Progress at Sandia on NCSP Integral Experiments

Nuclear Criticality Safety Program Technical Review Meeting

Washington, D. C.
May 30, 2013

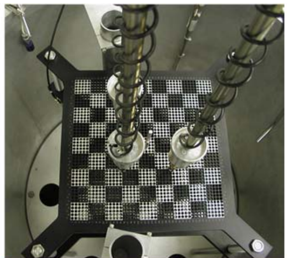
Gary A. Harms
Sandia National Laboratories

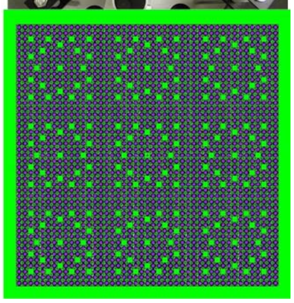
SAND2013-XXXX

What is ahead

- The evaluation of the experiments we completed last year
- The experiments we are doing now
- Our plans for the future

The Seven Percent Critical Experiment (7uPCX) is a NERI project





Project Objective: ***Design, perform, and analyze critical benchmark experiments for validating reactor physics methods and models for fuel enrichments greater than 5-wt% ^{235}U***

- **We built new 7% enriched experiment fuel**
- **We built critical assembly hardware to accommodate the new core**
- **The core is a 45x45 array of rods to simulate 9 commercial fuel elements in a 3x3 array**
- **The experiment is a reactor physics experiment as well as a critical experiment**
- **Additional measurements will be made**
  - **Fission density profiles**
  - **Poison worth**
  - **Effect of water holes**

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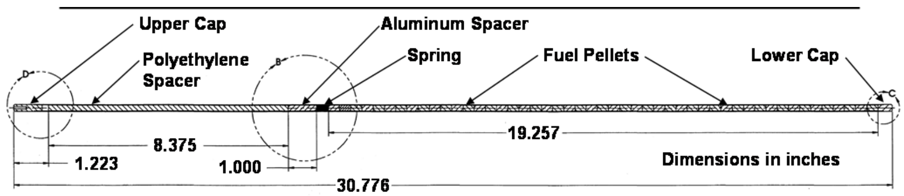
The 7uPCX core uses a new set of fuel rods



- **The fuel is 6.90% enriched, 0.207” (0.536 cm) in diameter**
- **The fuel rods are 0.25” (0.635 cm) in diameter**
- **The fuel rod cladding and end caps are aluminum**
- **The fuel rods extend above the upper grid plate – the upper cap is above the highest level of the moderator**
- **A polyethylene spacer above the upper grid plate replaces the water**

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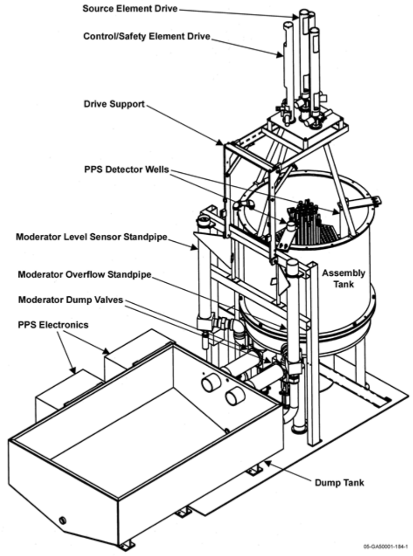
An Overview of the Critical Assembly



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The assembly in person

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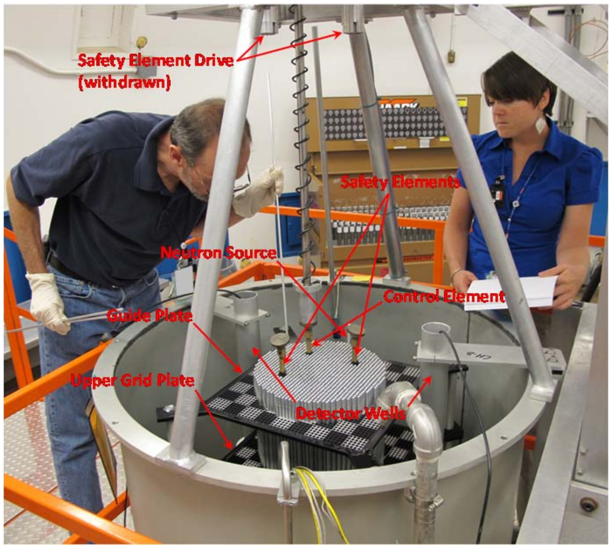
Loading the core



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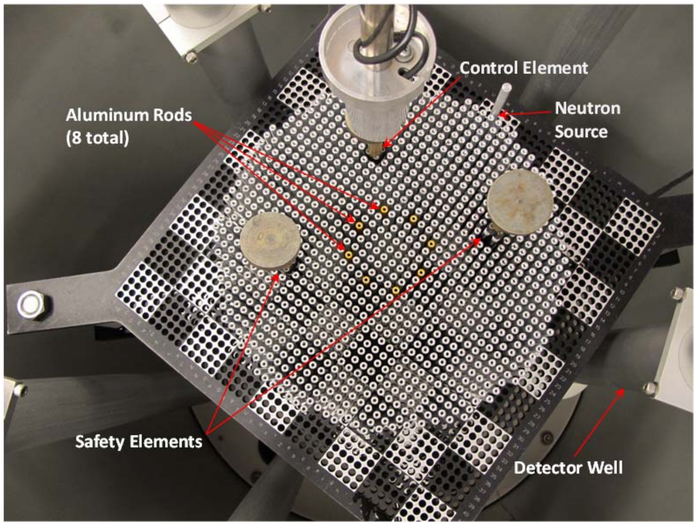
A completed core (LCT078 Case 7)



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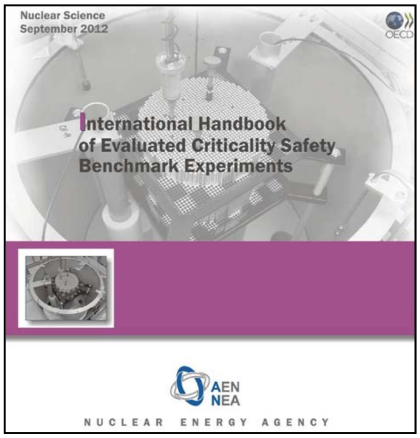
LEU-COMP-THERM-080 is in the book



NEA/NSC/DOC/(95)03/IV
Volume IV

LEU-COMP-THERM-080

WATER-MODERATED SQUARE-PITCHED $U(6.90)O_2$ FUEL ROD LATTICES WITH 0.67 FUEL TO WATER VOLUME RATIO

Evaluator

Gary A. Harms
Sandia National Laboratories

Internal Reviewer
Allison D. Miller

Independent Reviewer

Nicolas Leclaire
Institut de Radioprotection et de Sûreté Nucléaire, IRSN

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LEU-COMP-THERM-078 is in review

NEA/NSC/DOC/(95)03/IV
Volume IV

LEU-COMP-THERM-078

WATER-MODERATED SQUARE-PITCHED $U(6.90)O_2$ FUEL ROD LATTICES WITH 0.52 FUEL-TO-WATER VOLUME RATIO

Evaluator

Gary A. Harms
Sandia National Laboratories

Internal Reviewer

Allison D. Miller

Independent Reviewers

Nicolas Leclaire
François-Xavier Le Dauphin
Institut de Radioprotection et de Sûreté Nucléaire, IRSN

David P. Heinrichs
Allan W. Krass
Lawrence Livermore National Laboratory

Sandia National Laboratories

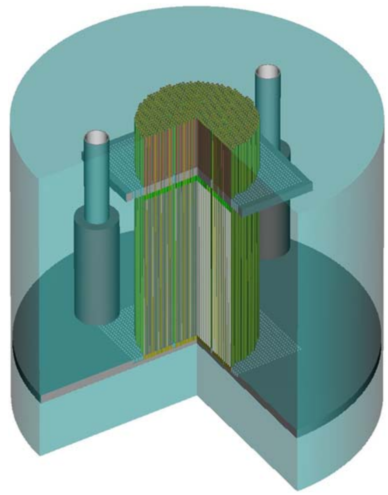
LEU-COMP-THERM-078 Case 8 Benchmark Model

k_{eff} = 0.9987

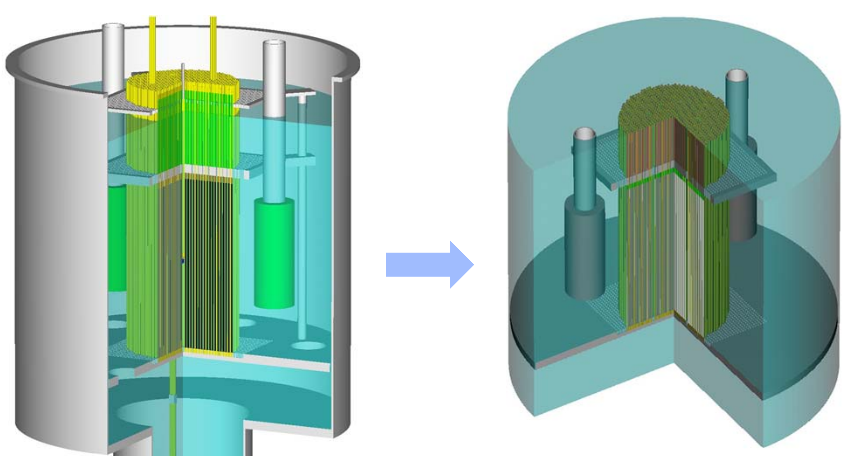
Includes a total bias of 0.00011 to 0.00015 from:

- **Temperature Difference**
- **Fuel Mass Difference**
- **Fuel Stack Length Difference**
- **Fuel Rod OD Difference**
- **Source Removal**
- **Convert CE/SE to Fuel Rods**
- **Remove everything above the water level**
- **Regularize Design Irregularities**

The included biases were individually less than 0.0001 in magnitude.

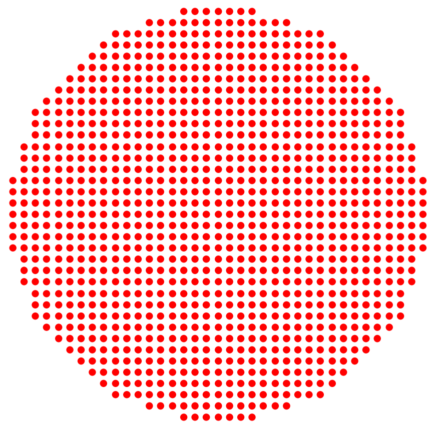


A comparison of the detailed assembly with the benchmark model



LEU-COMP-THERM-078 Case 1

-



1057 rods

k_{eff} = 0.9995

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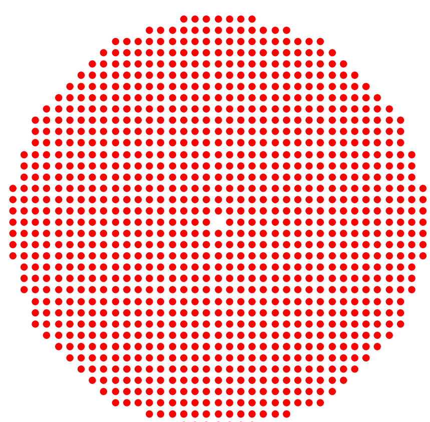
LEU-COMP-THERM-078 Case 2

