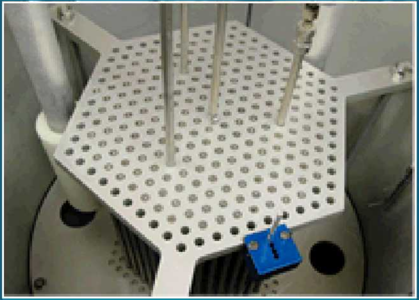
SAND2019-13814C

Sandia BUCCX Titanium and Aluminum Sleeve Experiments



PRESENTED BY

David Ames

2019 ANS Winter Meeting
Washington, DC

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Introduction

Sandia Critical Experiments Facility
- 7uPCX
- BUCCX

Titanium and Aluminum Sleeves
- Centering Pieces

Experimental Method

Results
- Critical Arrays
- Sleeve Reactivity Worth
- Uncertainty Analysis
- Benchmark Model
- Reactivity Offset

Conclusions

Acknowledgements

Sandia Critical Experiments Facility

The Seven Percent Critical Experiment (7uPCX)

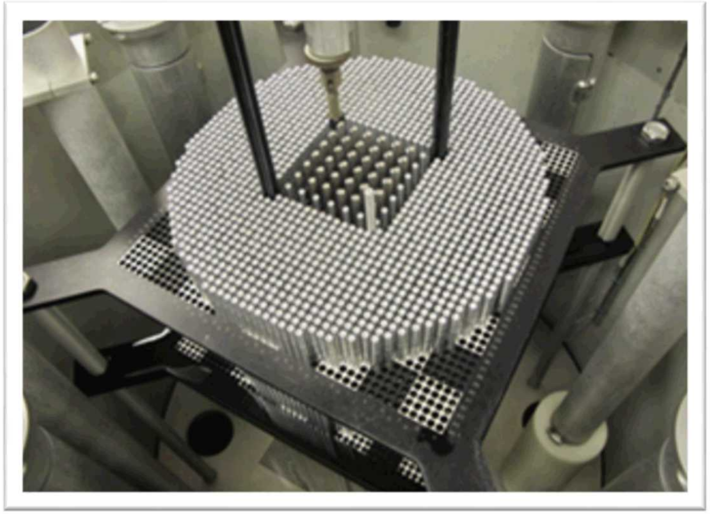
- UO_2 fuel (6.9%)
- 45x45 Square array (pitch 0.315 and 0.337 inch)
- Fuel locations 2025
- Fuel rod diameter 0.25 inch
- Fuel length 19.25 inch
- LCT-078, 080, 096, 097, 101 (experiments completed earlier this year)

The Burnup Credit Critical Experiment (BUCCX)

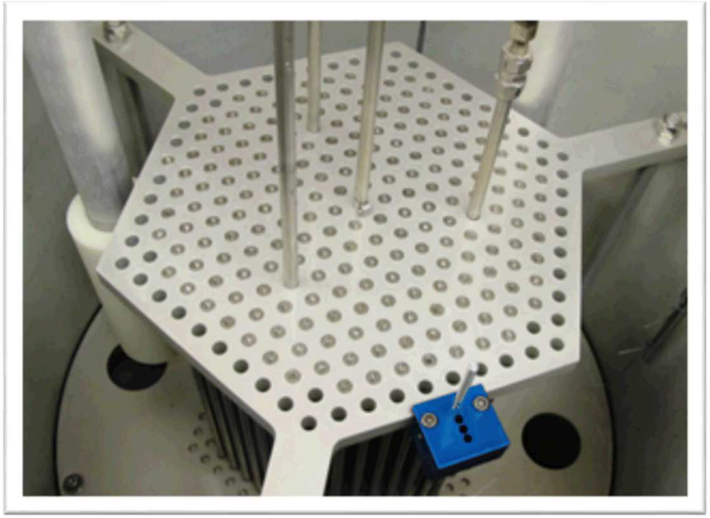
- UO_2 fuel (4.3%)
- Triangular pitch (0.787 and 1.1 inch)
- Fuel locations 397 and 271
- Fuel rod diameter 0.544 inch
- Fuel length 19.37 inch
- LCT-079, 099

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 Sleeves Experiments

<u>Experiment motivation</u>

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

<u>Titanium sleeves</u>

- 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

<u>Aluminum sleeves</u>

- 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

<u>Polyethylene Centering Pieces</u>

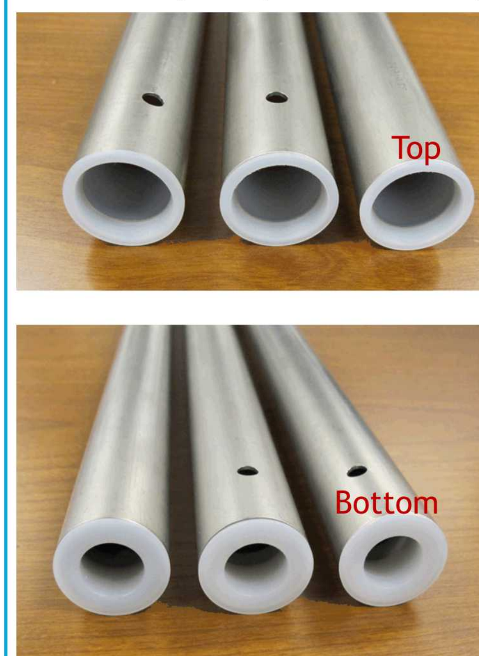
- Length 0.85 inch (2.159 cm)
- O-rings hold in place

Sleeve ID number

Top and bottom centering pieces

Top centering piece inserted

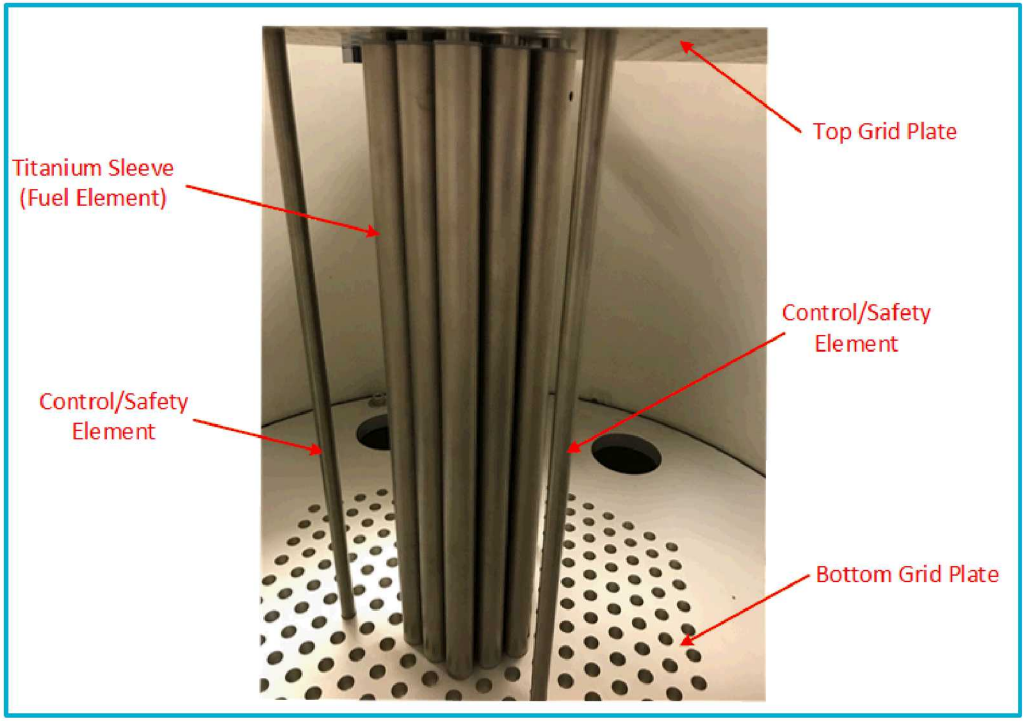
Sleeves ready to be placed in assembly

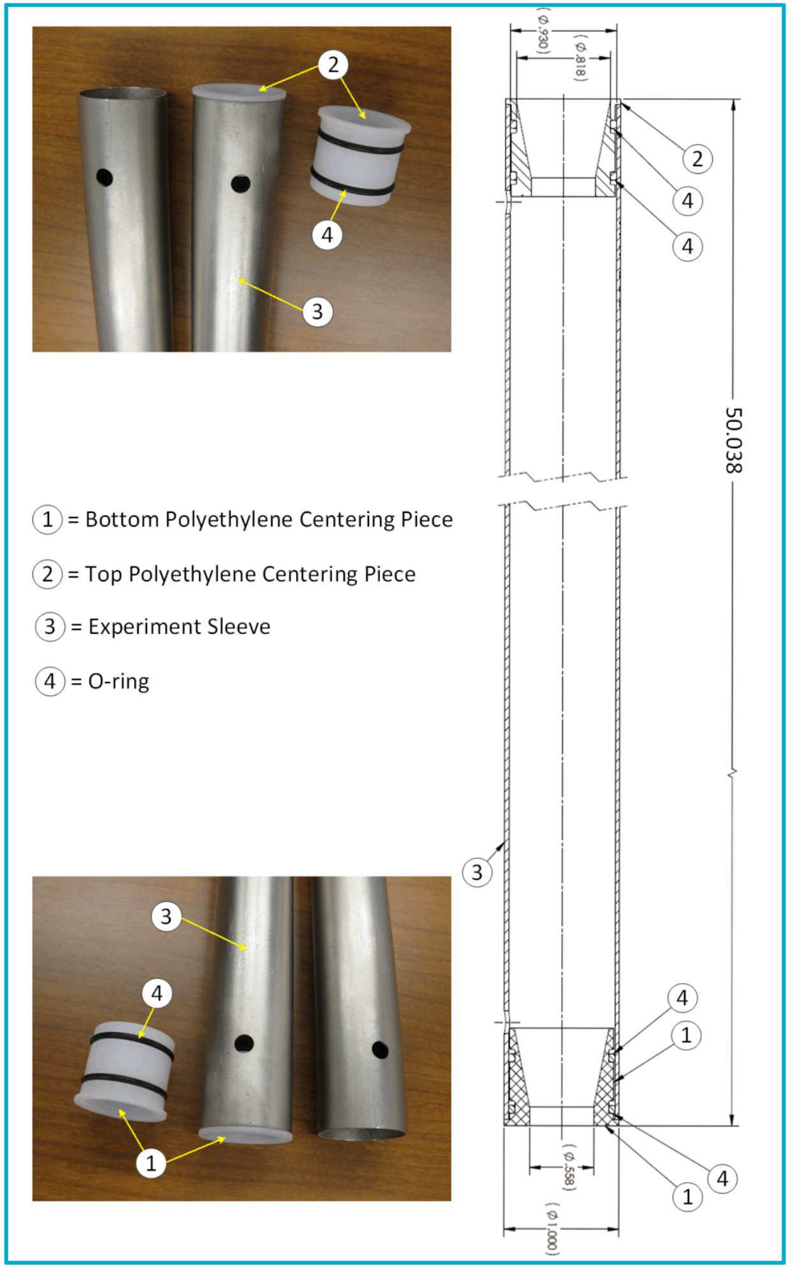


Titanium and Aluminum Sleeves

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.

