Results of Critical Experiments on Water-Moderated Fully-Reflected 6.90% Enriched UO_2 Fuel Pin Arrays with a Fuel-to-Water Volume Ratio of 0.52

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Sandia National Laboratories

SAND2013-8211C

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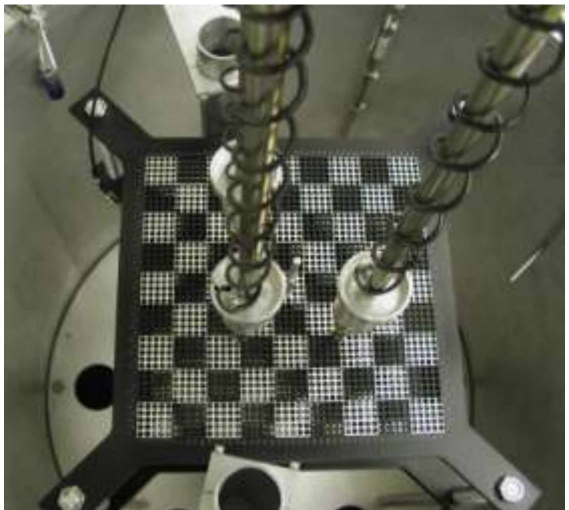
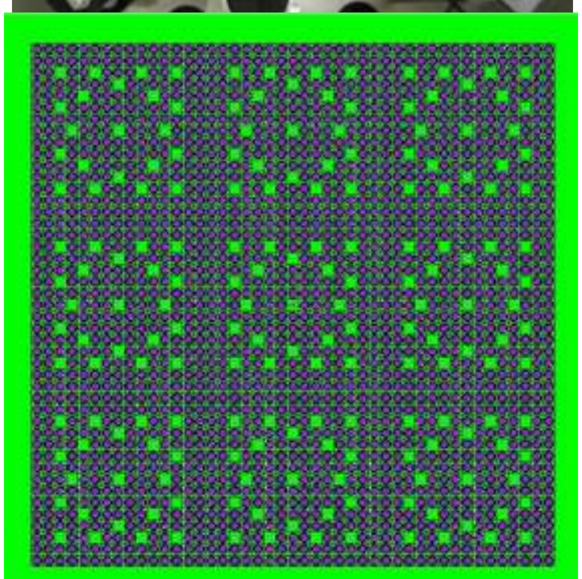
Summary of the paper

- We have completed a second set of experiments in the Seven Percent Critical Experiment (7uPCX)
- We completed an evaluation of the experiments as criticality safety benchmark experiments
- The reviews of the benchmark evaluation have been completed
- The evaluation will be published in the 2013 edition of the International Handbook of Evaluated Criticality Benchmark Experiments as LEU-COMP-THERM-078 (LCT078)
- This presentation is a brief tour of the experiments

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 can be made**
  - **Fission density profiles**
  - **Poison worth**
  - **Effect of water holes**

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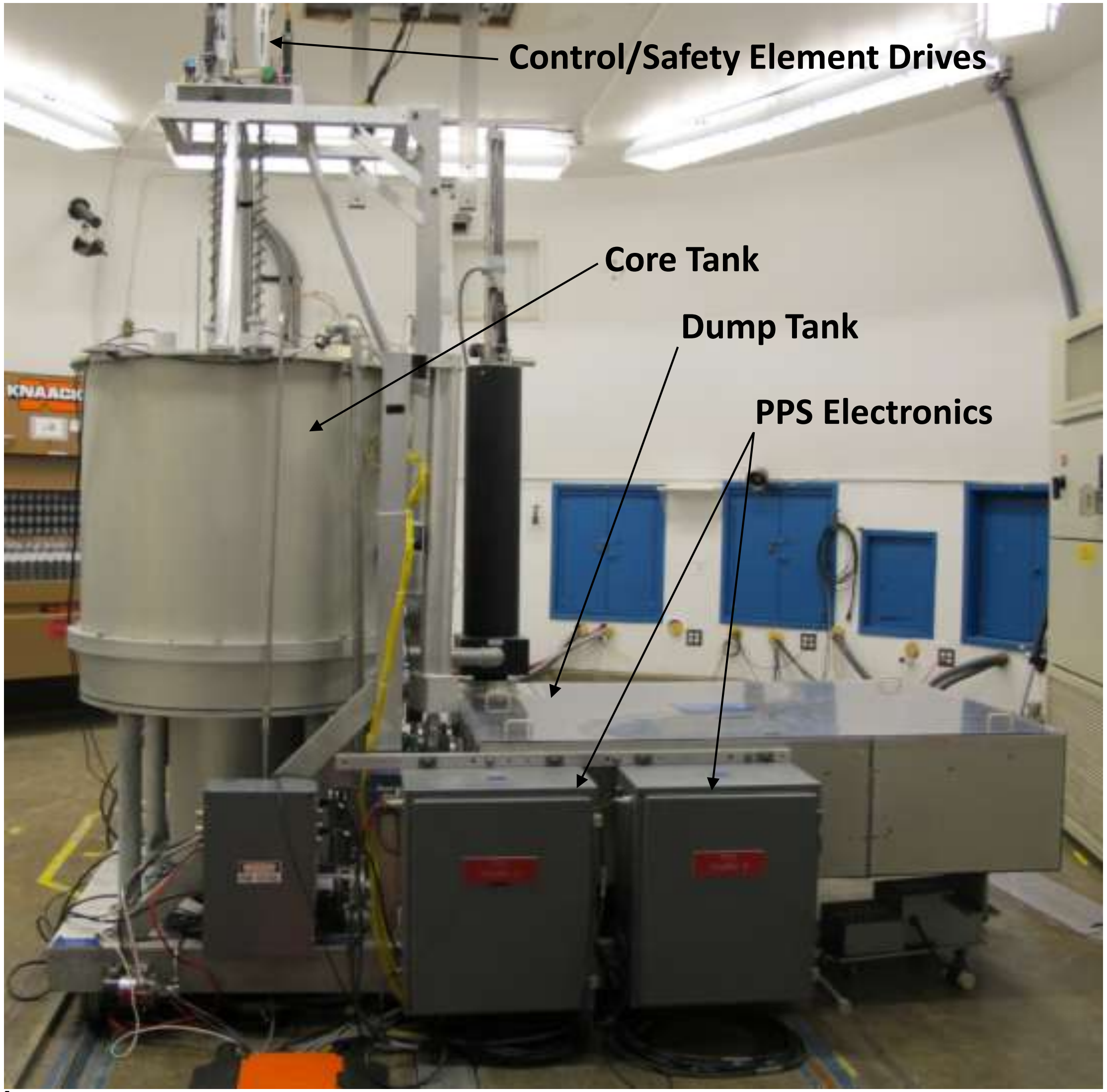
The critical assembly in person



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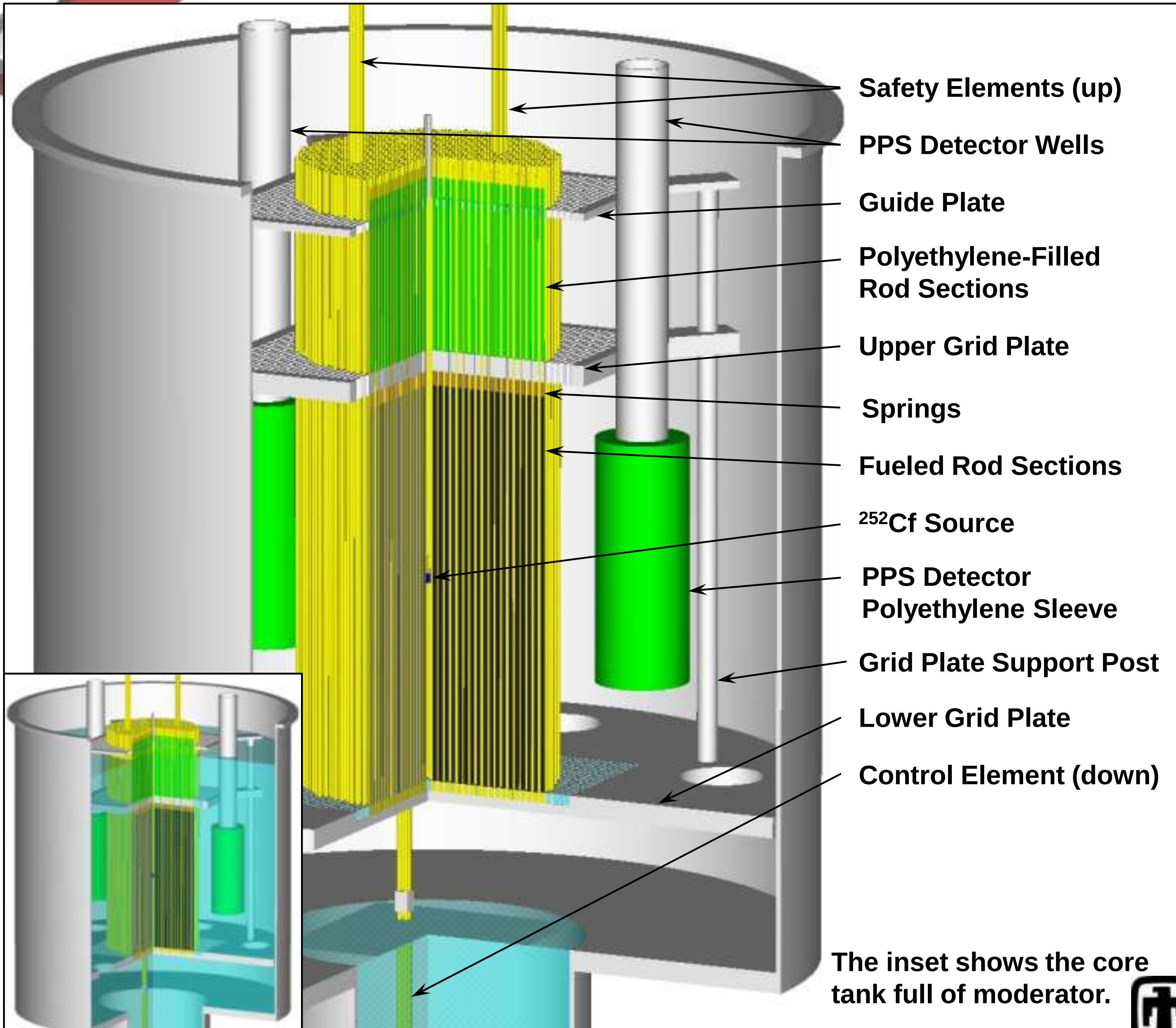
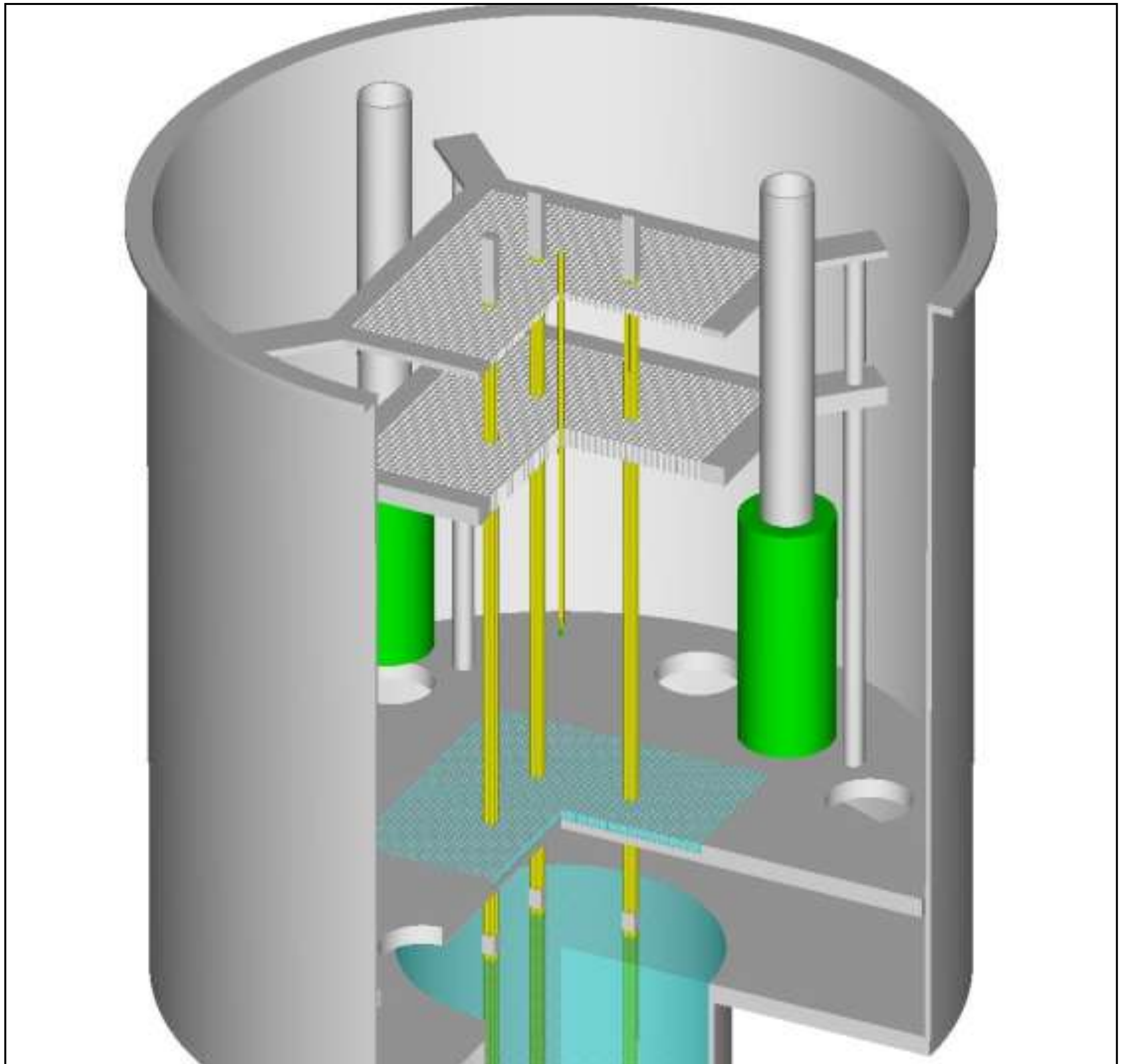


The inset shows the core tank full of moderator.