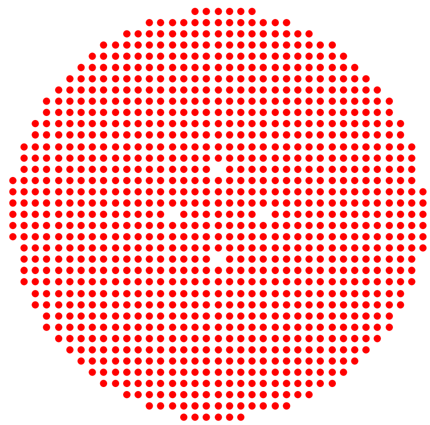
-



1056 rods

k_{eff} = 0.9999

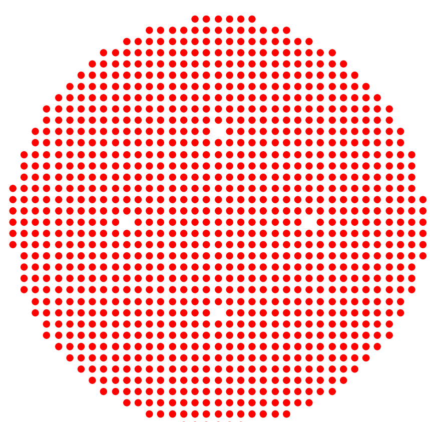
LEU-COMP-THERM-078 Case 3



1041 rods

k_{eff} = 0.9990

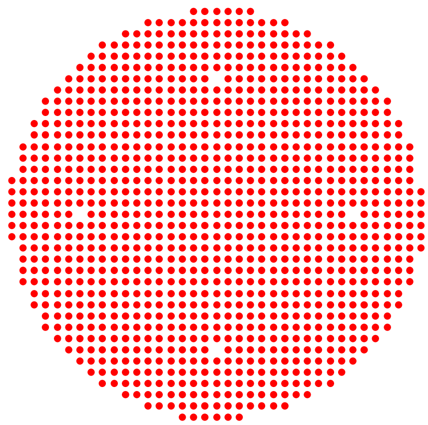
LEU-COMP-THERM-078 Case 4



1041 rods

k_{eff} = 0.9986

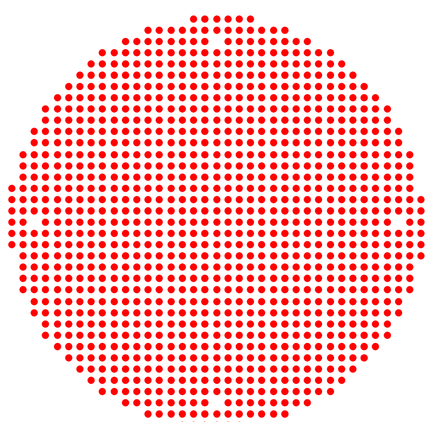
LEU-COMP-THERM-078 Case 5



1041 rods

k_{eff} = 0.9980

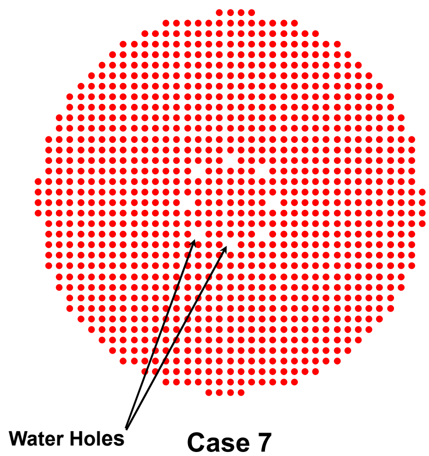
LEU-COMP-THERM-078 Case 6



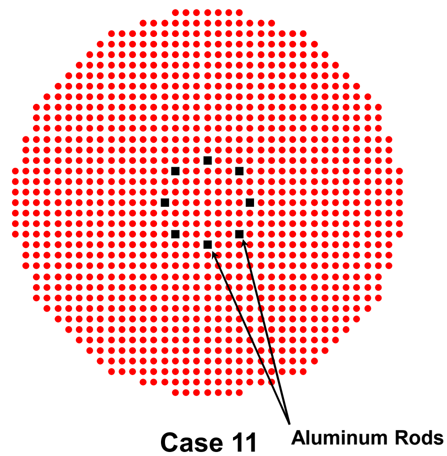
1041 rods

k_{eff} = 0.9974

LEU-COMP-THERM-078 Cases 7 and 11

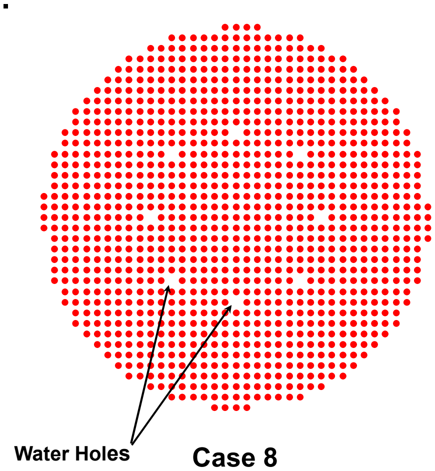


Case 7
1029 rods
k_{eff} = 0.9994

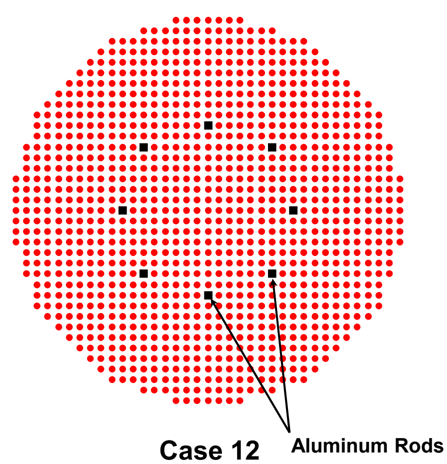


Case 11
1049 rods
k_{eff} = 0.9994

LEU-COMP-THERM-078 Cases 8 and 12

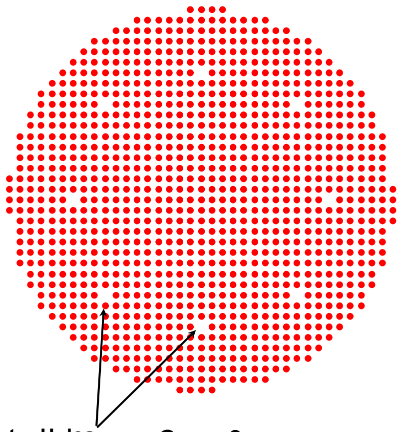


Case 8
1029 rods
k_{eff} = 0.9987

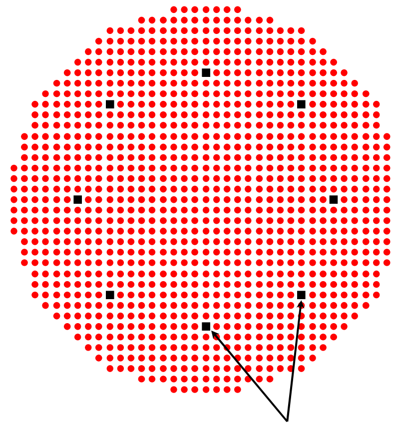


Case 12
1049 rods
k_{eff} = 0.9993

LEU-COMP-THERM-078 Cases 9 and 13



Case 9
1029 rods
k_{eff} = 0.9978



Case 13
1049 rods
k_{eff} = 0.9993

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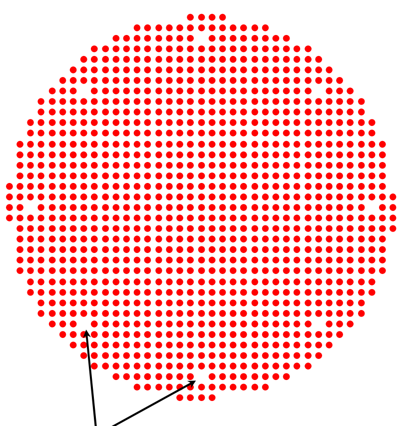
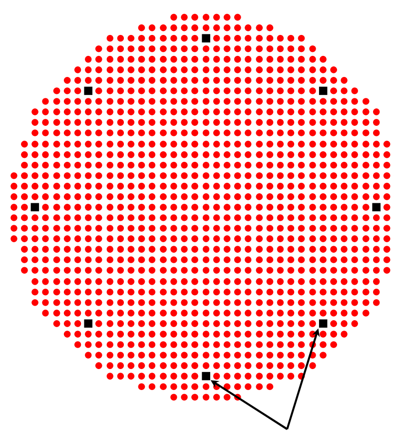
LEU-COMP-THERM-078 Cases 10 and 14



Case 10
1029 rods
k_{eff} = 0.9969



Case 14
1049 rods
k_{eff} = 0.9991

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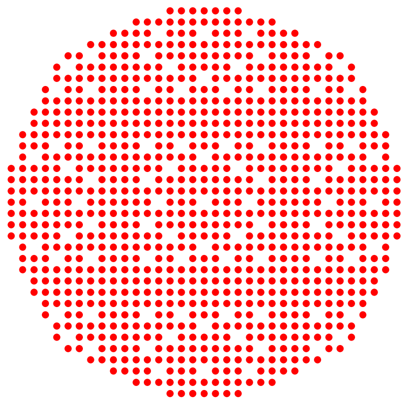
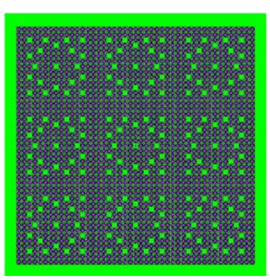
LEU-COMP-THERM-078 Case 15

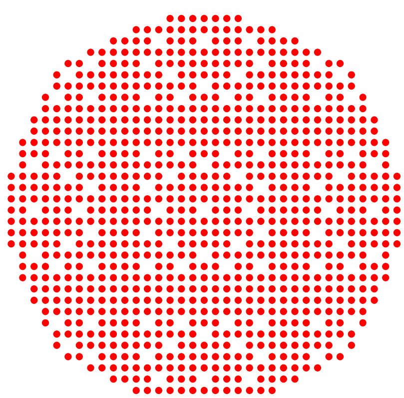


872 rods

k_{eff} = 0.9996

LEU-COMP-THERM-078 Case 15

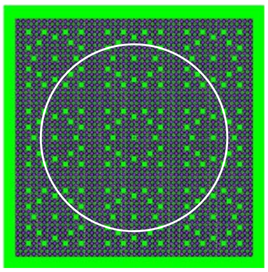


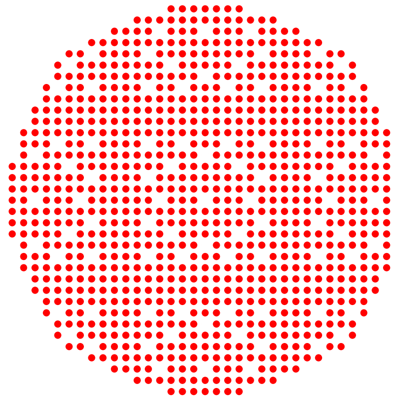


872 rods

k_{eff} = 0.9996

LEU-COMP-THERM-078 Case 15

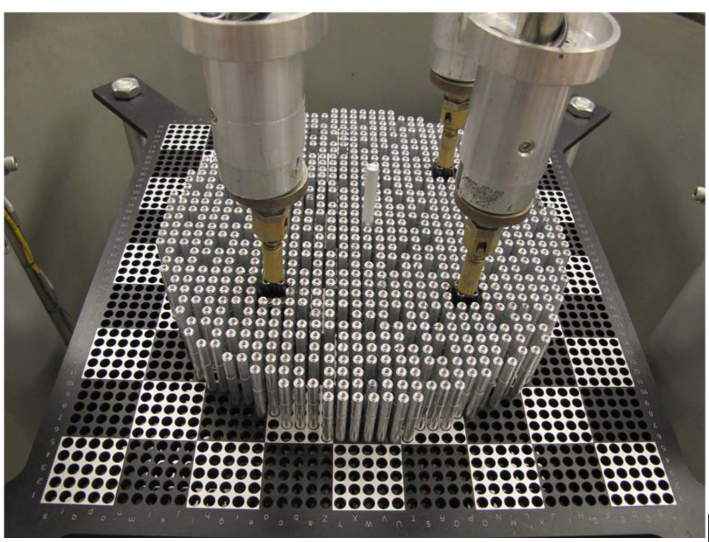




872 rods

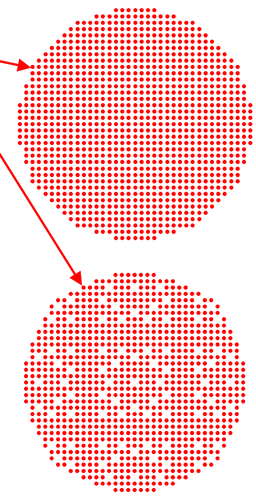
k_{eff} = 0.9996

The 7uPCX core at the end of an approach – LCT078 Case 15



The uncertainties in the benchmarks are relatively small

Uncertainty Source	Case 1 Δk_{eff}	Case 15 Δk_{eff}
Pitch of Fuel Rods	0.00073	0.00069
Clad OD	-0.00010	-0.00008
Clad ID	-0.00001	-0.00001
Fuel Pellet OD	0.00000	0.00000
Water Depth	0.00000	0.00000
Rod Fuel Mass	0.00002	0.00002
Rod Fuel Length	0.00004	0.00003
Enrichment	0.00012	0.00013
^{234}U	-0.00001	-0.00001
^{236}U	-0.00001	-0.00001
UO_2 Stoichiometry	-0.00049	-0.00055
Measured Fuel Impurities	-0.00012	-0.00011
Undetected Fuel Impurities	-0.00010	-0.00007
Clad Composition	-0.00027	-0.00026
Grid Plate Composition	-0.00011	-0.00012
Water Composition	-0.00021	-0.00024
Temperature	-0.00005	-0.00004
Sum in Quadrature	**0.0010**	**0.0010**



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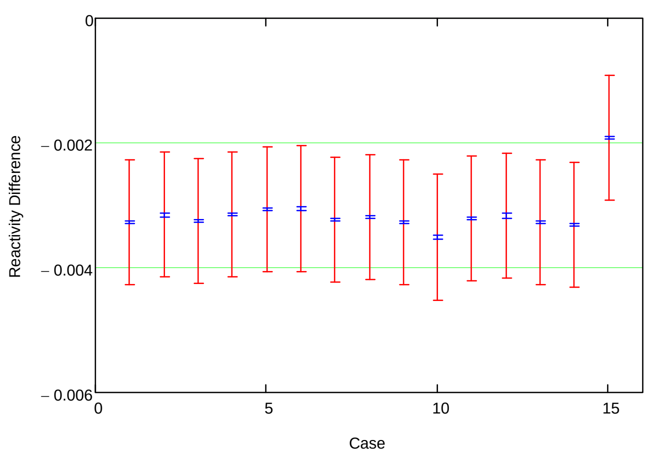
Reactivity Difference – KENO V.a + ENDF/B-VII.0 (MG) vs Benchmark Model k_{eff}



The mean reactivity difference is about 3.2 × experiment uncertainty.
The red error bars show the benchmark uncertainties.
The blue error bars show the stochastic uncertainties in the calculations.

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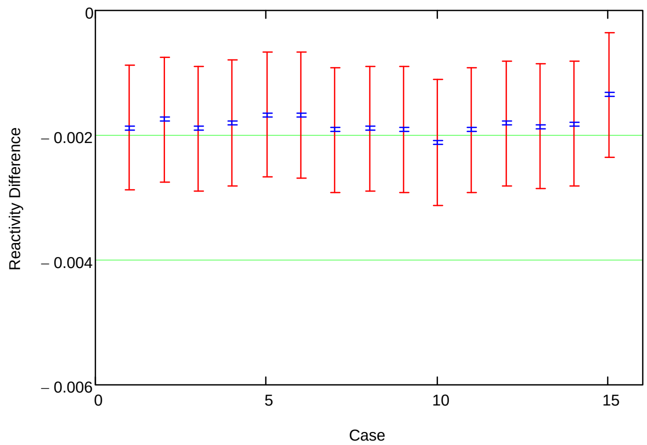
Reactivity Difference – KENO V.a + ENDF/B-VII.0 (CE) vs Benchmark Model k_{eff}



The mean reactivity difference is about 1.8 × experiment uncertainty.
The red error bars show the benchmark uncertainties.
The blue error bars show the stochastic uncertainties in the calculations.

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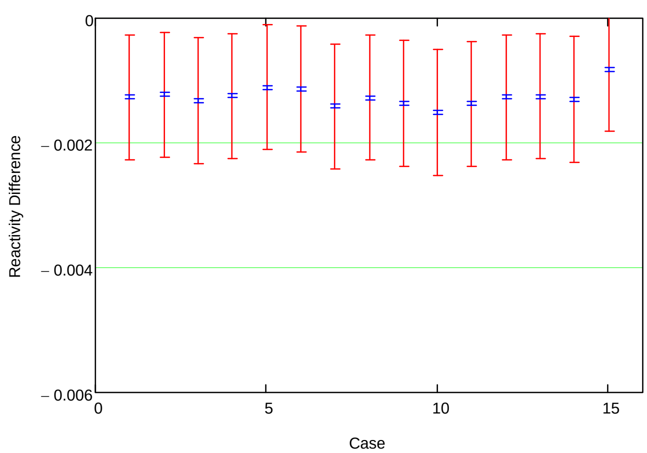
Reactivity Difference – MCNP5 + ENDF/B-VII.0 (CE) vs Benchmark Model k_{eff}



The mean reactivity difference is about 1.3 × experiment uncertainty.
The red error bars show the benchmark uncertainties.
The blue error bars show the stochastic uncertainties in the calculations.

