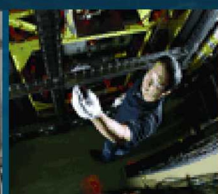
SAND2019-10459C

Titanium and Aluminum Sleeve Experiments in Water Moderated 4.31% Enriched UO_2 Fuel Element Lattices



PRESENTED BY

David Ames

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Sandia Critical Experiments Facility

The Seven Percent Critical Experiment (7uPCX)

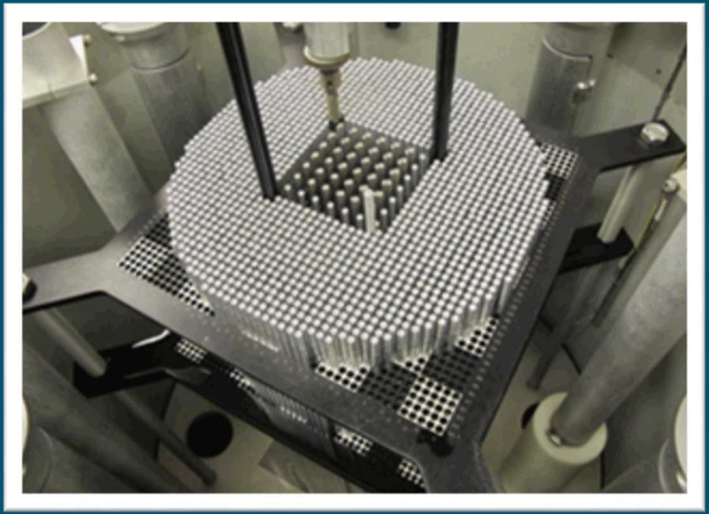
- UO_2 fuel (6.9%)
- 45x45 Square array (pitch 0.315 and 0.337 inch)
- Fuel locations 2025
- Fuel rod diameter 0.25 inch
- Fuel length 19.25 inch
- LCT-078, 080, 096, 097, 101 (experiments completed earlier this year)

The Burnup Credit Critical Experiment (BUCCX)

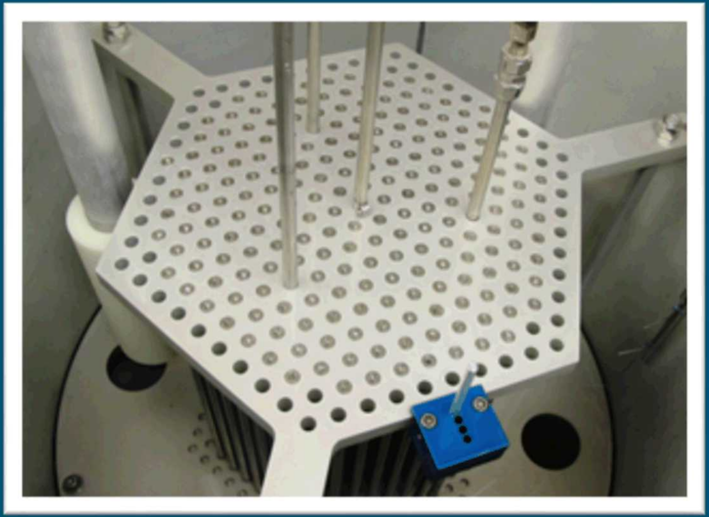
- UO_2 fuel (4.3%)
- Triangular pitch (0.787 and 1.1 inch)
- Fuel locations 397 and 271
- Fuel rod diameter 0.544 inch
- Fuel length 19.37 inch
- LCT-079, 099

Critical Experiment	BUCCX		7uPCX	
Fuel	UO_2		UO_2	
Enrichment (%)	4.306		6.903	
Moderator	Light Water		Light Water	
Fuel OD (cm)	1.265		0.526	
Fuel Length (cm)	48.7		48.8	
Fuel Density (g/cm^3)	10.4		10.3	
Fuel Rod OD (cm)	1.382		0.635	
Array Configuration	Triangular Pitch		Square Pitch	
Pitch (cm)	2.0	2.8	0.800	0.855
Fuel to Water Volume Ratio	0.640	0.238	0.672	0.524
H to ^{235}U Atom Ratio	131	332	62.0	79.5
H to U Atom Ratio	4.48	12.1	4.33	5.55

7uPCX



BUCCX



Titanium and Aluminum Sleeve Experiments

Experiment motivation

- Criticality Safety Benchmarks (ICSBEP)
- Test of newly evaluated nuclear data
- Allow credit for thermal absorption of titanium in waste processing systems

Titanium sleeves

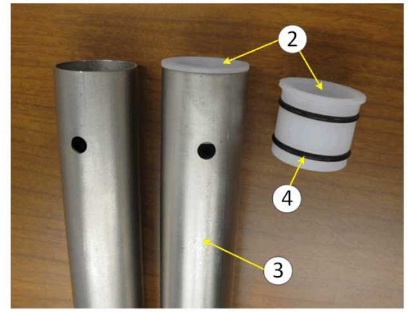
- Grade 2
- Outer diameter 1.0 inch (2.54 cm)
- Wall thickness 0.035 inch (0.0889 cm)
- Length 19.7 inch (50.038 cm)
- Laser etched with ID number

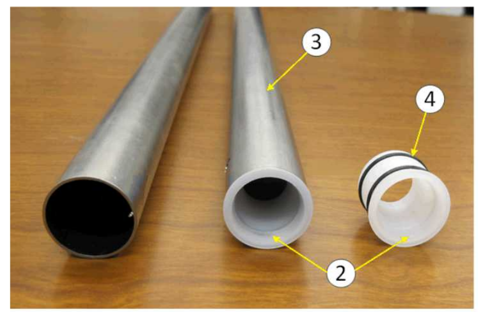
Aluminum sleeves

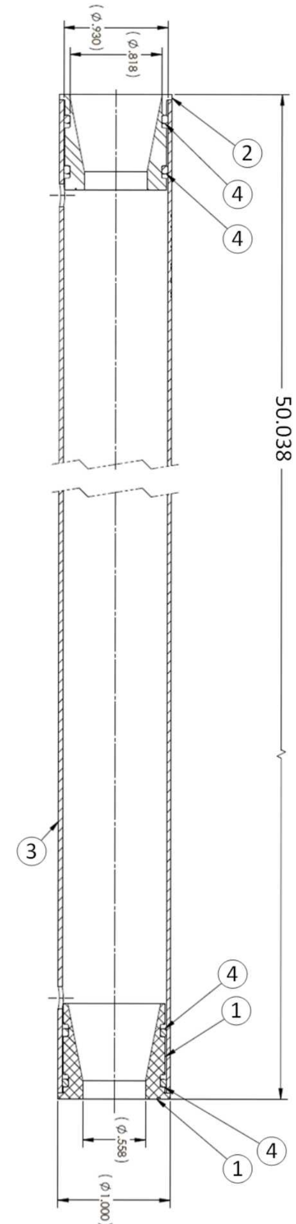
- 6061-T6
- Outer diameter 1.0 inch (2.54 cm)
- Wall thickness 0.035 inch (0.0889 cm)
- Length 19.7 inch (50.038 cm)
- Laser etched with ID number