The Shut-Down Configuration of the Assembly



Fuel: 12 - CE/SE only

$k_{eff} \approx 0.139$

Safety Elements: Down

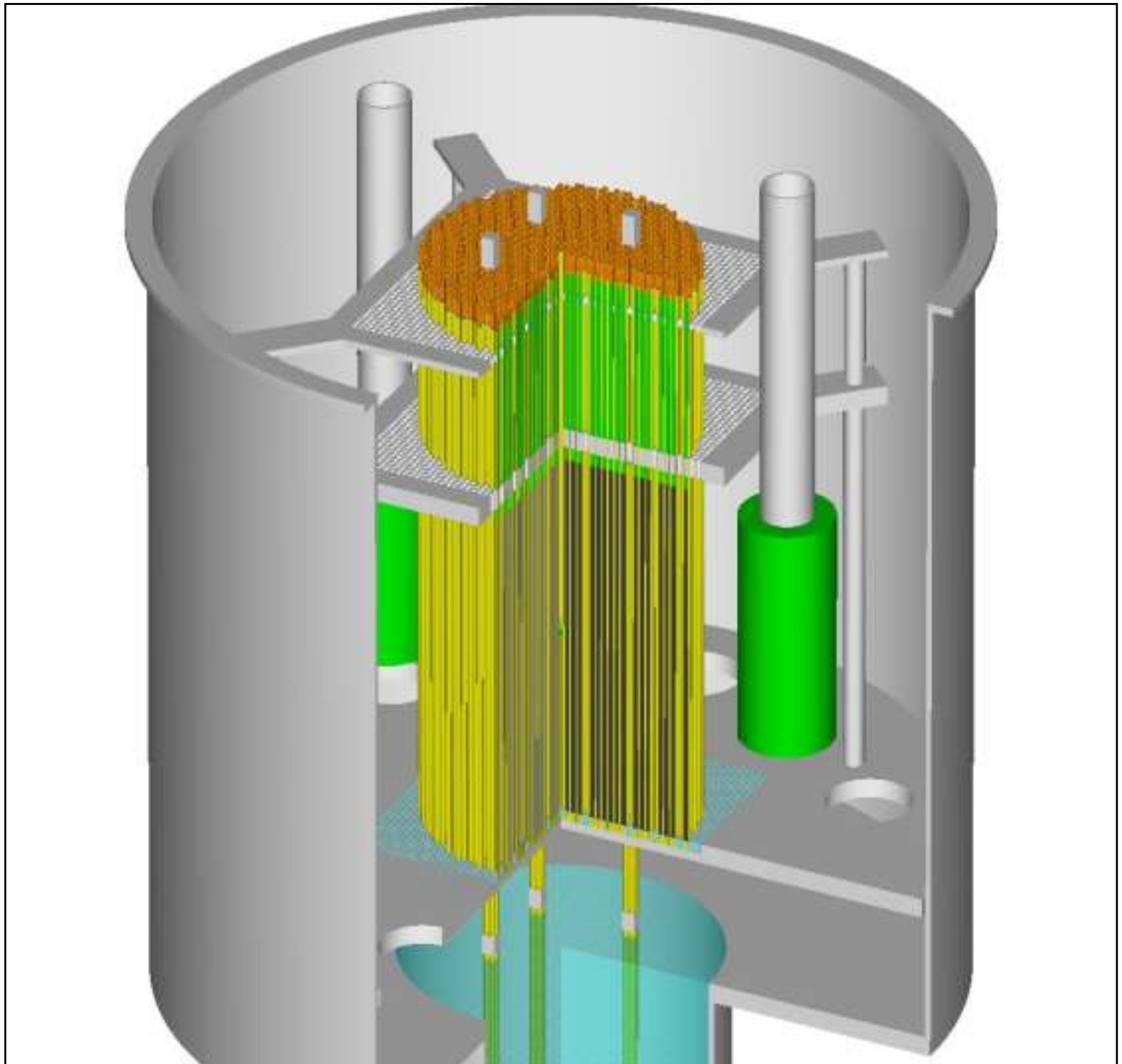
Control Element: Down

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.

The Desired Fuel Array is Complete



Fuel: 1136

k_{eff} ≈ 0.140

Safety Elements: Down

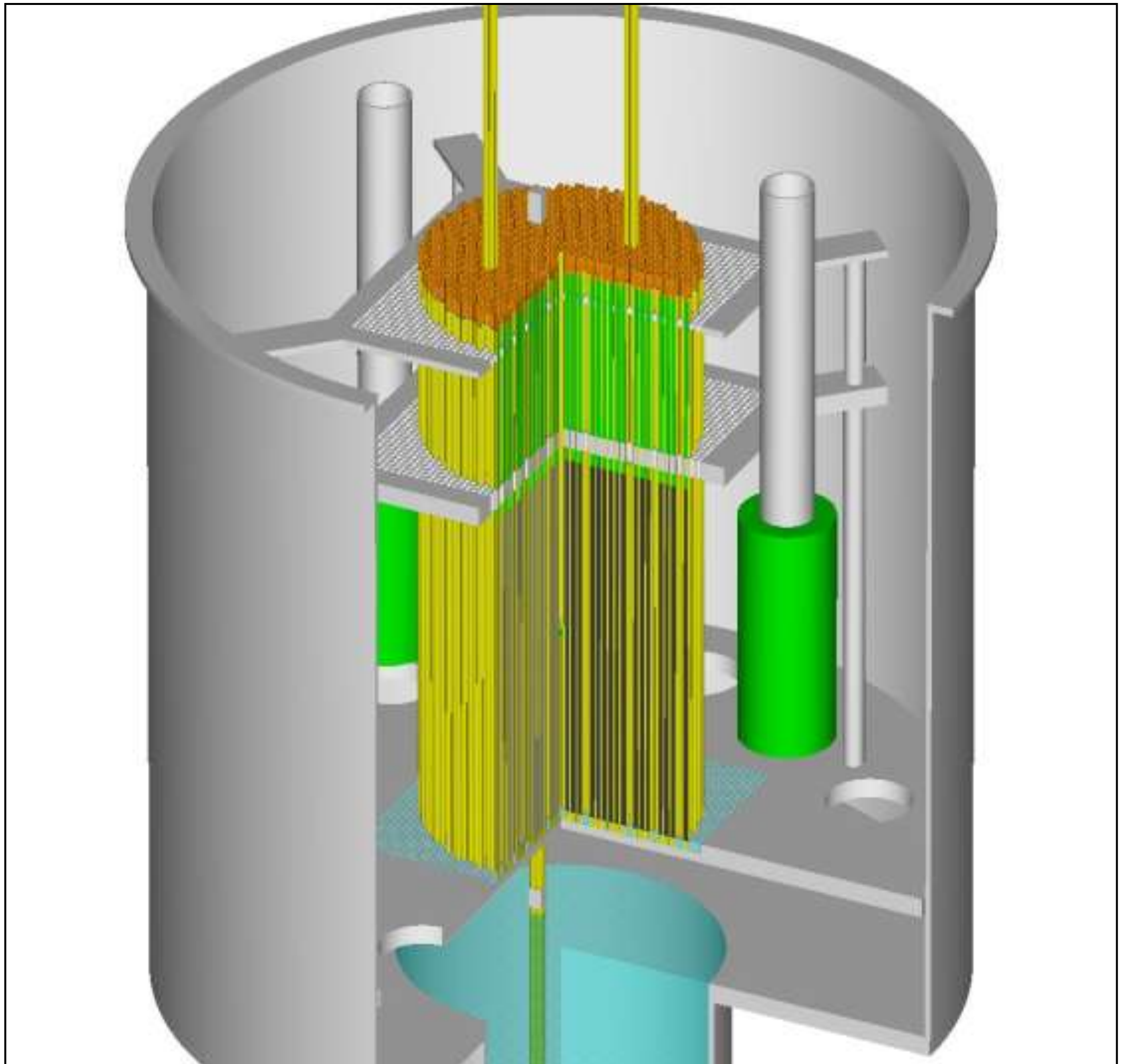
Control Element: Down

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.

The Safety Elements are Up



Fuel: 1136

k_{eff} ≈ 0.128

Safety Elements: Up

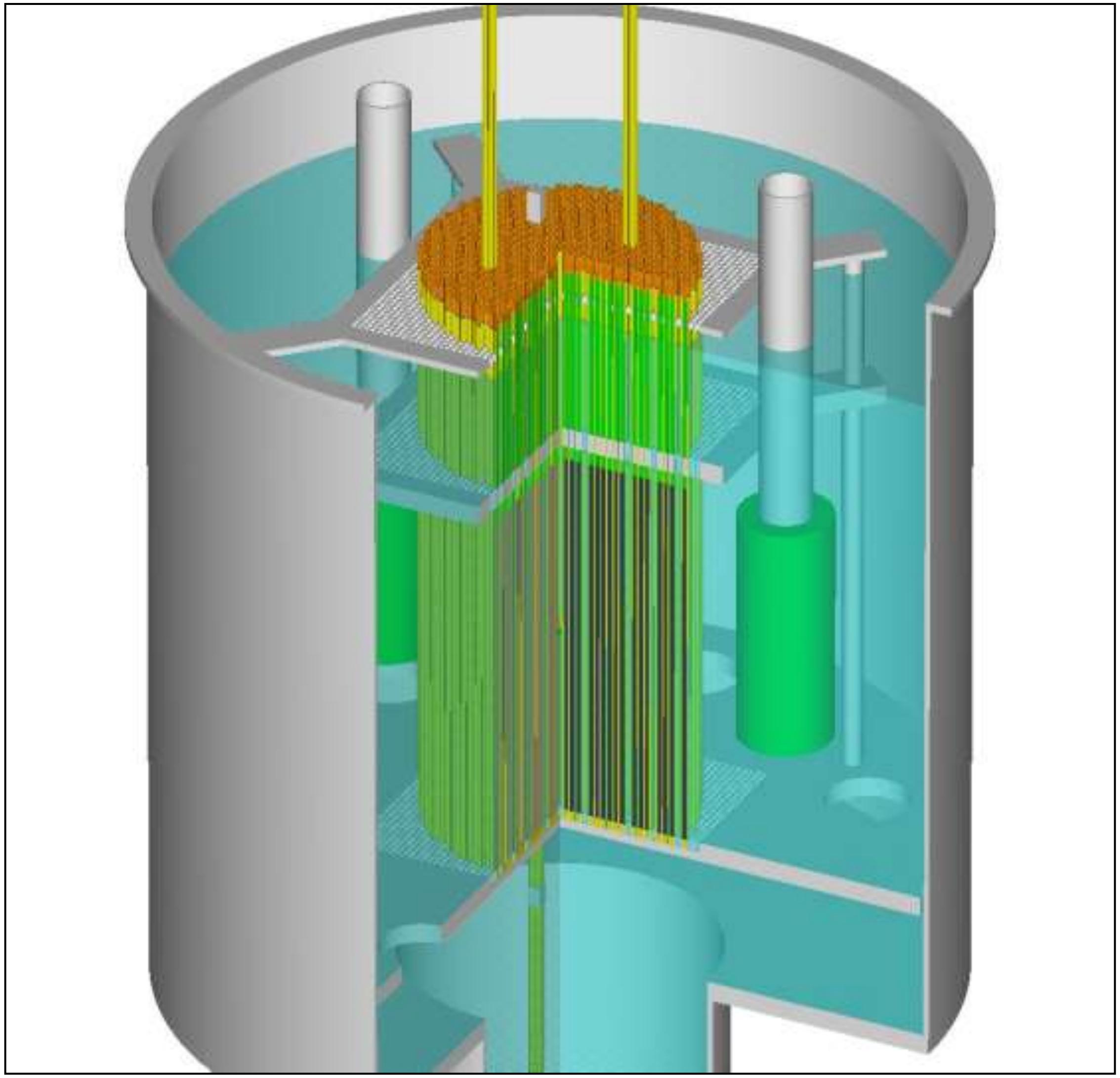
Control Element: Down

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.