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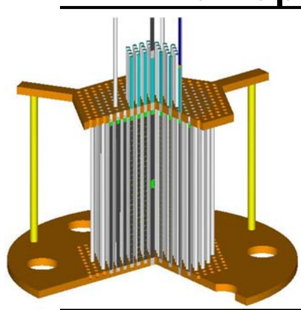
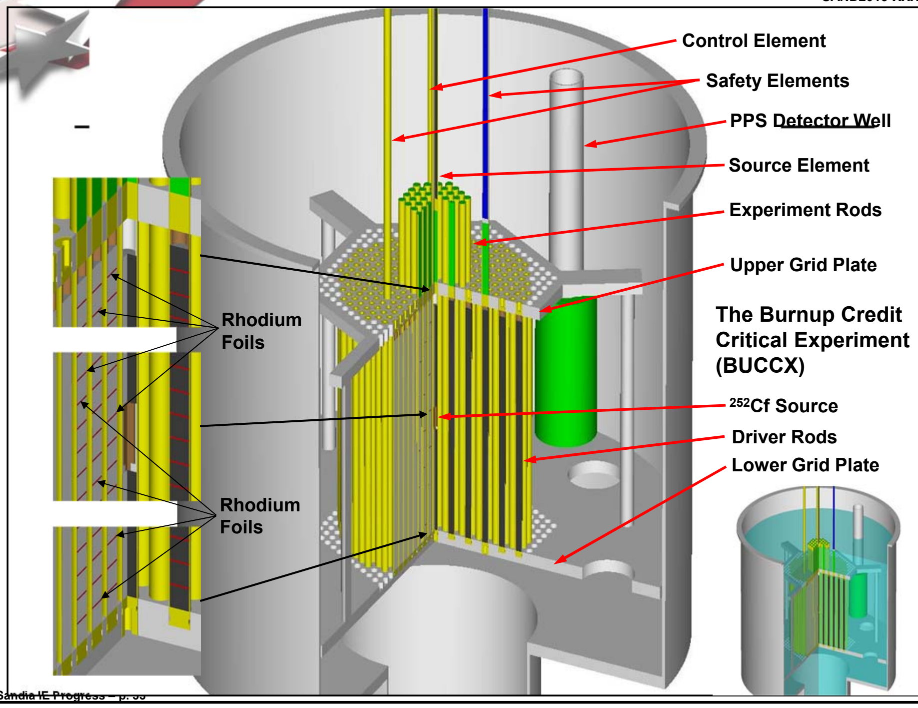
What are We Up To Now?

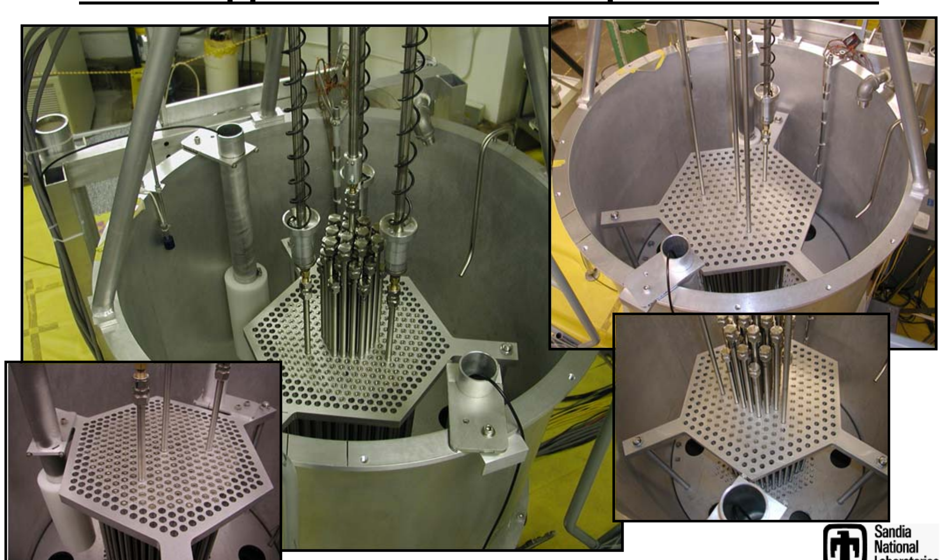
Restart the 4.3% Enriched Burnup Credit Critical Assembly



- In 2002, we built a critical assembly in which we could insert fission product materials to measure reactivity effects
- The assembly was a triangular-pitched array of Zircaloy-4 clad U(4.31%)O2 fuel (driver) elements
- Test materials were placed between the fuel pellets in "experiment elements"
- We completed a set of experiments with rhodium as the test material
- The experiment is documented as LEU-COMP-THERM-079 in the International Handbook of Evaluated Criticality Safety Benchmark Experiments



The BUCCX core shown at the end of approach-to-critical experiments



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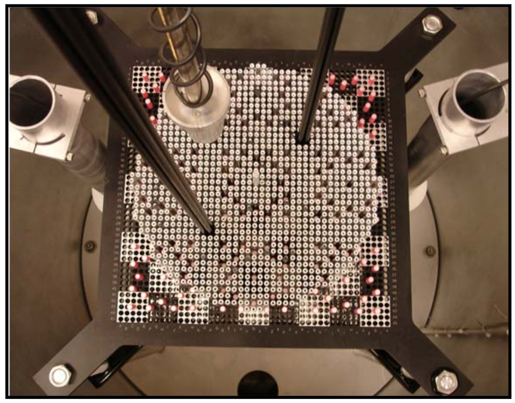
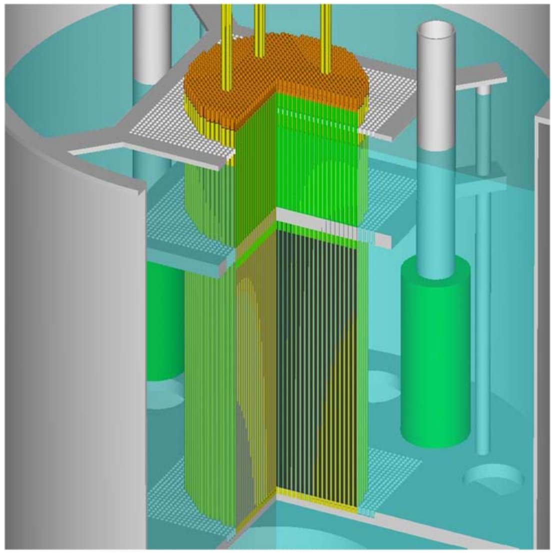
A Comparison of the BUCCX and 7uPCX Cores



The cores (fuel, grid plates, etc.) are different. The balance of the assembly hardware is the same

Measure Critical Water Depth as a Function of Fuel Loading

Fully-Reflected Critical Array With 1057 Fuel Rods – 0.855 cm Pitch



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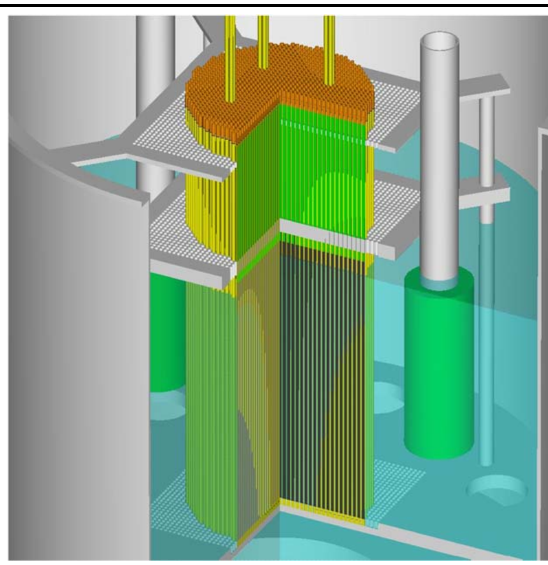
An Array with 1137 Fuel Rods Needs a Water Depth That Covers Most of the Fuel



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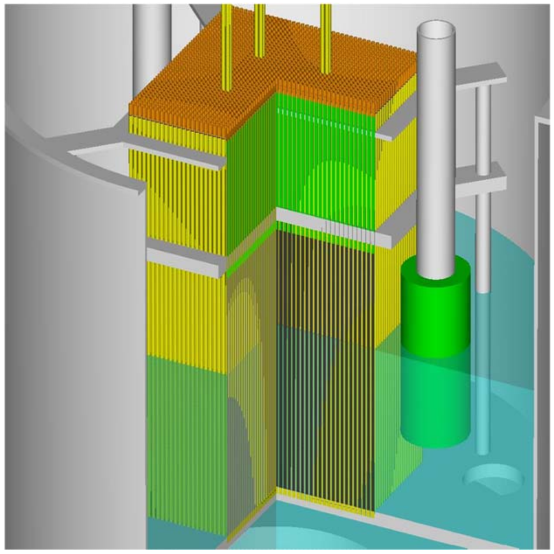
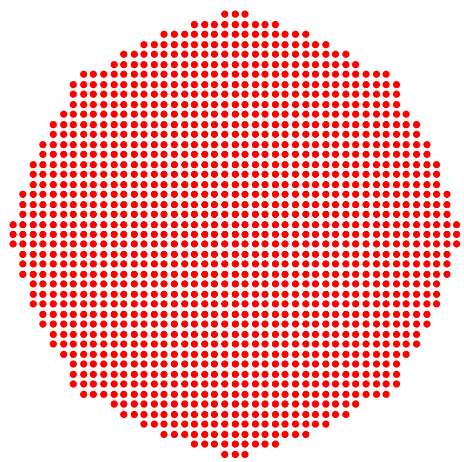
A 2025 Rod Array is Critical with the Water Level Slightly Above the Fuel Midplane



Measure Critical Fuel Loading as a Function of Pitch (Fully Reflected)

LCT080 Case 1 Configuration
Pitch 0.800 cm – Critical with ~1461 Rods



p800B0000B
1461

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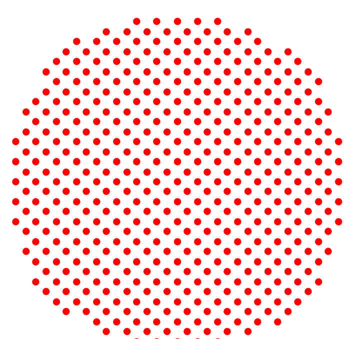
Remove 1 in 2 Rods – Pitch 1.132 cm
Critical with ~454 Rods

Leave Every Other Position Open in a Checkerboard Pattern



p1132B0000B
454

Pitch Increases by a Factor of $\sqrt{2}$
The Diagonals Become the Fuel Rows

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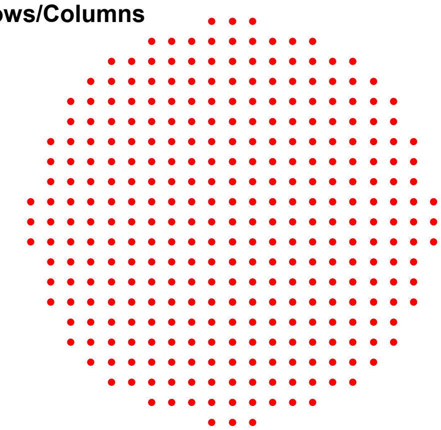
Remove 3 in 4 Rods – Pitch 1.600 cm
Critical with ~328 Rods

Leave Three of Four Positions Open

Remove Alternate Rows/Columns



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328

Pitch Increases by a Factor of 2

Changing the Pitch by Removing Rods

Grid Plate Pitch (cm)	Effective Pitch (cm)	Rods Removed	Critical Array Size (rods)
0.800	0.800	None	1461
0.855	0.855	None	1059
0.800	1.132	1 in 2	454
0.855	1.209	1 in 2	403
0.800	1.600	3 in 4	328
0.855	1.710	3 in 4	340

Concluding Remarks

- We have evaluated two 7uPCX experiment series
  - LEU-COMP-THERM-080 using a 0.800 cm pitch array with full reflection is in the 2012 edition of the benchmark book
  - LEU-COMP-THERM-078 using a 0.855 cm pitch array with full reflection has been accepted for inclusion in the 2013 edition
- We are working on future directions for our experiments
  - 7uPCX experiments with larger arrays and the approach done on moderator/reflector depth
  - BUCCX
  - Different pitch arrays with the 7uPCX fuel

Critical Experiments at Sandia

Backup Slides

What is in the Works for the Future?

Restart the 4.3% Enriched Assembly We Used for LEU-COMP-THERM-079

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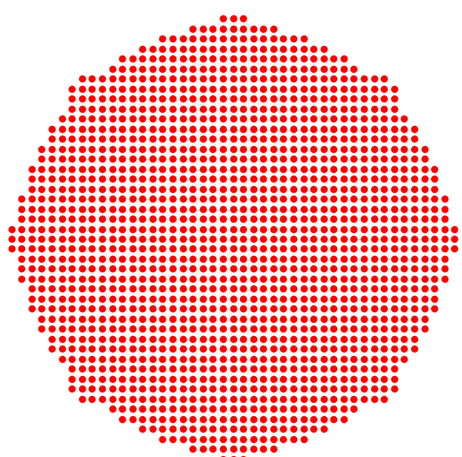
LCT080 Case 1 Configuration Pitch 0.800 cm – Critical with ~1461 Rods



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1461

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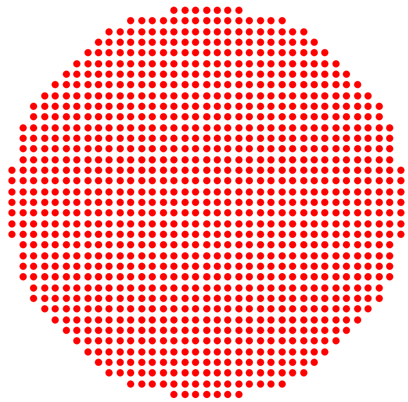
LCT078 Case 1 – Pitch 0.855 cm Critical with ~1059 Rods



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1065

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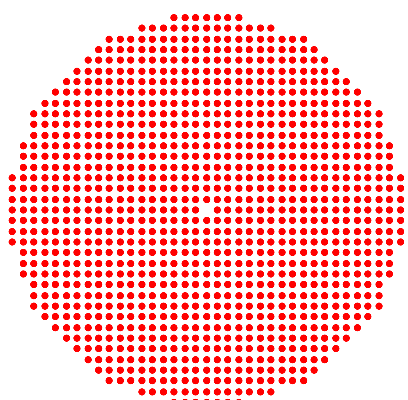
LCT078 Case 2 – Pitch 0.855 cm Critical with ~1056 Rods



p855B0000A
1056

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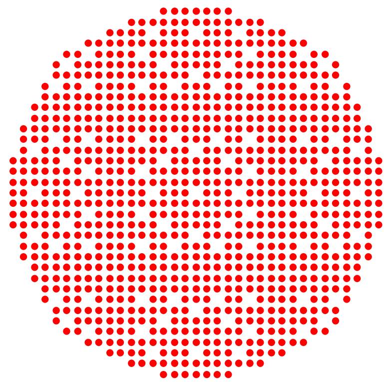
LCT078 Case 15 – Pitch 0.855 cm Critical with ~872 Rods



