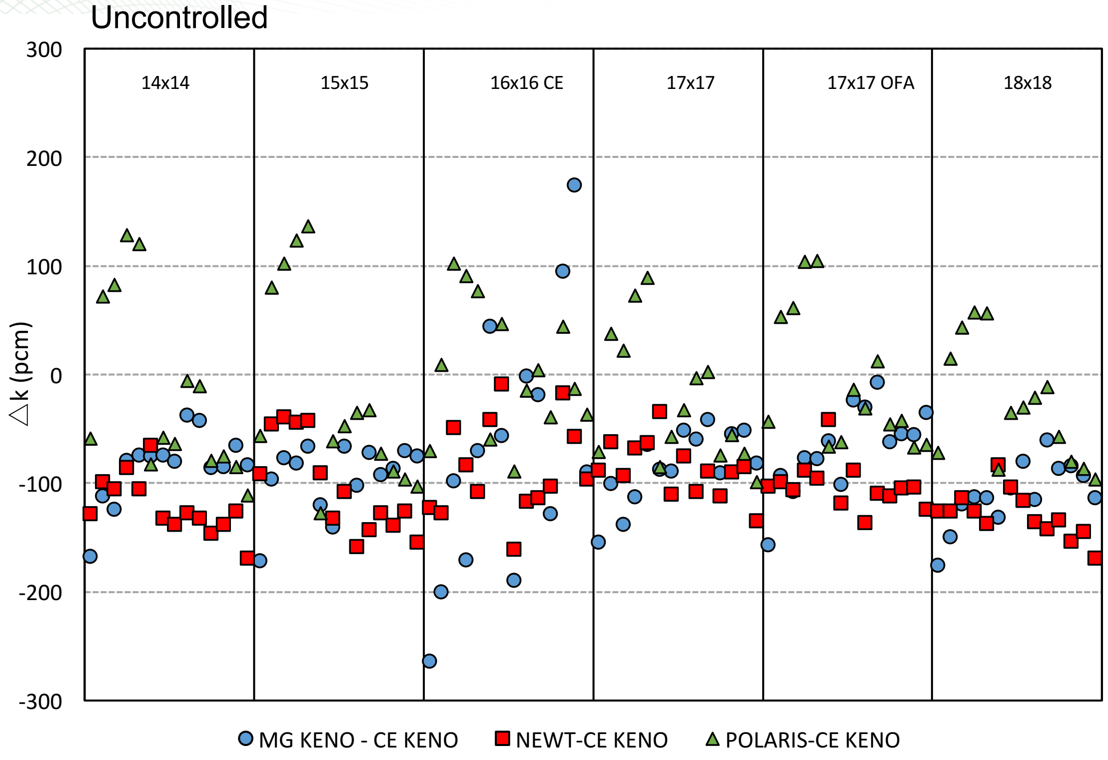
0.84%	0.67%	0.11%	-0.10%	-0.36%	-0.31%	-0.32%	-0.19%	0.51%	0.75%
0.67%	0.45%	0.18%	0.00%	-0.16%	-0.08%	-0.08%	-0.03%	0.23%	0.14%
0.11%	0.18%	-0.07%	-0.09%	-0.17%	-0.14%	-0.10%	-0.32%	-0.09%	-0.02%
-0.10%	0.00%	-0.09%	-0.10%	0.05%	N/A	N/A	0.00%	-0.17%	-0.01%
-0.36%	-0.16%	-0.16%	0.05%	0.17%	N/A	N/A	-0.09%	-0.10%	-0.18%
-0.30%	-0.08%	-0.14%	N/A	N/A	0.32%	0.19%	-0.08%	-0.13%	-0.22%
-0.32%	-0.08%	-0.10%	N/A	N/A	0.19%	0.04%	-0.16%	-0.13%	-0.31%
-0.18%	-0.03%	-0.31%	0.00%	-0.09%	-0.08%	-0.16%	-0.23%	-0.03%	0.05%
0.52%	0.24%	-0.09%	-0.17%	-0.10%	-0.13%	-0.13%	-0.03%	0.07%	0.18%
0.76%	0.15%	-0.02%	-0.01%	-0.18%	-0.22%	-0.31%	0.05%	0.18%	0.66%

Polaris 40% Void Controlled (RMS=0.43%, MAX=1.71%)

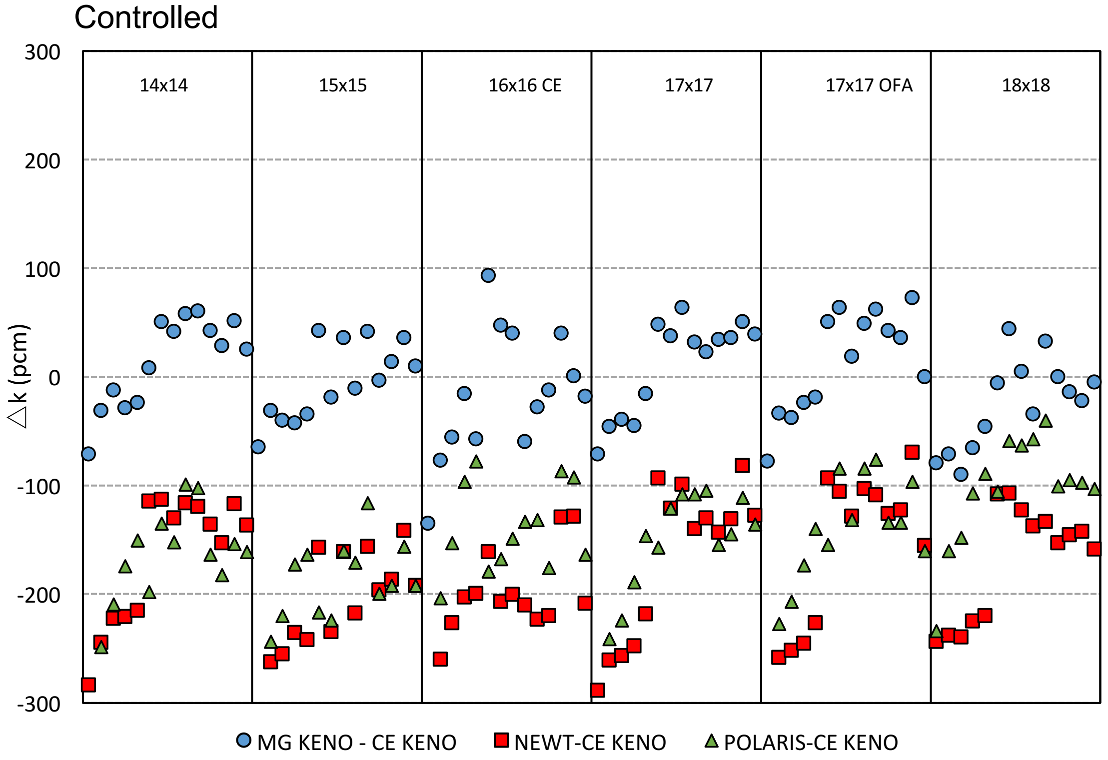
0.29%	0.33%	0.45%	0.26%	0.15%	0.01%	-0.17%	-0.67%	-1.71%	-1.30%
0.33%	0.38%	0.22%	0.12%	0.19%	0.14%	0.07%	0.05%	-0.70%	-0.87%
0.45%	0.22%	0.27%	0.21%	0.19%	0.24%	0.15%	0.00%	0.04%	-0.74%
0.26%	0.12%	0.21%	0.29%	0.16%	N/A	N/A	0.15%	0.17%	-0.13%
0.15%	0.19%	0.19%	0.16%	0.44%	N/A	N/A	0.23%	0.12%	-0.13%
0.01%	0.14%	0.24%	N/A	N/A	-0.29%	0.22%	0.21%	0.11%	0.43%
-0.17%	0.07%	0.15%	N/A	N/A	0.22%	0.32%	0.25%	0.27%	0.14%
-0.67%	0.05%	0.00%	0.15%	0.23%	0.21%	0.25%	0.13%	0.20%	-0.02%
-1.71%	-0.70%	0.04%	0.17%	0.12%	0.11%	0.27%	0.20%	0.09%	-0.08%
-1.30%	-0.87%	-0.74%	-0.13%	-0.13%	0.43%	0.14%	-0.02%	-0.08%	0.10%

✓ The largest differences shift to narrow-narrow gap and around blade tips

Trends in Lattice Geometry (PWR)