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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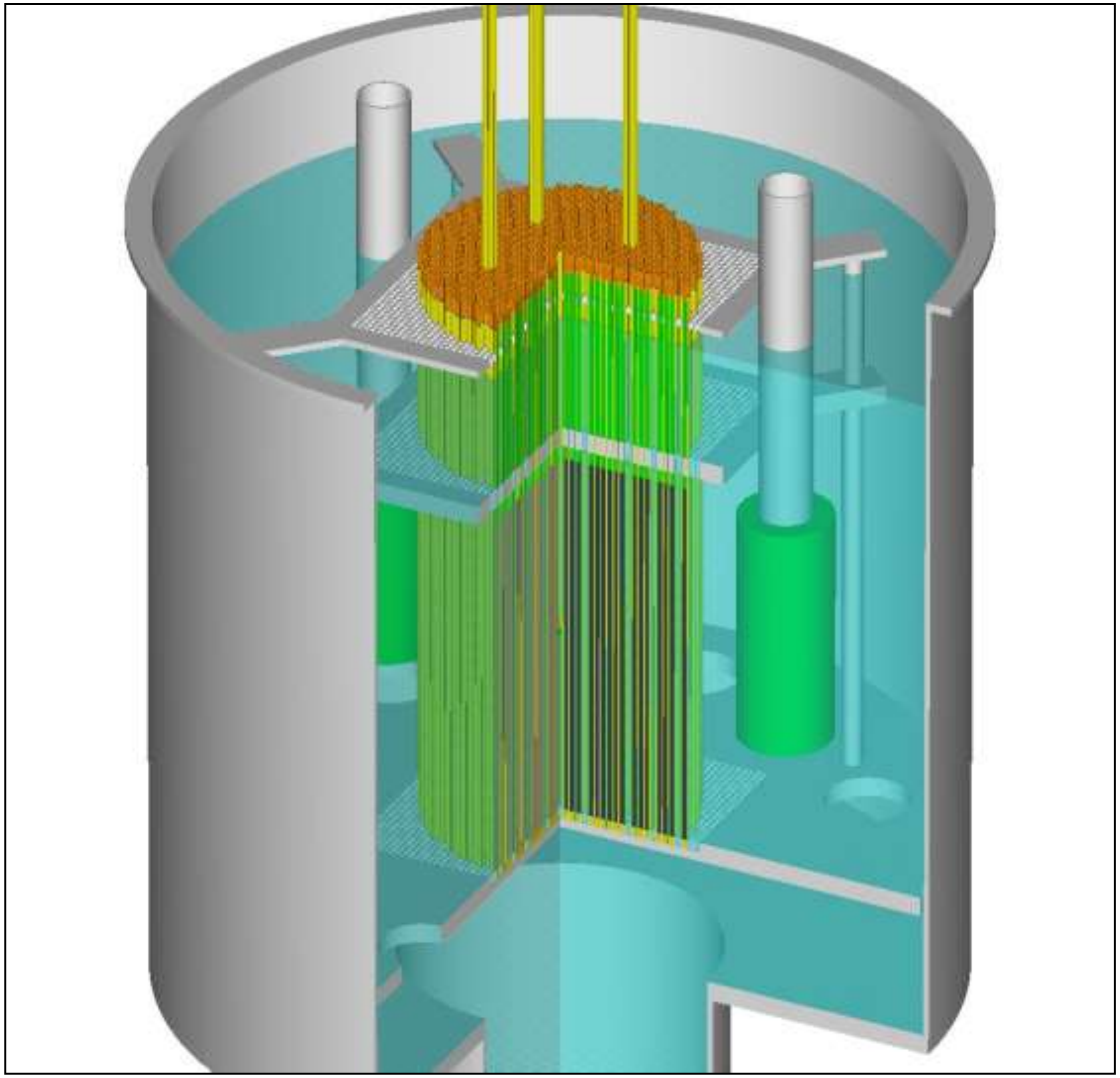
The Assembly Reaches Its Most Reactive State



Fuel: 1136

$k_{eff} \approx 0.998$

Safety Elements: Up

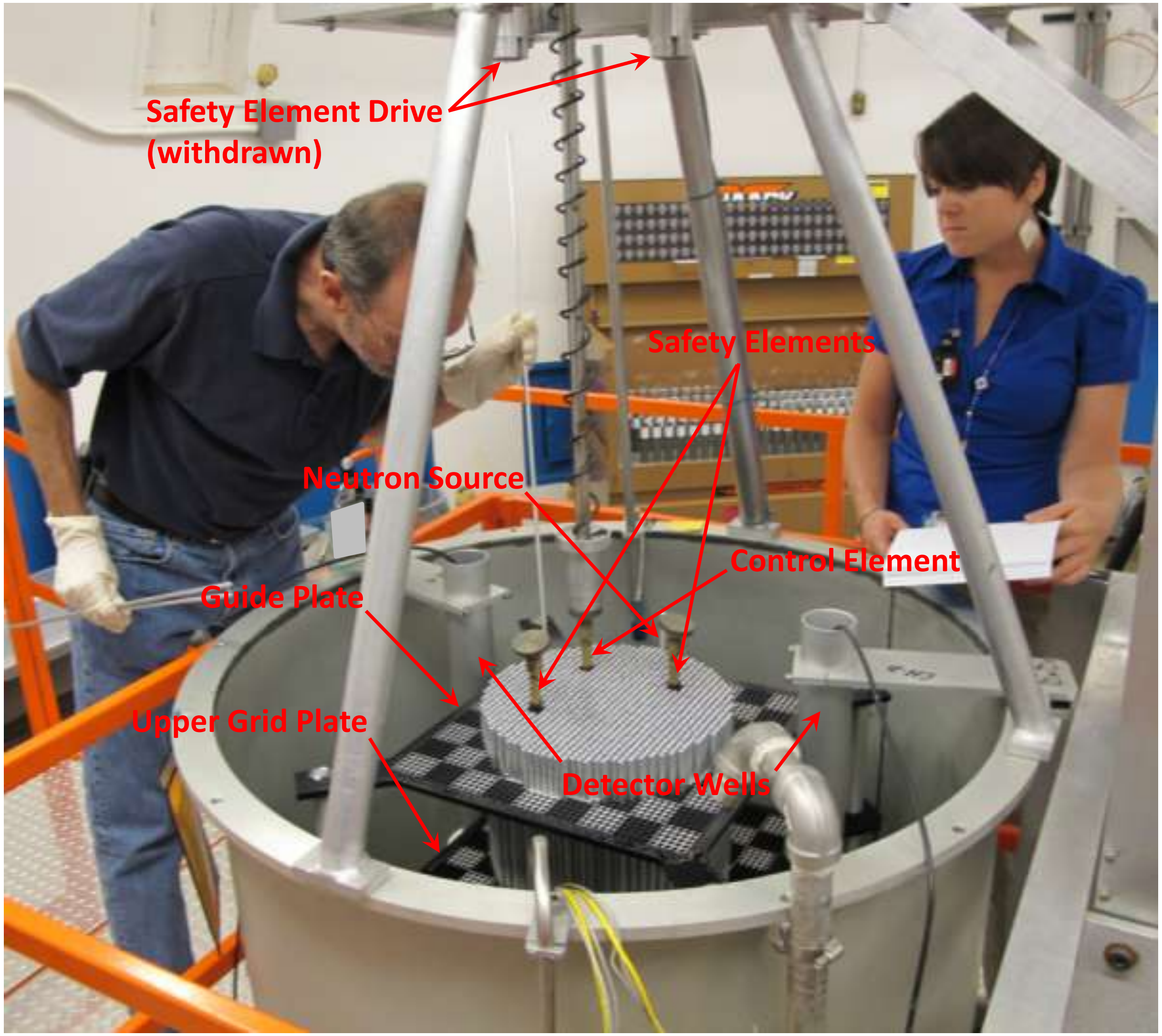
Control Element: Up

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.

Loading the core



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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
- At delayed critical, the multiplication and the count rates are infinite – the inverses are ZERO
- Estimates are made of the critical condition of the assembly by projecting inverse count rates to zero

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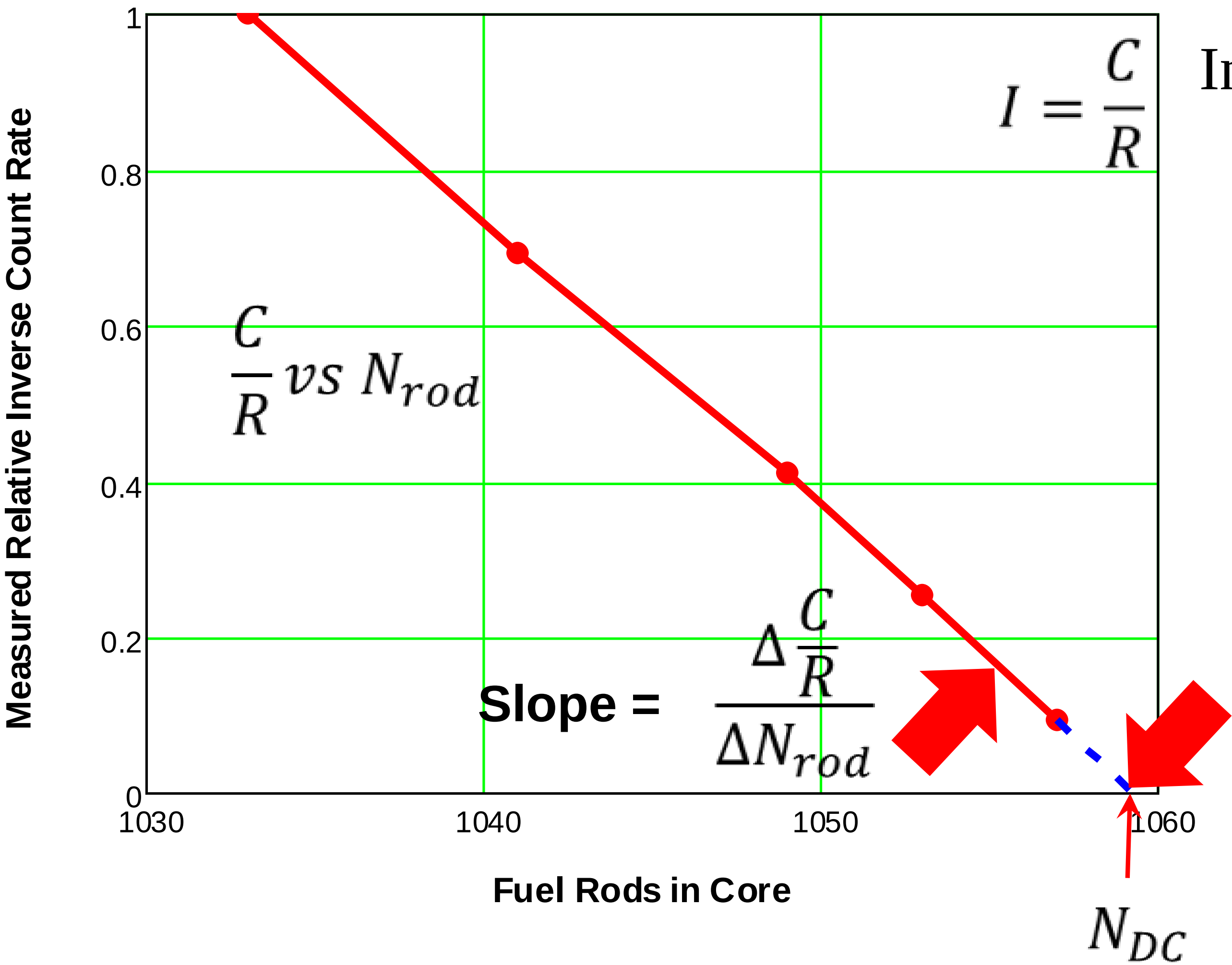
Inverse count rates during the approach to critical for LCT078 Case 1