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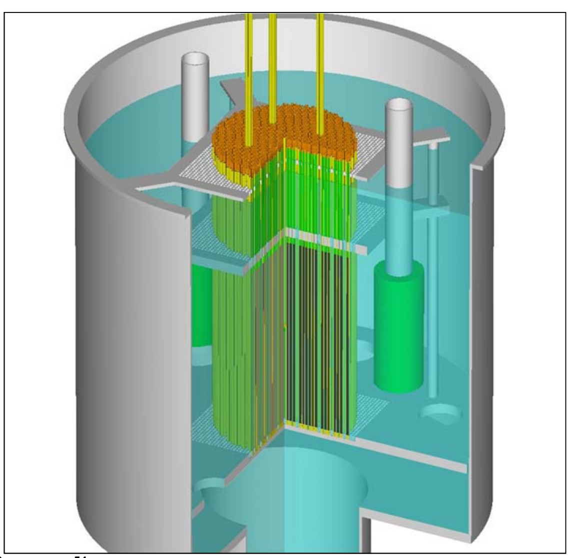
872

The Assembly In Its Most Reactive State (LEU-COMP-THERM-080 Case 11)



Fuel: 1136

k_{eff} ≈ 0.998

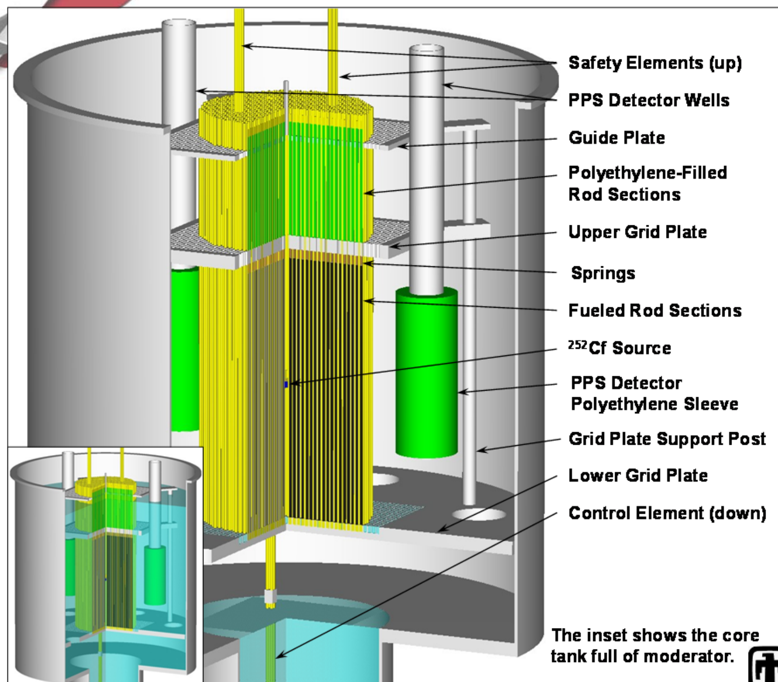
Safety Elements: Up

Control Element: Up

Core Tank: Full

Personnel: Excluded

With all control and safety elements up and full reflection (>6 in. of water on all sides), this is the highest reactivity state of the assembly. Multiplication measurements are made in this configuration.

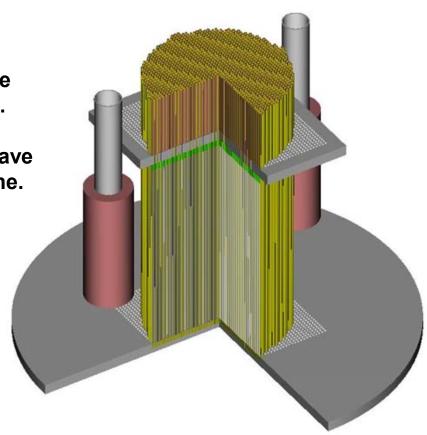


The inset shows the core tank full of moderator.

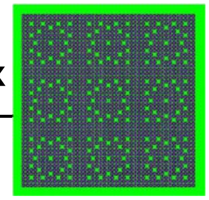
LEU-COMP-THERM-080 Case 1 Benchmark Model

k_{eff} = 0.9976

The configuration is shown with the water moderator/reflector removed. Removal of the PPS detector wells was considered – the bias would have been 0.0005 to 0.0006 – but not done.



The 7uPCX experiment matrix



- We have two grid plate sets
  - The sets were chosen to bound the fuel-to-water ratio of commercial PWRs
  - A full set of experiments will be done at each pitch
- We will find the array that is critical with pure water moderator
- We will search for the boric acid concentration in the moderator that gives a critical array with all fuel element positions filled
- Fission density measurements will be made on the fully-loaded core

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Access controls ensure personnel safety

- We have limited ourselves to low-enriched (<20%) fuel
  - 1000 kg of the fuel is subcritical without water moderator
  - Reactor room is limited to 500 kg of fuel
  - The fuel cannot go critical without water
- The key that closes the dump valves and allows water to accumulate in the core tank is tied to the key to the facility door
  - When people are in the reactor room, the key is out of the console and the dump valves are open (core tank cannot hold water)
  - When the dump valves are closed, the reactor area is locked and people are excluded from the reactor room
  - FUEL – WATER – PEOPLE – pick any TWO

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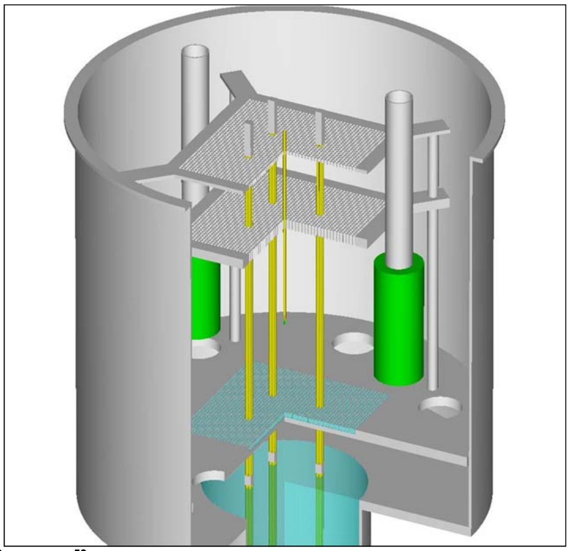
The Shut-Down Configuration of the Assembly



Fuel: 12 - CE/SE only

$k_{eff} \approx 0.139$

Safety Elements: Down

Control Element: Down

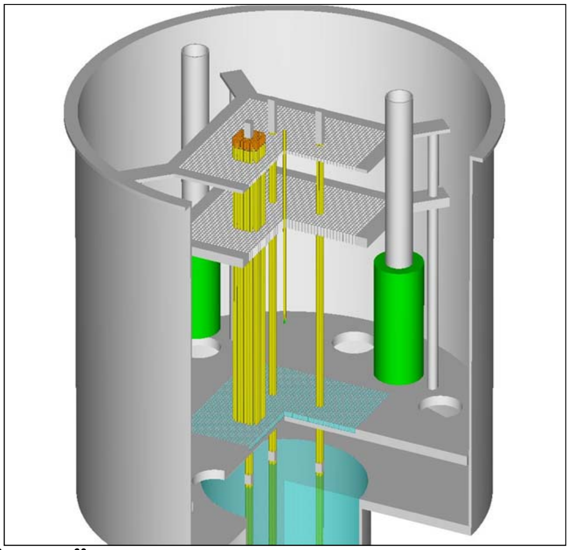
Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

SAND2013-XXXXP

Load Fuel



Fuel: 64

$k_{eff} \approx 0.139$

Safety Elements: Down

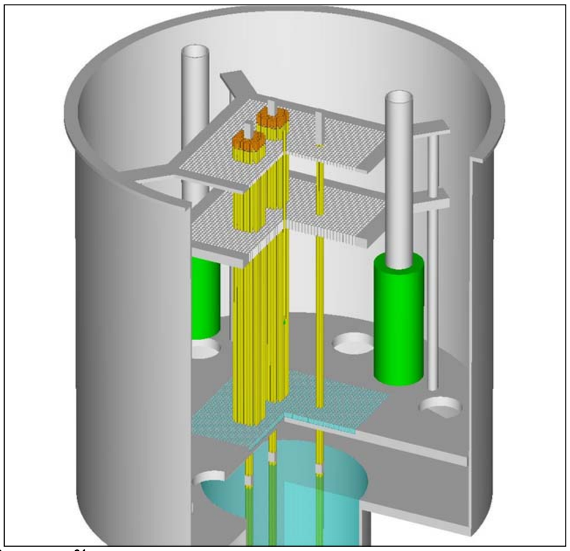
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 116

k_{eff} ≈ 0.139

Safety Elements: Down

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

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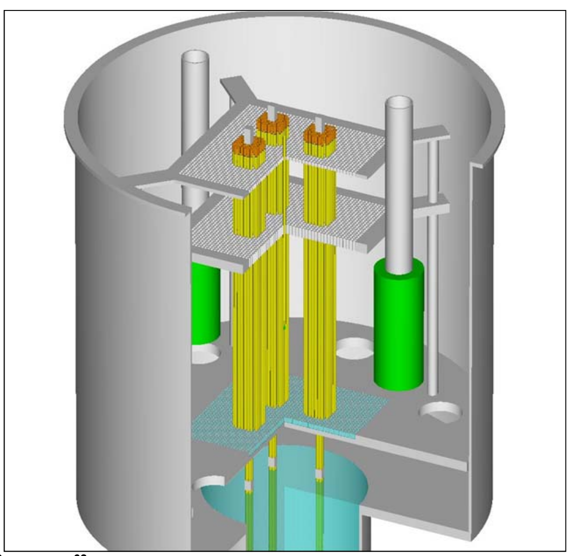
Load Fuel



Fuel: 168

k_{eff} ≈ 0.139

Safety Elements: Down

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

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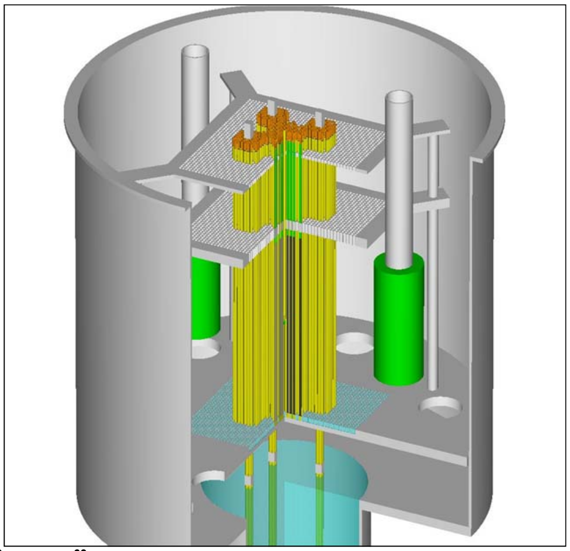
Load Fuel



Fuel: 318

k_{eff} ≈ 0.140

Safety Elements: Down

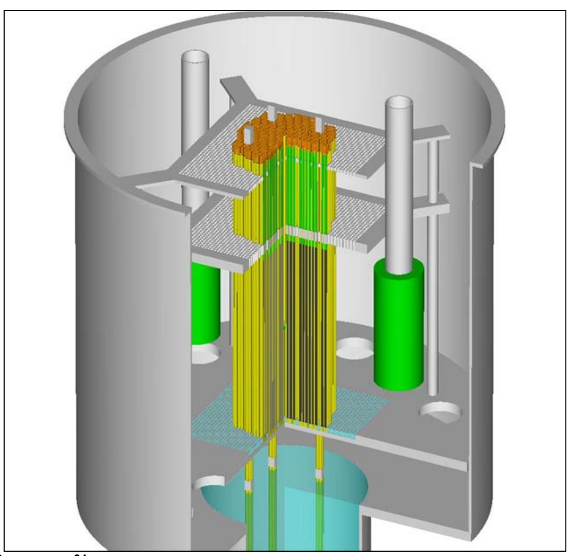
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 548

k_{eff} ≈ 0.140

Safety Elements: Down

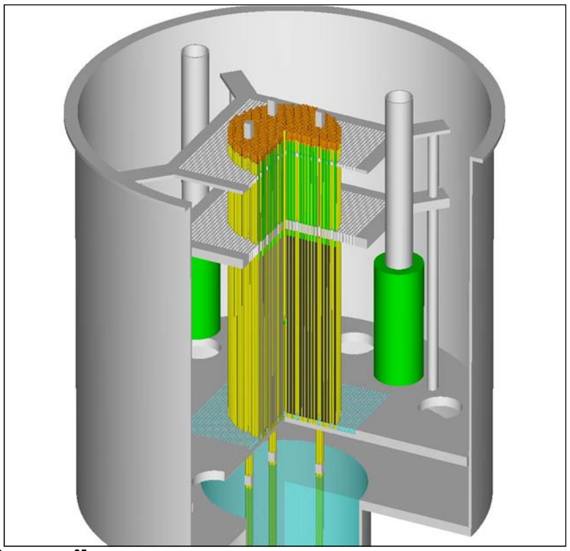
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 740

k_{eff} ≈ 0.140

Safety Elements: Down

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

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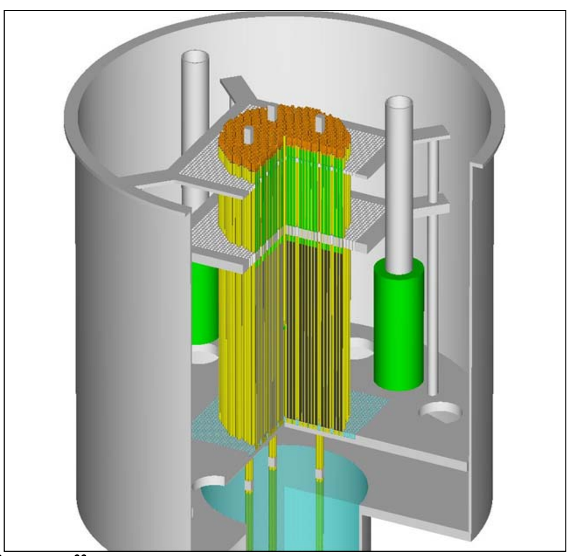
Load Fuel