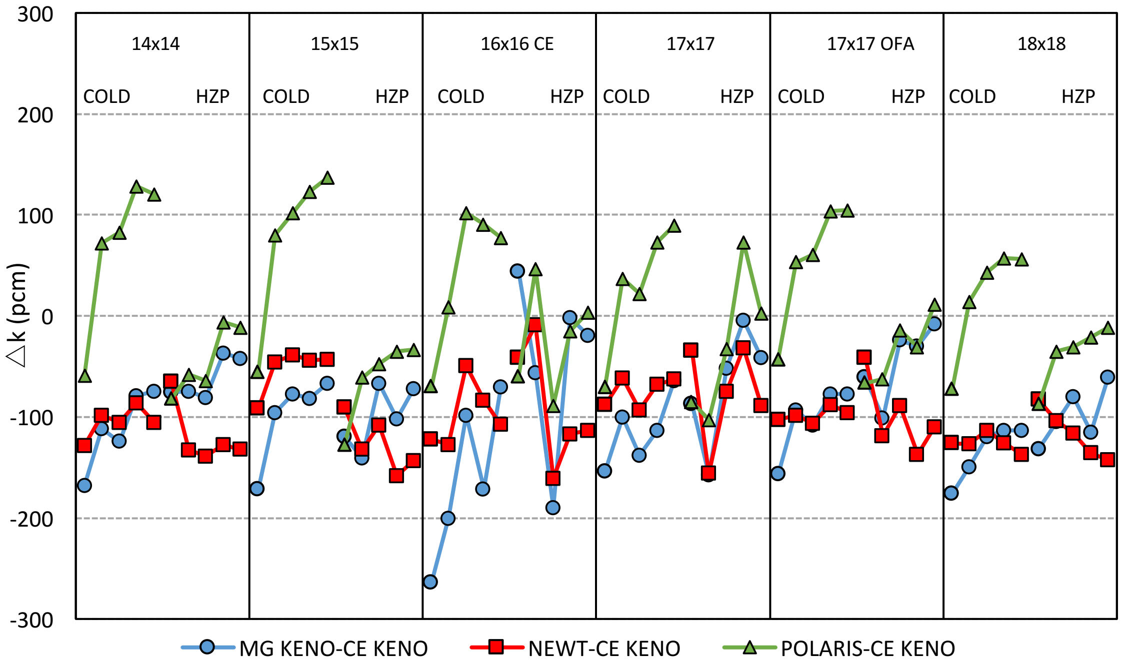
- ✓ NEWT and MG KENO results are consistent
- ✓ There are outliers in MG KENO results for 16x16 CE geometry



- ✓ NEWT and Polaris results are consistent for controlled cases (except 18x18 geometry)
- ✓ There is a bias between MG KENO and NEWT/Polaris results
  - ✓ Average △k(MG KENO) = 0 pcm Average △k(NEWT/Polaris) =-200 pcm

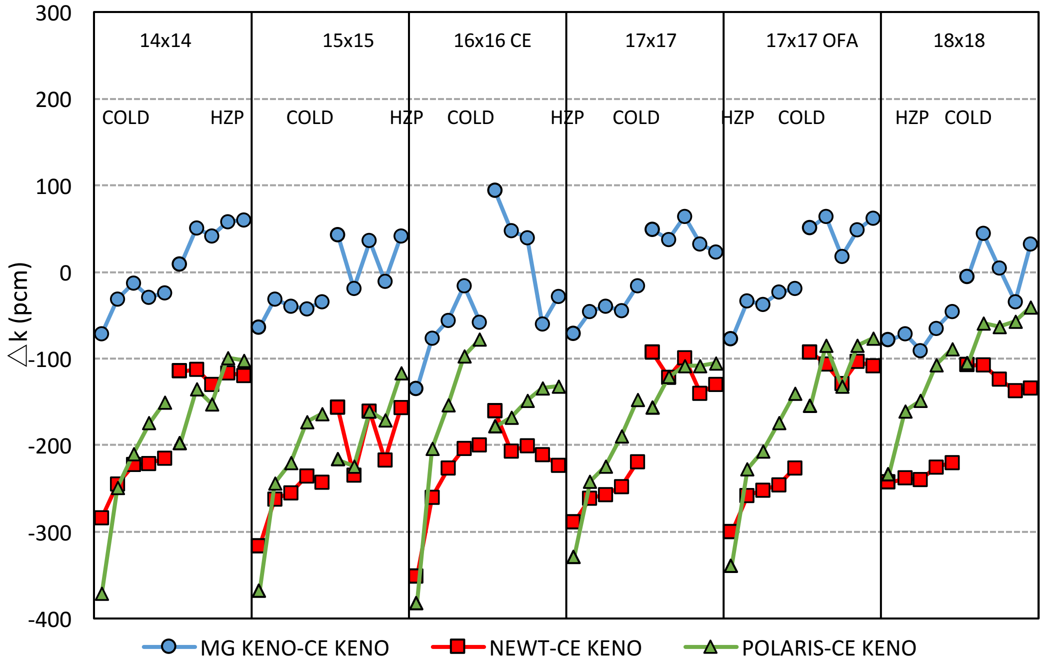
Trend in Boron Concentration (17x17 PWR)

Uncontrolled



- ✓ Similar Polaris boron trend and bias are observed across different geometries
- ✓ Boron trend and bias in Polaris results are significant for cold cases

Controlled



- ✓ Boron bias in Polaris results disappears for controlled cases
- ✓ MG-KENO demonstrates a small bias in the opposite direction
  - ✓ Controlled △k – Uncontrolled △k ~ 100 pcm

Case	Boron (ppm)
1	0
2	1000
3	1300
4	2000
5	2500

OAK RIDGE National Laboratory

Uncontrolled and Controlled Pin Powers (17x17 PWR)

NEWT (RMS= 0.10%, MAX=0.23%)

N/A								
0.08%	-0.07%							
0.09%	-0.05%	-0.13%						
N/A	-0.06%	0.01%	N/A					
-0.01%	0.04%	0.00%	0.05%	0.19%				
0.17%	-0.09%	-0.04%	0.09%	0.13%	N/A			
N/A	0.16%	0.23%	N/A	0.10%	0.12%	0.01%		
-0.01%	-0.07%	0.00%	0.06%	0.06%	0.03%	-0.06%	-0.16%	
-0.07%	-0.10%	-0.03%	-0.10%	-0.04%	-0.12%	-0.13%	-0.13%	-0.20%

Polaris (RMS= 0.07%, MAX=0.19%)

N/A								
0.07%	-0.09%							
0.08%	-0.07%	-0.16%						
N/A	-0.07%	-0.02%	N/A					
-0.04%	0.01%	-0.04%	0.01%	0.11%				
0.16%	-0.11%	-0.06%	0.07%	0.04%	N/A			
N/A	0.13%	0.19%	N/A	0.03%	0.07%	0.03%		
-0.01%	-0.08%	0.00%	0.04%	0.05%	0.07%	0.00%	-0.11%	
0.00%	-0.05%	0.02%	-0.03%	0.00%	-0.05%	-0.05%	-0.06%	-0.11%

2.0%
1.6%
1.2%
0.8%
0.4%
0.0%
-0.4%
-0.8%
-1.2%
-1.6%
-2.0%

NEWT [Controlled] (RMS=0.22%, MAX=0.54%)

N/A								
0.13%	-0.07%							
-0.14%	-0.03%	0.06%						
N/A	-0.10%	-0.27%	N/A					
-0.46%	-0.08%	-0.15%	-0.26%	-0.09%				
-0.05%	-0.16%	-0.12%	-0.36%	-0.10%	N/A			
N/A	-0.21%	-0.28%	N/A	-0.18%	-0.03%	0.20%		
0.00%	-0.11%	-0.02%	-0.06%	0.23%	0.38%	0.29%	0.45%	
0.07%	0.09%	0.12%	0.07%	0.01%	0.35%	0.27%	0.38%	0.54%

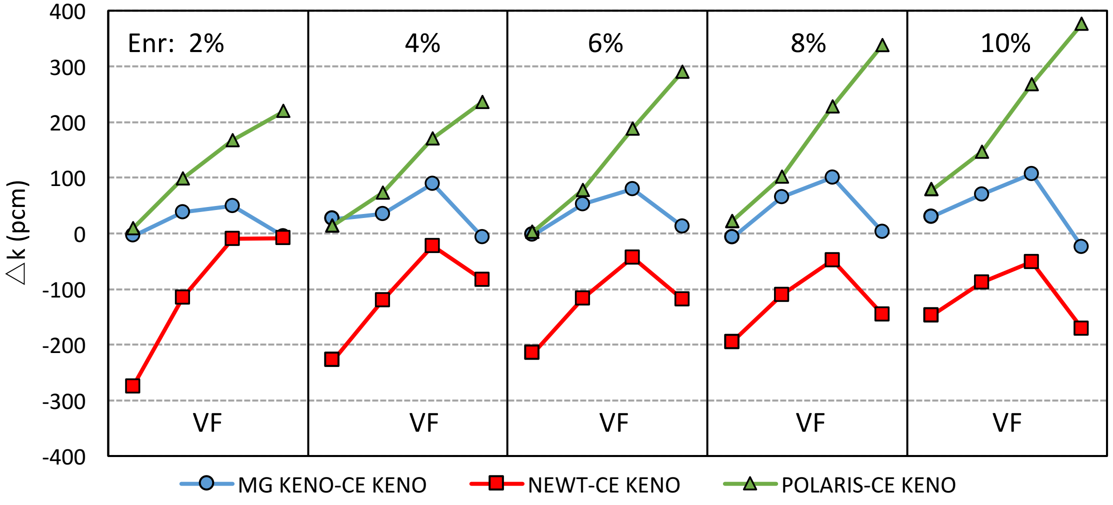
Polaris [Controlled] (RMS=0.11%, MAX=0.27%)