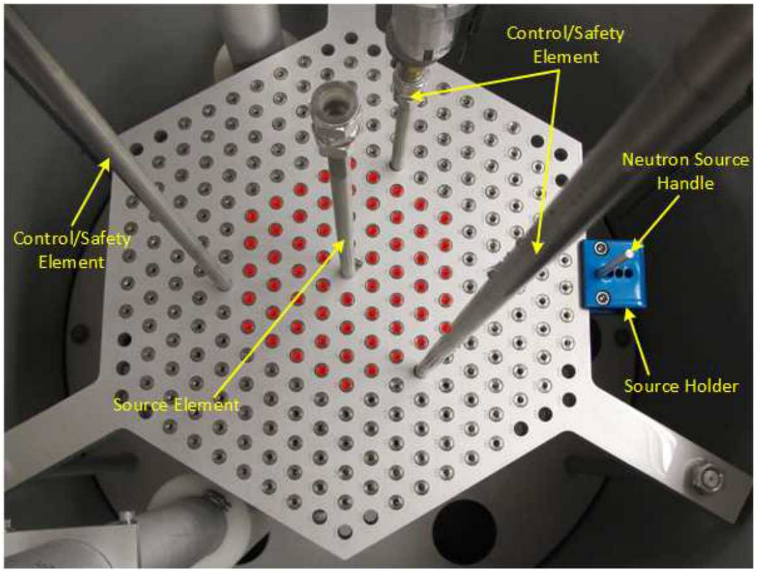
- All titanium experiments have corresponding aluminum experiments
  - Configuration of the sleeves (titanium and aluminum) the same for each case
  - Number of fuel rods in the array will differ due to the effects of titanium and aluminum

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

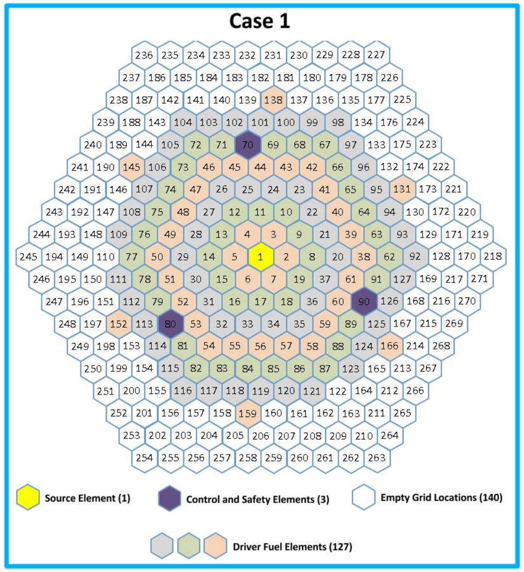
- Array fully reflected by water
- Approach parameter is the number of fuel rods
  - Load from center toward the outside while maintaining a roughly cylindrical cross section of the array
  - Inverse count rate as function of number of fuel rods extrapolated to zero to obtain critical array size
- Initial 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
  - Loading order guided by fuel element incremental worth calculations

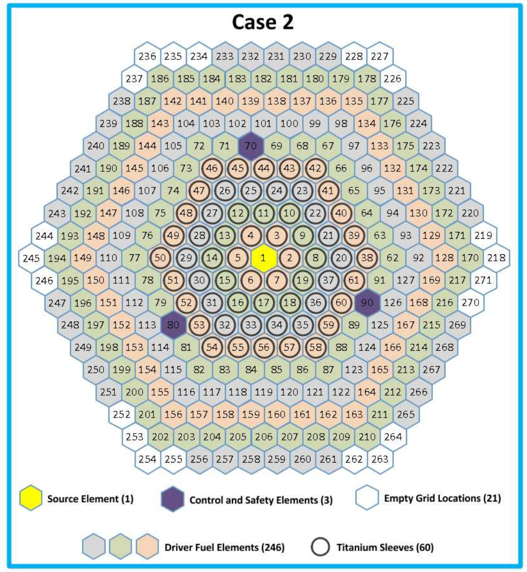
17 critical experiments performed

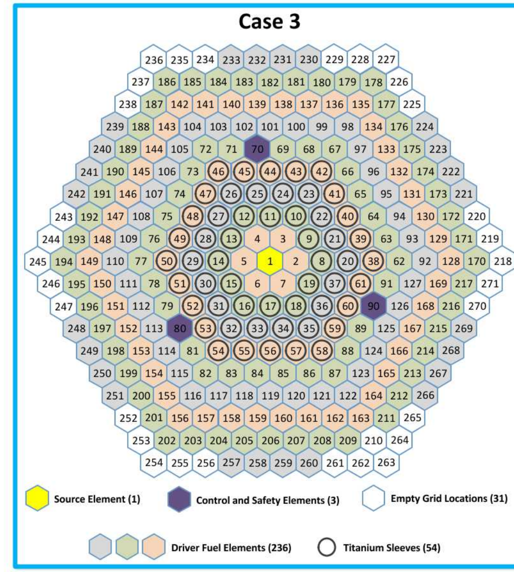
- 1 with no sleeves
- 8 cases with titanium sleeves (varying configurations)
- 8 cases with aluminum sleeves (matching titanium cases)

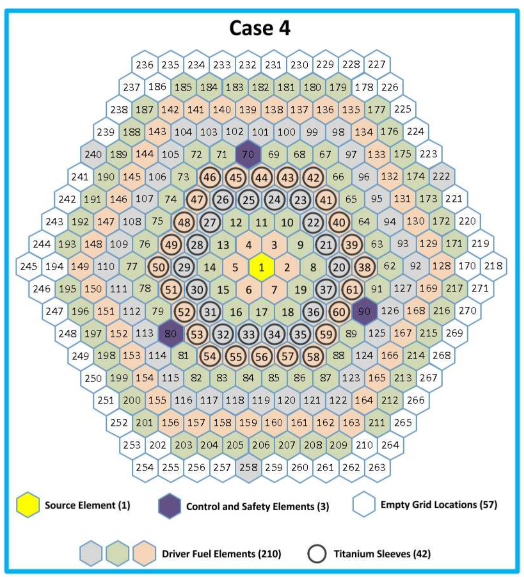


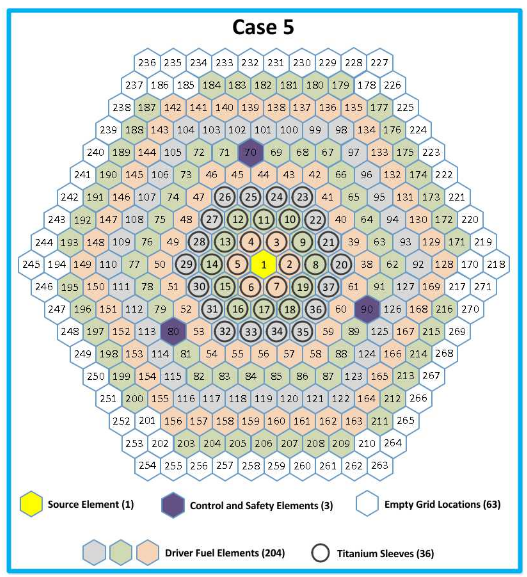
Fuel Element Layout for Largest Array Measured(17 cases)

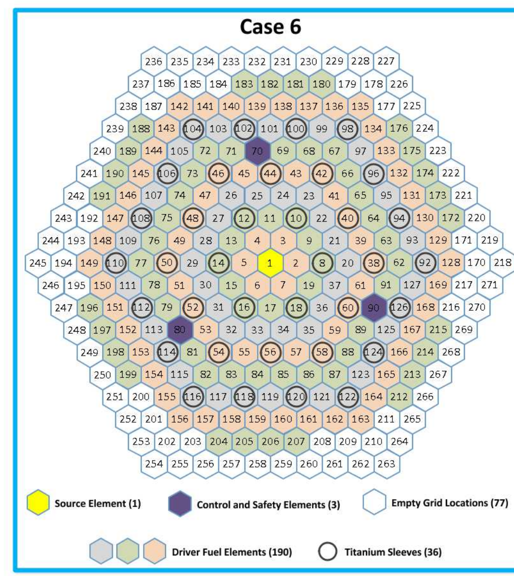






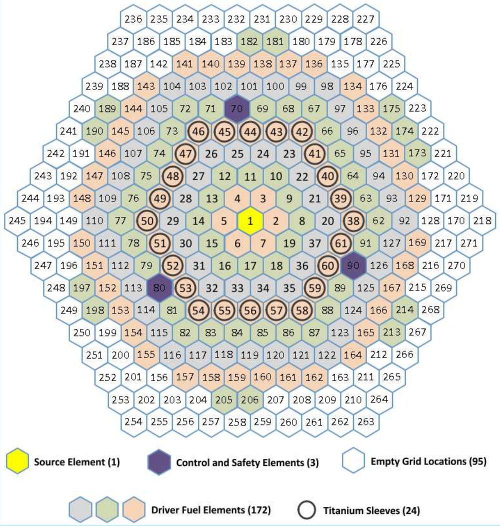




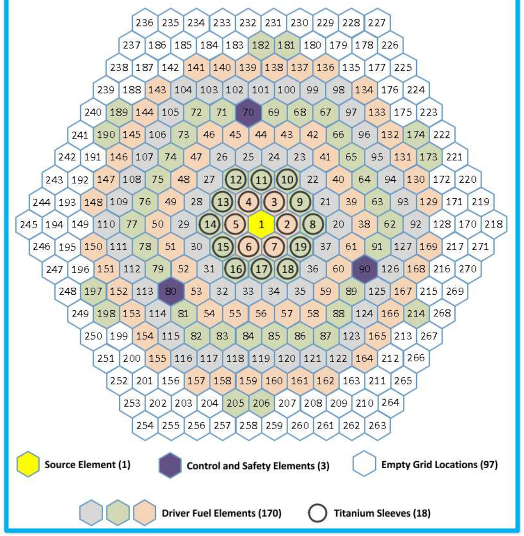


Fuel Element Layout for Largest Array Measured(17 cases)