Fuel: 956

k_{eff} ≈ 0.140

Safety Elements: Down

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

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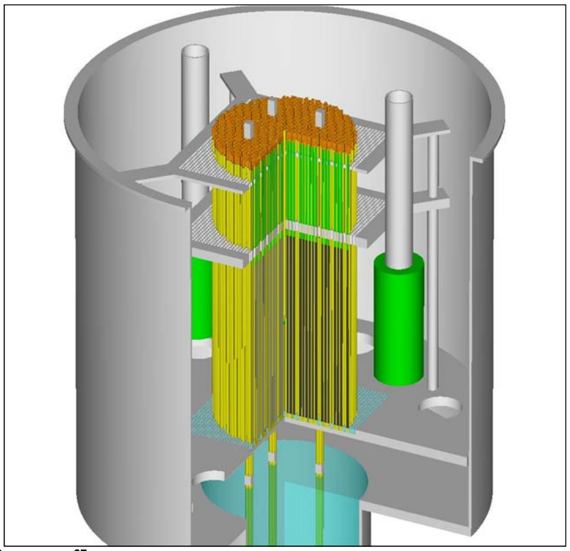
The Desired Fuel Array is Complete



Fuel: 1136

$k_{eff} \approx 0.140$

Safety Elements: Down

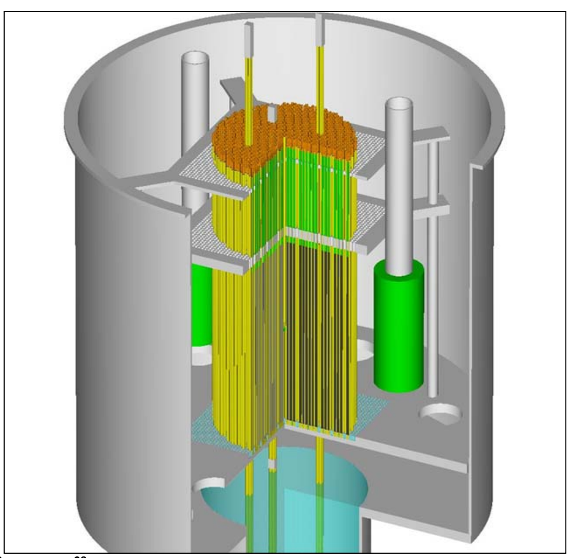
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Raise the Safety Elements



Fuel: 1136

$k_{eff} \approx 0.132$

Safety Elements: Raising

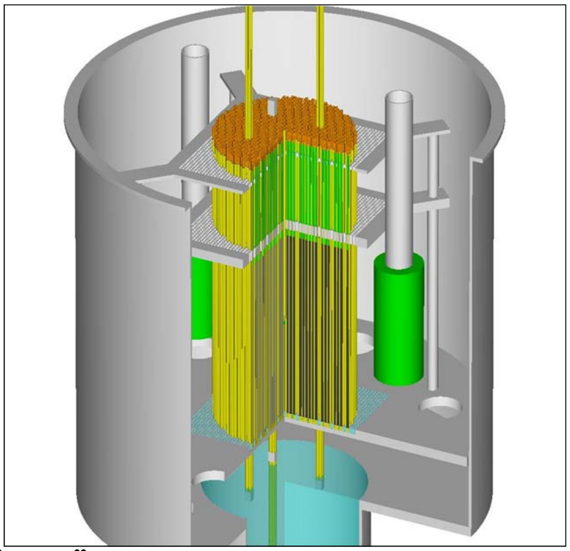
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "operating" and a qualified operator must be at the controls at all times. Entry into the reactor room is allowed. Fuel may be added to or removed from the array.

Raise the Safety Elements



Fuel: 1136

$k_{eff} \approx 0.127$

Safety Elements: Raising

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "operating" and a qualified operator must be at the controls at all times. Entry into the reactor room is allowed. Fuel may be added to or removed from the array.

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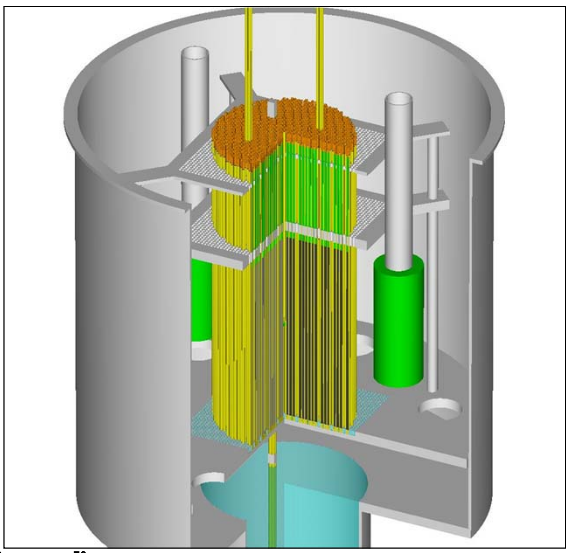
The Safety Elements are Up



Fuel: 1136

$k_{eff} \approx 0.128$

Safety Elements: Up

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "operating" and a qualified operator must be at the controls at all times. Entry into the reactor room is allowed. Fuel may be added to or removed from the array.

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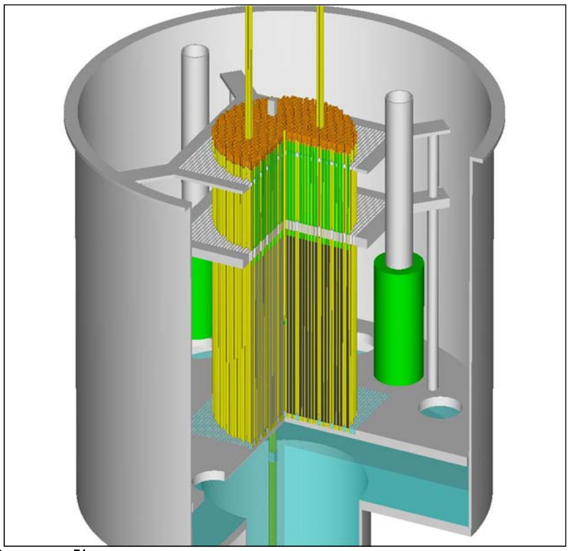
Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.139$

Safety Elements: Up

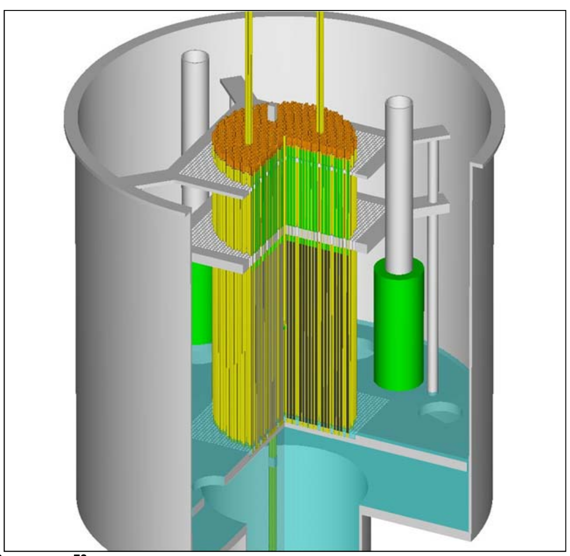
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.178$

Safety Elements: Up

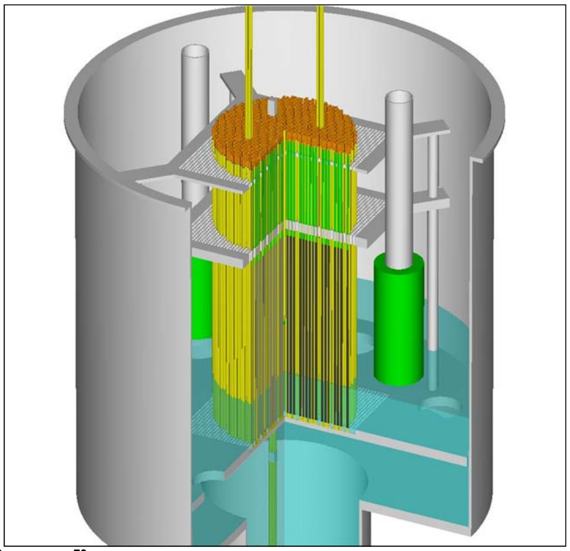
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.594

Safety Elements: Up

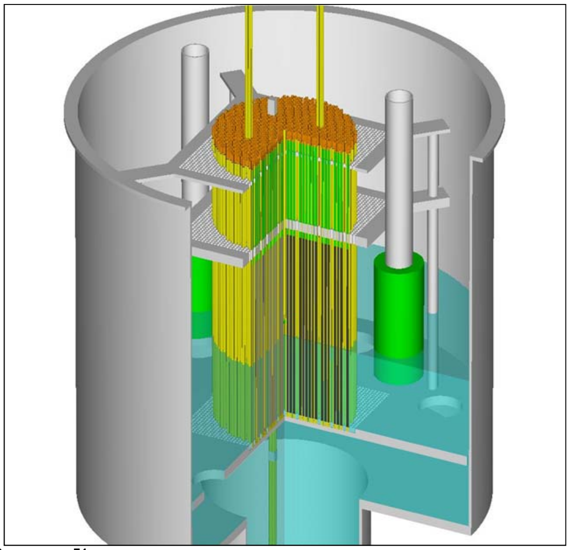
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.804

Safety Elements: Up

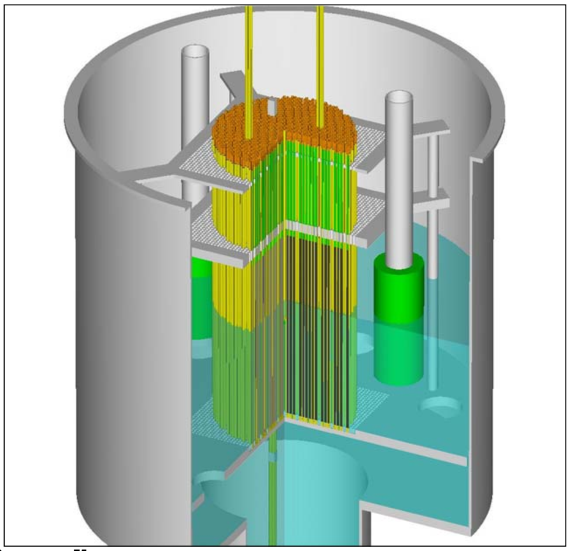
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.901

Safety Elements: Up

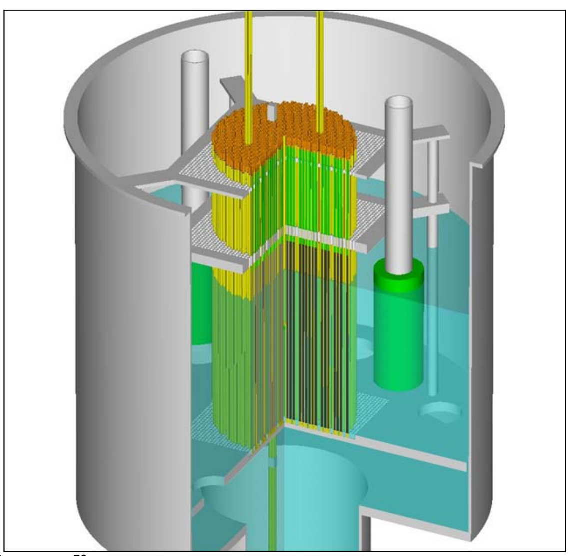
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.953

Safety Elements: Up

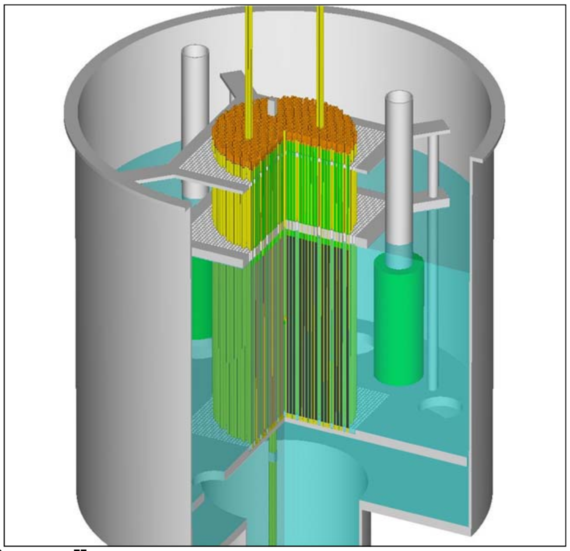
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.981

Safety Elements: Up

Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

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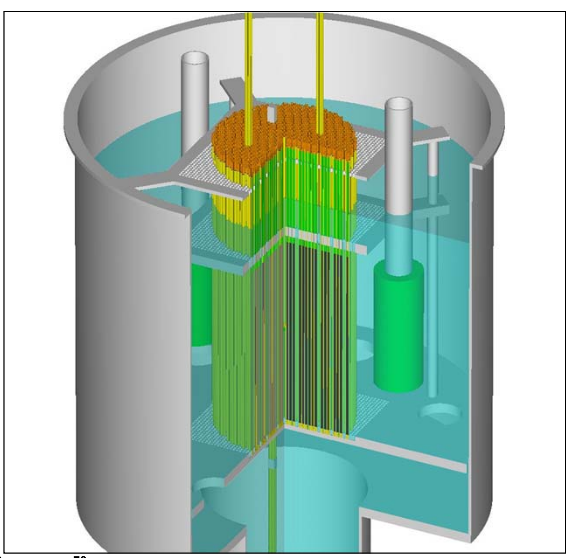
Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.986

Safety Elements: Up

Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

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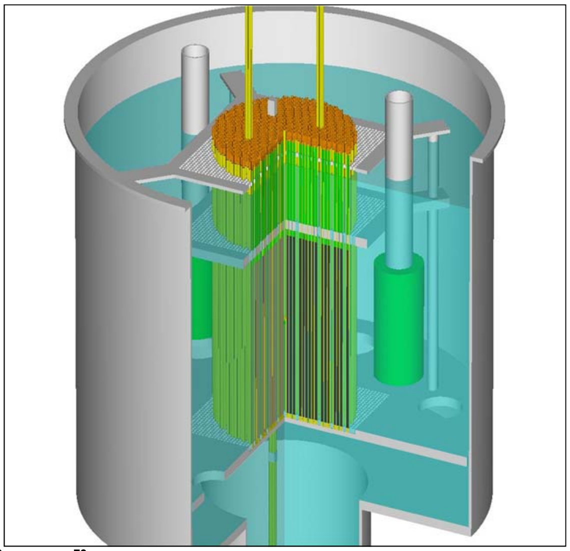
The Core Tank is Full



Fuel: 1136

k_{eff} ≈ 0.986

Safety Elements: Up

Control Element: Down

Core Tank: Full

Personnel: Excluded

At this point, the "fast" fill pump is disabled by an interlock and the recirculation pump is turned on. Moderator enters under the water's surface and drains to the dump tank through a standpipe.