Polyethylene Centering Pieces

- Length 0.85 inch (2.159 cm)
- O-rings hold in place







1 = Bottom Polyethylene Centering Piece

2 = Top Polyethylene Centering Piece

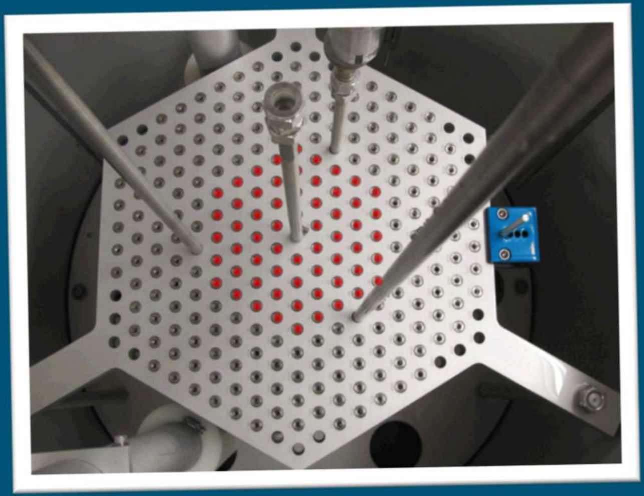
3 = Experiment Sleeve

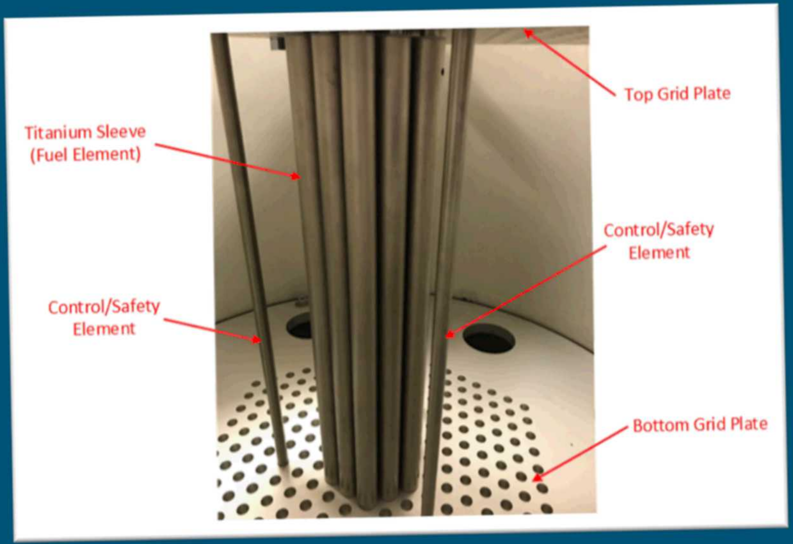
4 = O-ring

Titanium and Aluminum Sleeve Experiments

Sleeves are placed between the top and bottom grid plates (fueled section)

- Fuel element fed through top grid plate hole into the sleeve and into bottom grid plate hole
- Fuel element outer diameter 0.544 inch
- Sleeve inner diameter 0.93 inch





Experiment Method

Measure the effects of titanium and aluminum sleeves in the fuel array on the critical array size.

- All titanium experiments have corresponding aluminum experiments
  - Number of fuel rods in the array will differ due to the effects of titanium and aluminum

Critical array size for each configuration determined by an approach-to-critical experiment

- Array fully reflected by water
- Approach parameter is the number of fuel rods
  - Load from center toward the outside while maintaining a roughly cylindrical cross section of the array
  - Inverse count rate as function of number of fuel rods extrapolated to zero to obtain critical array size
- Initial two arrays for each configuration determined by calculations
  - 1^{st} array: $k_{eff} = 0.90$
  - 2^{nd} array: $k_{eff} = 0.95$
- Subsequent measurements guided by count rate results

17 critical experiments performed

- 1 with no sleeves
- 8 cases with titanium sleeves (varying quantities and configurations)
- 8 cases with aluminum sleeves (matching titanium cases)