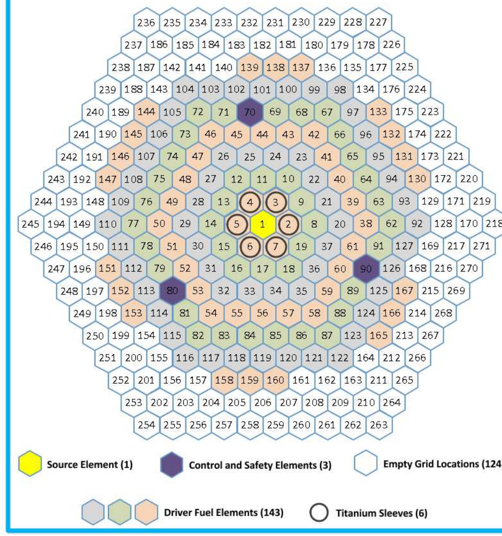
Case 7



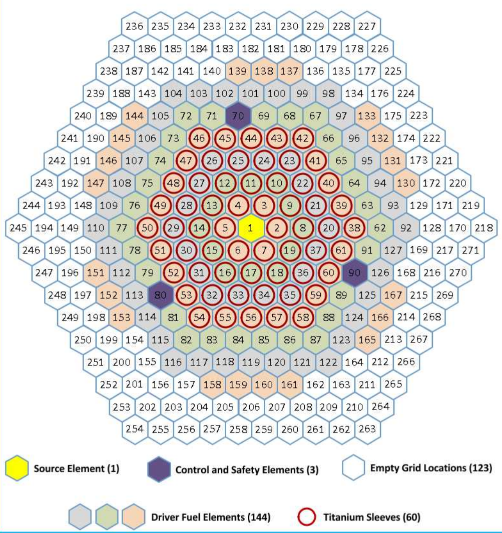
Case 8



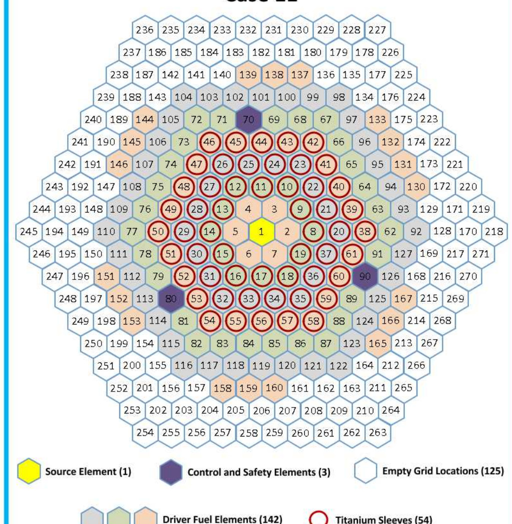
Case 9



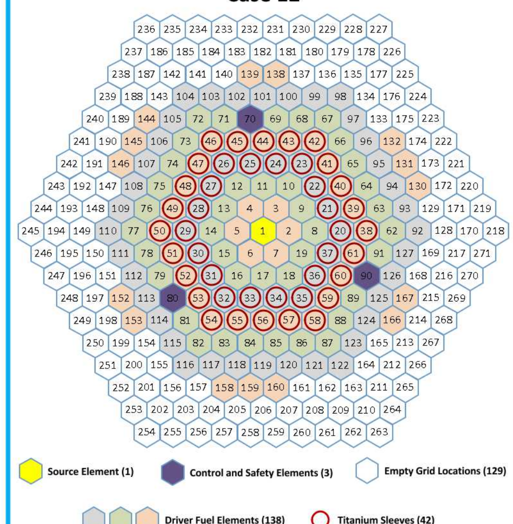
Case 10



Case 11

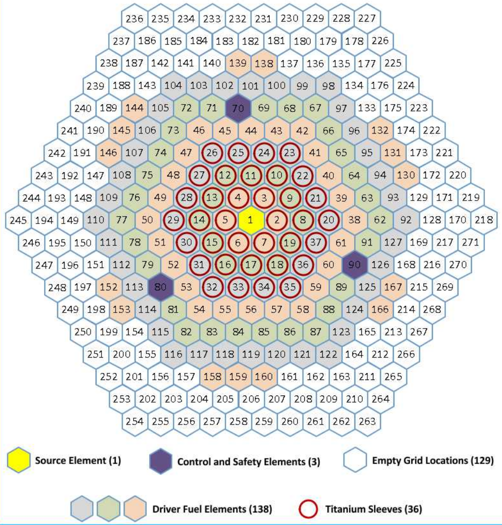


Case 12

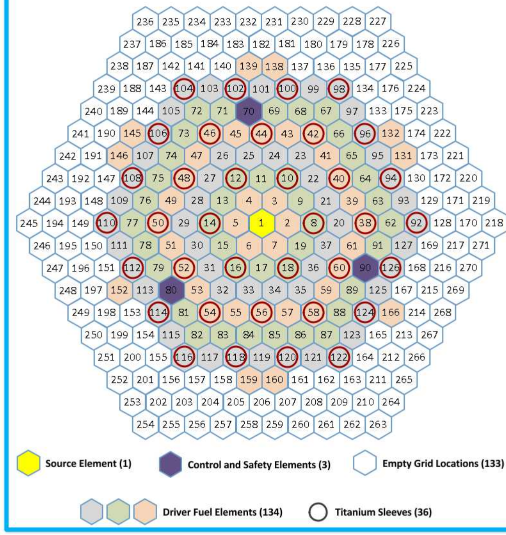


Fuel Element Layout for Largest Array Measured(17 cases)