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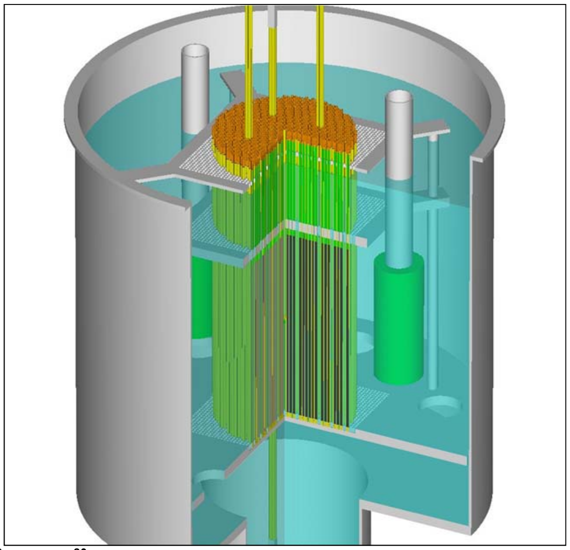
Raise the Control Element



Fuel: 1136

k_{eff} ≈ 0.992

Safety Elements: Up

Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element. The maximum reactivity insertion rate during control element withdrawal is less than 4 ¢ per second.

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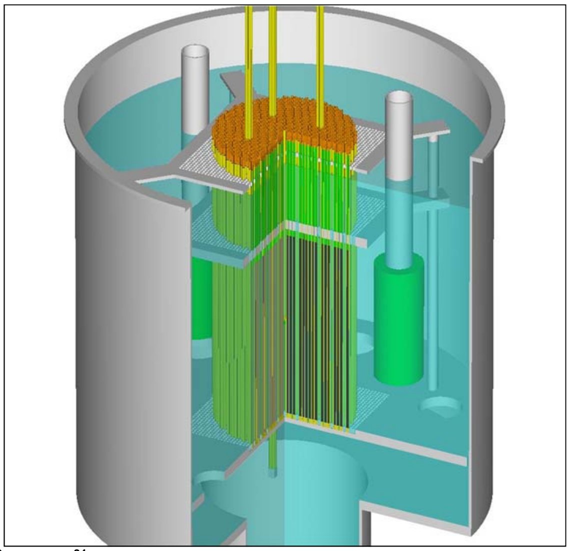
Raise the Control Element



Fuel: 1136

k_{eff} ≈ 0.998

Safety Elements: Up

Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element. The maximum reactivity insertion rate during control element withdrawal is less than 4 ¢ per second.

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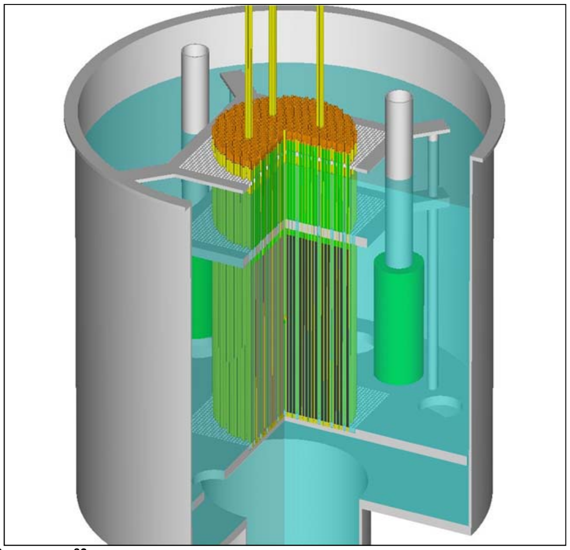
The Assembly Reaches Its Most Reactive State



Fuel: 1136

k_{eff} ≈ 0.999

Safety Elements: Up

Control Element: Up

Core Tank: Full

Personnel: Excluded

With all control and safety elements up and full reflection (>6 in. of water on all sides), this is the highest reactivity state of the assembly. Multiplication measurements are made in this configuration.

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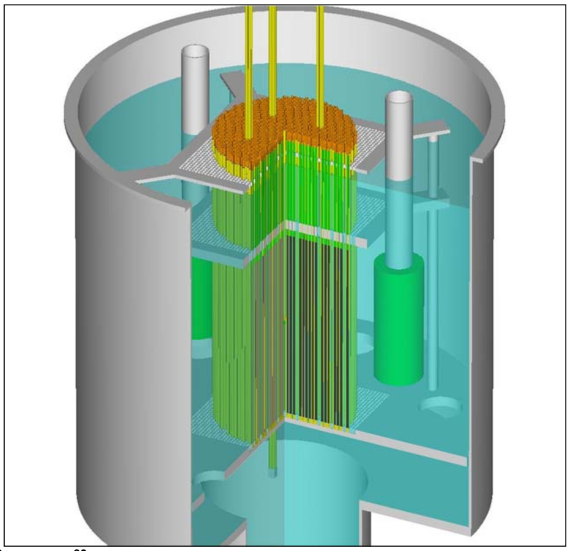
Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.998$

Safety Elements: Up

Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to lower the control element.

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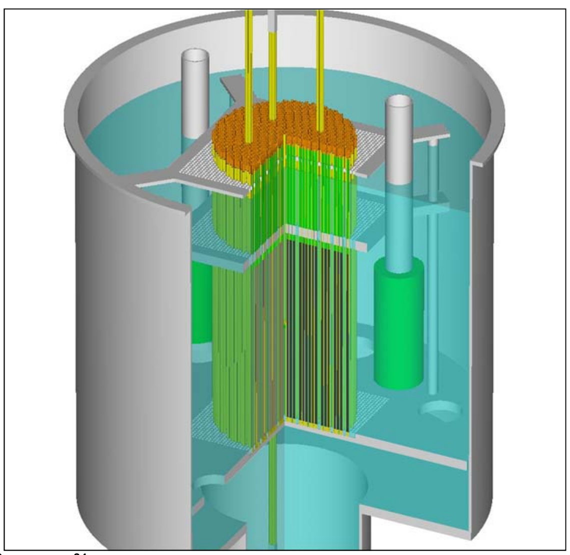
Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.992$

Safety Elements: Up

Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to lower the control element.

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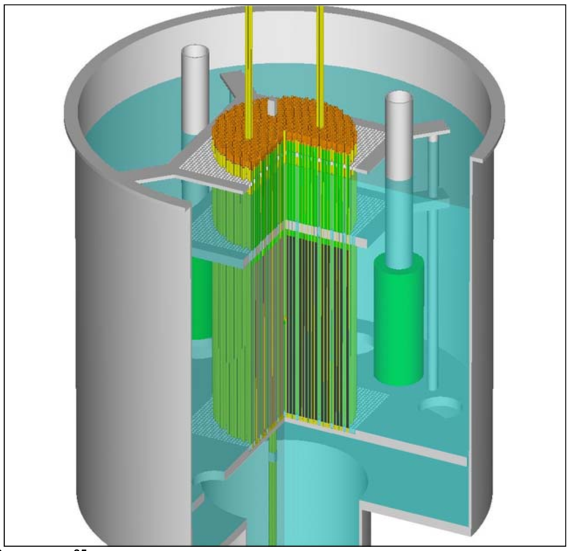
Lower the Control Element



Fuel: 1136

k_{eff} ≈ 0.986

Safety Elements: Up

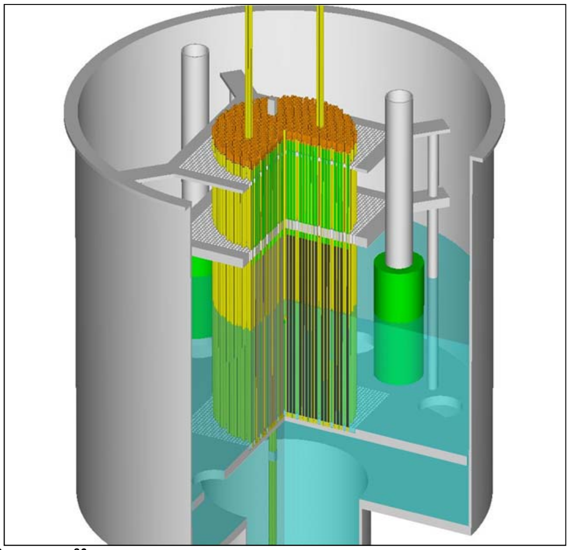
Control Element: Down

Core Tank: Full

Personnel: Excluded

SAND2013-XXXXP

Drain the Core Tank



Fuel: 1136

k_{eff} ≈ 0.901

Safety Elements: Up

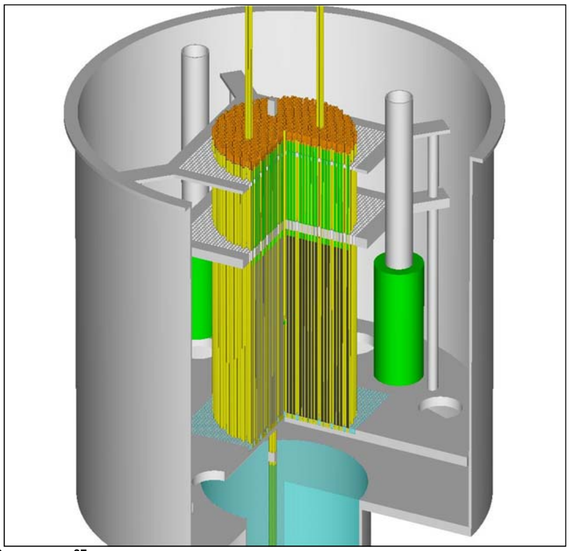
Control Element: Down

Core Tank: Draining

Personnel: Excluded

It takes about 15 seconds to completely drain the core tank.

Drain the Core Tank



Fuel: 1136

k_{eff} ≈ 0.128

Safety Elements: Up

Control Element: Down

Core Tank: Empty

Personnel: Allowed

Now we are back to a condition where fuel may be added to or removed from the array.

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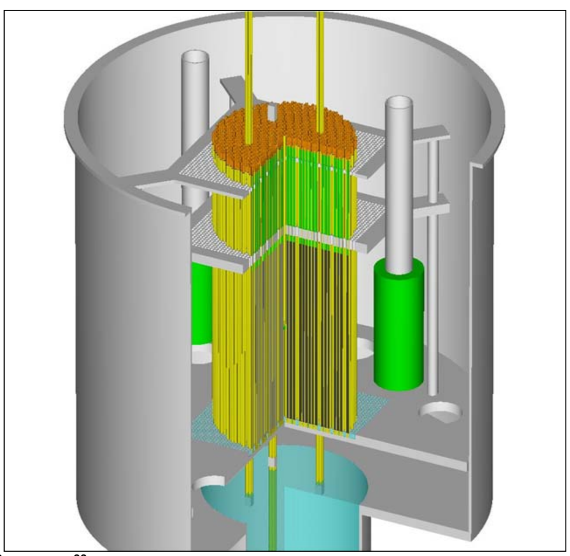
Lower the Safety Elements



Fuel: 1136

k_{eff} ≈ 0.127

Safety Elements: Lowering

Control Element: Down

Core Tank: Empty

Personnel: Allowed

Now we are back to a condition where fuel may be added to or removed from the array.

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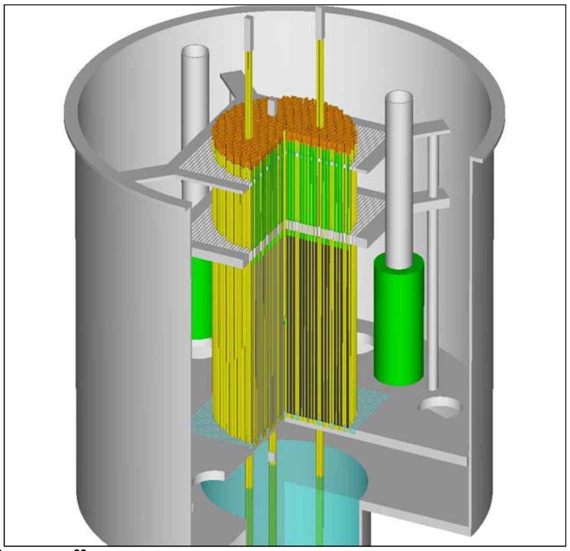
Lower the Safety Elements



Fuel: 1136

k_{eff} ≈ 0.132

Safety Elements: Lowering

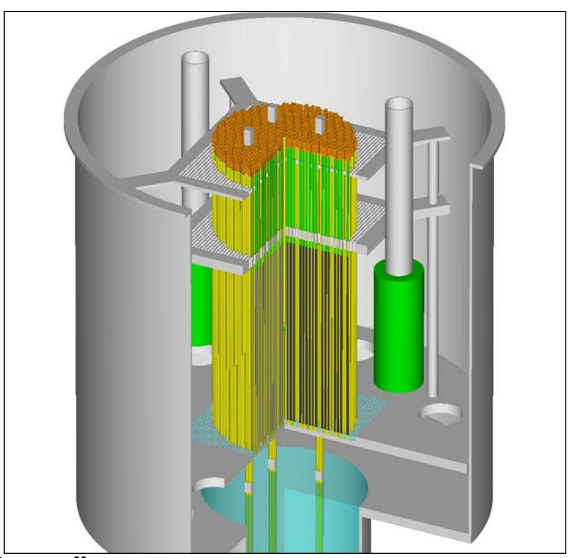
Control Element: Down

Core Tank: Empty

Personnel: Allowed

Now we are back to a condition where fuel may be added to or removed from the array.

The Assembly Reaches its Shutdown Condition



Fuel: 1136

k_{eff} ≈ 0.140

Safety Elements: Down

Control Element: Down

Core Tank: Empty

Personnel: Allowed

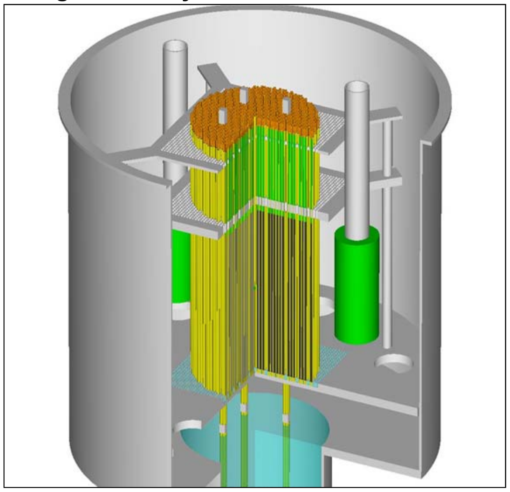
In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Some interesting physics . . .