N/A								
-0.03%	-0.07%							
-0.03%	0.08%	0.26%						
N/A	0.08%	-0.01%	N/A					
-0.27%	0.11%	0.10%	0.00%	0.20%				
0.08%	0.01%	0.04%	-0.20%	0.08%	N/A			
N/A	-0.10%	-0.19%	N/A	-0.11%	-0.07%	-0.02%		
0.20%	-0.03%	0.02%	-0.10%	0.16%	0.19%	0.06%	0.01%	
0.00%	0.05%	0.01%	-0.10%	-0.14%	0.03%	-0.07%	-0.07%	0.06%

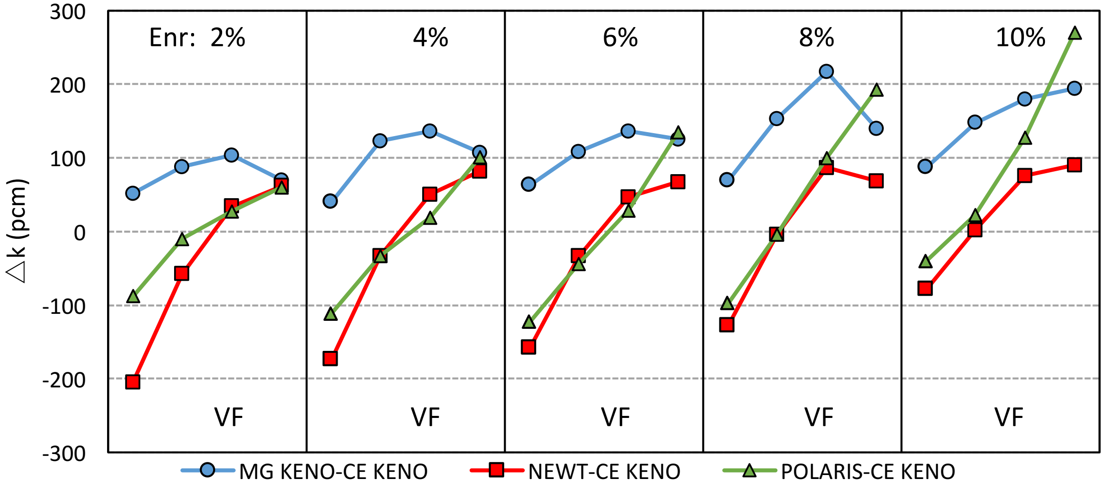
- ✓ Large differences are observed around guide tubes for both geometries
- ✓ Polaris and NEWT demonstrate good agreement