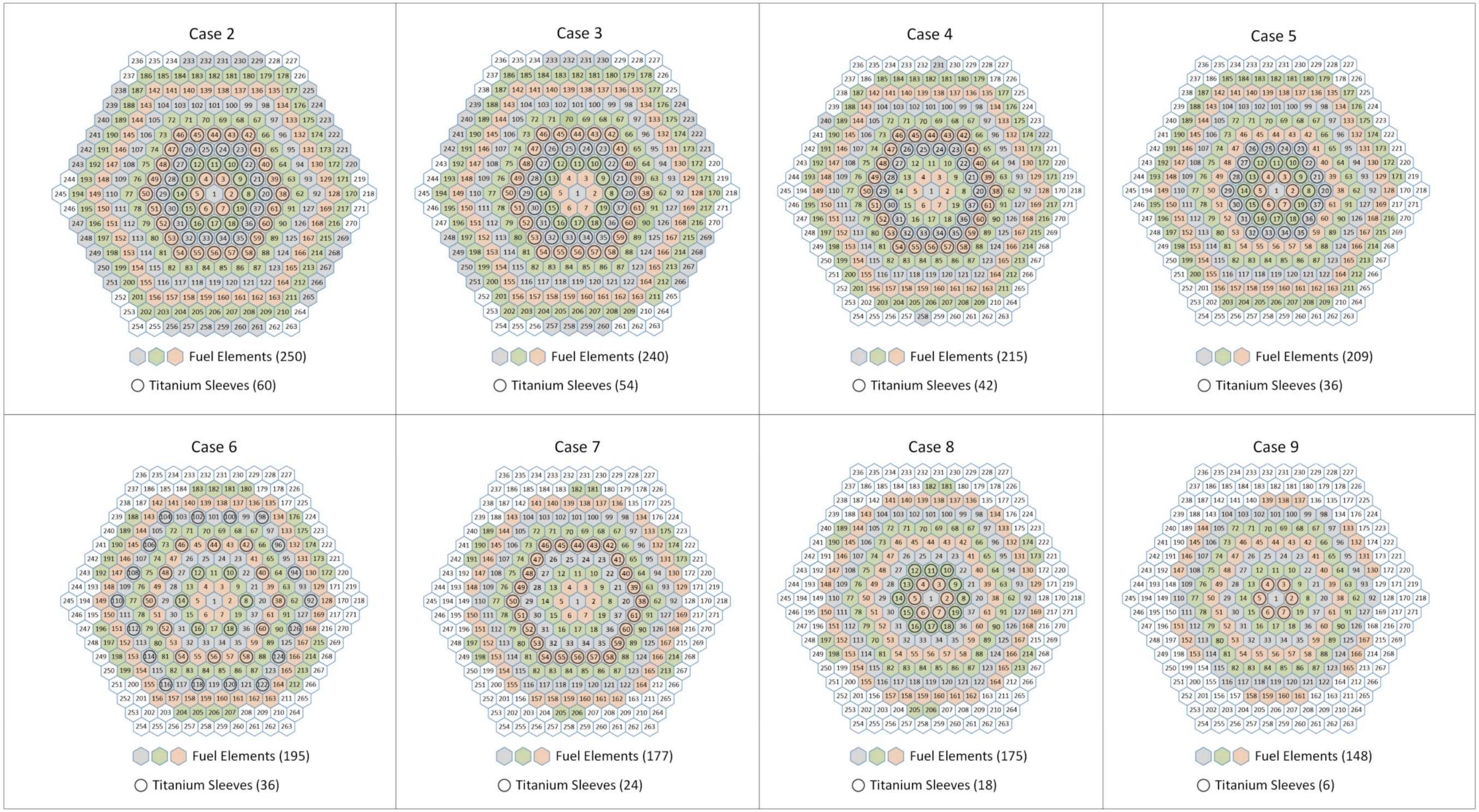
Critical Experiments (17 configurations)

Case 1 : no sleeves

Cases 2 – 9 : titanium sleeves

Cases 10 – 17 : aluminum sleeves

Largest measured arrays containing titanium sleeves (cases 2 – 9)



Titanium and Aluminum Sleeve Reactivity Worth

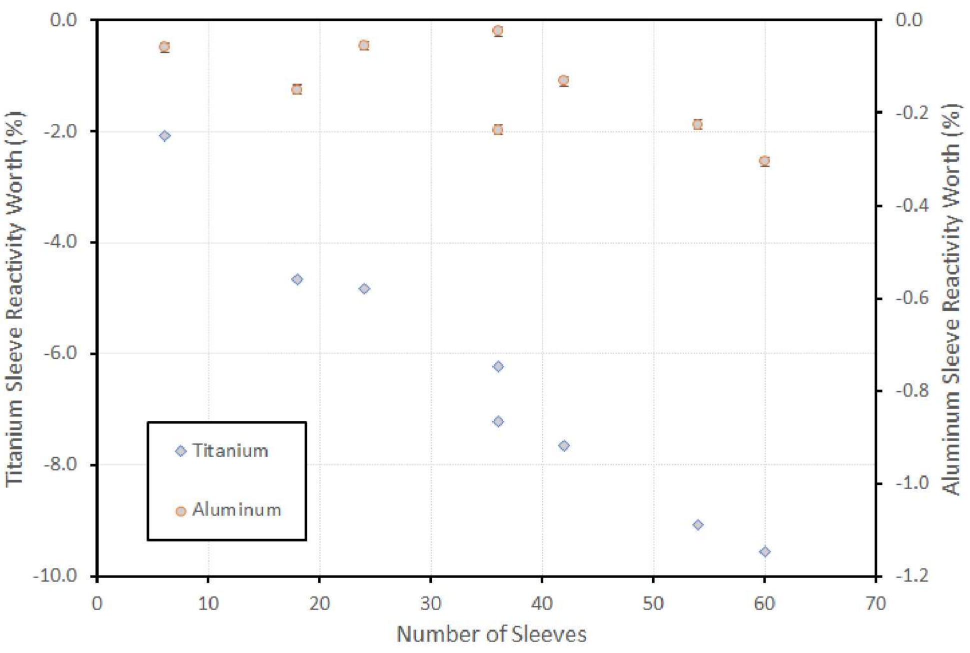
The worth of the sleeves was evaluated by calculating the multiplication factor with the sleeves present and voided.

$$\rho = \frac{k_x - k_v}{k_x \cdot k_v}$$

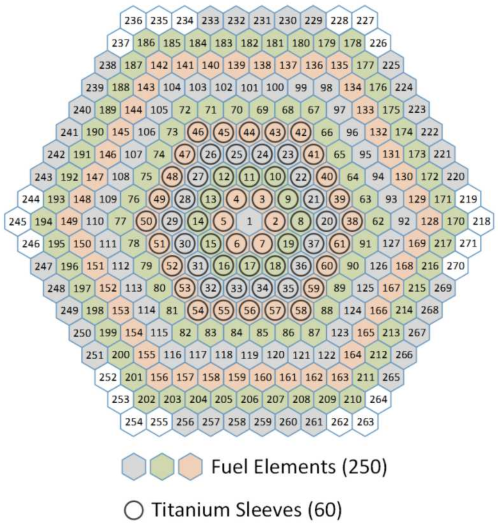
$k_x =$ calculated k_{eff} with sleeves present