Looking at k_{eff} during the fuel loading and safety element withdrawal:

Fuel	SE	Water [1]	CE	k_{eff} [2]
12	Down	-19.1	Down	0.1394
64	Down	-19.1	Down	0.1394
116	Down	-19.1	Down	0.1394
168	Down	-19.1	Down	0.1394
318	Down	-19.1	Down	0.1396
548	Down	-19.1	Down	0.1397
740	Down	-19.1	Down	0.1396
956	Down	-19.1	Down	0.1398
1136	Down	-19.1	Down	0.1402
1136	1/3 Up	-19.1	Down	0.1321
1136	2/3 Up	-19.1	Down	0.1273
1136	Up	-19.1	Down	0.1277

Note 1: Water level referenced to the bottom of the fuel stack.
Note 2: Calculated with MCNP5.1.51, ENDF/B-VII.0



Why does k_{eff} seem independent of the fuel loading?

Some interesting physics . . .

Looking at k_{eff} during the fuel loading and safety element withdrawal:

Fuel	SE	Water [1]	CE	k_{eff} [2]
12	Down	-19.1	Down	0.1394
64	Down	-19.1	Down	0.1394
116	Down	-19.1	Down	0.1394
168	Down	-19.1	Down	0.1394
318	Down	-19.1	Down	0.1396
548	Down	-19.1	Down	0.1397
740	Down	-19.1	Down	0.1396
956	Down	-19.1	Down	0.1398
1136	Down	-19.1	Down	0.1402
1136	1/3 Up	-19.1	Down	0.1321
1136	2/3 Up	-19.1	Down	0.1273
1136	Up	-19.1	Down	0.1277

Note 1: Water level referenced to the bottom of the fuel stack.
Note 2: Calculated with MCNP5.1.51, ENDF/B-VII.0

Fuel	SE	Water [1]	CE	k_{eff} [2]
12	Up	-19.1	Up	0.0268
64	Up	-19.1	Up	0.0358
116	Up	-19.1	Up	0.0410
168	Up	-19.1	Up	0.0444
318	Up	-19.1	Up	0.0631
548	Up	-19.1	Up	0.0917
740	Up	-19.1	Up	0.1050
956	Up	-19.1	Up	0.1182
1136	Up	-19.1	Up	0.1282

Note 1: Water level referenced to the bottom of the fuel stack.
Note 2: Calculated with MCNP5.1.51, ENDF/B-VII.0

Compare k_{eff} for the control and safety elements (12 fuel rods) down and up.

Adding moderator is the big reactivity insertion

Fuel	SE	Water [1]	CE	k_{eff} [2]
1136	Up	-19.1	Down	0.1277
1136	Up	-9.3	Down	0.1391
1136	Up	0.7	Down	0.1782
1136	Up	10.7	Down	0.5944
1136	Up	20.7	Down	0.8038
1136	Up	30.7	Down	0.9013
1136	Up	40.7	Down	0.9536
1136	Up	50.7	Down	0.9818
1136	Up	60.7	Down	0.9855
1136	Up	68.3	Down	0.9856
1136	Up	68.3	1/3 Up	0.9919
1136	Up	68.3	2/3 Up	0.9983
1136	Up	68.3	Up	0.9985

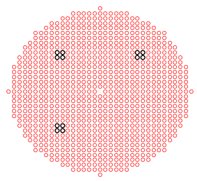
Note 1: Water level referenced to the bottom of the fuel stack.

Note 2: Calculated with MCNP5.1.51, ENDF/B-VII.0

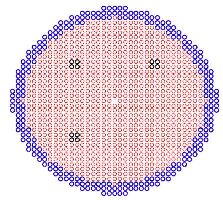
Approach to Critical

- **We determine critical conditions for a given set of assembly conditions in an “approach-to-critical” experiment**
- **The goal of the experiment is to find the conditions where the multiplication of the assembly is infinite**
- **Under those conditions, the inverse of the multiplication is zero**
- **Count-rate measurements are made on the assembly as the approach variable is changed to make the system more reactive**
- **When the assembly is nearly critical, the count rates follow the assembly multiplication**
- **Estimates are made of the critical condition of the assembly from the measurements**

Core configurations during the 800B0000A approach-to-critical experiment (1)

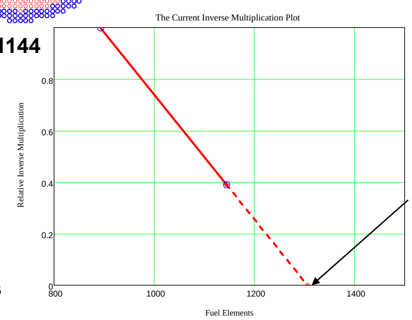


892



1144

The first two arrays have k_{eff} ~ 0.9 and k_{eff} ~ 0.95 (calculated)



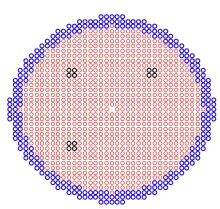
Multiplication: $$M = \frac{1}{1 - k_{eff}}$$

$$\frac{1}{M} = 1 - k_{eff}$$

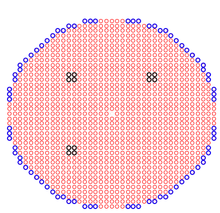
Project the two inverse multiplication measurements to zero and add half the increment to get the next array – in this case 1224 elements

The incremental fuel elements are shown in blue

Core configurations during the 800B0000A approach-to-critical experiment (2)



1144

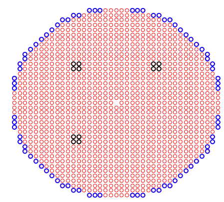


1224

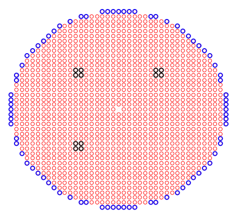
The next array: 1304

The incremental fuel elements are shown in blue

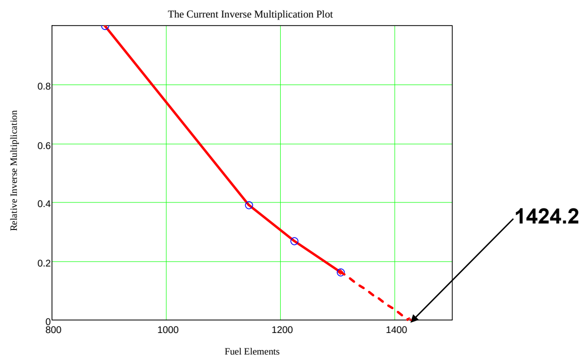
Core configurations during the 800B0000A approach-to-critical experiment (3)



1224



1304



The next array: 1360

The incremental fuel elements are shown in blue

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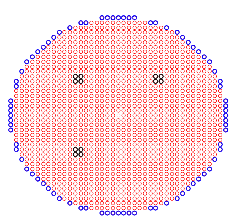
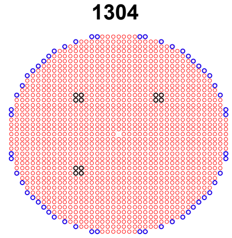
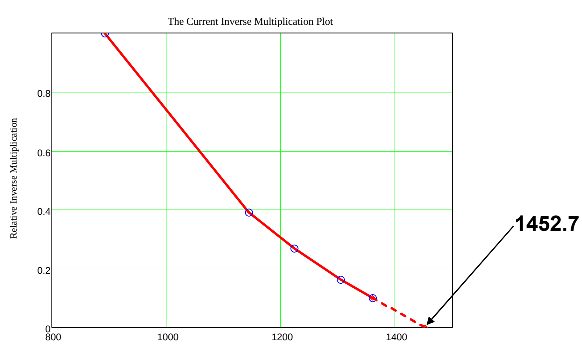
Core configurations during the 800B0000A approach-to-critical experiment (4)



1304



1360



The next array: 1404

The incremental fuel elements are shown in blue

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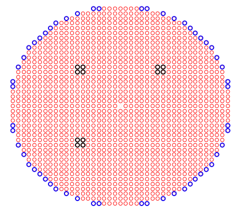
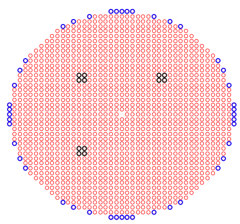
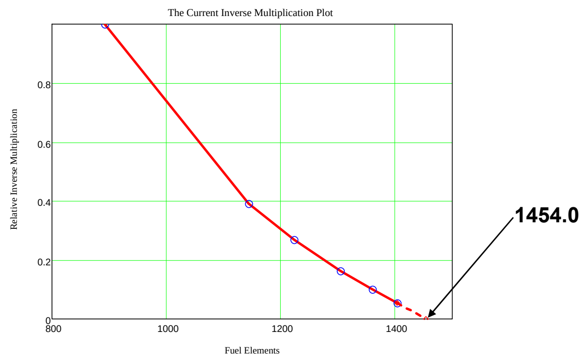
Core configurations during the 800B0000A approach-to-critical experiment (5)



1360



1404

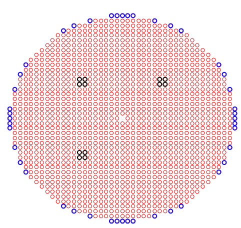


The next array: 1424

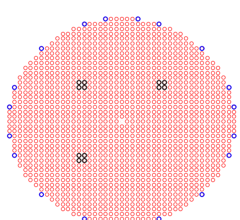
The incremental fuel elements are shown in blue

SAND2013-XXXXP

Core configurations during the 800B0000A approach-to-critical experiment (6)



1404

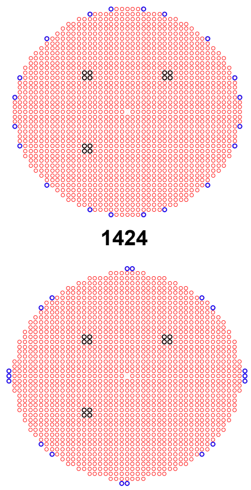


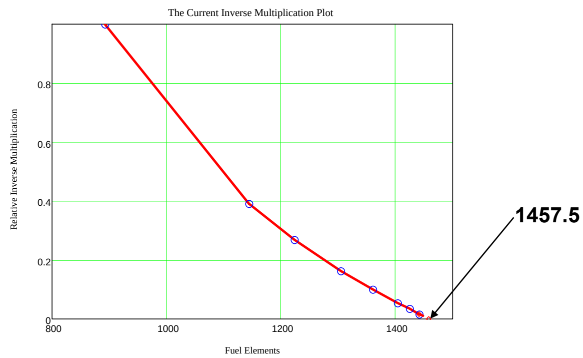
1424

The next array: 1442

The incremental fuel elements are shown in blue

Core configurations during the 800B0000A approach-to-critical experiment (7)





The next array: 1449

The incremental fuel elements are shown in blue

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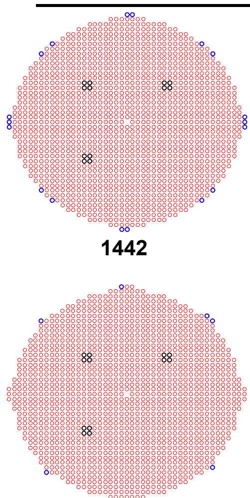
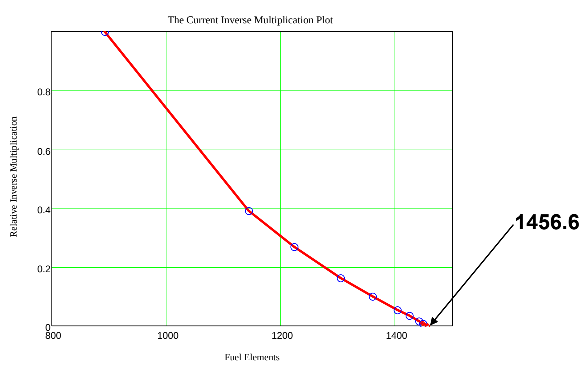
Core configurations during the 800B0000A approach-to-critical experiment (8)





The next array: 1452

The incremental fuel elements are shown in blue

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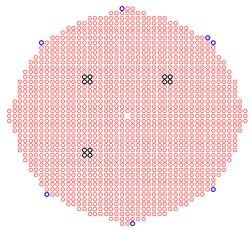
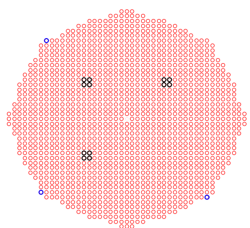
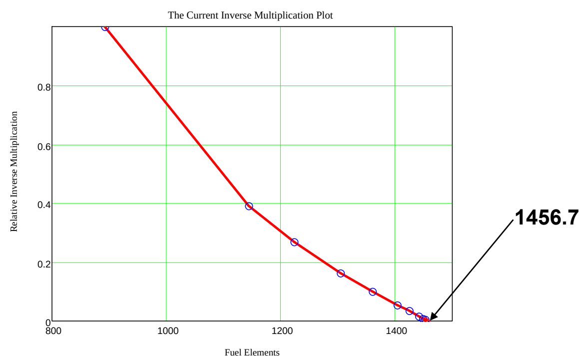
Core configurations during the 800B0000A approach-to-critical experiment (9)



1449



1452



The next array: 1456

The incremental fuel elements are shown in blue

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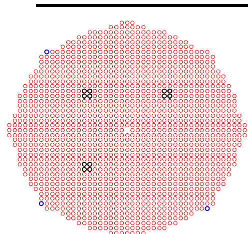
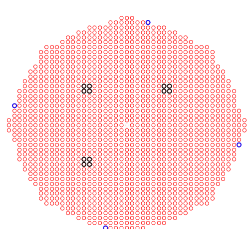
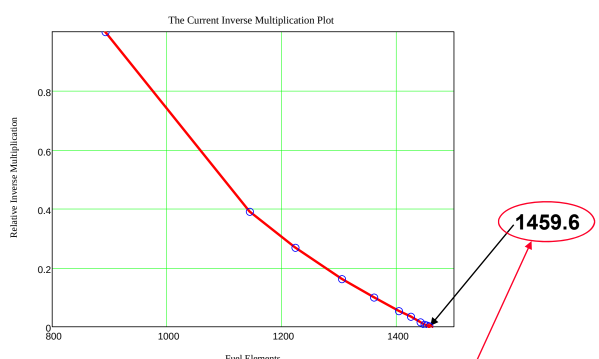
Core configurations during the 800B0000A approach-to-critical experiment (10)



1452



1456



The next array: 1460

Should be just critical??