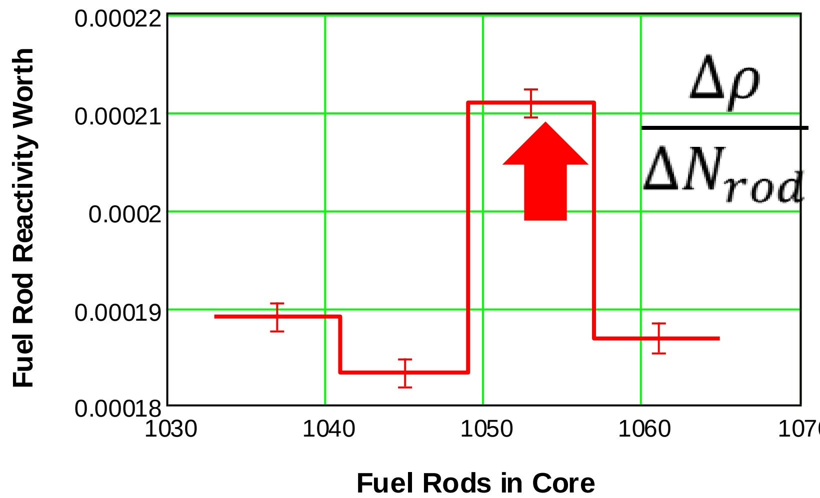
$R = measured\ count\ rate$

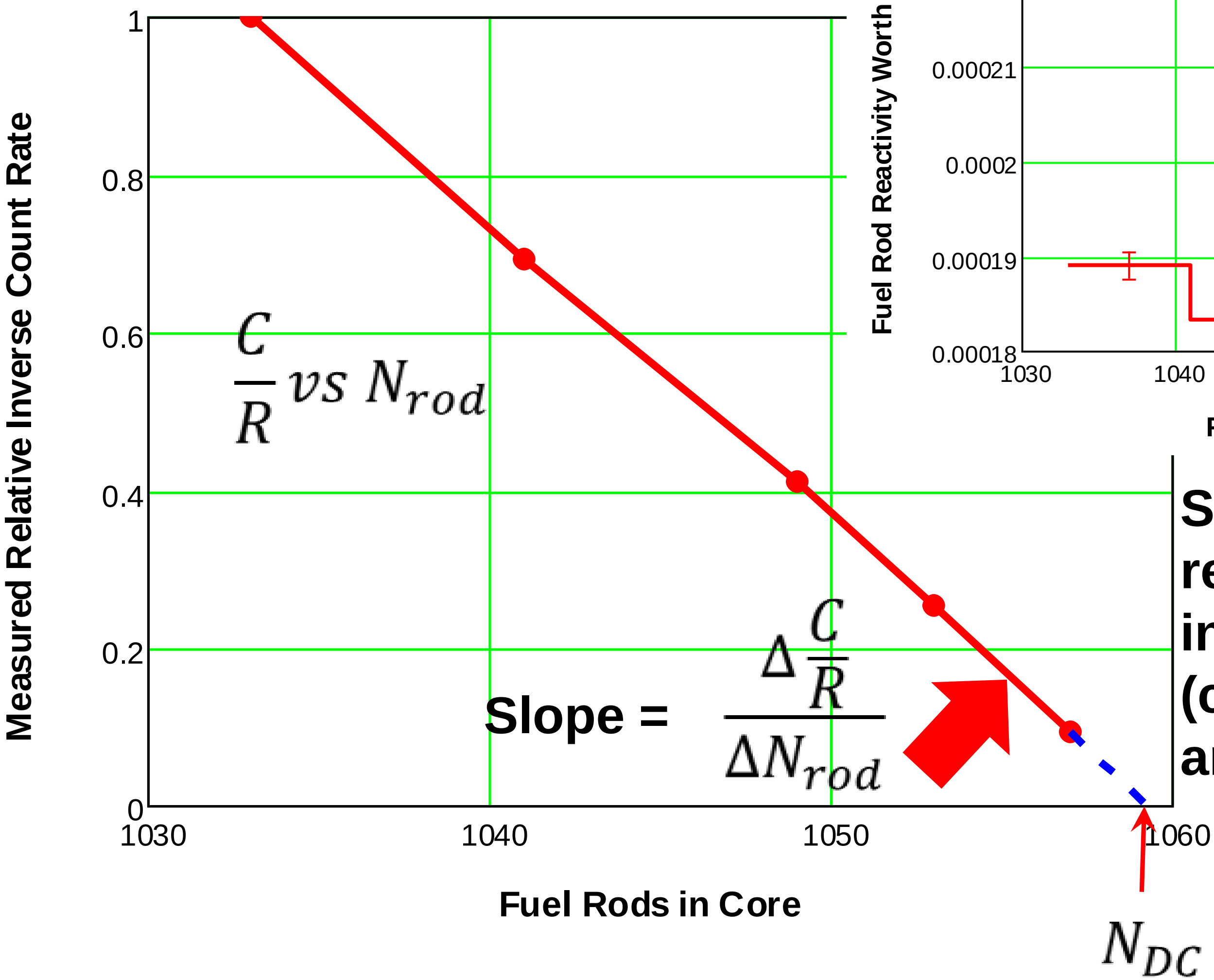


Inverse Count Rate
(C is a constant)

Project to I = 0

Calculating keff from approach data



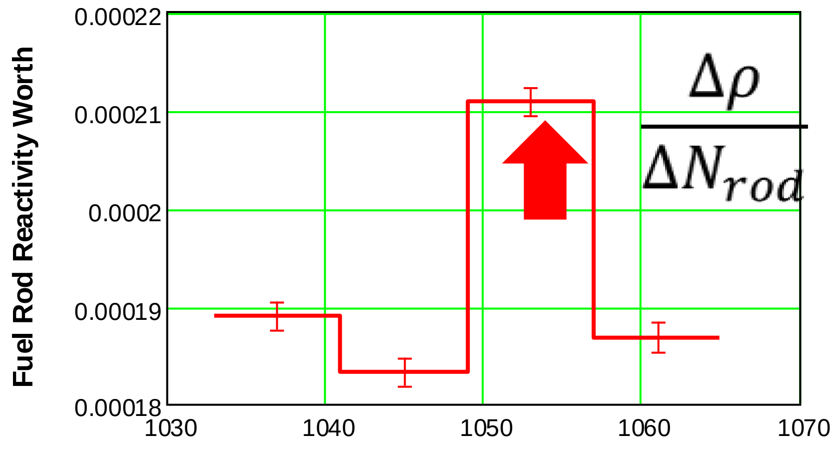


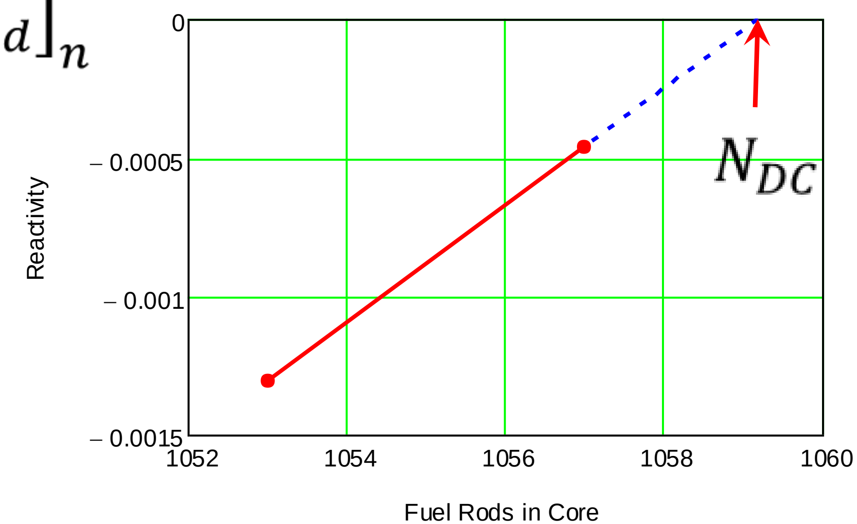
Separately calculate the reactivity worth of individual fuel rods (composite of MCNP5 and SCALE6.1 results)

Calculating keff from approach data

The method yields an estimate of N_{DC} for every two pairs of count rate measurements. The reactivity at loading N_n is obtained from:

$$\rho_n = (N_n - N_{DC(n)})\left[\frac{\Delta\rho}{\Delta N_{rod}}\right]_n$$





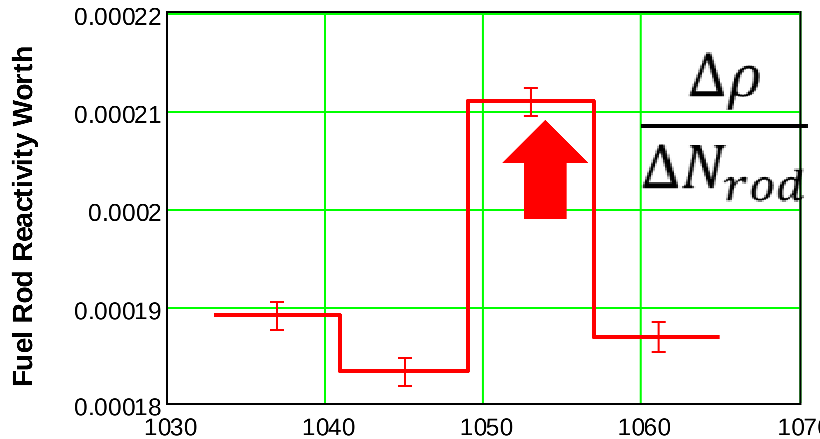
Calculating keff from approach data

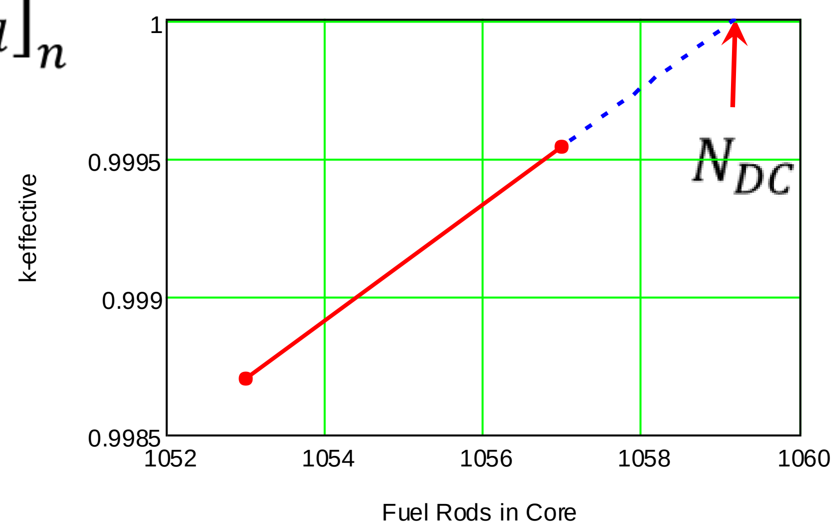
The method yields an estimate of N_{DC} for every two pairs of count rate measurements. The reactivity at loading N_n is obtained from:

$$\rho_n = (N_n - N_{DC(n)})\left[\frac{\Delta\rho}{\Delta N_{rod}}\right]_n$$

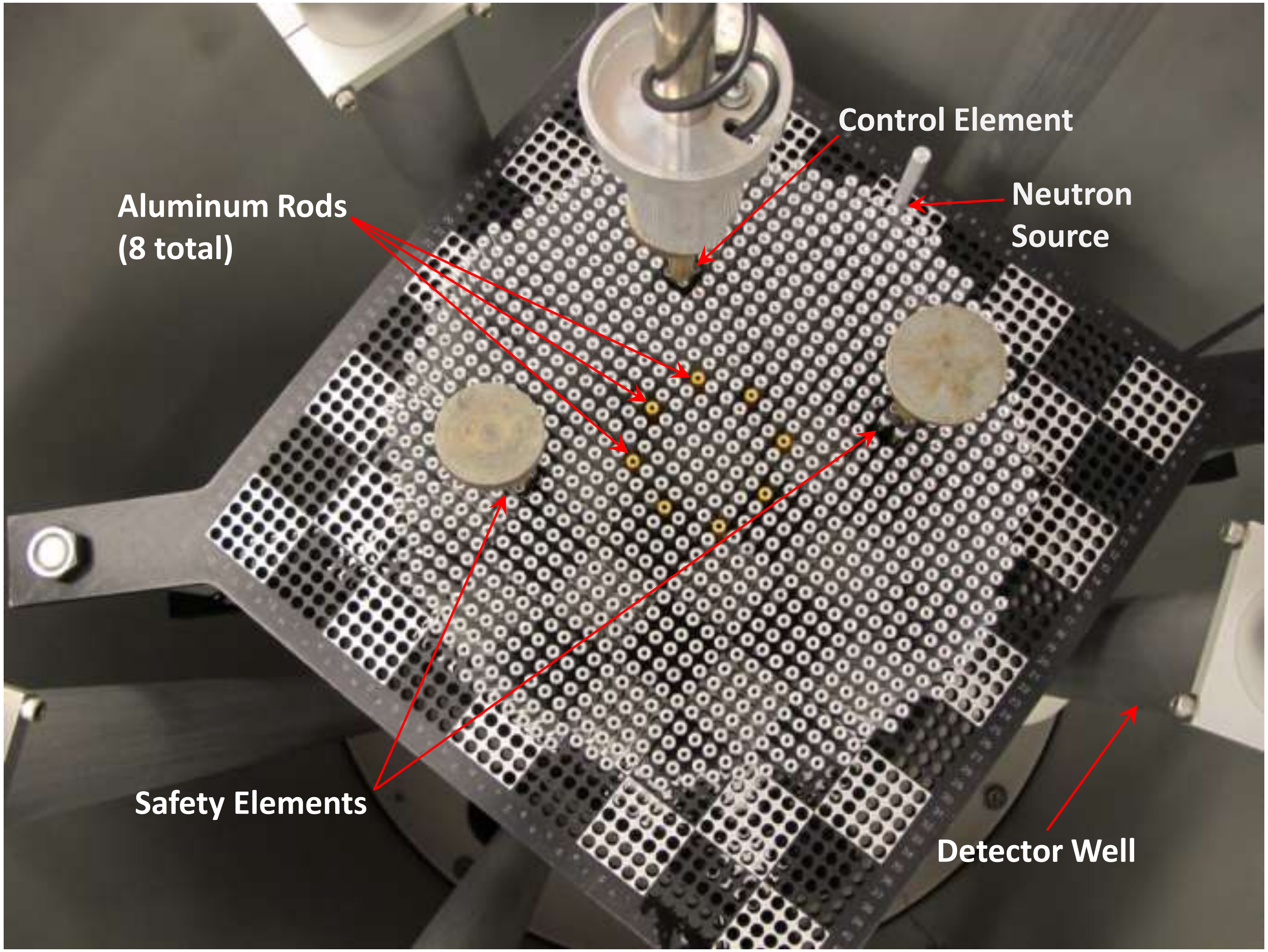
Invert the definition of the reactivity to get k_{eff} at N_n