$k_v = calculated\ k_{eff}$ with sleeves voided

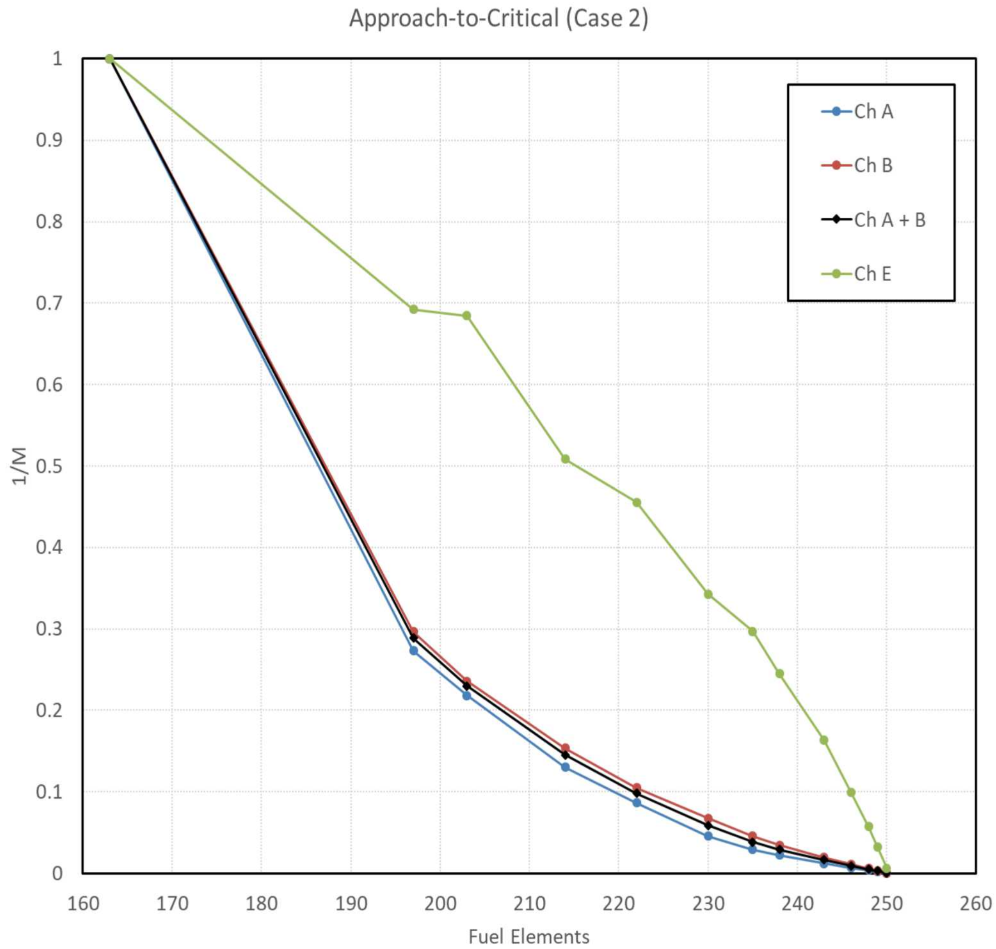
Case	Number of Experiment Sleeves		Experiment Sleeve Reactivity Worth (%)
	Titanium	Aluminum	
1	0	0	0
2	60	0	-9.57 ± 0.01
3	54	0	-9.07 ± 0.01
4	42	0	-7.67 ± 0.01
5	36	0	-7.23 ± 0.01
6	36	0	-6.23 ± 0.01
7	24	0	-4.84 ± 0.01
8	18	0	-4.67 ± 0.01
9	6	0	-2.07 ± 0.01
10	0	60	-0.31 ± 0.01
11	0	54	-0.23 ± 0.01
12	0	42	-0.13 ± 0.01
13	0	36	-0.24 ± 0.01
14	0	36	-0.02 ± 0.01
15	0	24	-0.06 ± 0.01
16	0	18	-0.15 ± 0.01
17	0	6	-0.06 ± 0.01



Approach-to-Critical (case 2 with 60 titanium sleeves)

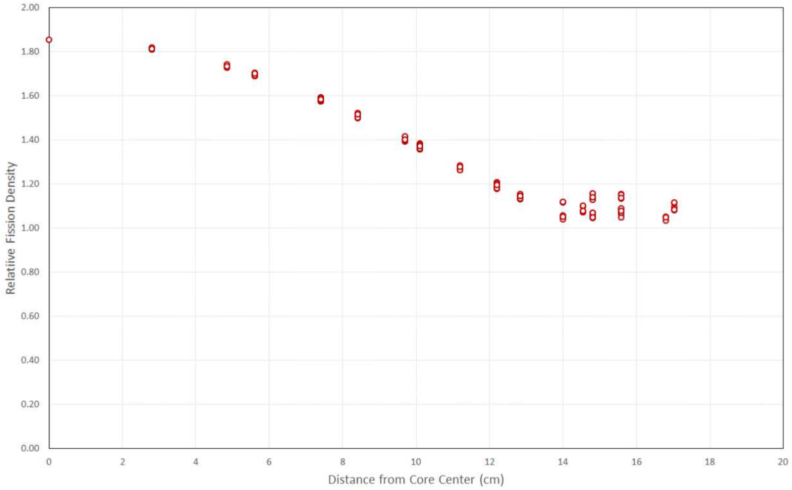


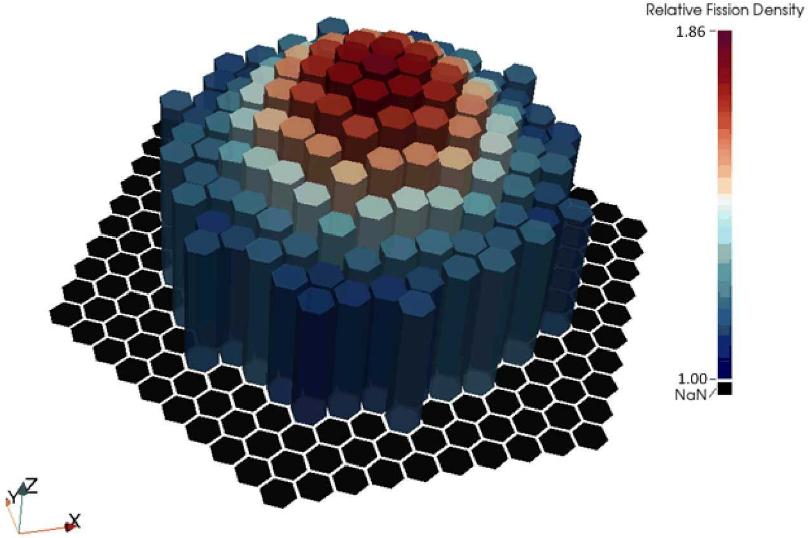
Fuel elements	Projection (A+B)	Uncertainty
163	-	-
197	210.7931	0.3524
203	226.4541	1.2581
214	232.8661	0.5437
222	238.6815	0.4697
230	241.8655	0.2289
235	244.5458	0.1571
238	247.5537	0.1218
243	249.2936	0.0355
246	249.8935	0.0167
248	250.2748	0.0068
249	250.1985	0.0027
250	250.2276	0.0002