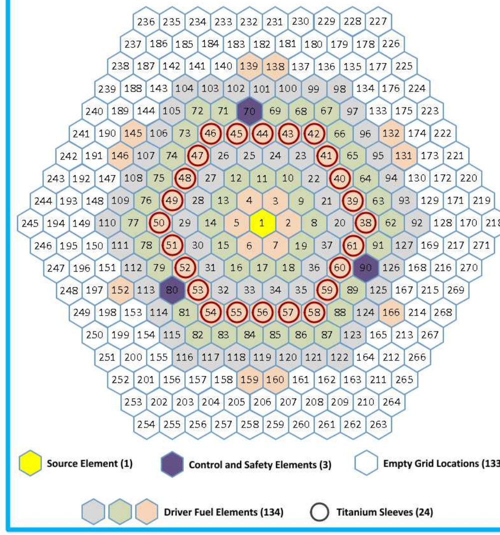
Case 13



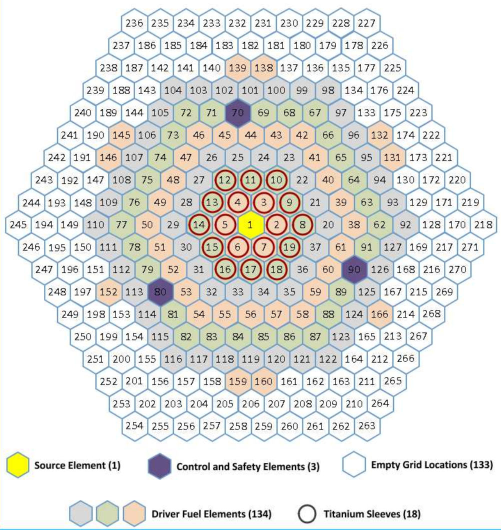
Case 14



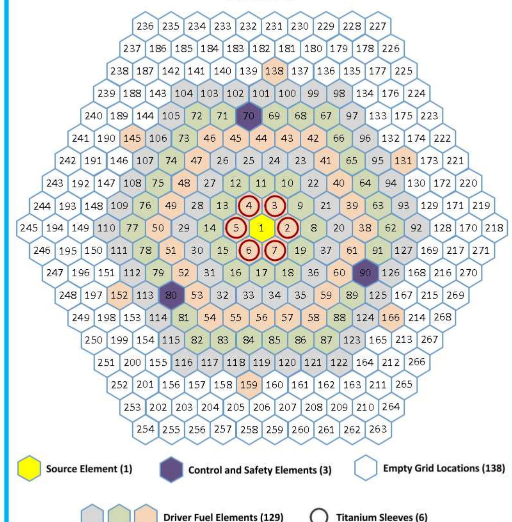
Case 15



Case 16

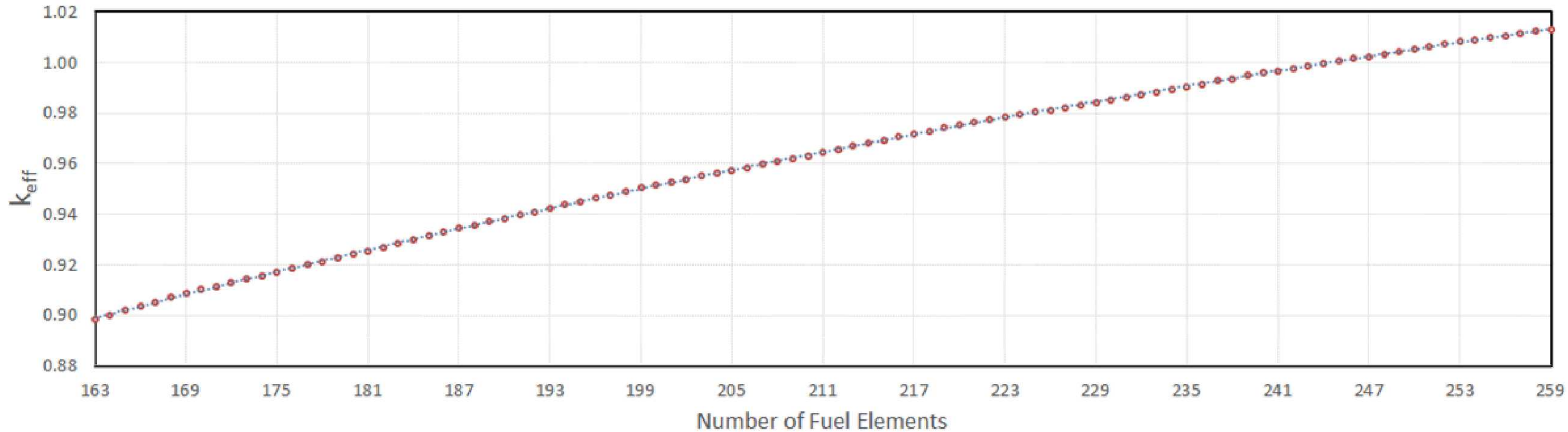


Case 17

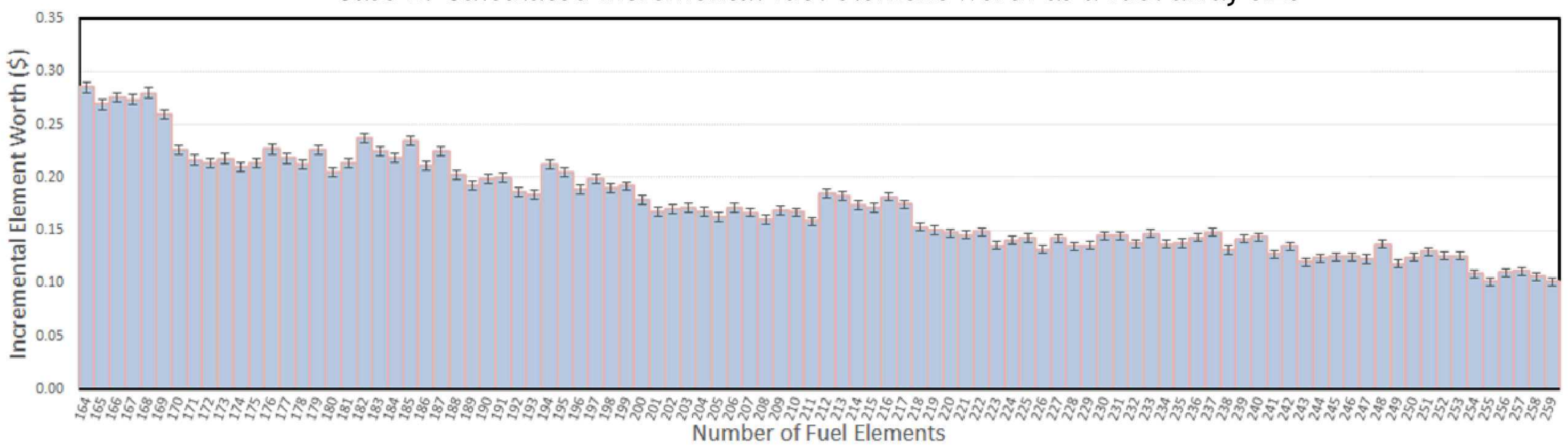


Core Analysis (critical fuel load and fuel element worth)

Case 2: Calculated k_{eff} for the assembly as a function of fuel elements

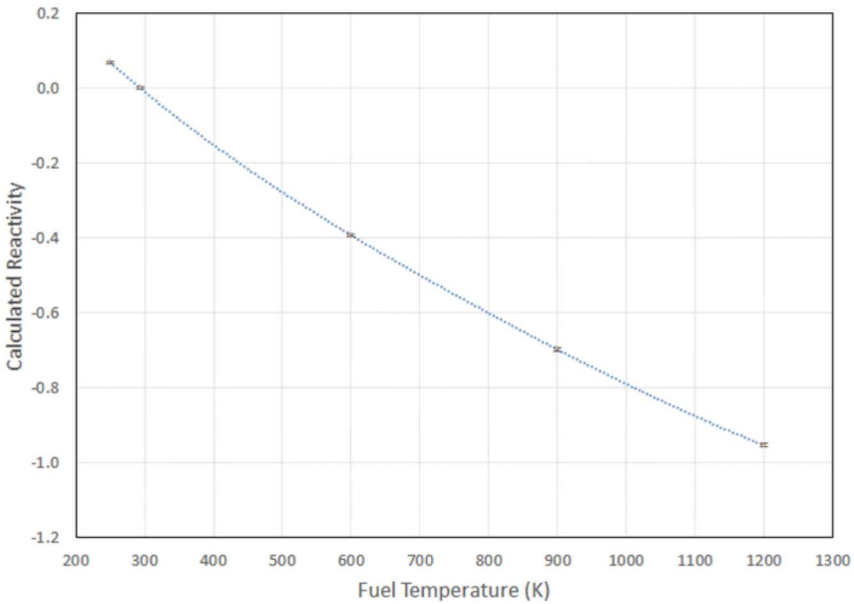


Case 2: Calculated incremental fuel element worth as a fuel array size

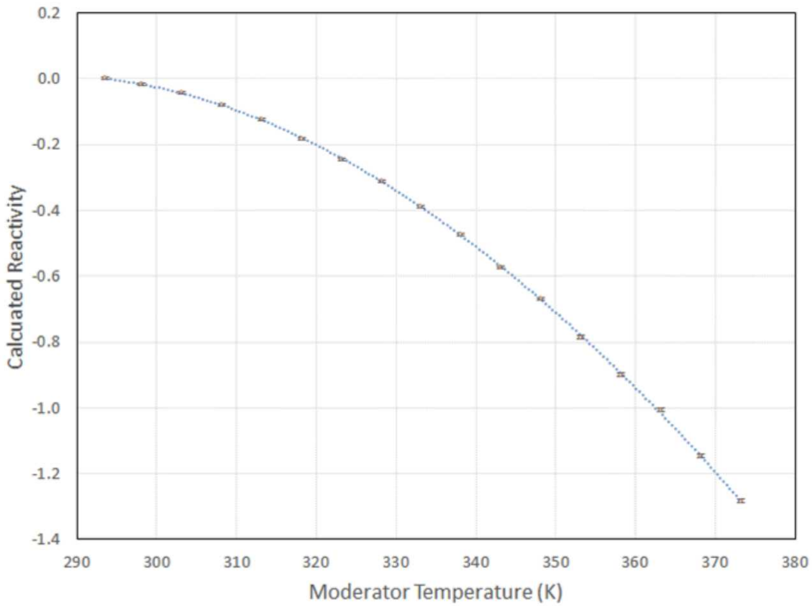


Core Analysis (reactivity temperature coefficients)

Case 1: Core reactivity as function of fuel temperature



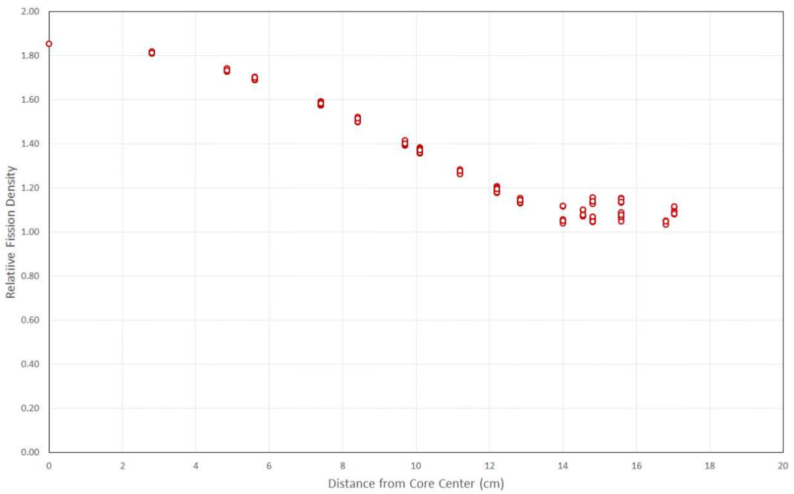
Case 1: Core reactivity as function of moderator temperature

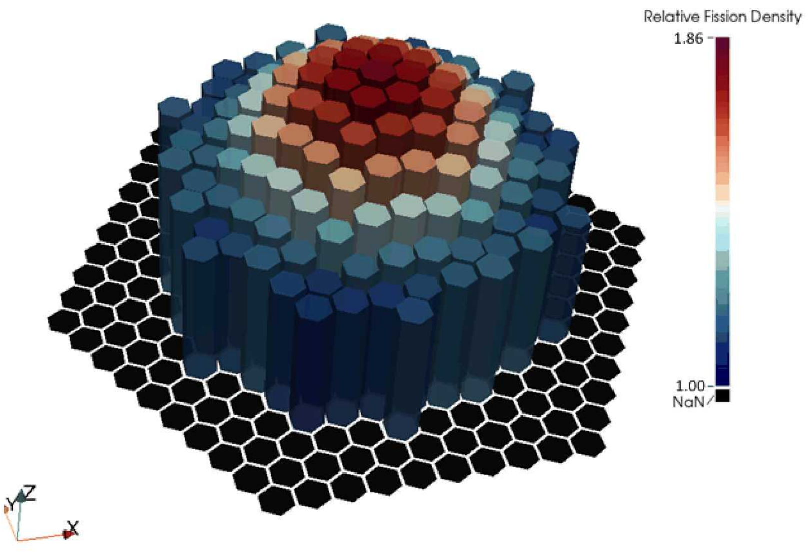


Fuel temperature coefficient at 25°C	-0.0015 $/°C
Moderator temperature coefficient at 25°C	-0.0045 $/°C
Isothermal temperature coefficient at 25°C	-0.0059 $/°C