$$k_n = \frac{1}{1-\rho_n}$$



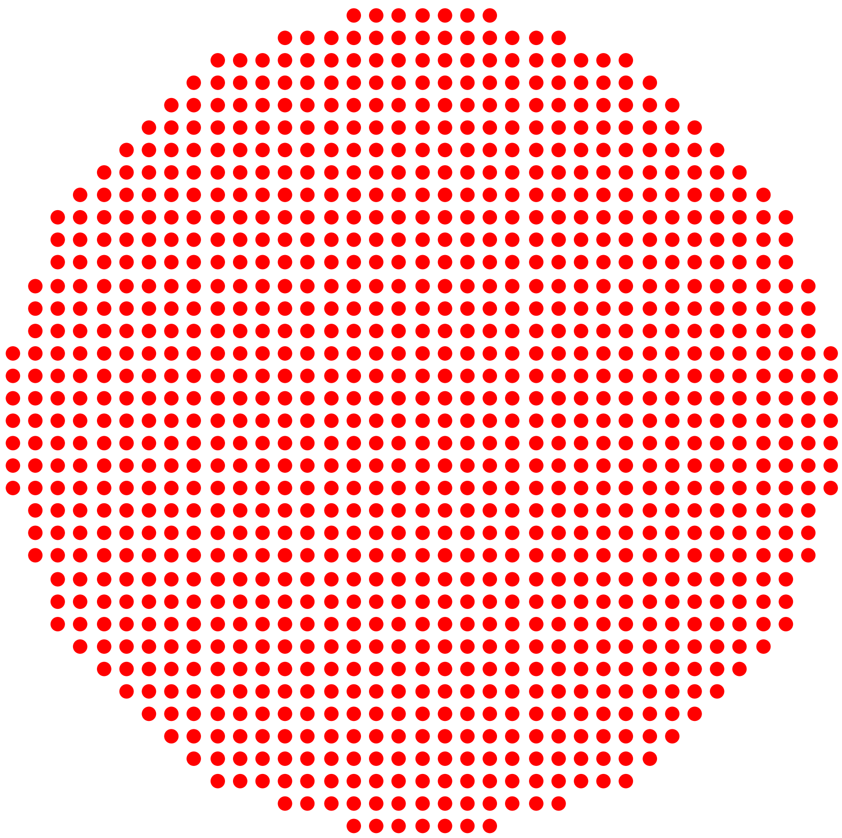


A completed core (LCT078 Case 11)