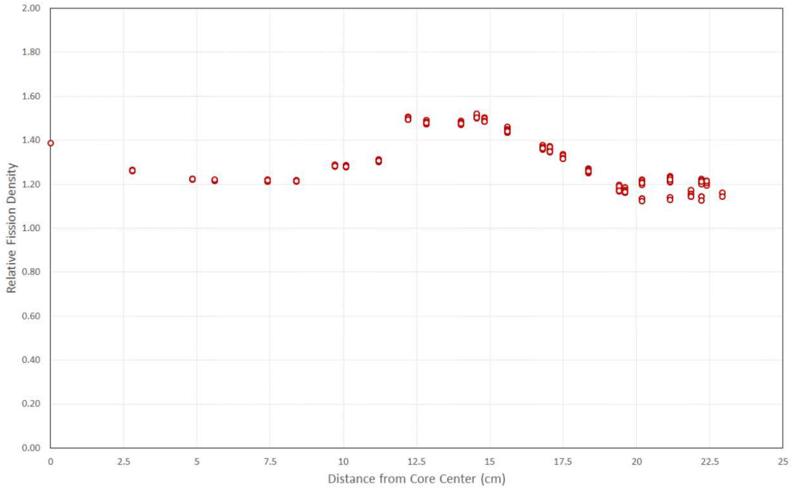
Core Analysis (Fission Density)

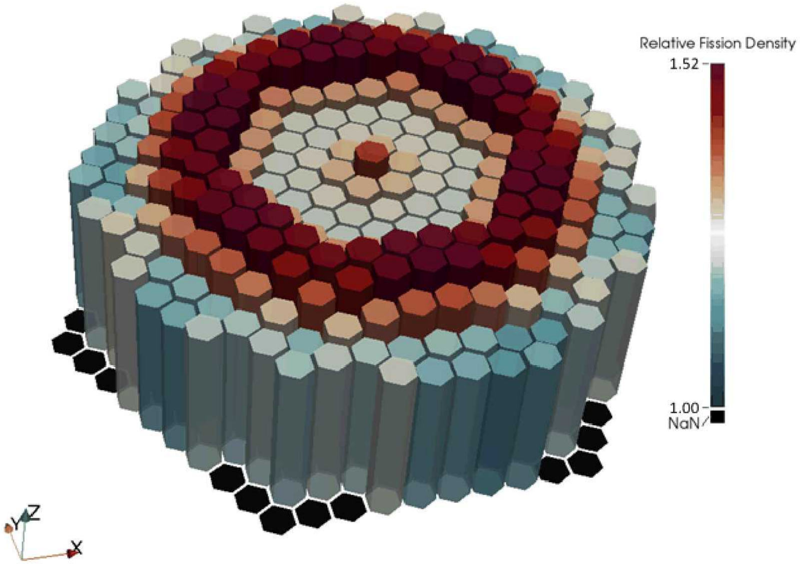
Case 1 (no sleeves)





Case 2 (60 titanium sleeves)





Approach-to-Critical Experiment Results

Detailed records kept of location and identity of each fuel element in each core

- Fuel elements placed in same grid location in each core

Critical array size extrapolated from largest measured subcritical array

- Most measured cases within a fraction of a single element from delayed critical
- Uncertainties in count rate propagated through the extrapolation

Case	Extrapolated Critical Array Size	Nearest Integral Array Size	Experiment Temperature (°C)
1	131.877 ± 0.004	132	25.1
2	250.228 ± 0.000	250	25.0
3	240.296 ± 0.000	240	25.1
4	215.098 ± 0.003	215	24.9
5	209.016 ± 0.003	209	24.8
6	194.502 ± 0.001	195	24.7
7	177.050 ± 0.004	177	24.6
8	174.741 ± 0.002	175	24.8
9	148.088 ± 0.006	148	24.6
10	148.493 ± 0.001	148	25.0
11	146.560 ± 0.002	147	24.5
12	142.565 ± 0.002	143	25.0
13	142.889 ± 0.004	143	24.7
14	137.960 ± 0.005	138	25.1
15	137.283 ± 0.001	137	25.4
16	137.714 ± 0.003	138	24.6
17	133.952 ± 0.005	134	24.7

Uncertainty Analyses

Analyses performed with MCNP6.2 using Continuous-energy cross sections from ENDF/B-VII.1

- Direct Perturbations
  - Least-squares fit with uncertainty propagation
- Sensitives to materials (KSEN)
  - Combined to assess uncertainties
- Temperature (makxsf)
  - Thermal expansion of fuel, density of water, Doppler broadening, thermal scattering

Type A uncertainty:

Random, based on a finite number of measurements proper for statistical analyses

Type B uncertainty:

Scientific judgement based on all available information

Case 1: No Sleeves

Uncertainty Source	Type	Uncertainty Value	Sensitivity		Δk_{eff}
			Value	Unc.	
Pitch of Fuel Elements (cm)	B	0.00239	0.0264	0.00025	0.00006
Clad OD (cm)	A	0.000106	-0.08200	0.00023	-0.00001
Clad Thickness (cm)	B	0.00293	0.03867	0.00023	0.00011
Fuel OD (cm)	A	0.0025	0.02157	0.00015	0.00005
Upper Reflector (mm)	A	2	0.000002	0.000001	0.00000
Element Fuel Mass (cm)	A	0.011	0.00223	0.00002	0.00002
Fuel Enrichment (mass fraction)	A	0.00013	4.7751	0.0014	0.00062
^{234}U (mass fraction)	A	0.00002	-4.0658	0.0082	-0.00008
^{236}U (mass fraction)	A	0.00002	-0.9441	0.0076	-0.00002
UO_2 Stoichiometry (U mass fraction)	A	0.00261	0.06668	0.00077	0.00017
Clad Composition	B	Details within report			0.00008
Grid Plate Composition	B				0.00003
Water Composition	A				0.00024
Temperature (K)	A	1	0.000042	0.000003	0.00004
				Sum in Quadrature	0.00071

Uncertainty Analyses

Analyses performed with MCNP6.2 using Continuous-energy cross sections from ENDF/B-VII.1

- Direct Perturbations
  - Least-squares fit with uncertainty propagation
- Sensitives to materials (KSEN)
  - Combined to assess uncertainties
- Temperature (makxsf)
  - Thermal expansion of fuel, density of water, Doppler broadening, thermal scattering

Type A uncertainty:

Random, based on a finite number of measurements proper for statistical analyses

Type B uncertainty:

Scientific judgement based on all available information

Case 2: 60 Titanium Sleeves

Uncertainty Source	Type	Uncertainty Value	Sensitivity		Δk_{eff}
			Value	Unc.	
Pitch of Fuel Elements (cm)	B	0.00239	-0.0100	0.00019	-0.00002
Clad OD (cm)	A	0.000106	-0.04187	0.00023	0.00000
Clad Thickness (cm)	B	0.00293	0.01080	0.00017	0.00003
Fuel OD (cm)	A	0.0025	0.03139	0.00015	0.00008
Upper Reflector (mm)	A	2	0.000002	0.000001	0.00000
Element Fuel Mass (cm)	A	0.01	0.00268	0.00002	0.00003
Experiment Sleeve OD (cm)	A	0.00019	-0.0118	0.0001	0.00000
Experiment Sleeve ID (cm)	B	0.00020	0.3434	0.0001	0.00007
Fuel Enrichment (mass fraction)	A	0.00013	5.4569	0.0016	0.00071
^{234}U (mass fraction)	A	0.00002	-4.0470	0.0082	-0.00008
^{236}U (mass fraction)	A	0.00002	-0.9957	0.0078	-0.00002
UO_2 Stoichiometry (U mass fraction)	A	0.00261	0.12909	0.00075	0.00034
Clad Composition	B	Details within report			0.00009
Grid Plate Composition	B				0.00003
Experiment Sleeve Composition	A				0.00001
Water Composition	A				0.00019
Temperature (K)	A	1	0.000069	0.000003	0.00007
				Sum in Quadrature	0.00083

Uncertainty Analyses

Analyses performed with MCNP6.2 using Continuous-energy cross sections from ENDF/B-VII.1

- Direct Perturbations
  - Least-squares fit with uncertainty propagation
- Sensitives to materials (KSEN)
  - Combined to assess uncertainties
- Temperature (makxsf)
  - Thermal expansion of fuel, density of water, Doppler broadening, thermal scattering

Type A uncertainty:

Random, based on a finite number of measurements proper for statistical analyses

Type B uncertainty:

Scientific judgement based on all available information

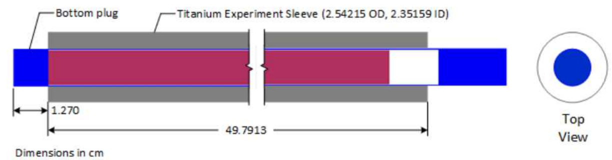
Case 10: 60 Aluminum Sleeves

Uncertainty Source	Type	Uncertainty Value	Sensitivity		Δk_{eff}
			Value	Unc.	
Pitch of Fuel Elements (cm)	B	0.00239	0.0590	0.0003	0.00014
Clad OD (cm)	A	0.000106	-0.09467	0.00023	-0.00001
Clad Thickness (cm)	B	0.00293	0.04067	0.00023	0.00012
Fuel OD (cm)	A	0.0025	0.01896	0.00015	0.00005
Upper Reflector (mm)	A	2	0.000002	0.000001	0.00000
Element Fuel Mass (cm)	A	0.01	0.00240	0.00002	0.00003
Experiment Sleeve OD (cm)	A	0.00019	-0.1220	0.0001	-0.00002
Experiment Sleeve ID (cm)	B	0.00020	0.1273	0.0001	0.00003
Fuel Enrichment (mass fraction)	A	0.00013	4.7135	0.0019	0.00061
^{234}U (mass fraction)	A	0.00002	-4.2092	0.0090	-0.00008
^{236}U (mass fraction)	A	0.00002	-1.0083	0.0073	-0.00002
UO_2 Stoichiometry (U mass fraction)	A	0.00261	0.05977	0.00079	0.00016
Clad Composition	B	Details within report			0.00009
Grid Plate Composition	B				0.00003
Experiment Sleeve Composition	A				0.00005
Water Composition	A				0.00022
Temperature (K)	A	1	0.000030	0.000003	0.00003
				Sum in Quadrature	0.00071