Trends in Enrichment

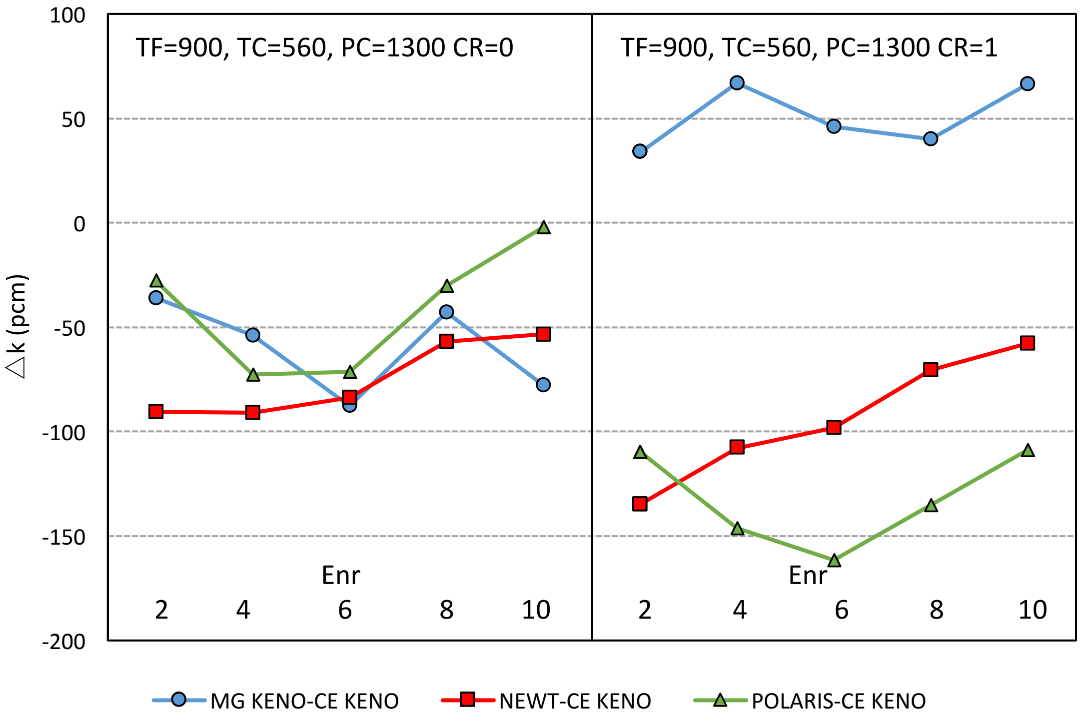
10x10 BWR Uncontrolled



10x10 BWR Controlled

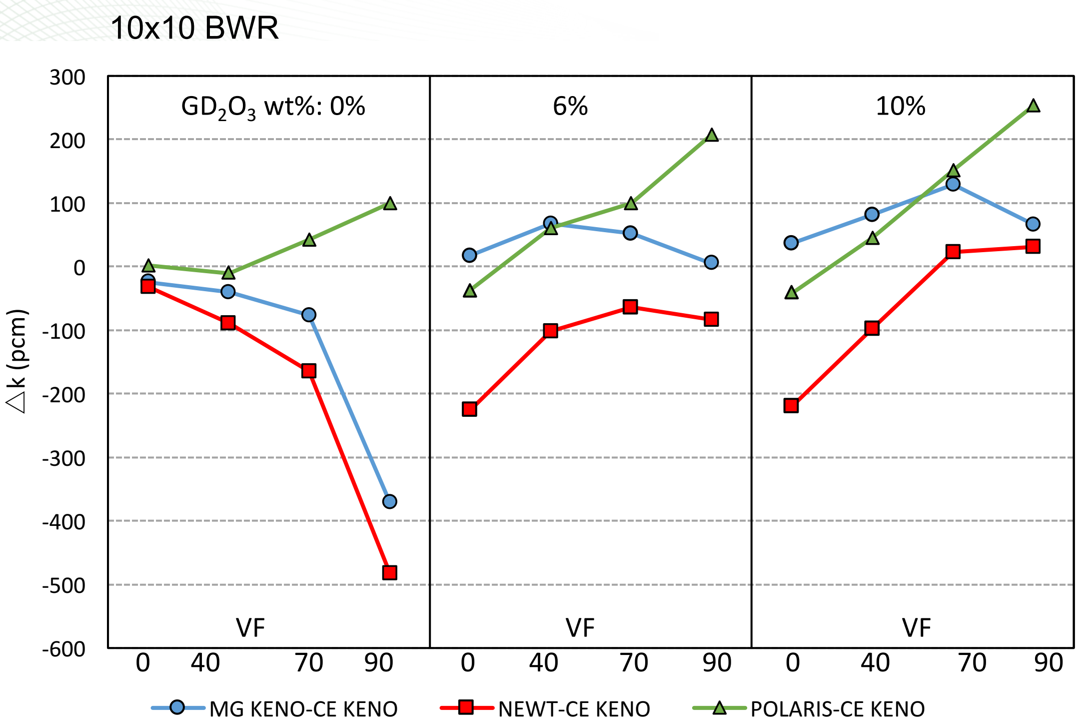


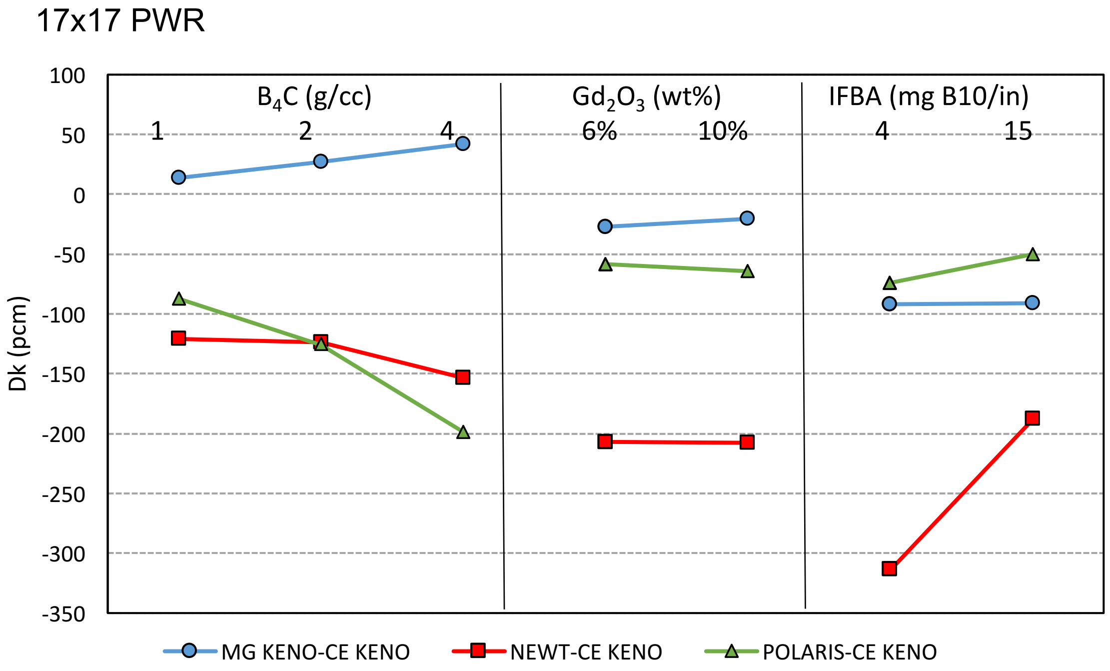
17x17 PWR Uncontrolled Controlled



- ✓ No significant trends in enrichment for all codes (beyond currently allowed enrichments, Polaris exhibits a trend)
- ✓ Consistent control element bias
- ✓ Consistent void fraction trend

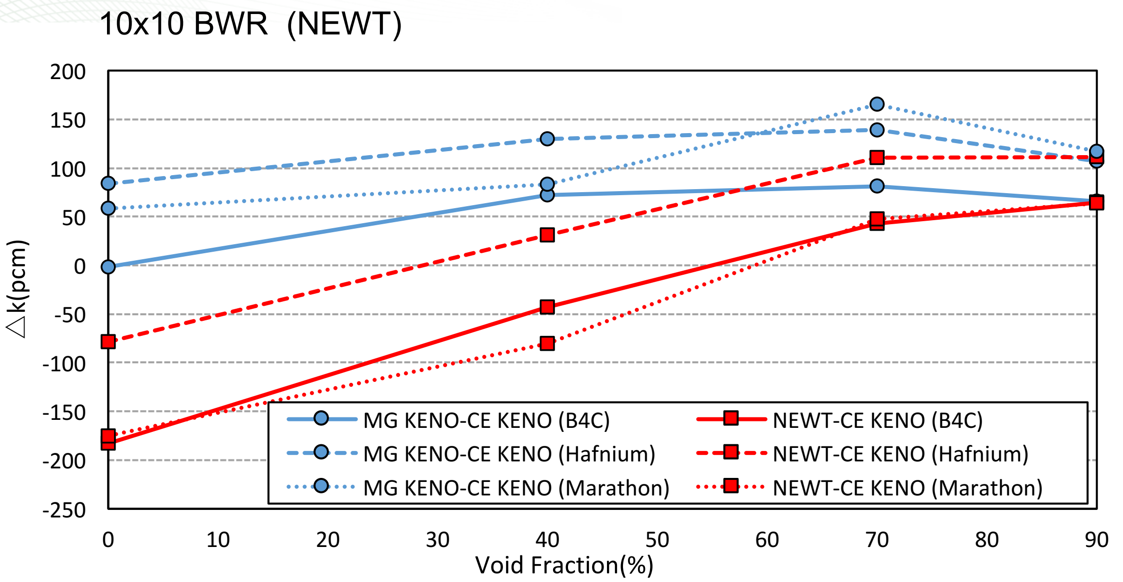
Trends in BP Loading

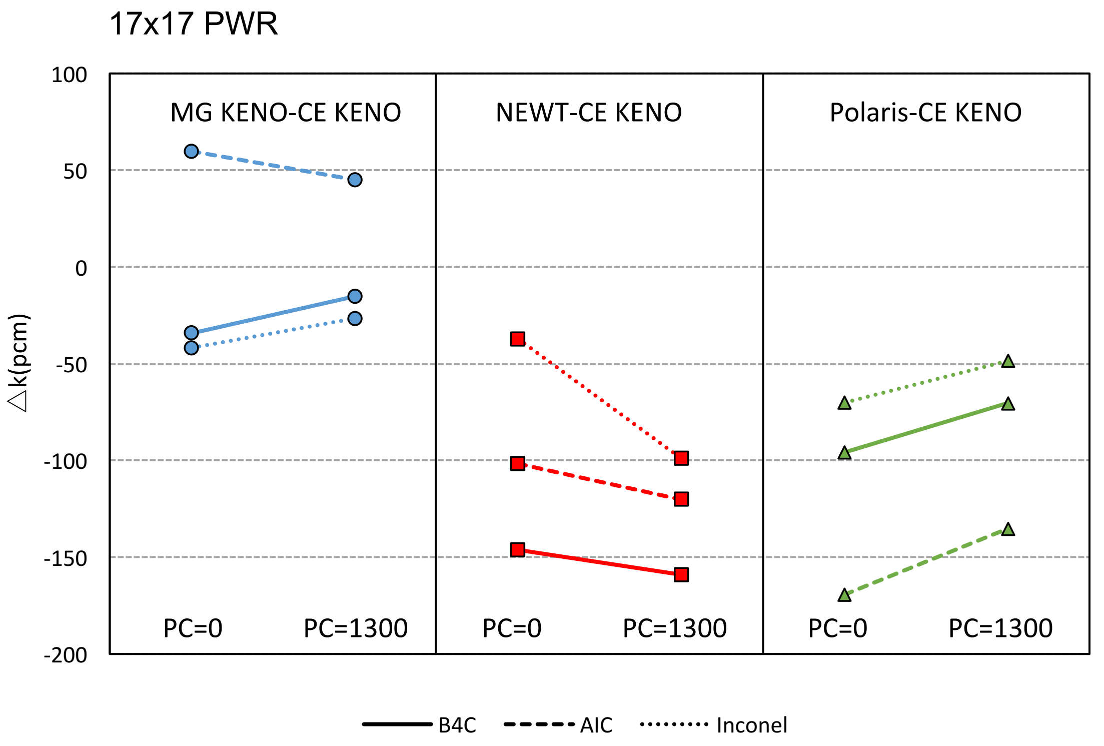


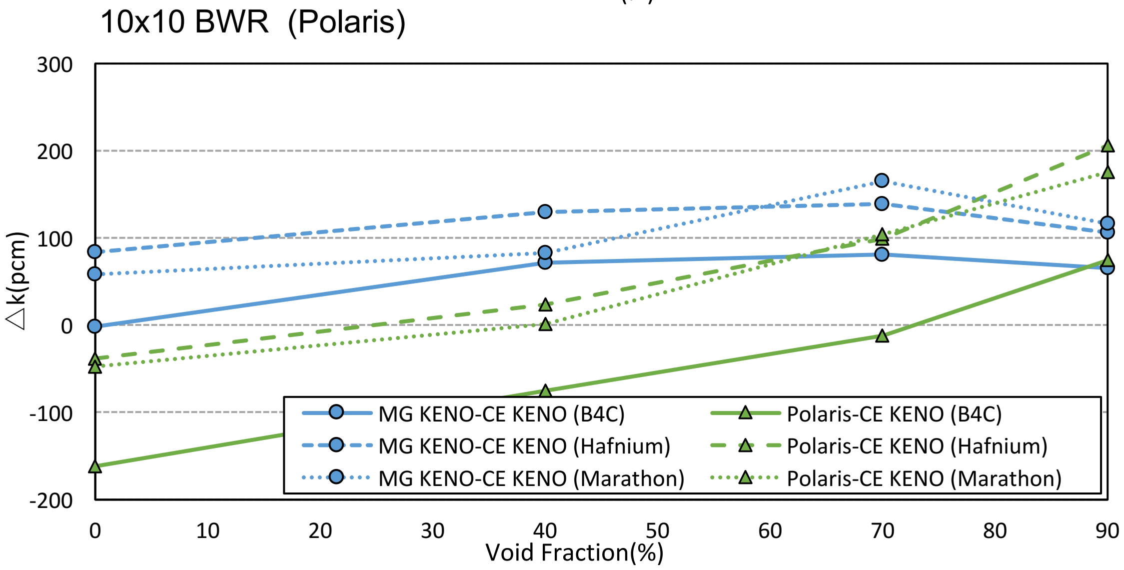


- ✓ As Gd concentration increases, void trends become consistent
- ✓ No significant trends in BP loadings from PWR (except NEWT IFBA)