LEU-COMP-THERM-078 Case 1

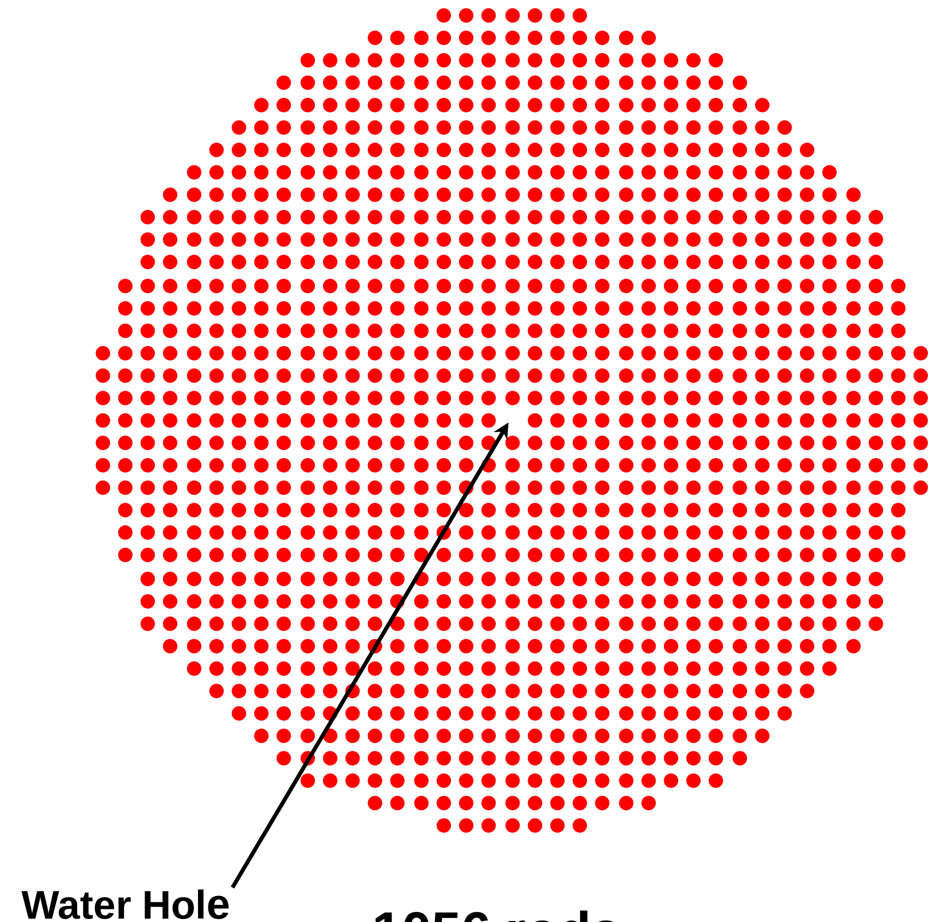
▪



1057 rods

k_{eff} = 0.9995

LEU-COMP-THERM-078 Case 2

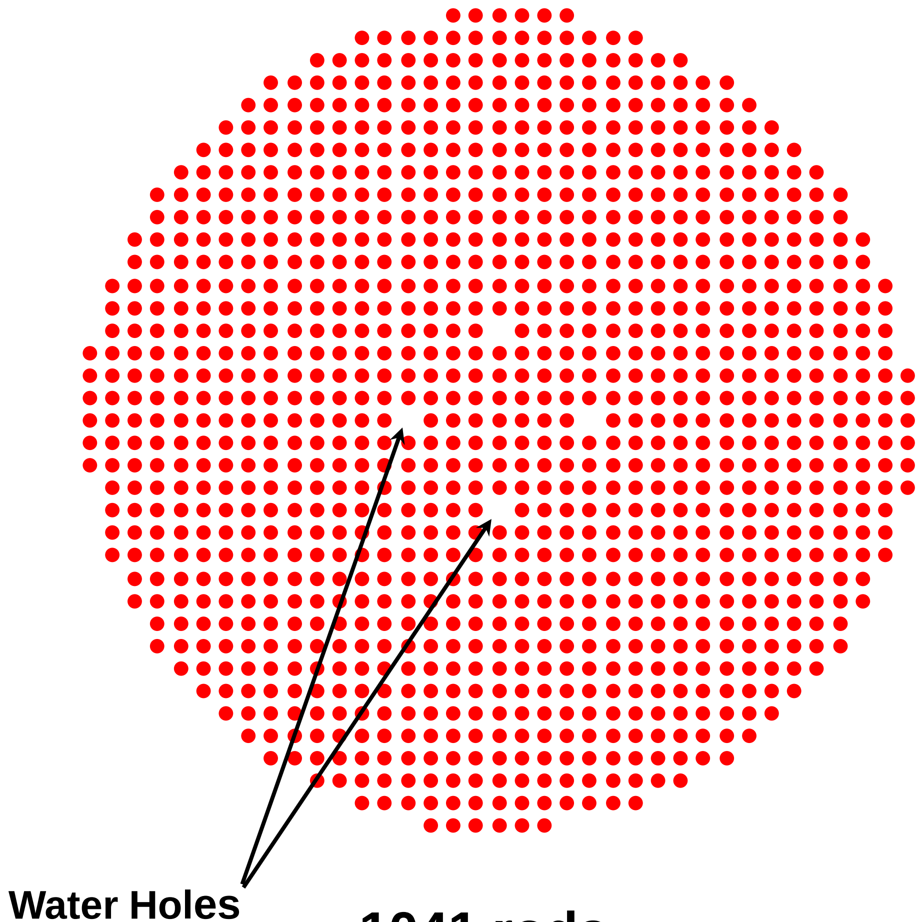


1056 rods

k_{eff} = 0.9999

LEU-COMP-THERM-078 Case 3

▪

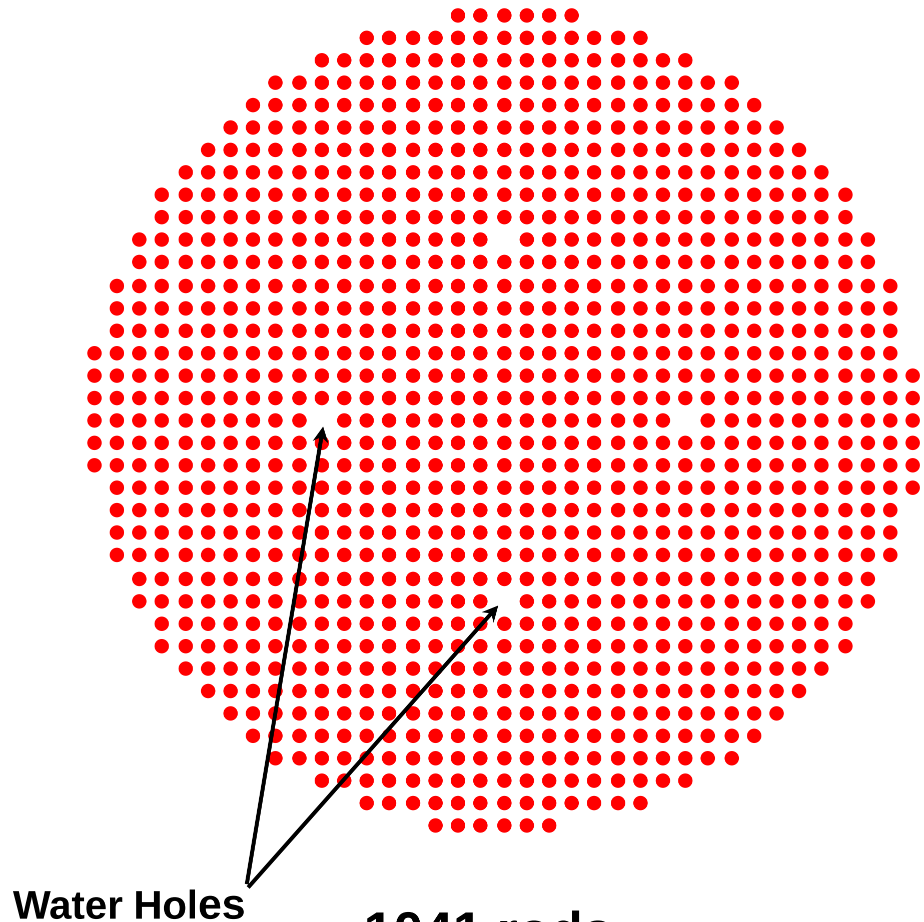


1041 rods

k_{eff} = 0.9990

LEU-COMP-THERM-078 Case 4

▪

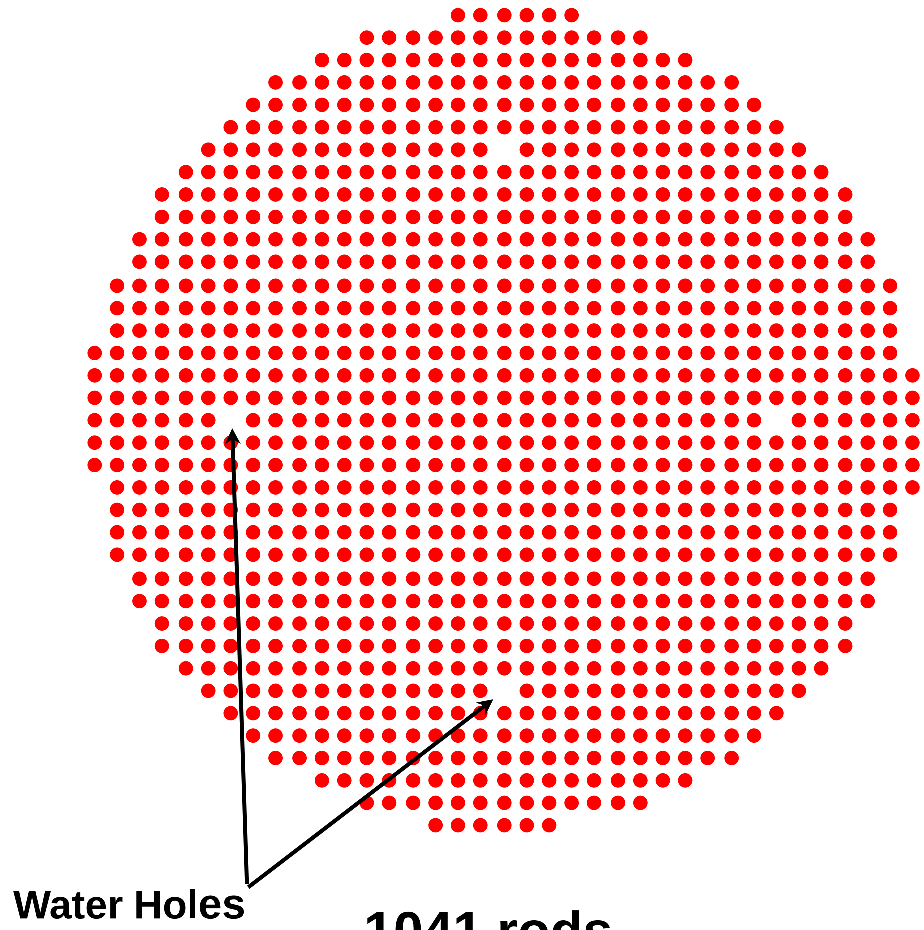


1041 rods

k_{eff} = 0.9986

LEU-COMP-THERM-078 Case 5

▪



1041 rods

k_{eff} = 0.9980

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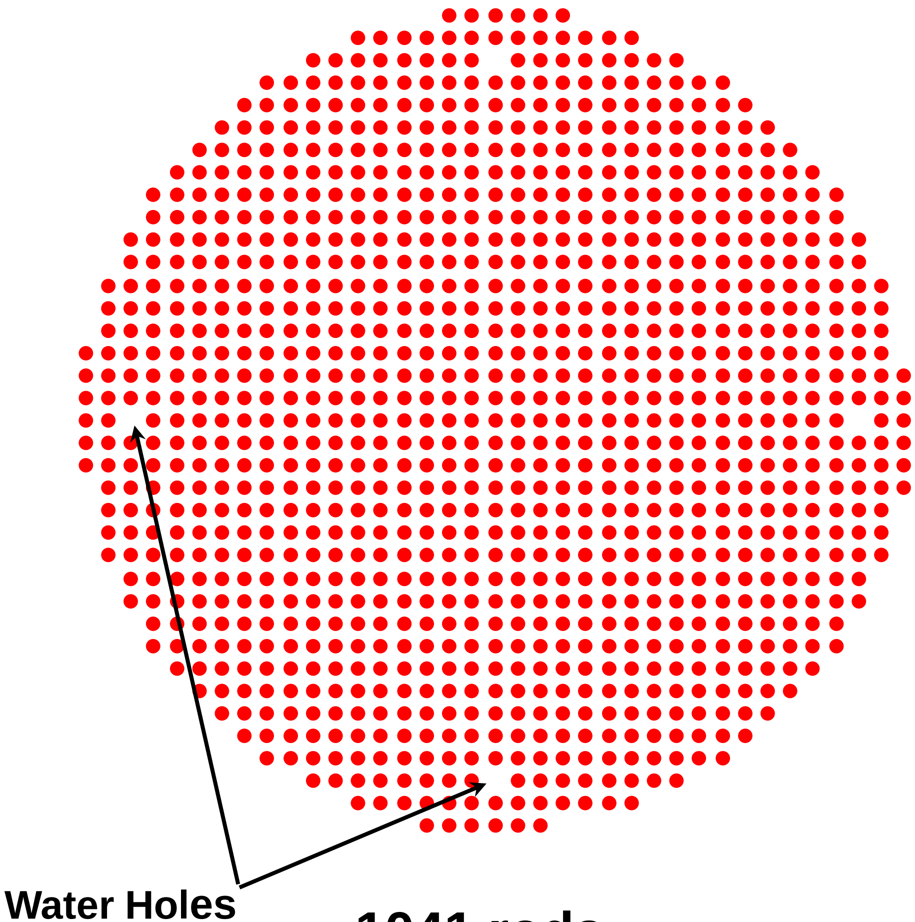
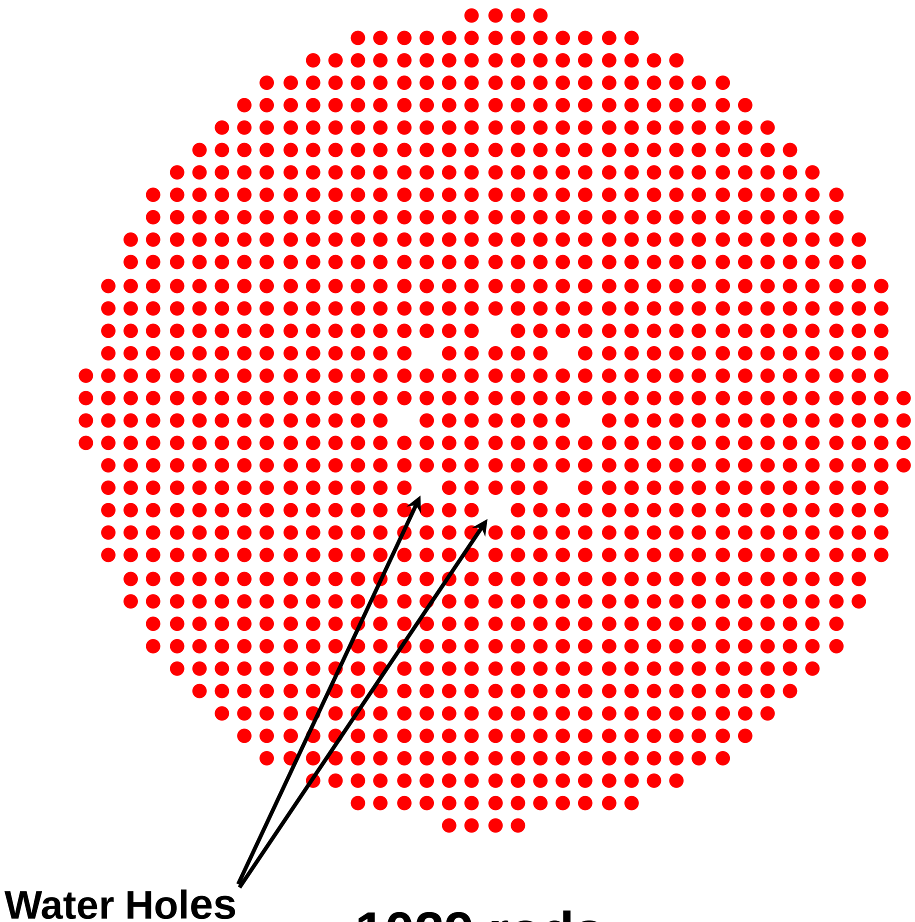
LEU-COMP-THERM-078 Case 6