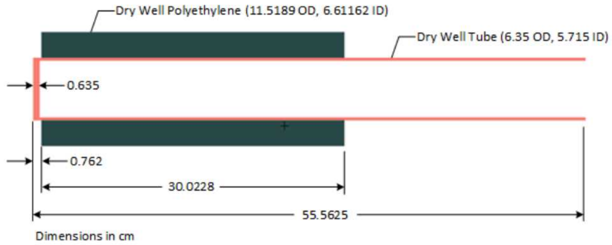
Benchmark Model

Fuel Element

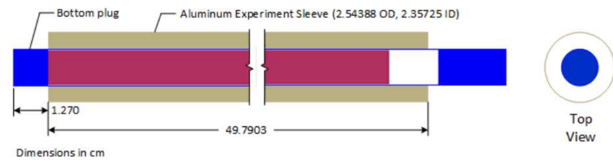
Fuel Element with Titanium Sleeve



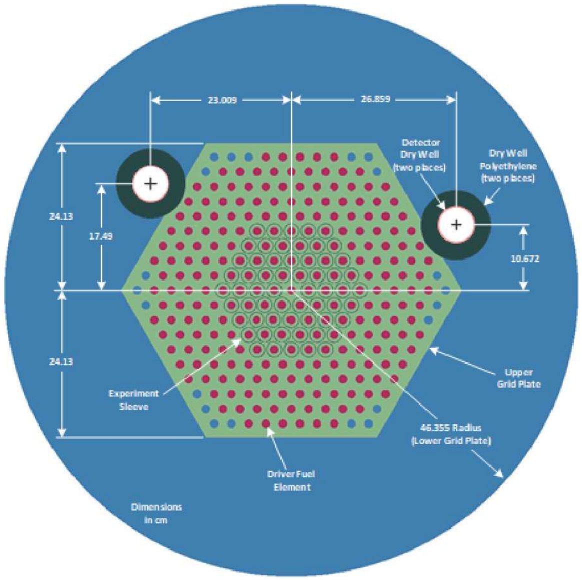
Detector Dry Well



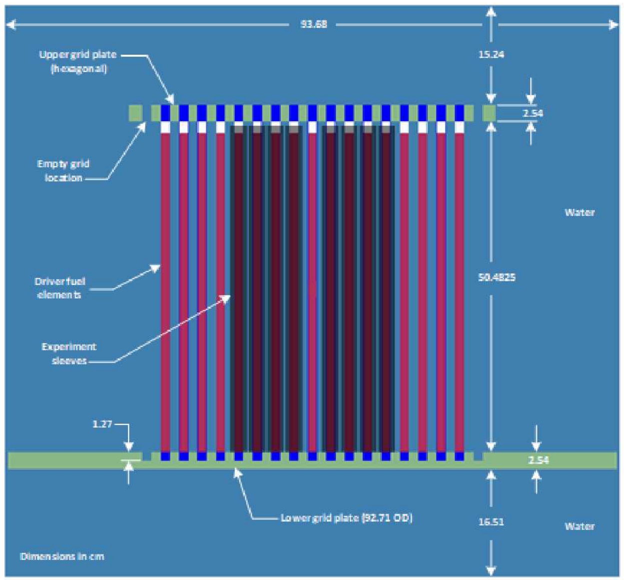
Fuel Element with Aluminum Sleeve



Top View Layout



Cut-Away Core



Benchmark Model

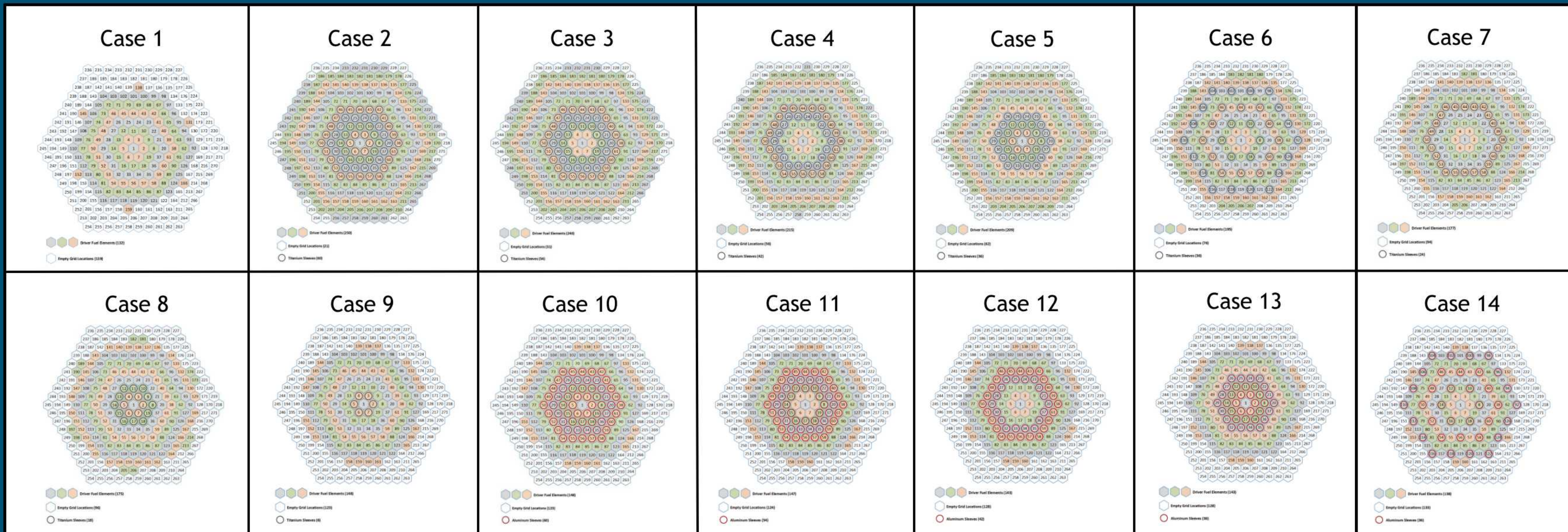
Analyses performed with MCNP6.2 using Continuous-energy cross sections from ENDF/B-VII.1

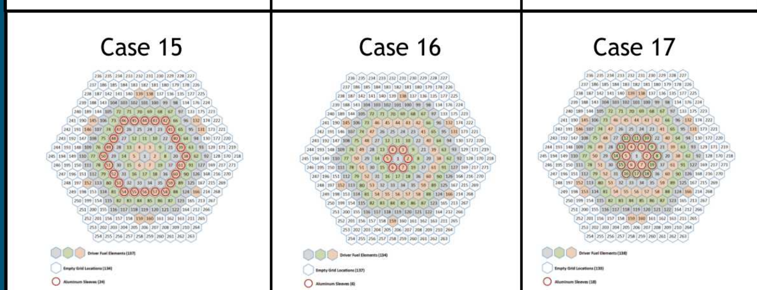
- Simplifications
  - Springs from all fuel elements removed
  - Control and safety elements replaced with driver fuel elements
  - Gap between the grid plates and the end plugs of fuel elements removed
  - Grooves in end plugs of fuel elements filled in
  - Population average value for fuel mass was used
  - Population average value for fuel element outer diameter was used
  - All materials outside the core tank were removed
  - Sleeve drain holes removed
  - Neutron detectors removed
  - Centering pieces replaced with water
  - Source and source holder removed
  - Population average used for sleeve OD
  - Source element converted to fuel element
- Temperature corrections
- Fractional fuel element bias
- Overall reactivity bias

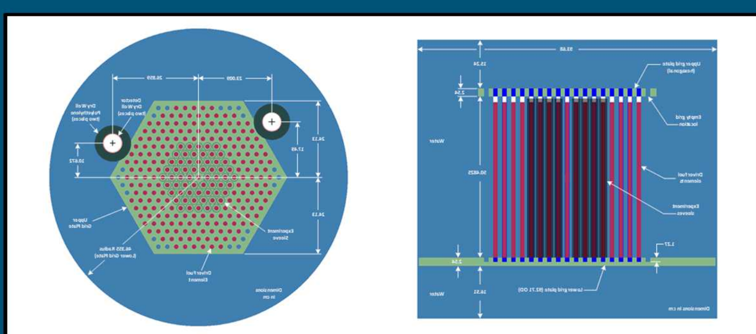
Overall Bias

Case	Simplification Bias		Integral Fuel Element Bias		Overall Bias	
	Bias	Uncertainty	Bias	Uncertainty	Bias	Uncertainty
1	-0.00001	0.00001	0.000183	0.000006	0.00017	0.00002
2	-0.00012	0.00001	-0.000230	0.000003	-0.00035	0.00001
3	0.00009	0.00001	-0.000297	0.000004	-0.00021	0.00001
4	-0.00026	0.00001	-0.000099	0.000004	-0.00036	0.00001
5	0.00003	0.00001	-0.000006	0.000003	0.00002	0.00001
6	0.00000	0.00001	0.000541	0.000007	0.00054	0.00002
7	-0.00006	0.00001	-0.000034	0.000004	-0.00009	0.00001
8	0.00024	0.00001	0.000308	0.000005	0.00055	0.00001
9	-0.00033	0.00001	-0.000115	0.000009	-0.00045	0.00002
10	-0.00015	0.00001	-0.000758	0.000007	-0.00091	0.00002
11	-0.00015	0.00001	0.000689	0.000007	0.00054	0.00002
12	-0.00011	0.00001	0.000620	0.000007	0.00051	0.00002
13	-0.00011	0.00001	0.000174	0.000006	0.00006	0.00002
14	-0.00006	0.00001	0.000058	0.000007	0.00000	0.00002
15	-0.00004	0.00001	-0.000441	0.000004	-0.00048	0.00001
16	-0.00008	0.00001	0.000453	0.000006	0.00037	0.00002
17	-0.00004	0.00001	0.000088	0.000008	0.00005	0.00002