Trends in Control Elements



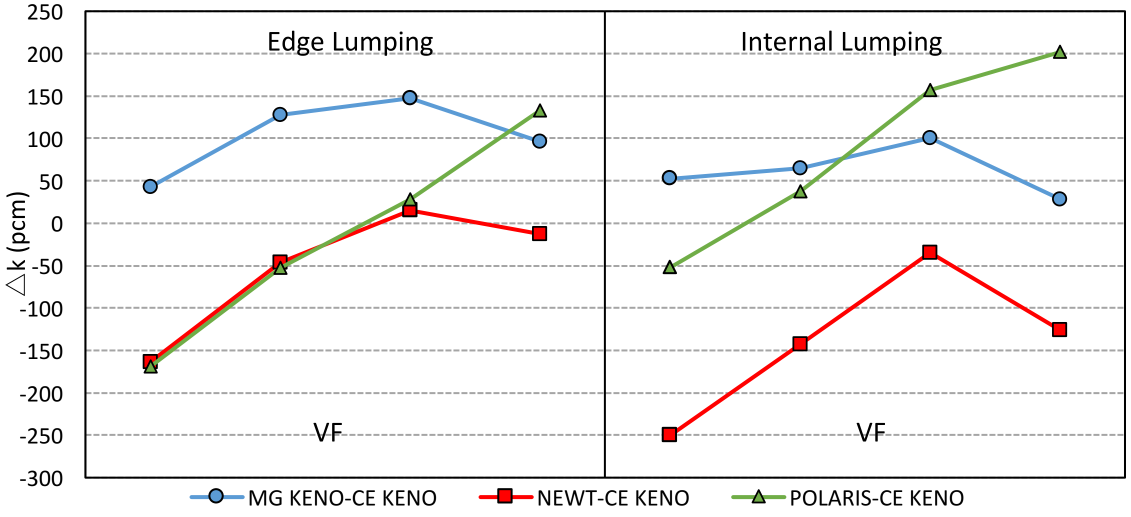


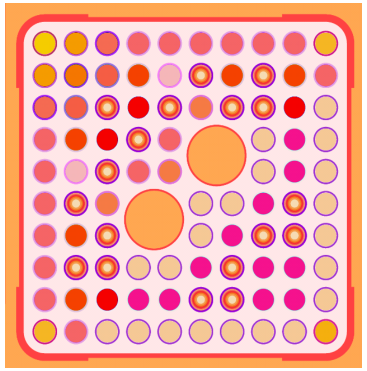


- ✓ The largest difference between different control blades (B_4C-Hafnium) and control rods (B_4C-Inconel) is ~100 pcm
- ✓ Consistent void fraction trend