1041 rods

k_{eff} = 0.9974

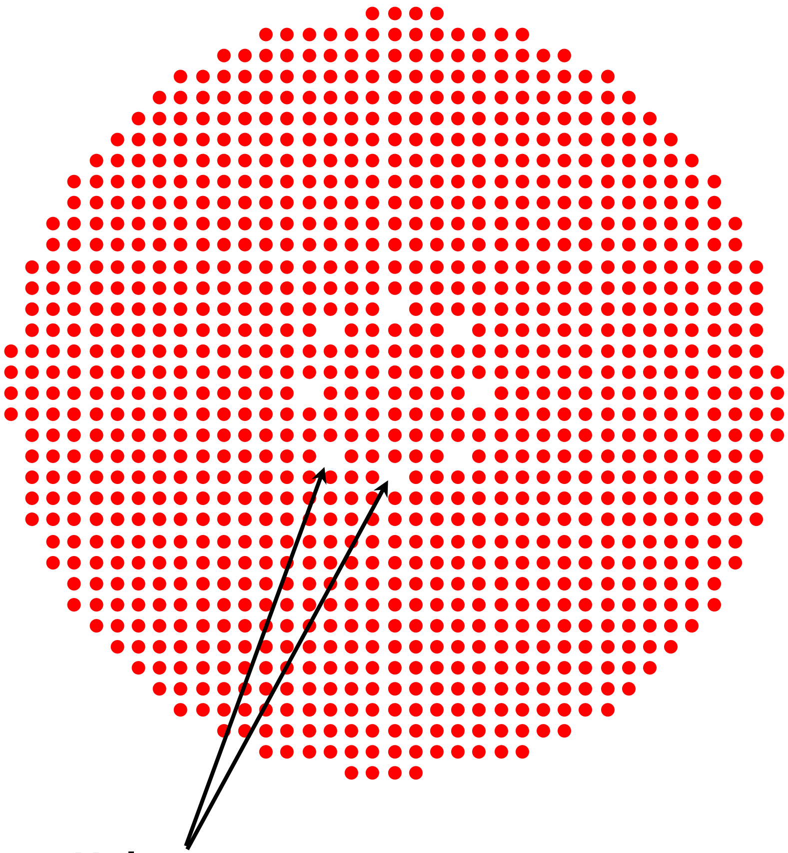
LEU-COMP-THERM-078 Case 7



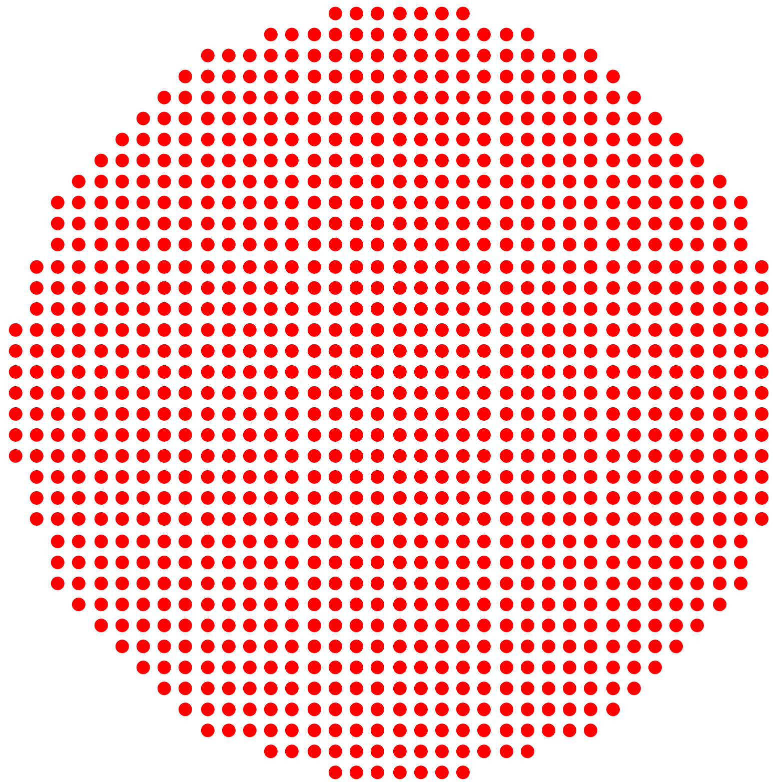
1029 rods

k_{eff} = 0.9994

LEU-COMP-THERM-078 Cases 7 and 1

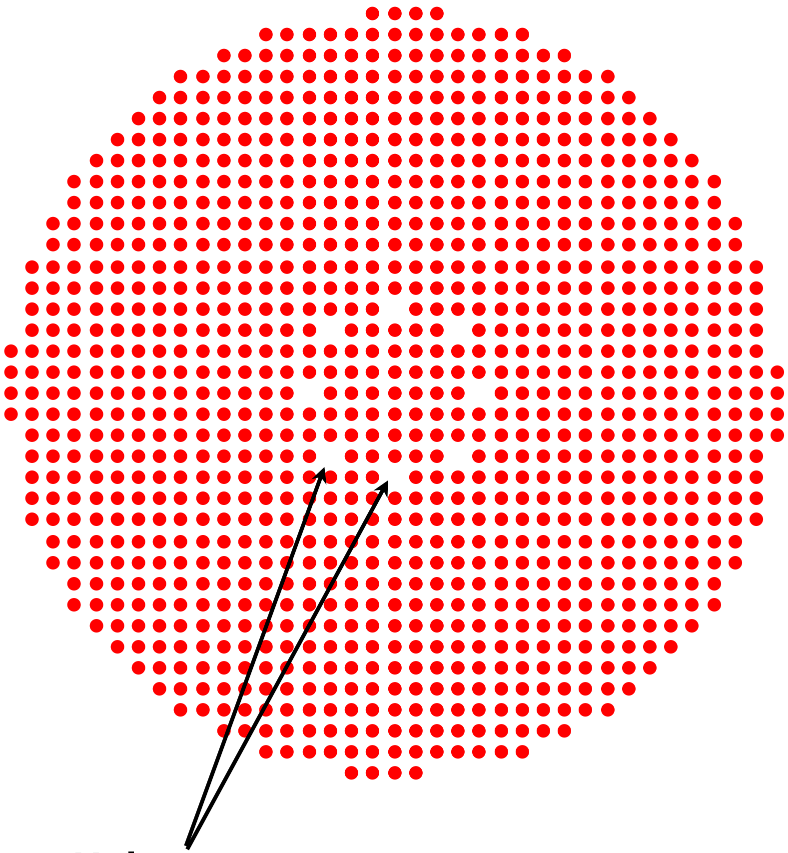


Case 7
1029 rods (1037 positions)
k_{eff} = 0.9994



Case 1
1057 rods
k_{eff} = 0.9995

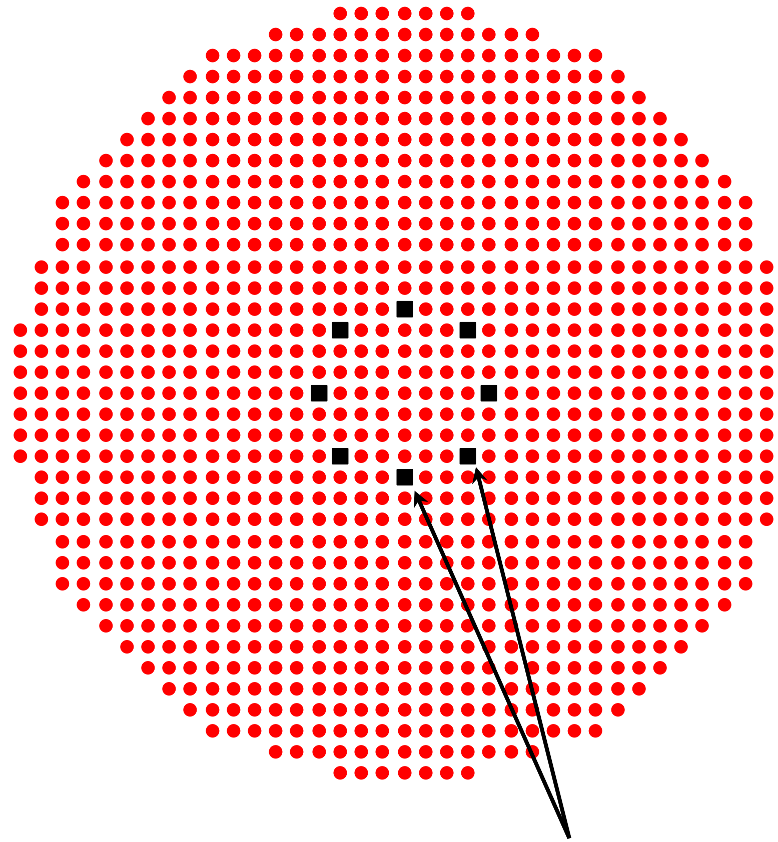
LEU-COMP-THERM-078 Cases 7 and 11



Case 7

1029 rods (1037 positions)

$k_{eff} = 0.9994$



Case 11

1049 rods (1057 positions)

$k_{eff} = 0.9994$

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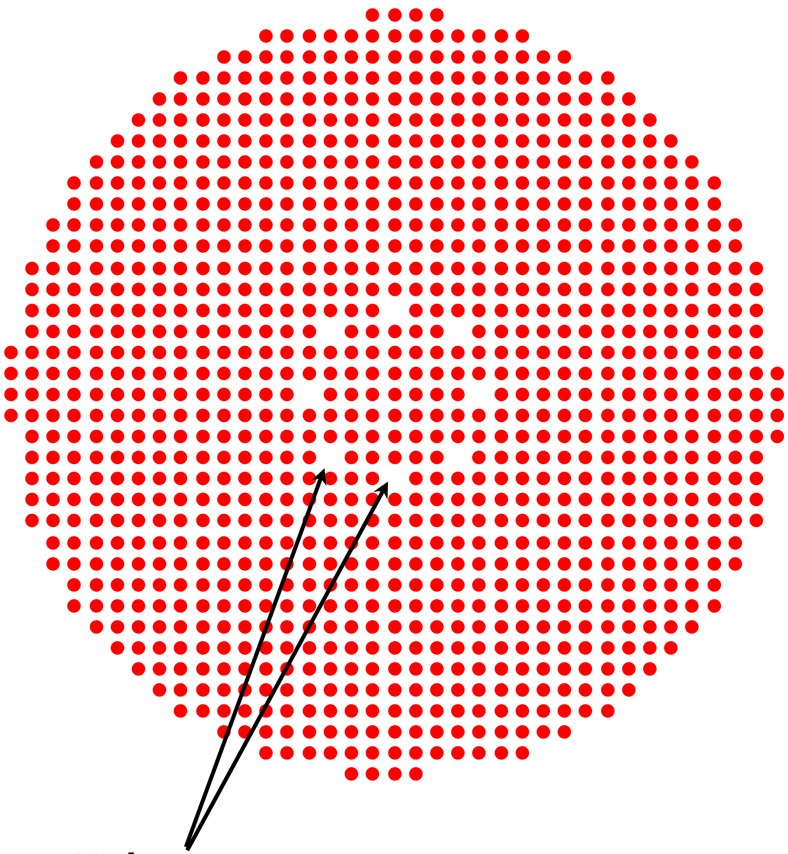
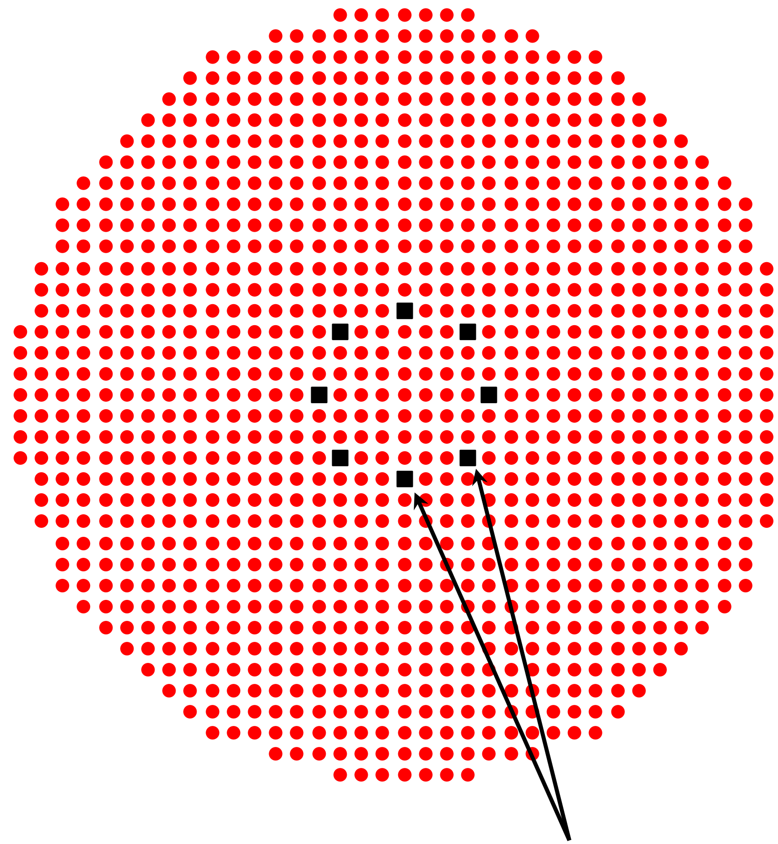
LEU-COMP-THERM-078 Cases 7 and 11