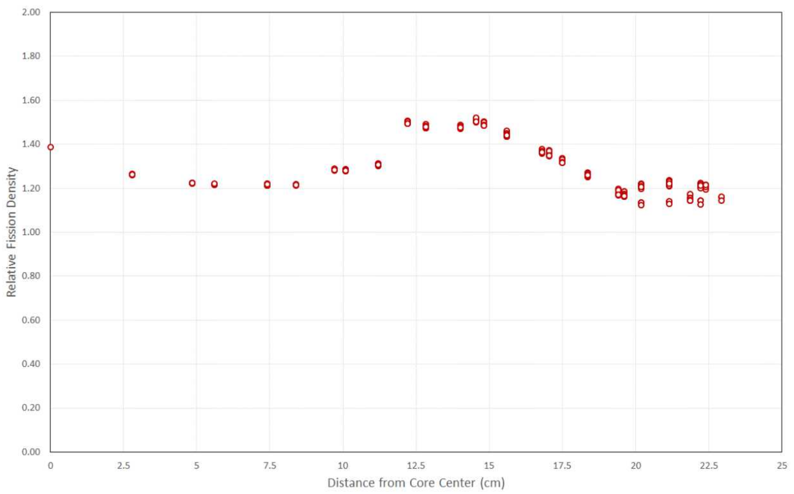
Core Analysis (fission density)

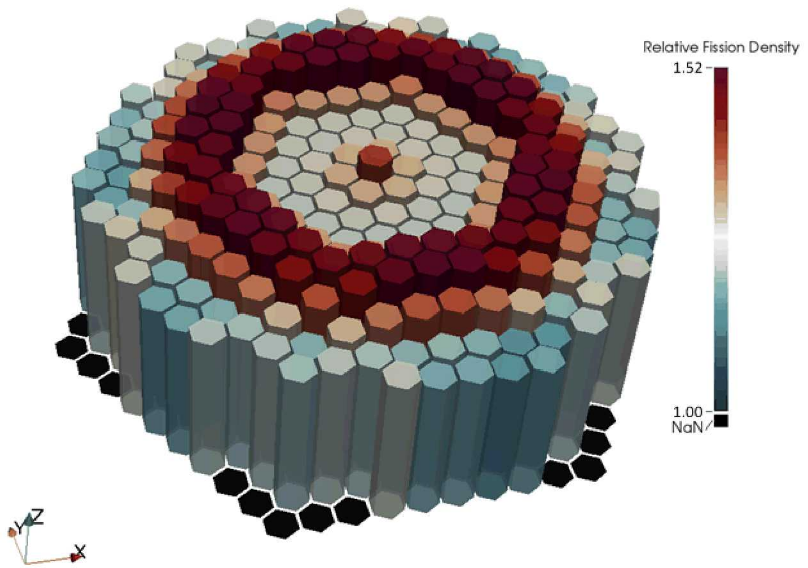
Case 1 (no sleeves)



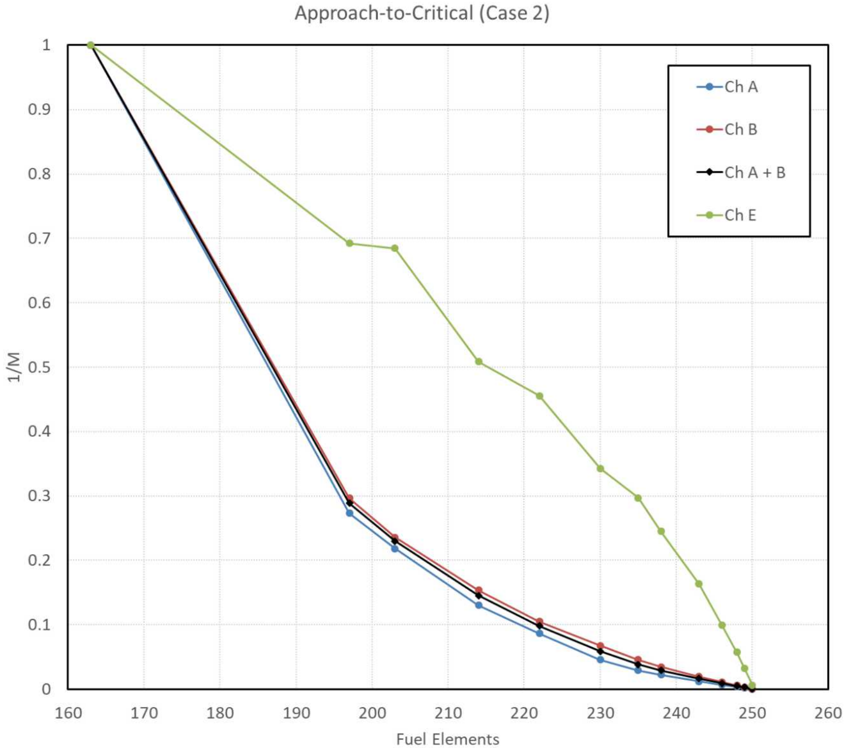


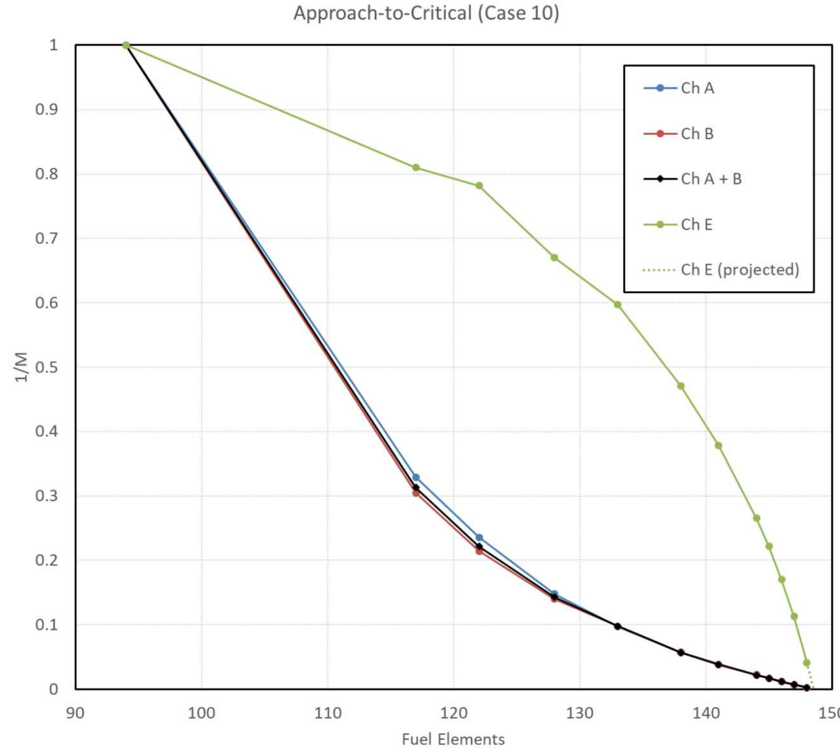
Case 2 (60 titanium sleeves)

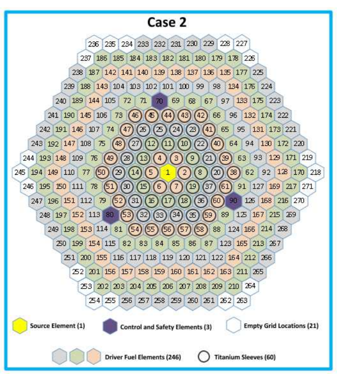




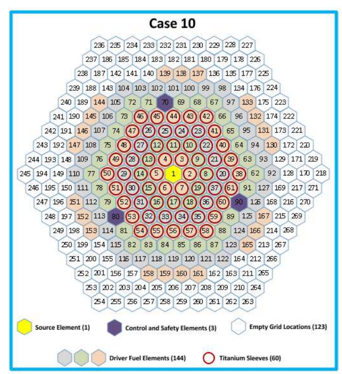
Approach-to-Critical (case 2 and 10)







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



Fuel elements	Projection (A+B)	Uncertainty
94	-	-
117	127.4899	0.3654
122	134.0724	0.7031
128	138.8769	0.4713
133	143.7873	0.4024
138	145.0113	0.1653
141	147.0648	0.1404
144	148.0980	0.0500
145	148.3521	0.0537
146	148.2732	0.0235
147	148.4754	0.0093
148	148.4934	0.0013

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	Largest Subcritical Array Measured			Extrapolated Critical Array Size (Elements)	Nearest Integral Array Size (Elements)	Experiment Temperature (°C)
	Number of Fuel Elements	Number of Driver Fuel Elements[(a)]	Driver Element UO_2 Mass (g)			
1	131	127	81127.50	131.877 ± 0.004	132	25.1
2	250	246	156832.50	250.228 ± 0.000	250	25.0
3	240	236	150400.00	240.296 ± 0.000	240	25.1
4	214	210	133721.00	215.098 ± 0.003	215	24.9
5	208	204	129868.50	209.016 ± 0.003	209	24.8
6	194	190	120915.50	194.502 ± 0.001	195	24.7
7	176	172	109586.00	177.050 ± 0.004	177	24.6
8	174	170	108327.00	174.741 ± 0.002	175	24.8
9	147	143	91273.00	148.088 ± 0.006	148	24.6
10	148	144	91912.50	148.493 ± 0.001	148	25.0
11	146	142	90634.50	146.560 ± 0.002	147	24.5
12	142	138	88096.00	142.565 ± 0.002	143	25.0
13	142	138	88096.00	142.889 ± 0.004	143	24.7
14	137	133	84920.50	137.960 ± 0.005	138	25.1
15	137	133	84920.50	137.283 ± 0.001	137	25.4
16	137	133	84920.50	137.714 ± 0.003	138	24.6
17	133	129	82390.00	133.952 ± 0.005	134	24.7

(a) All cores include a source element and three control/safety elements.