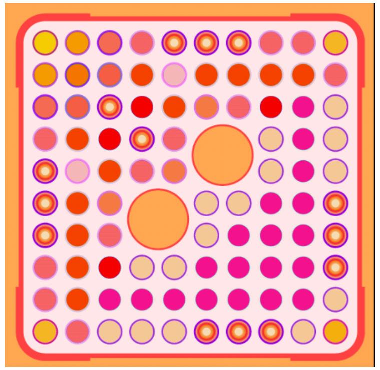
OAK RIDGE National Laboratory

Trends in BP Spatial Variations

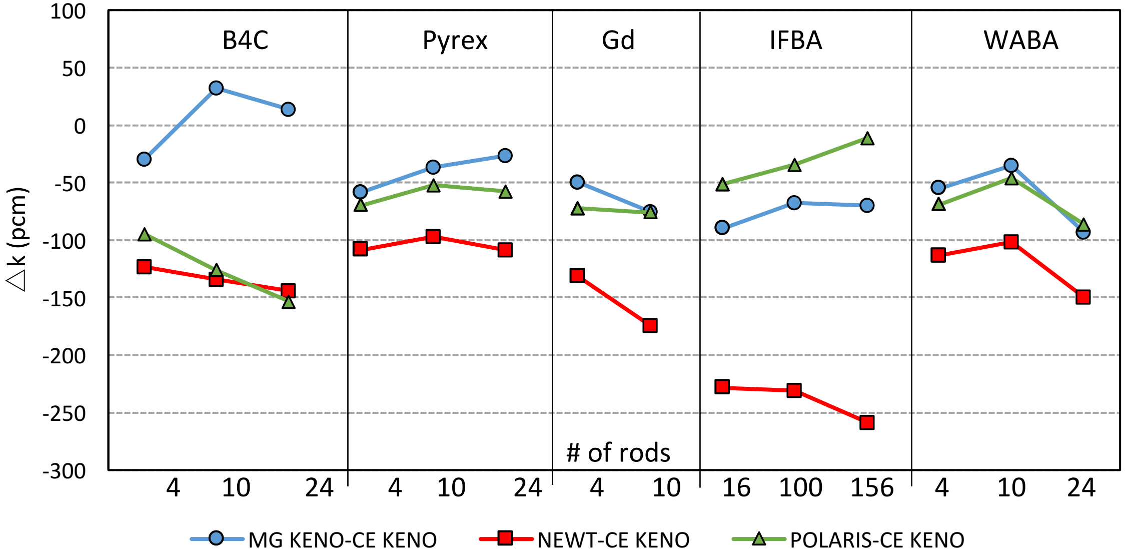




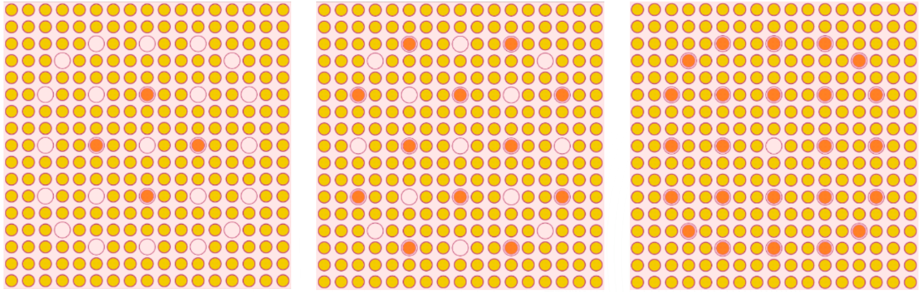
Internal gadolinia rod lumping



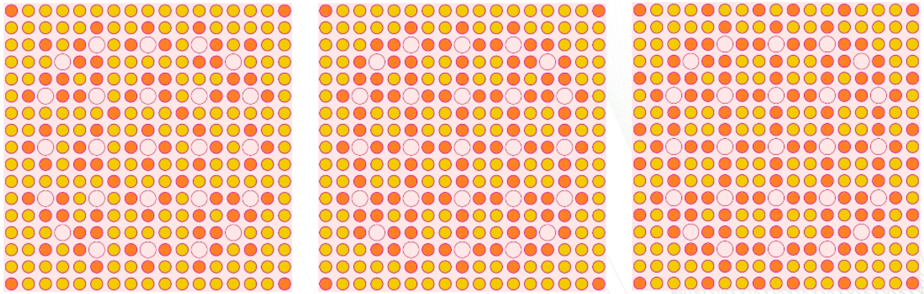
Edge gadolinia rod lumping



B_4C Patterns

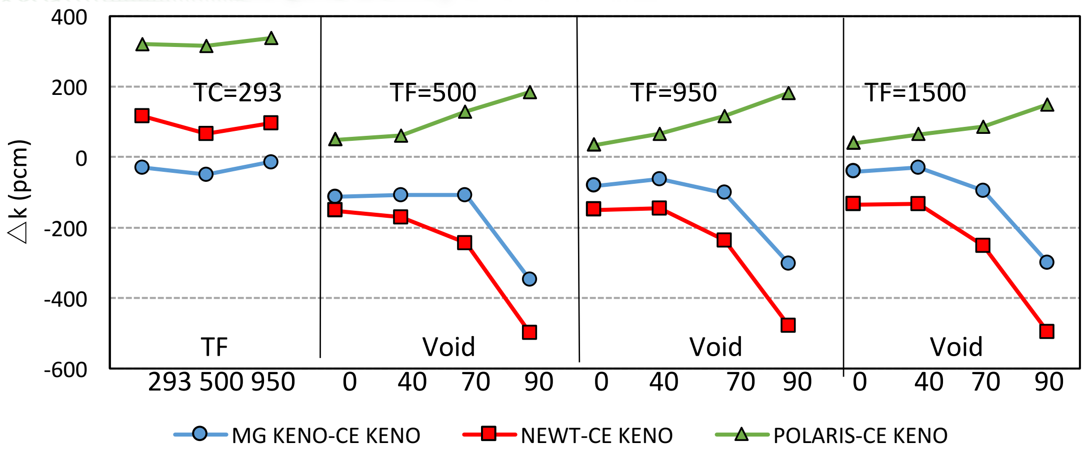


IFBA Patterns

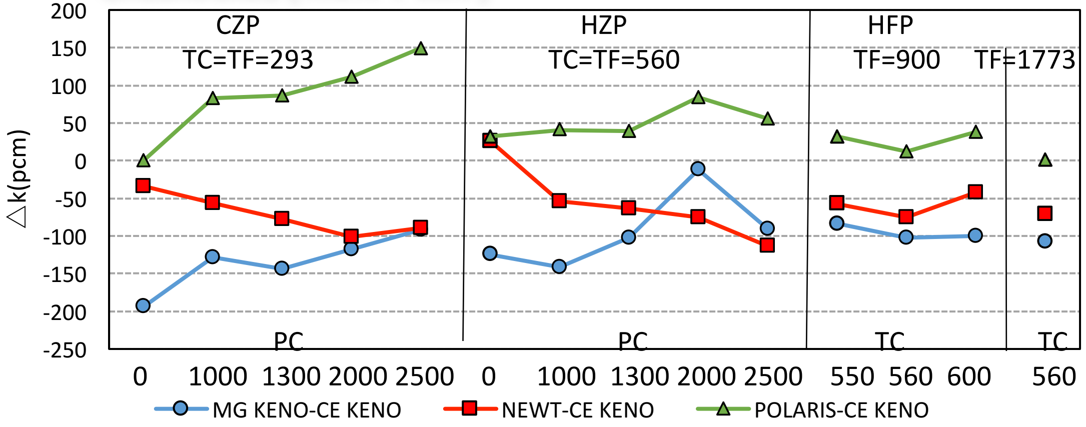


Trends in MOX Fuel

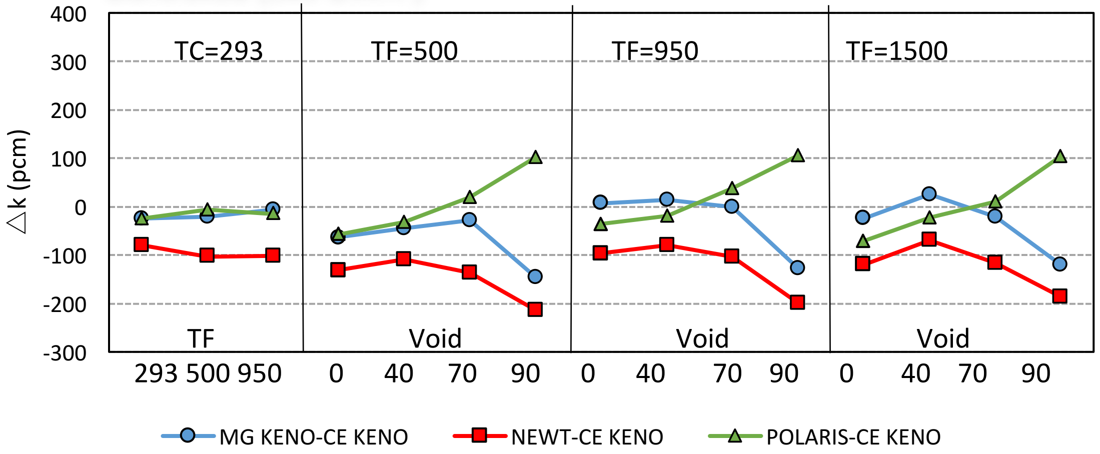
Uncontrolled (9x9 BWR)



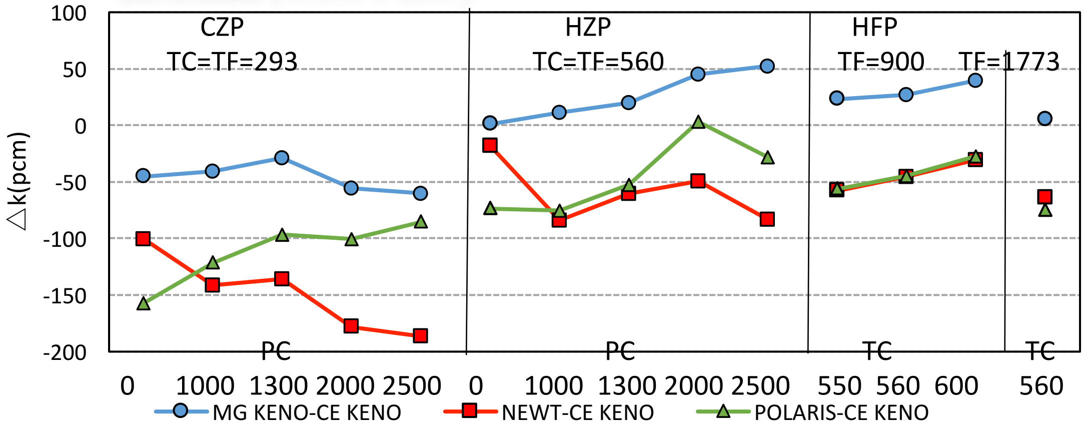
Uncontrolled (17x17 PWR)



Controlled (9x9 BWR)

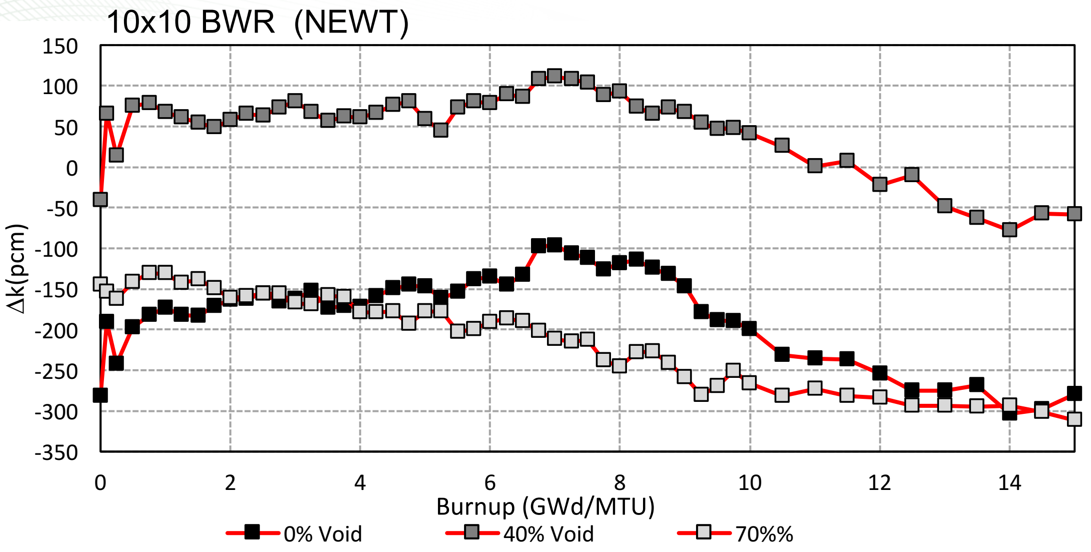


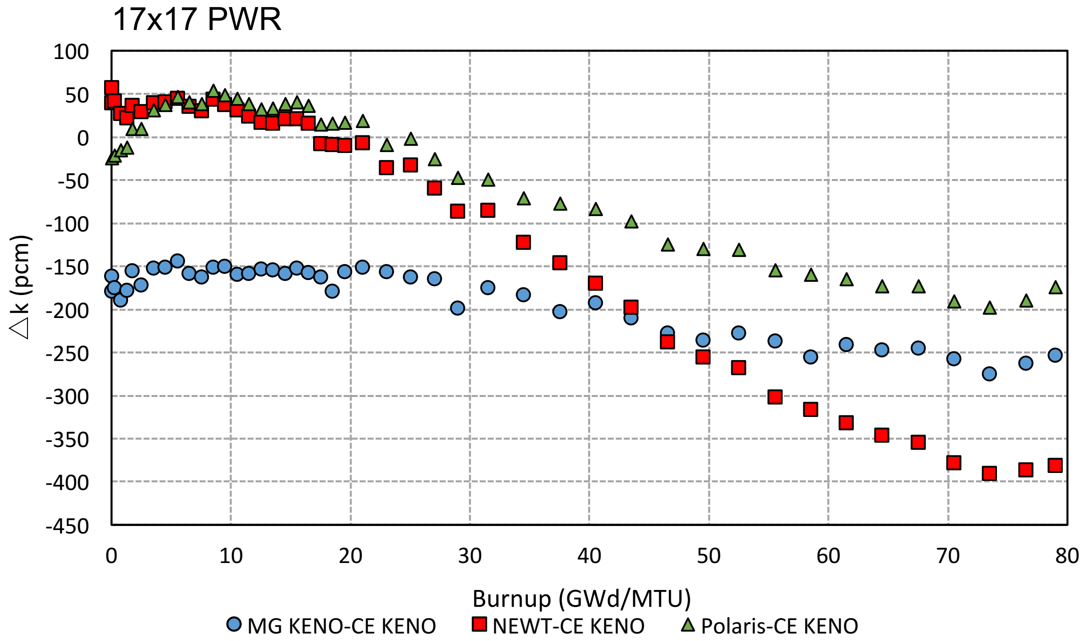
Controlled (17x17 PWR)