The incremental fuel elements are shown in blue

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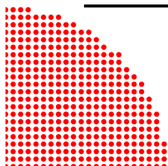
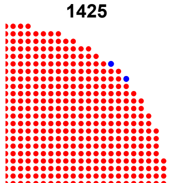
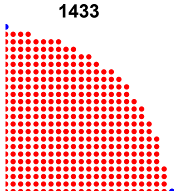
k_{eff} from Approach Data



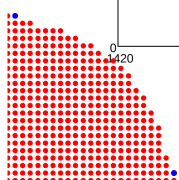
1425



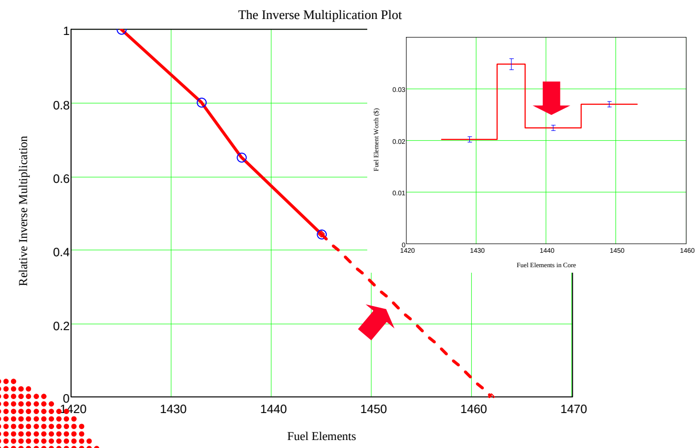
1433



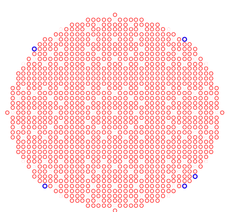
1437 k = 0.9964



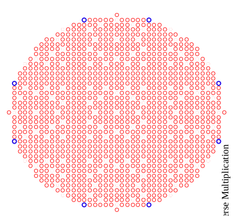
1445 k = 0.9975



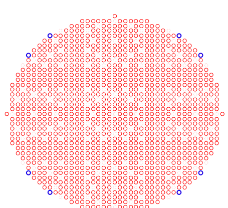
Core 800B0000 configurations during the first approach-to-critical experiment



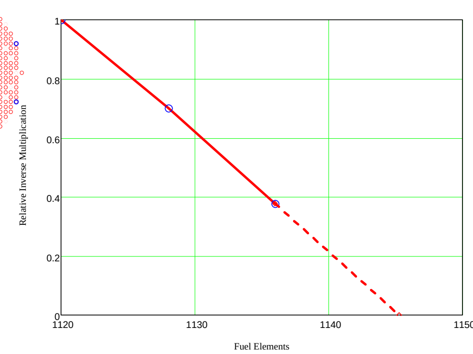
1120



1128



1136



At 1128 fuel elements:

k_{eff} = 0.9970

M ~ 330

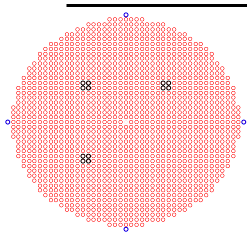
At 1136 fuel elements:

k_{eff} = 0.9984

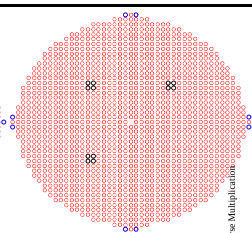
M ~ 620

The incremental fuel elements are shown in blue

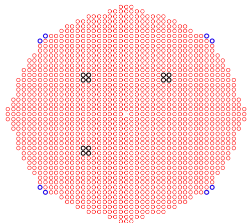
Core 800B0000A configurations near delayed critical



1436



1444



1452

At 1444 fuel elements:

k_{eff} = 0.9980

M ~ 490

At 1452 fuel elements:

k_{eff} = 0.9992

M ~ 1340

The incremental fuel elements are shown in blue

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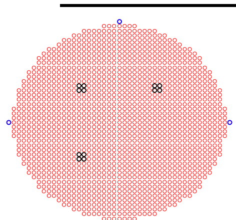
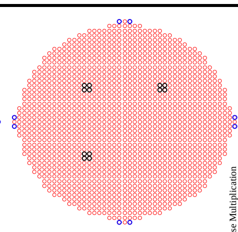
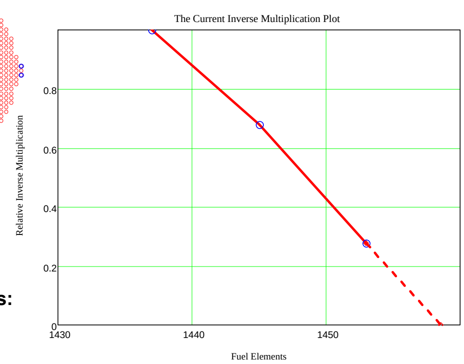
Core 800B0000B configurations during the first approach-to-critical experiment

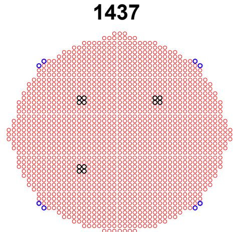


1437



1445





1453

At 1445 fuel elements:

k_{eff} = 0.9975

M ~ 400

At 1453 fuel elements:

k_{eff} = 0.9990

M ~ 1020

The incremental fuel elements are shown in blue

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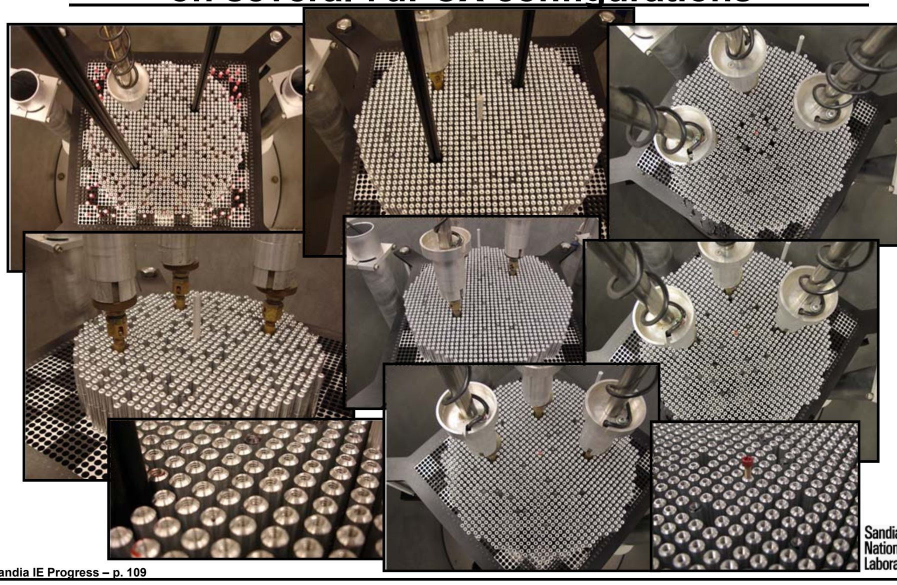
We have performed critical experiments on several 7uPCX configurations



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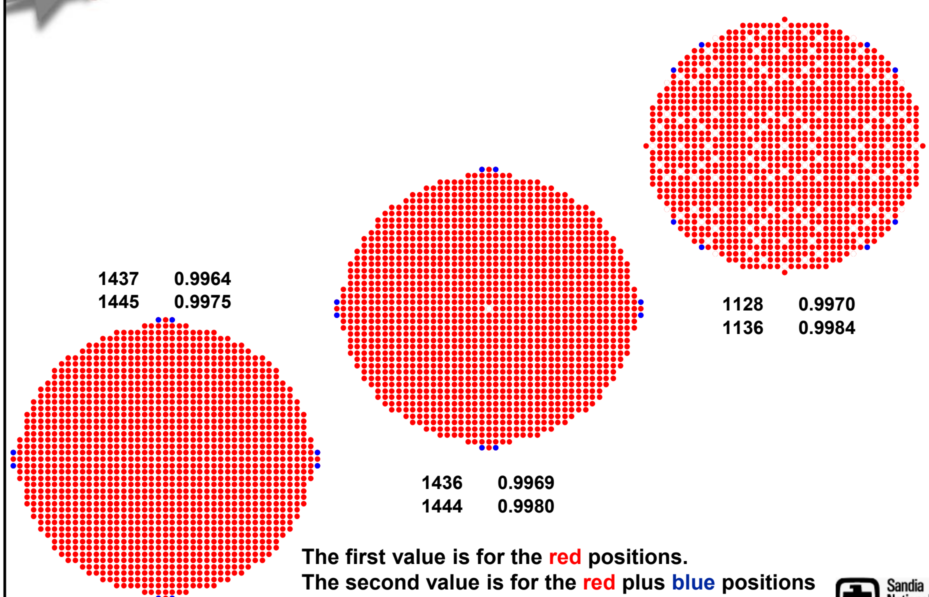
7uPCX Critical Configurations (1)



The first value is for the red positions.
The second value is for the red plus blue positions

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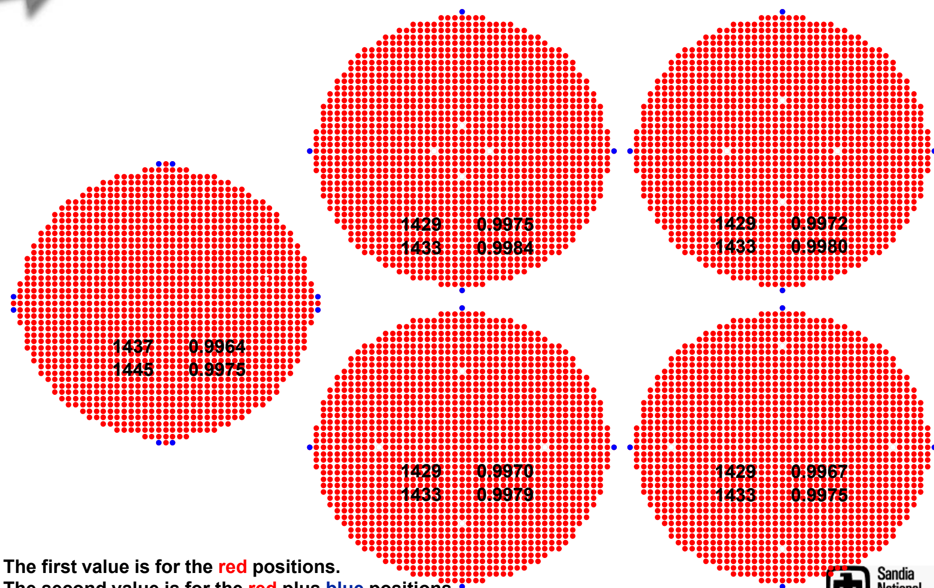
7uPCX Critical Configurations (2)



The first value is for the red positions.
The second value is for the red plus blue positions

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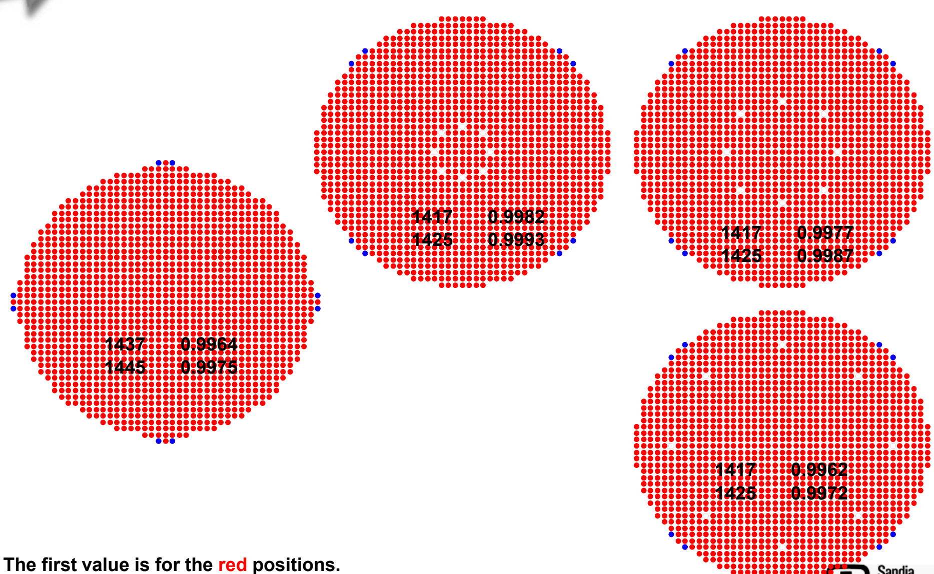
7uPCX Critical Configurations (3)



The first value is for the red positions.
The second value is for the red plus blue positions

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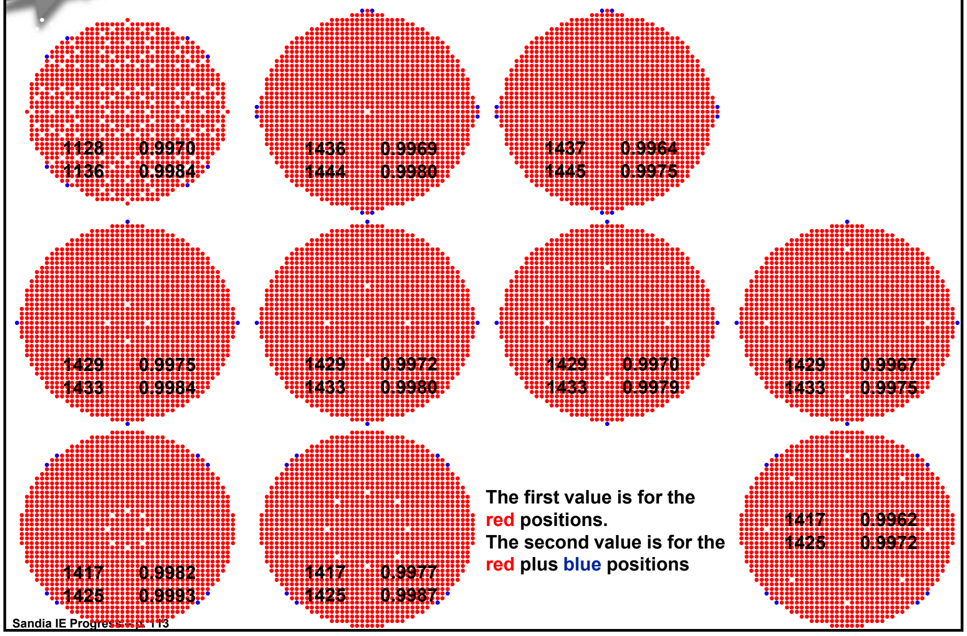
7uPCX Critical Configurations



The Future for the Sandia Criticals

- We will maintain the critical experiment capability for the foreseeable future
  - The NCSP plans to support the operation of the critical experiments
- We have developed a critical experiments training course module as part of the DOE NCSP Nuclear Criticality Safety Engineer training program
- We will continue to work through the 7uPCX experiment matrix
  - Complete measurements on the cores with pure water moderator
  - Perform experimentation with dissolved boron in the moderator
- Other experiments are under development

Sandia National Laboratories

The Phase Space our Authorization Basis Allows is Large

- Our design space:
  - UO_2 fuel
  - Metal Cladding
  - Light Water Moderator
  - <20% Enrichment
  - <500 kg of UO_2 in the reactor room
  - >50 kg of UO_2 in a critical configuration