Uncertainty Analyses

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

- Direct Perturbations (pitch, clad OD and thickness, fuel OD, water height, fuel mass, temperature)
  - Least-squares fit with uncertainty propagation
- Sensitives to materials (KSEN)
  - Combined to assess uncertainties
  - Fuel Enrichment Sensitivity: $S_E = \frac{A_U N_U}{A_{235} N_{235}} C_{235} - \frac{A_U N_U}{A_{238} N_{238}} C_{238}$, S=sensitivity, A=atomic mass, N=atom density, C=sensitivity coefficient
- 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 Value	Sensitivity Unc.	Δk_{eff}
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 contained in Benchmark 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 (pitch, clad OD and thickness, fuel OD, water height, fuel mass, temperature)
  - Least-squares fit with uncertainty propagation
- Sensitives to materials (KSEN)
  - Combined to assess uncertainties
  - Fuel Enrichment Sensitivity: $S_E = \frac{A_U N_U}{A_{235} N_{235}} C_{235} - \frac{A_U N_U}{A_{238} N_{238}} C_{238}$, S=sensitivity, A=atomic mass, N=atom density, C=sensitivity coefficient
- 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 contained in Benchmark 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 (pitch, clad OD and thickness, fuel OD, water height, fuel mass, temperature)
  - Least-squares fit with uncertainty propagation
- Sensitives to materials (KSEN)
  - Combined to assess uncertainties
  - Fuel Enrichment Sensitivity: $S_E = \frac{A_U N_U}{A_{235} N_{235}} C_{235} - \frac{A_U N_U}{A_{238} N_{238}} C_{238}$, S=sensitivity, A=atomic mass, N=atom density, C=sensitivity coefficient
- 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:

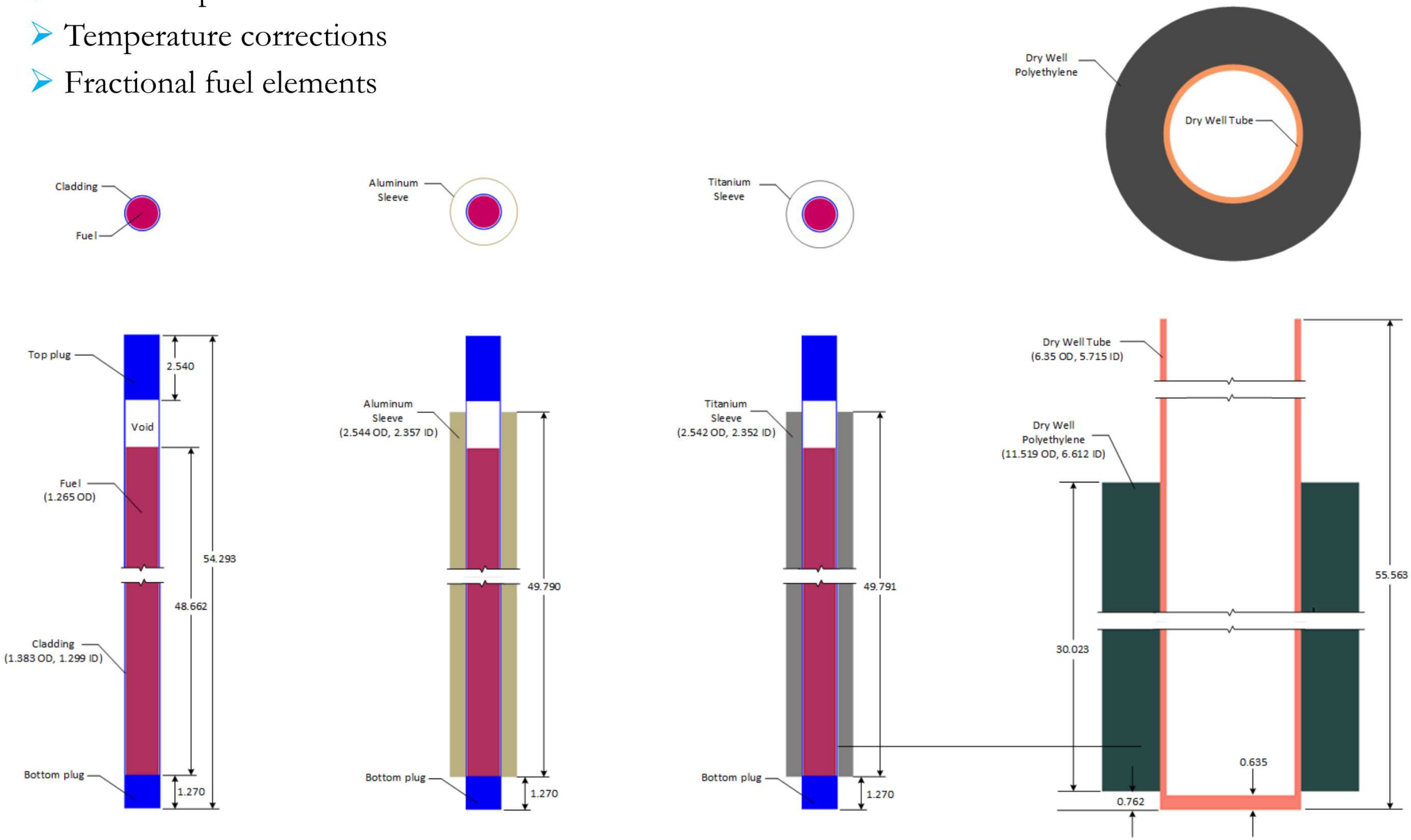
Scientific judgement based on all available information

Case 2: 60 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 contained in Benchmark 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

- Model Simplifications
- Temperature corrections
- Fractional fuel elements



Fuel Element

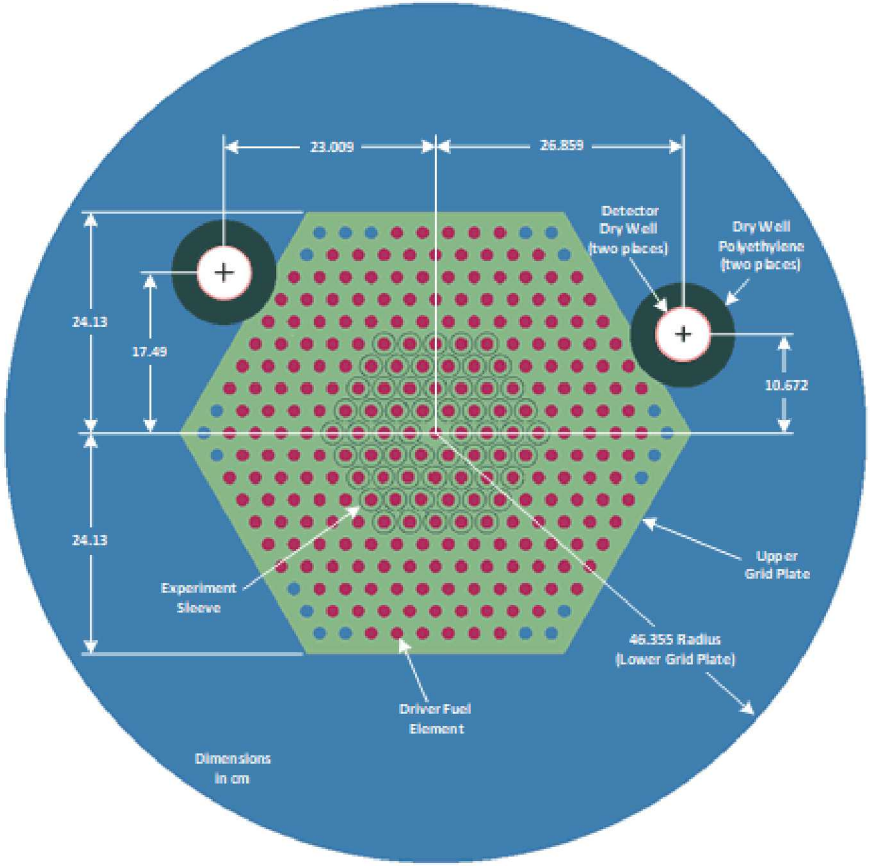
Fuel Element with Aluminum Sleeve

Fuel Element with Titanium Sleeve

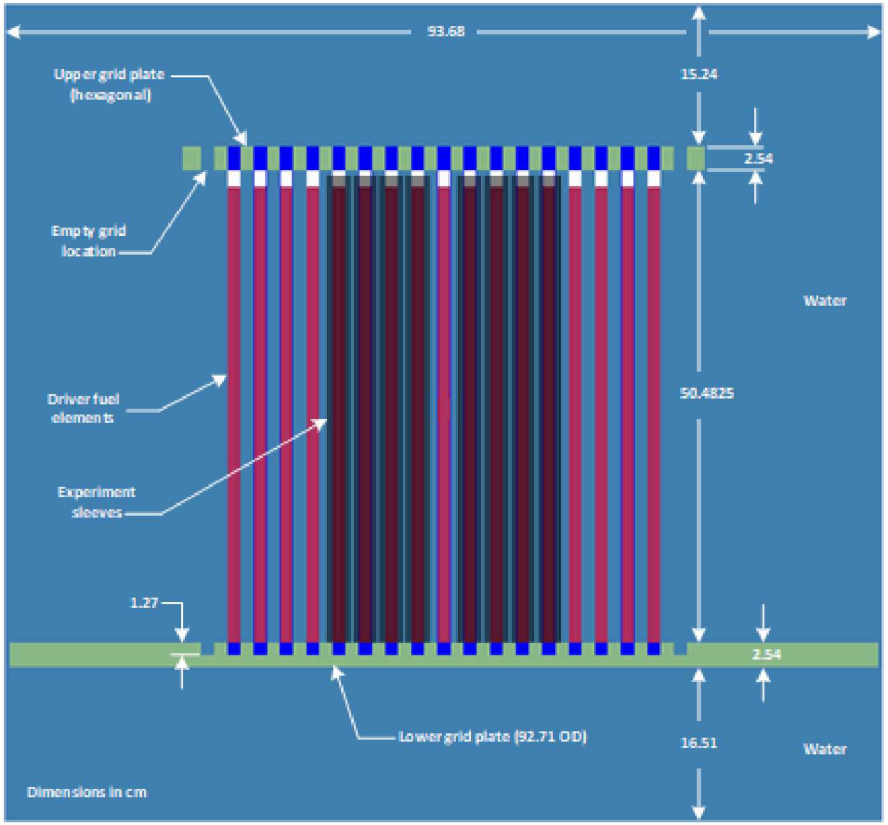
Detector Dry Well

Benchmark Model

Top View Layout



Cut-Away Core



Benchmark Model

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

➢ Model 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 outer and inner diameter
- Source element converted to fuel element