Benchmark Model k_{eff}







Benchmark Model Results

Case	Benchmark Model k_{eff}	Bias Uncertainty	Experiment Uncertainty	Total Benchmark Model Uncertainty
1	1.00017	0.00002	0.00071	0.00071
2	0.99965	0.00001	0.00083	0.00083
3	0.99979	0.00001	0.00083	0.00083
4	0.99964	0.00001	0.00083	0.00083
5	1.00002	0.00001	0.00083	0.00083
6	1.00054	0.00002	0.00083	0.00083
7	0.99991	0.00001	0.00083	0.00083
8	1.00055	0.00001	0.00083	0.00083
9	0.99955	0.00002	0.00083	0.00083
10	0.99909	0.00002	0.00071	0.00071
11	1.00054	0.00002	0.00071	0.00071
12	1.00051	0.00002	0.00071	0.00071
13	1.00006	0.00002	0.00071	0.00071
14	1.00000	0.00002	0.00071	0.00071
15	0.99952	0.00001	0.00071	0.00071
16	1.00037	0.00002	0.00071	0.00071
17	1.00005	0.00002	0.00071	0.00071

Results of Sample Calculations (MCNP 6.2)

Reactivity Offset

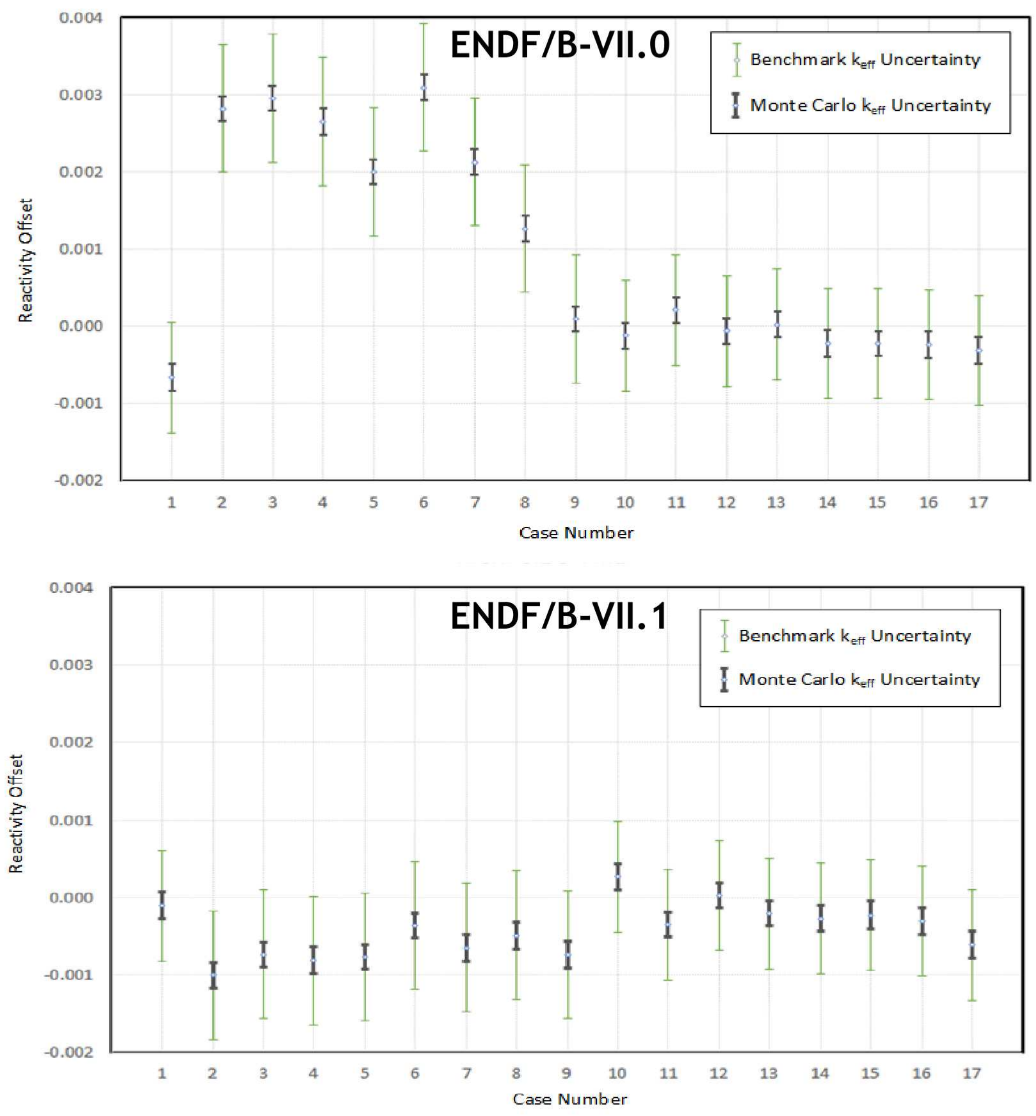
$$\rho = \frac{k_c - k_b}{k_c \cdot k_b}$$

$\rho =$ reactivity offset

$k_c =$ calculated k_{eff}

$k_b =$ evaluated benchmark k_{eff}

Library	ENDF/B-VII.0	ENDF/B-VII.1
Average Offset (titanium)	0.0021	-0.0007
Average Offset (aluminum)	-0.0001	-0.0002
Average Offset (all cases)	0.0009	-0.0004



Conclusions

- Second set of titanium experiments now complete.
  - First set LCT-097 for titanium rods in 7uPCX
- To be included as LCT-099 in 2019 ICSBEP Handbook

Acknowledgements

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