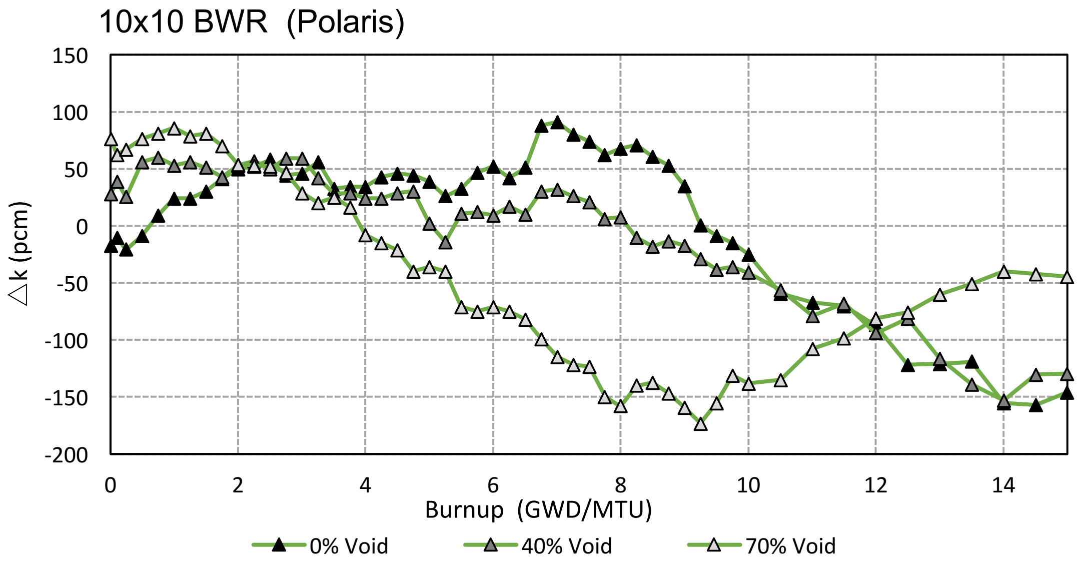


- ✓ Shape of the trends in void fraction, fuel temperature and controlled cases are consistent with UOX fuel while the max and min values are larger.

Depletion Calculations

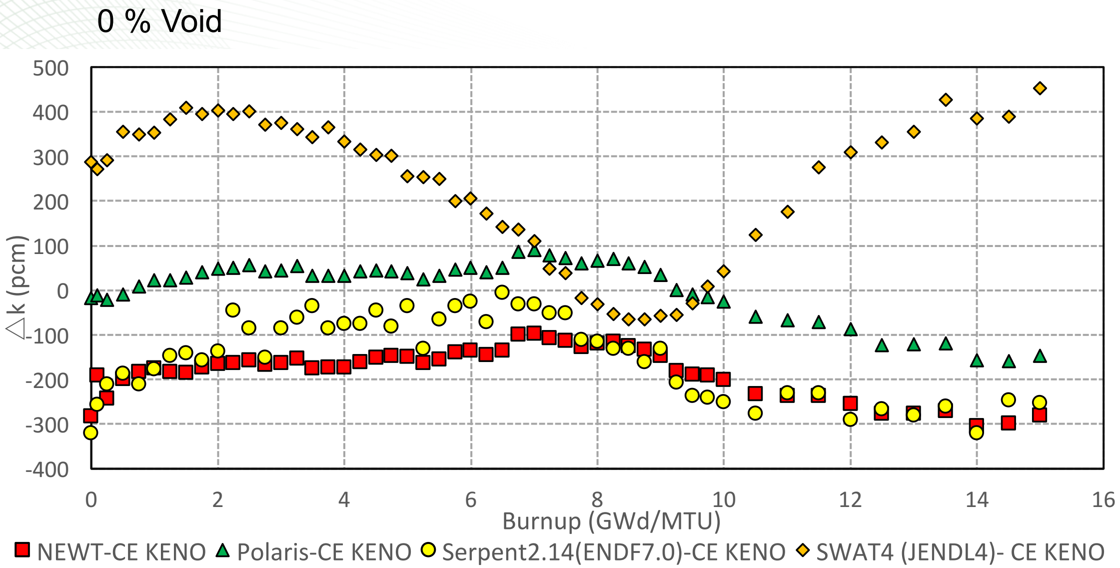


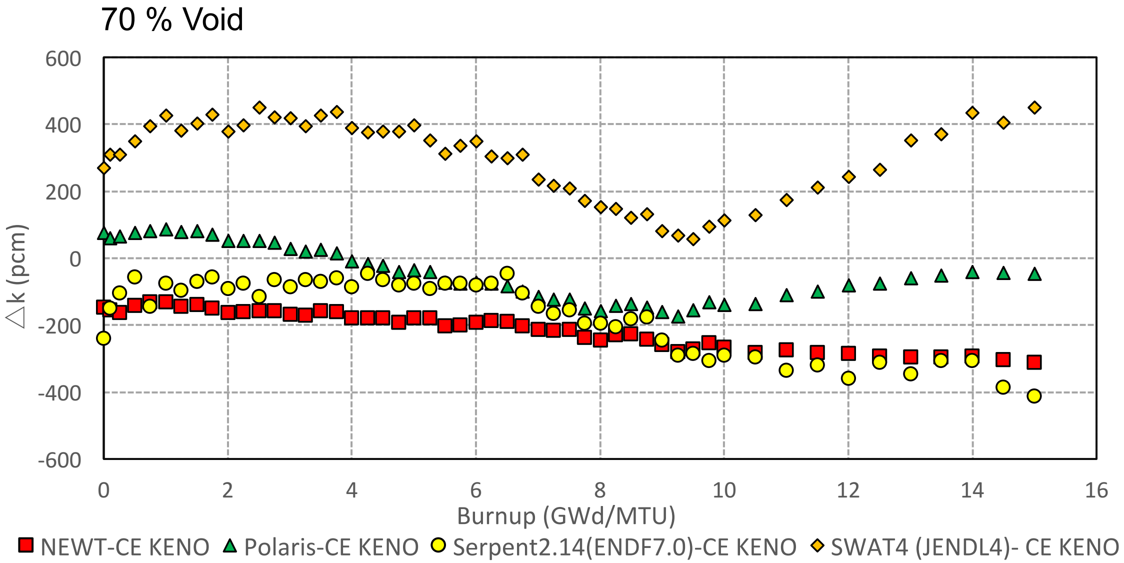


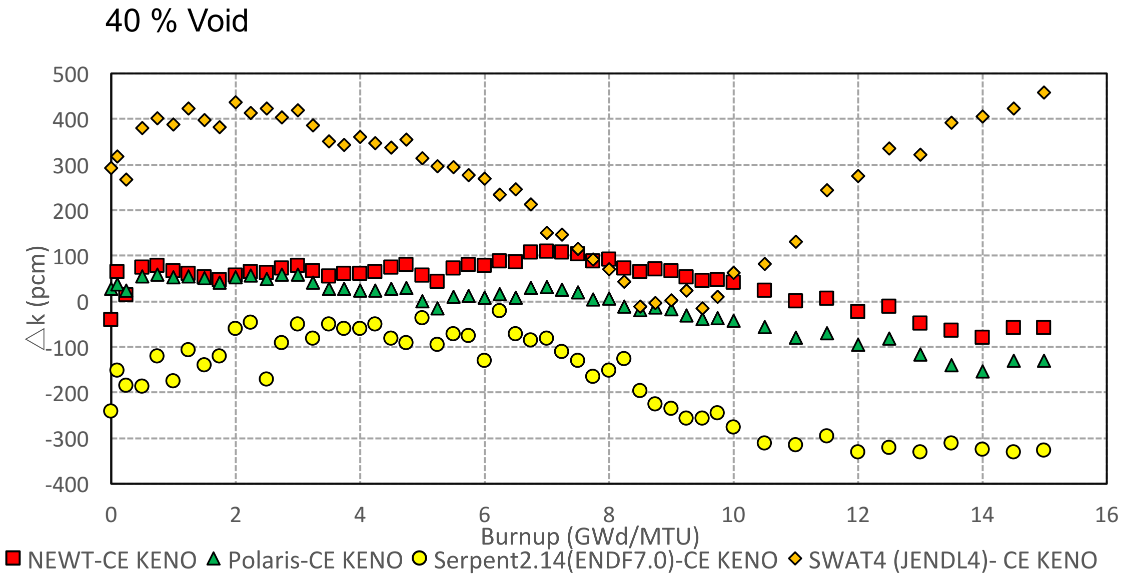


- ✓ Void fraction trends change with depletion.
- ✓ NEWT requires fine depletion steps (0.25 GWd/MTU) to resolve Gd depletion.
- ✓ Polaris and CE KENO agreement is ~200 pcm for both PWR and BWR depletion calculations.
- ✓ Although magnitudes are different, all codes show similar trends in PWR depletion.