➢ Temperature corrections

- Direct Perturbations

  Least-squares fit with uncertainty propagation

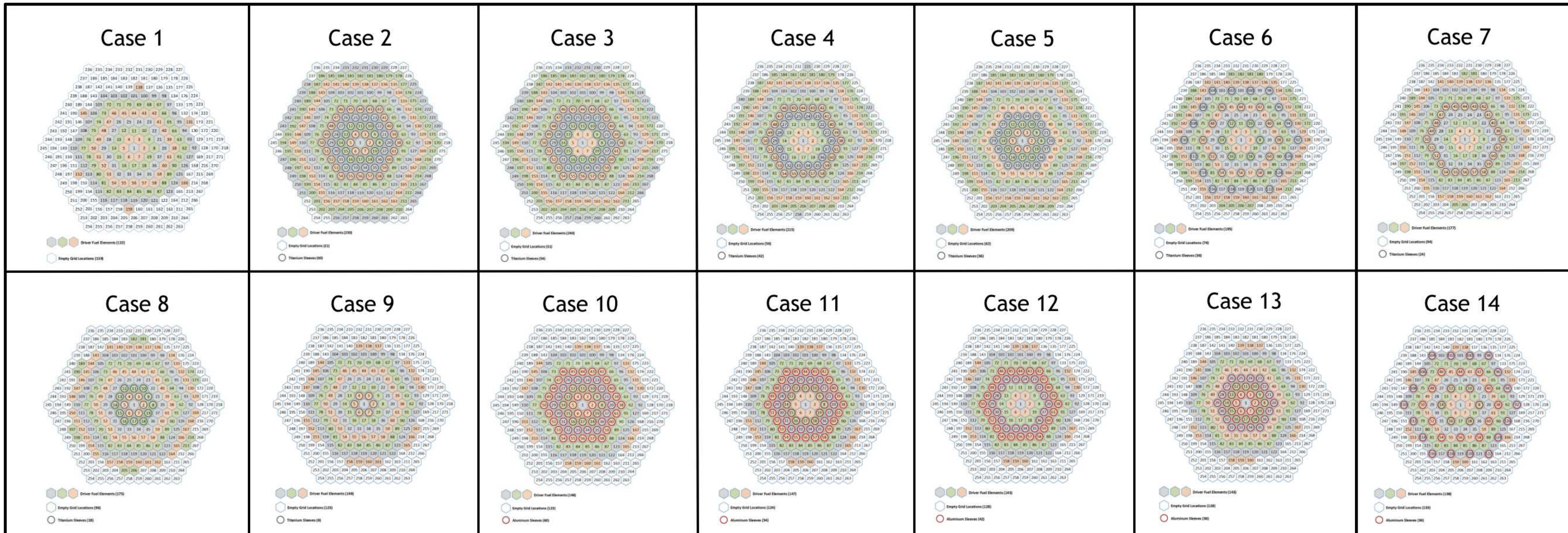
➢ Fractional fuel element bias

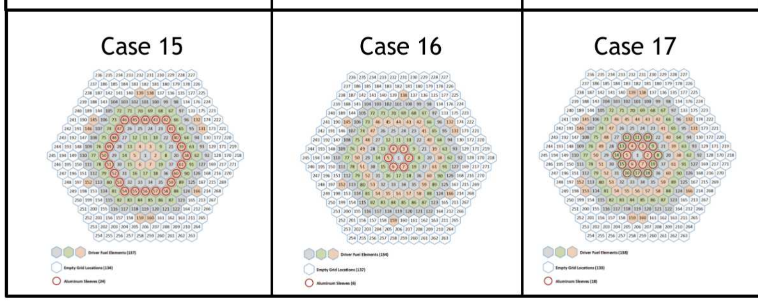
➢ Overall reactivity bias

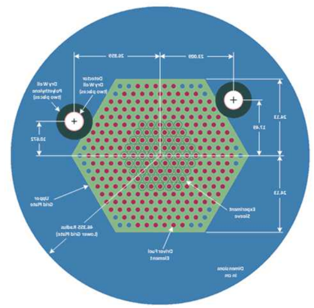
Reactivity Bias and Uncertainty in the Bias

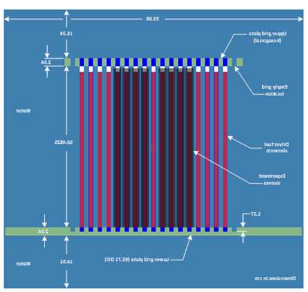
Case	Model Simplifications		Temperature Corrections		Fractional Fuel Elements		Overall	
	Bias	Unc.	Bias	Unc.	Bias	Unc.	Bias	Unc.
1	-0.00001	0.00001	0.00000	0.00000	0.00019	0.00000	0.00017	0.00001
2	-0.00012	0.00001	0.00000	0.00000	-0.00023	0.00000	-0.00035	0.00001
3	0.00009	0.00001	-0.00001	0.00000	-0.00029	0.00000	-0.00021	0.00002
4	-0.00026	0.00001	0.00001	0.00000	-0.00011	0.00000	-0.00036	0.00001
5	0.00003	0.00001	0.00001	0.00000	-0.00002	0.00000	0.00002	0.00001
6	0.00000	0.00001	0.00002	0.00000	0.00052	0.00001	0.00054	0.00002
7	-0.00006	0.00001	0.00002	0.00000	-0.00006	0.00000	-0.00009	0.00001
8	0.00024	0.00001	0.00001	0.00000	0.00030	0.00000	0.00055	0.00002
9	-0.00033	0.00001	0.00002	0.00000	-0.00013	0.00000	-0.00045	0.00001
10	-0.00015	0.00001	0.00000	0.00000	-0.00076	0.00001	-0.00091	0.00002
11	-0.00015	0.00001	0.00002	0.00000	0.00067	0.00001	0.00054	0.00002
12	-0.00011	0.00001	0.00000	0.00000	0.00062	0.00001	0.00051	0.00002
13	-0.00011	0.00001	0.00001	0.00000	0.00016	0.00000	0.00006	0.00001
14	-0.00006	0.00001	0.00000	0.00000	0.00006	0.00000	0.00000	0.00001
15	-0.00004	0.00001	-0.00001	0.00000	-0.00043	0.00000	-0.00048	0.00002
16	-0.00008	0.00001	0.00002	0.00000	0.00044	0.00000	0.00037	0.00002
17	-0.00004	0.00001	0.00001	0.00000	0.00007	0.00000	0.00005	0.00001

Benchmark Model k_{eff}









Benchmark Model Results

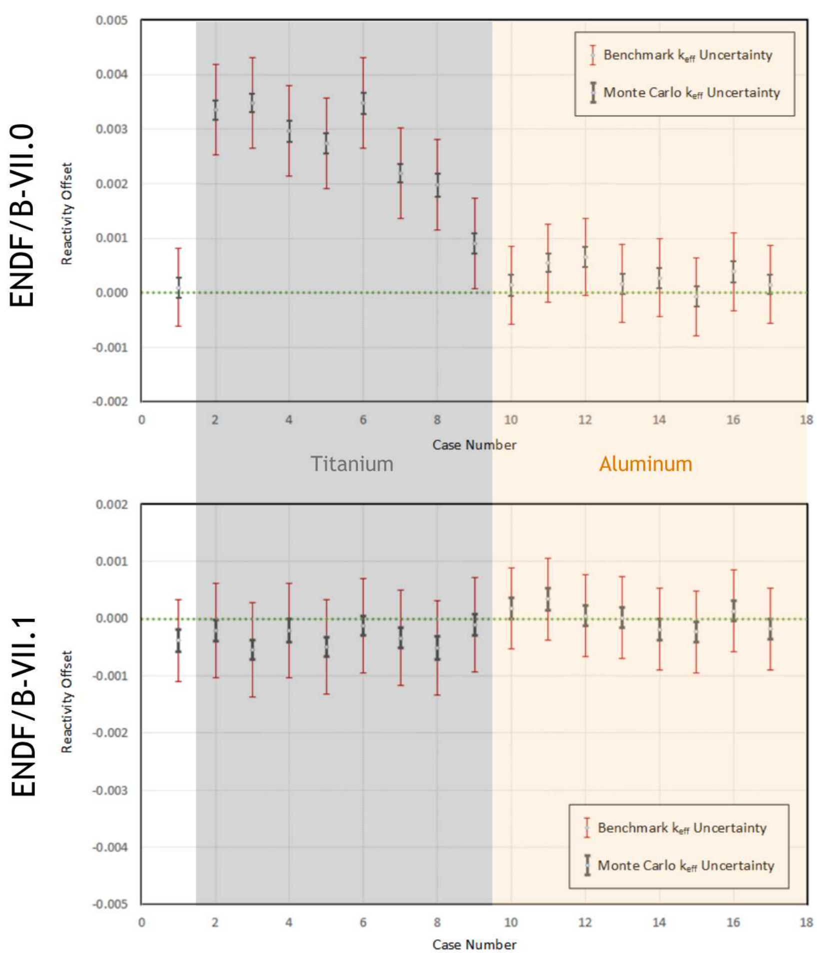
Case	Benchmark Model k_{eff}	Bias Uncertainty	Experiment Uncertainty	Total Benchmark Model Uncertainty
1	1.00017	0.00002	0.00071	0.00071
2	0.99965	0.00001	0.00083	0.00083
3	0.99979	0.00001	0.00083	0.00083
4	0.99964	0.00001	0.00083	0.00083
5	1.00002	0.00001	0.00083	0.00083
6	1.00054	0.00002	0.00083	0.00083
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

$$\rho = \frac{k_c - k_b}{k_c \cdot k_b} \qquad k_c = \text{calculated } k_{eff}$$