International Benchmarks (BWR EGUNF Phase II)

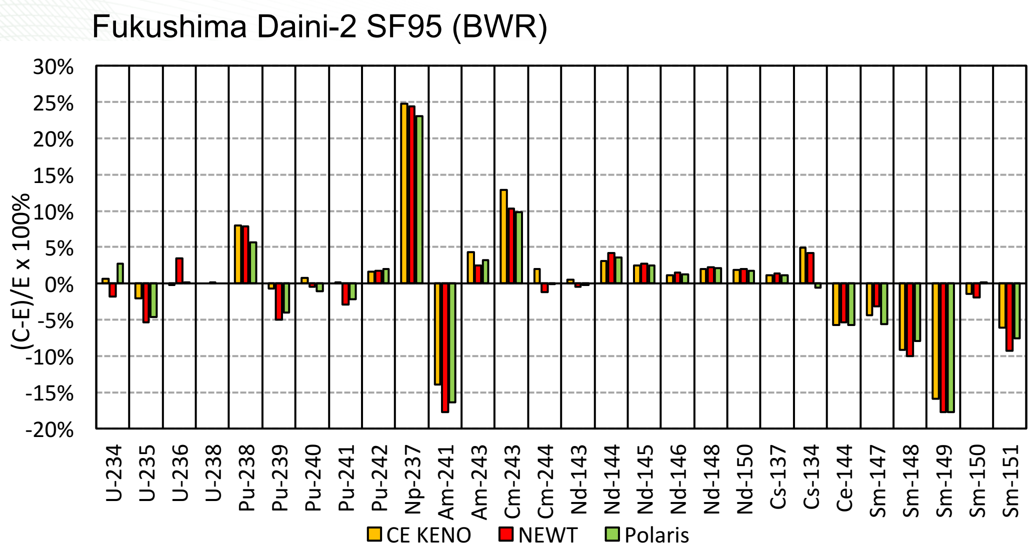


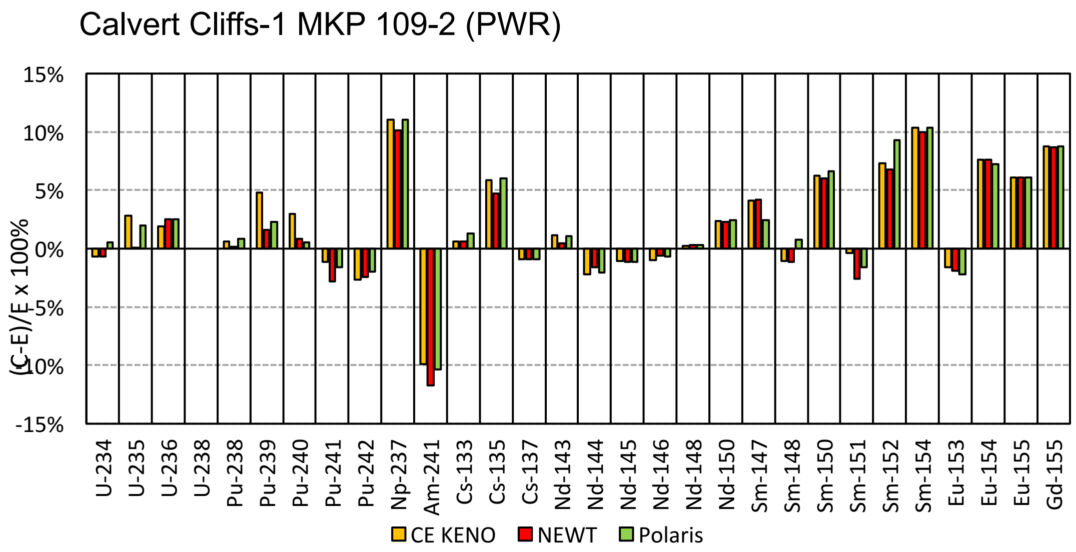


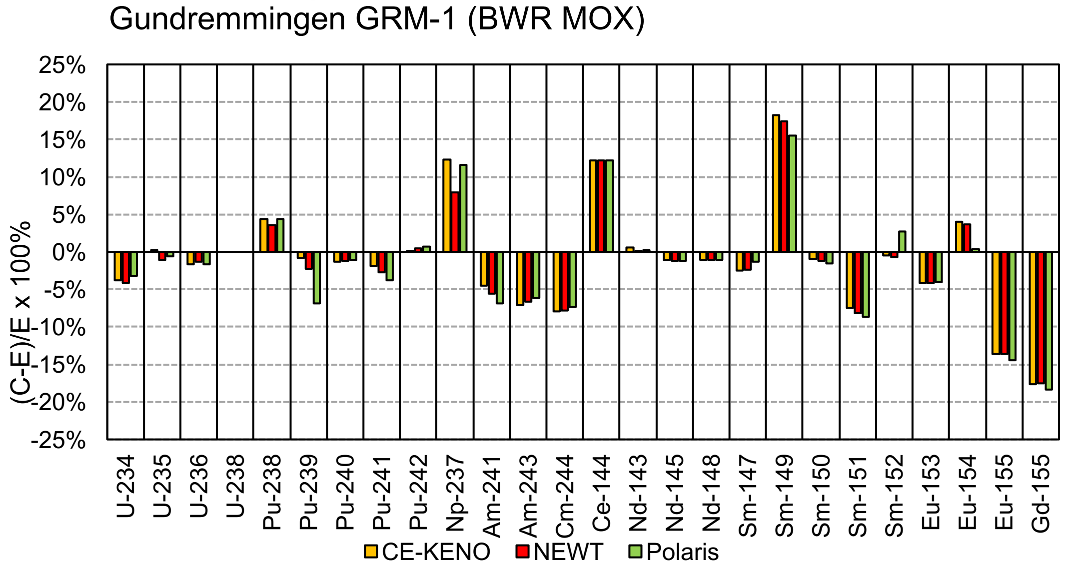


- ✓ Good agreement with Serpent depletion results
- ✓ ~300 pcm difference between Serpent and CE KENO results at Gd peak at 8 GWd/MTU

RCA Measurement Comparisons







- ✓ In general good agreement among all three codes is observed for all isotopes
- ✓ Discrepancy with measurements is less than 5% for most major actinides
- ✓ More RCA comparisons are needed to determine any biases in depletion calculations

Conclusion

- With some exceptions, test results satisfy acceptance criteria for each test (96.7% for NEWT, 99.7% for Polaris).

- We would like all of our test cases to satisfy target criteria (75% NEWT, 87% Polaris). To get there:
  - Investigate void fraction trends (cross section processing for all MG codes)
  - Implement a better quadrature set for NEWT
  - Investigate biases observed for MOX cases
  - More international numerical benchmark comparisons
  - More RCA measurement comparisons

Standard Case Matrix

BWR Case	Tf (K)	Tc(K)	Void Fraction	Pc (ppm)	Control Blade
Cold Zero Power	293	293	0	0	0
Cold Zero Power	500	293	0	0	0
Cold Zero Power	950	293	0	0	0
Hot Zero Branch	500	560	0	0	0
Hot Zero Branch	500	560	40	0	0
Hot Zero Branch	500	560	70	0	0
Hot Zero Branch	500	560	90	0	0
Hot Full Power	950	560	0	0	0
Hot Full Power	950	560	40	0	0
Hot Full Power	950	560	70	0	0
Hot Full Power	950	560	90	0	0
Hot Full Power	1500	560	0	0	0
Hot Full Power	1500	560	40	0	0
Hot Full Power	1500	560	70	0	0
Hot Full Power	1500	560	90	0	0
Cold Zero Power	293	293	0	0	1
Cold Zero Power	500	293	0	0	1
Cold Zero Power	950	293	0	0	1
Hot Zero Branch	500	560	0	0	1
Hot Zero Branch	500	560	40	0	1
Hot Zero Branch	500	560	70	0	1
Hot Zero Branch	500	560	90	0	1
Hot Full Power	950	560	0	0	1
Hot Full Power	950	560	40	0	1
Hot Full Power	950	560	70	0	1
Hot Full Power	950	560	90	0	1
Hot Full Power	1500	560	0	0	1
Hot Full Power	1500	560	40	0	1
Hot Full Power	1500	560	70	0	1
Hot Full Power	1500	560	90	0	1

PWR Case	Tf (K)	Tc(K)	Pc (ppm)	Control Rod
Cold Zero Power	293	293	0	0
Cold Zero Power	293	293	1000	0
Cold Zero Power	293	293	1300	0
Cold Zero Power	293	293	2000	0
Cold Zero Power	293	293	2500	0
Hot Zero Power	560	560	0	0
Hot Zero Power	560	560	1000	0
Hot Zero Power	560	560	1300	0
Hot Zero Power	560	560	2000	0
Hot Zero Power	560	560	2500	0
Hot Full Power	900	550	1300	0
Hot Full Power	900	560	1300	0
Hot Full Power	900	600	1300	0
Hot Full Power	1773	560	1300	0
Cold Zero Power	293	293	0	1
Cold Zero Power	293	293	1000	1
Cold Zero Power	293	293	1300	1
Cold Zero Power	293	293	2000	1
Cold Zero Power	293	293	2500	1
Hot Zero Power	560	560	0	1
Hot Zero Power	560	560	1000	1
Hot Zero Power	560	560	1300	1
Hot Zero Power	560	560	2000	1
Hot Zero Power	560	560	2500	1
Hot Full Power	900	550	1300	1
Hot Full Power	900	560	1300	1
Hot Full Power	900	600	1300	1
Hot Full Power	1773	560	1300	1