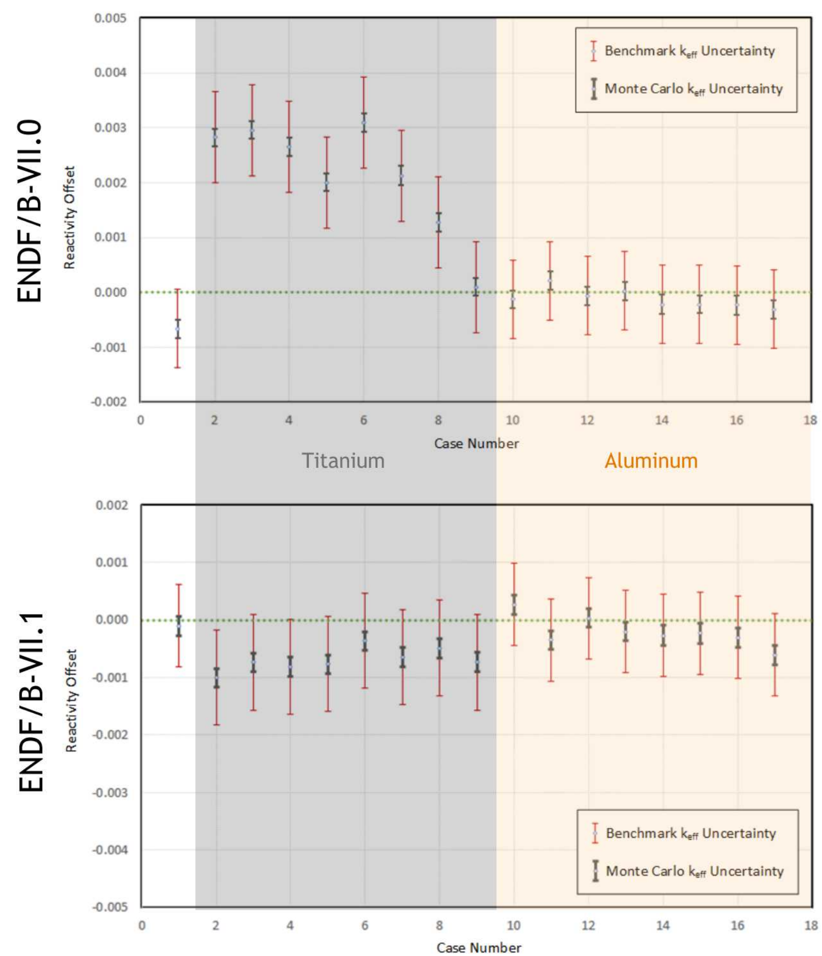
$$\rho = \text{reactivity offset} \qquad k_b = \text{evaluated benchmark } k_{eff}$$

SCALE6.2 KENO-VI CE



Library	Average Reactivity Offset (all cases)	Average Reactivity Offset (Ti cases)	Average Reactivity Offset (Al cases)
ENDF/B-VII.0	0.0014	0.0026	0.0003
ENDF/B-VII.1	-0.0002	-0.0003	-0.0000

MCNP6.2



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

Conclusions

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

Acknowledgements

Gary Harms, John Ford, and Rafe Campbell (Sandia National Laboratories).

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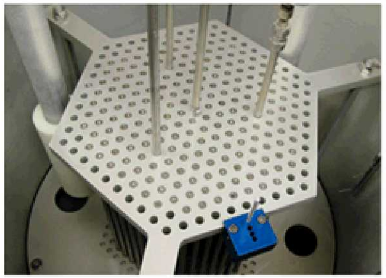
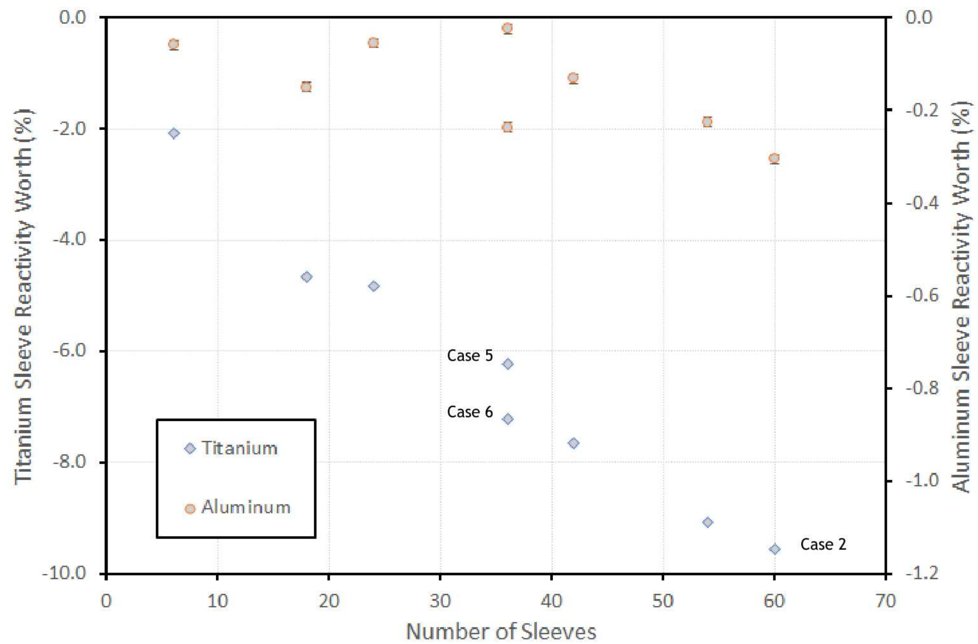
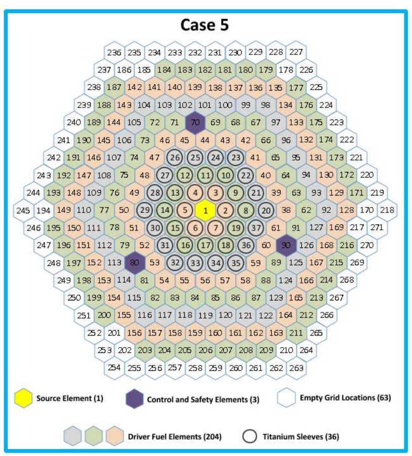
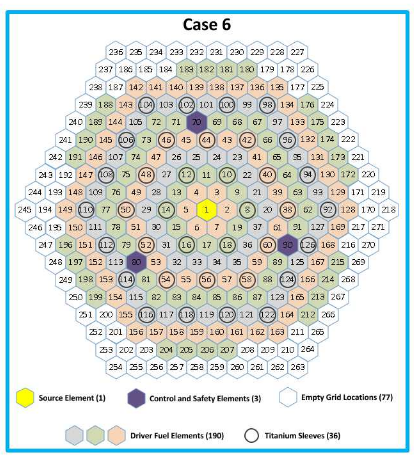


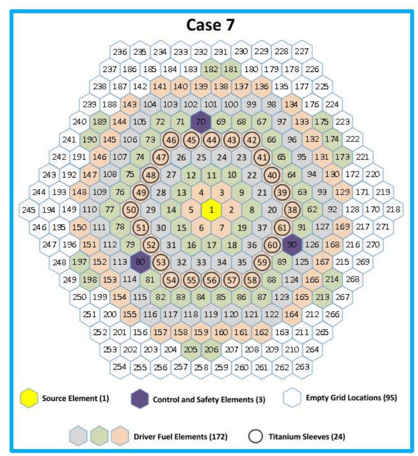

Titanium and Aluminum Sleeve Reactivity Worth

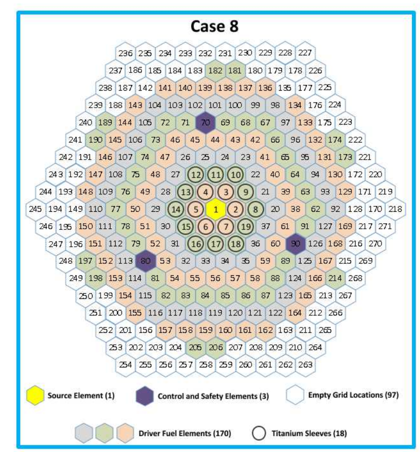
Case	Number of Experiment Sleeves		Experiment Sleeve Reactivity Worth (%)
	Titanium	Aluminum	
1	0	0	0
2	60	0	-9.57 ± 0.01
3	54	0	-9.07 ± 0.01
4	42	0	-7.67 ± 0.01
5	36	0	-7.23 ± 0.01
6	36	0	-6.23 ± 0.01
7	24	0	-4.84 ± 0.01
8	18	0	-4.67 ± 0.01
9	6	0	-2.07 ± 0.01
10	0	60	-0.31 ± 0.01
11	0	54	-0.23 ± 0.01
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 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	Largest Array Measured	Extrapolated Critical Array Size	Nearest Integral Array Size	Experiment Temperature (°C)
1	131	131.877 ± 0.004	132	25.1
2	250	250.228 ± 0.000	250	25.0
3	240	240.296 ± 0.000	240	25.1
4	214	215.098 ± 0.003	215	24.9
5	208	209.016 ± 0.003	209	24.8
6	194	194.502 ± 0.001	195	24.7
7	176	177.050 ± 0.004	177	24.6
8	174	174.741 ± 0.002	175	24.8
9	147	148.088 ± 0.006	148	24.6
10	148	148.493 ± 0.001	148	25.0
11	146	146.560 ± 0.002	147	24.5
12	142	142.565 ± 0.002	143	25.0
13	142	142.889 ± 0.004	143	24.7
14	137	137.960 ± 0.005	138	25.1
15	137	137.283 ± 0.001	137	25.4
16	137	137.714 ± 0.003	138	24.6
17	133	133.952 ± 0.005	134	24.7