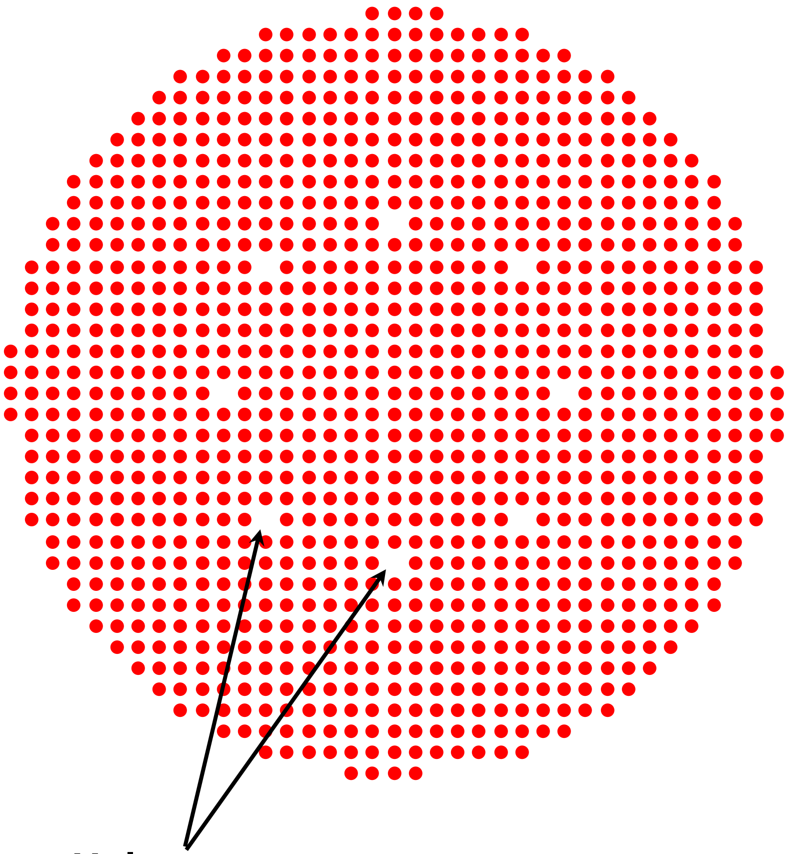


Case 7
1029 rods
k_{eff} = 0.9994

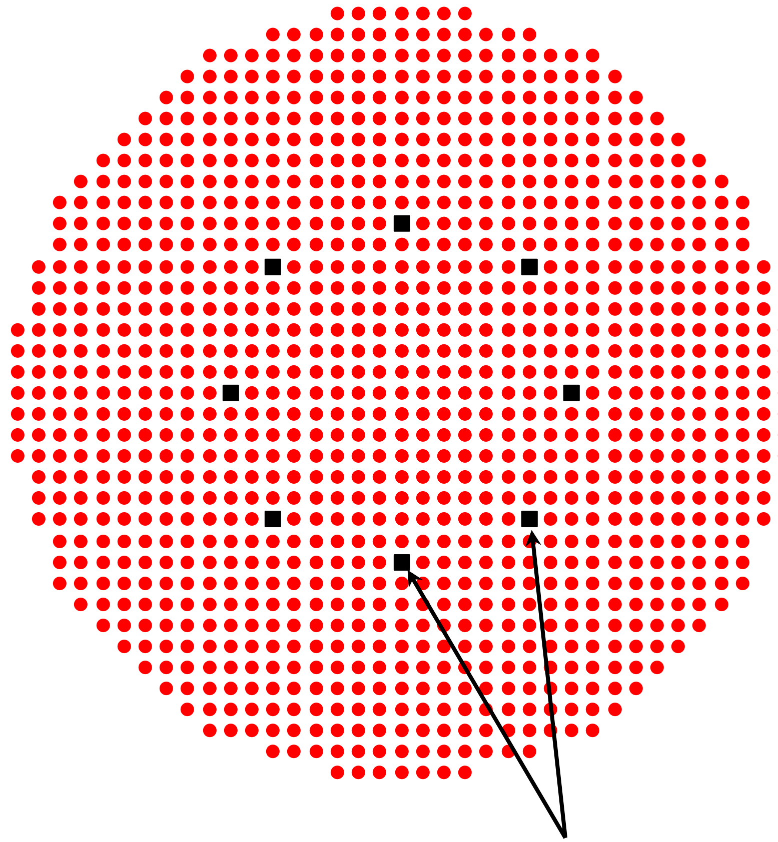


Case 11
1049 rods
k_{eff} = 0.9994

LEU-COMP-THERM-078 Cases 8 and 12

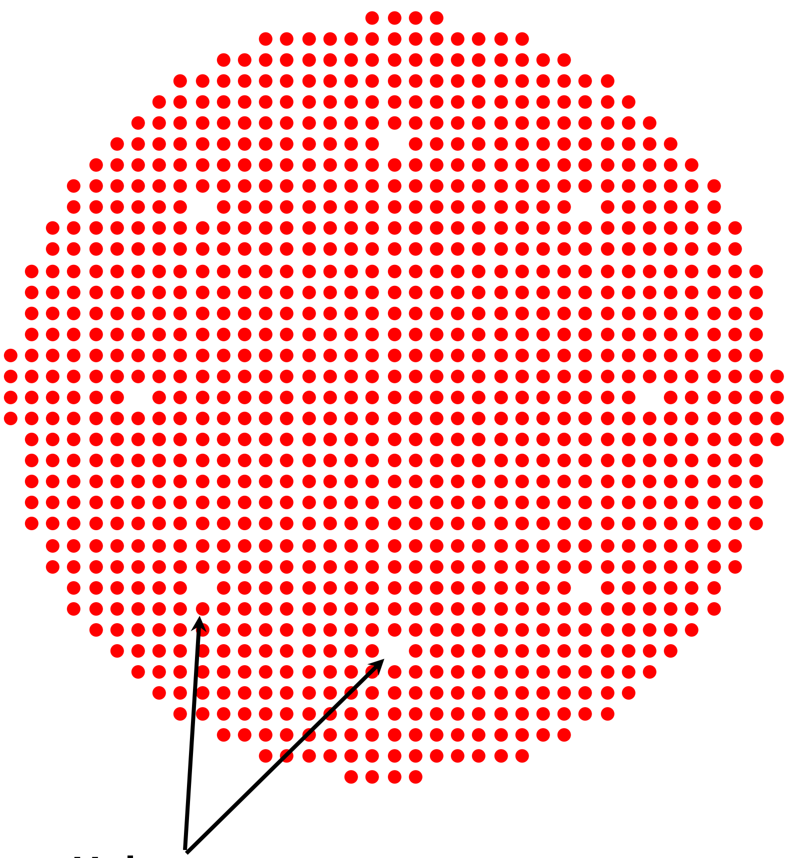


Case 8
1029 rods
k_{eff} = 0.9987

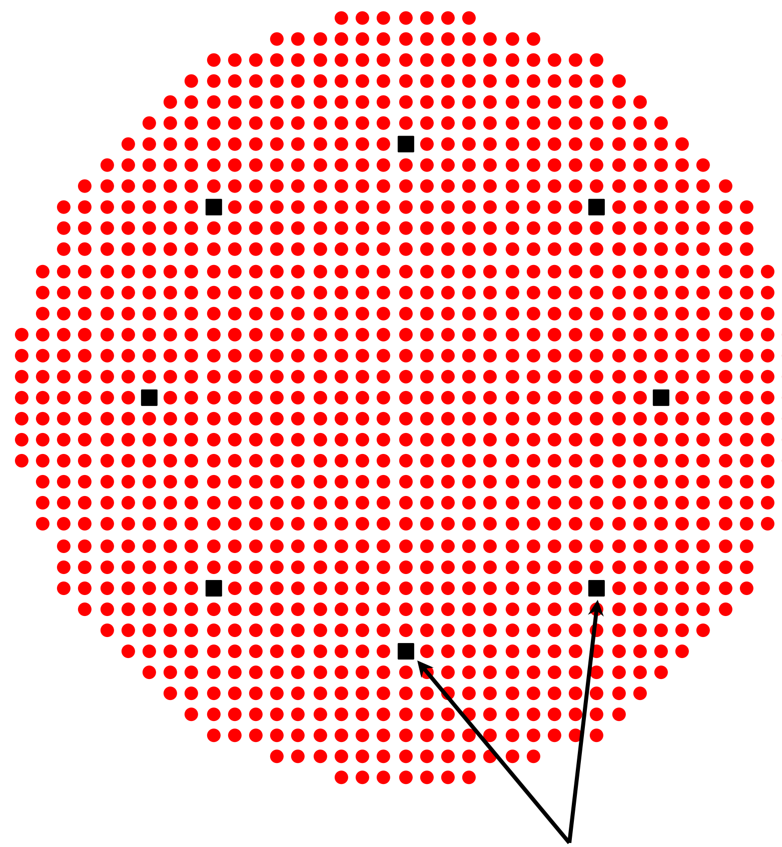


Case 12
1049 rods
k_{eff} = 0.9993

LEU-COMP-THERM-078 Cases 9 and 13

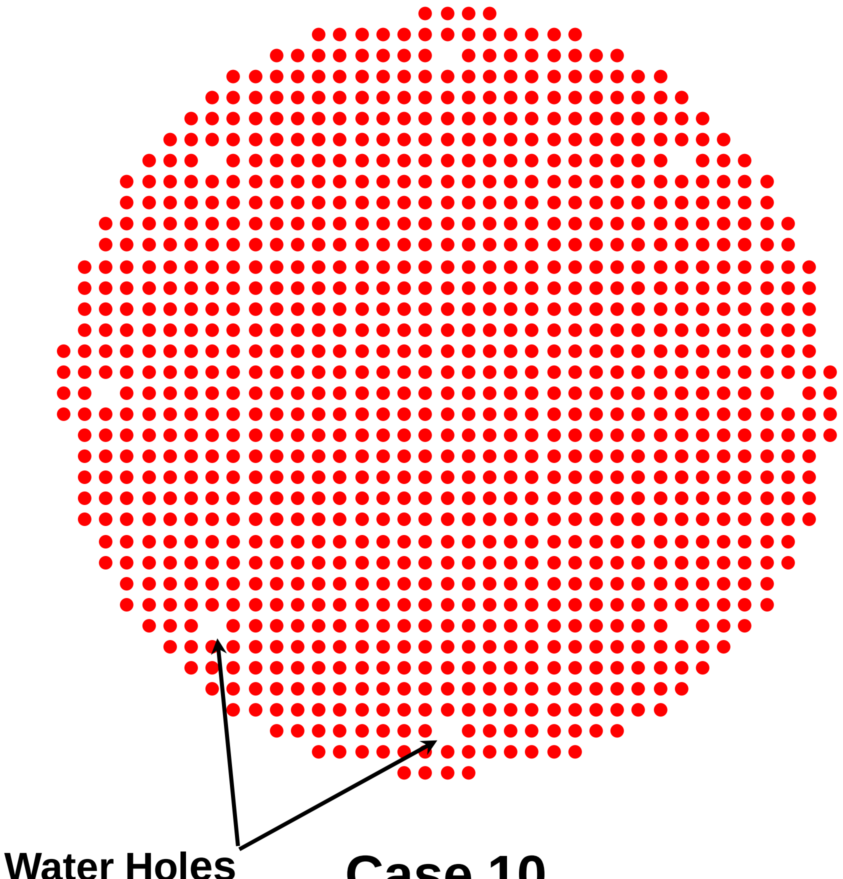


Case 9
1029 rods
k_{eff} = 0.9978

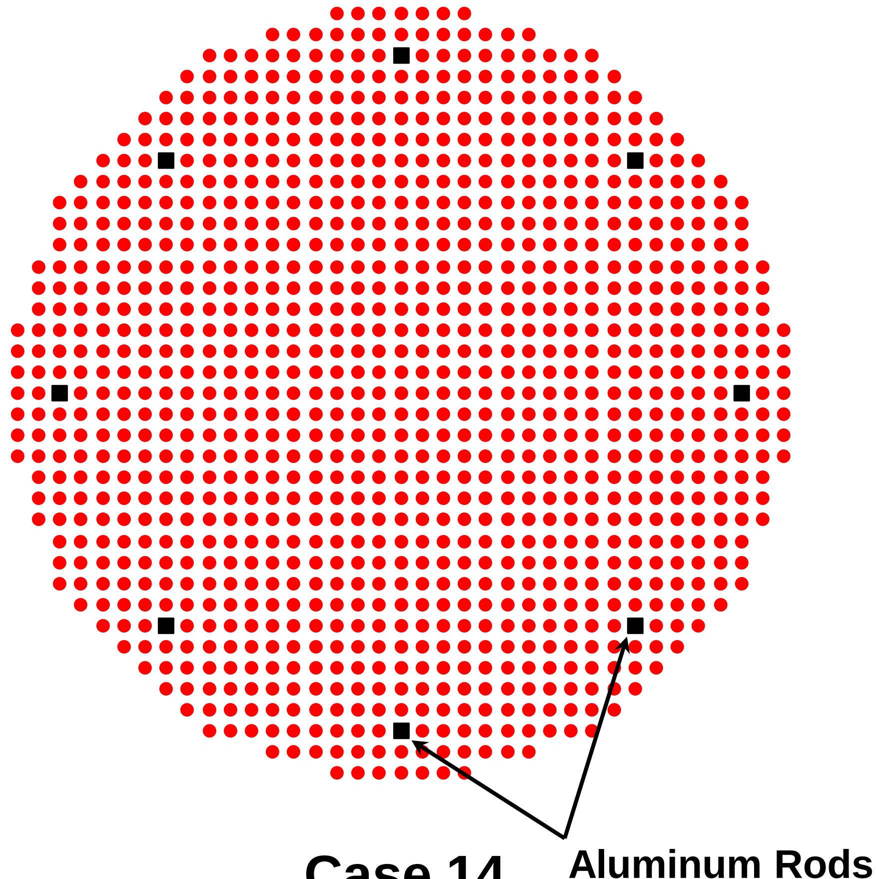


Case 13
1049 rods
k_{eff} = 0.9993

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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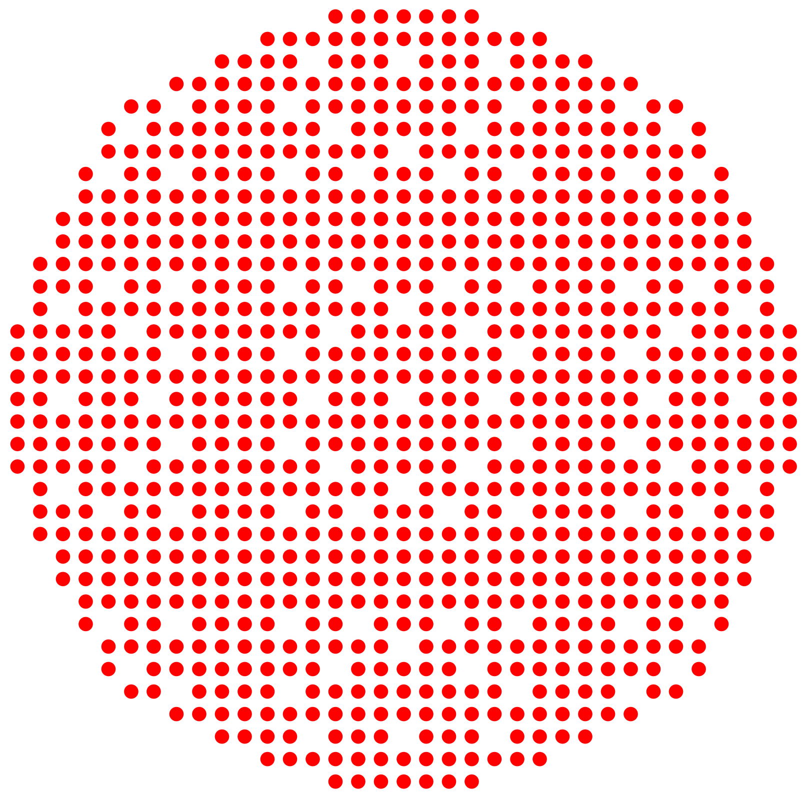
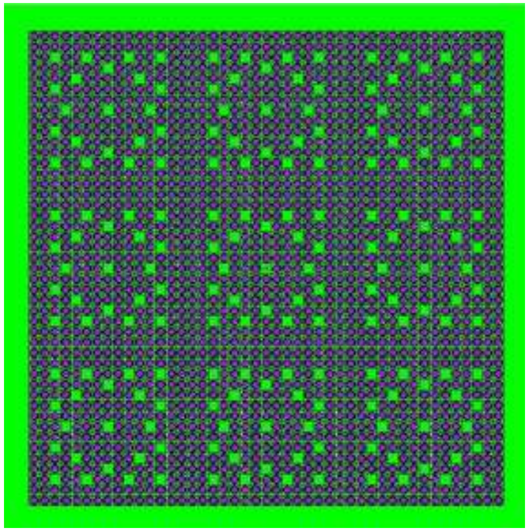
LEU-COMP-THERM-078 Case 15

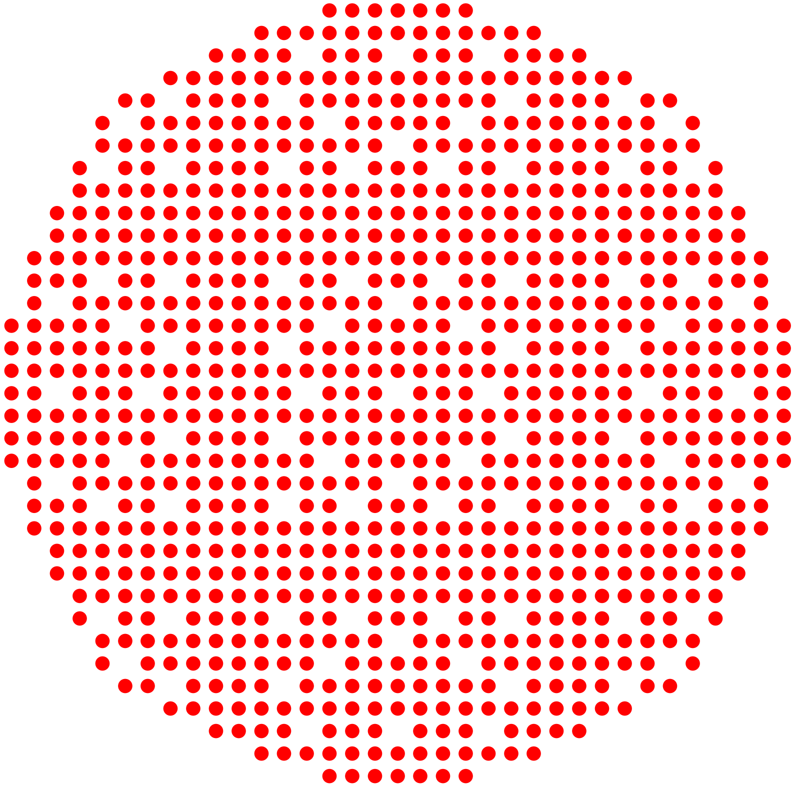


872 rods

k_{eff} = 0.9996

LEU-COMP-THERM-078 Case 15





872 rods

k_{eff} = 0.9996

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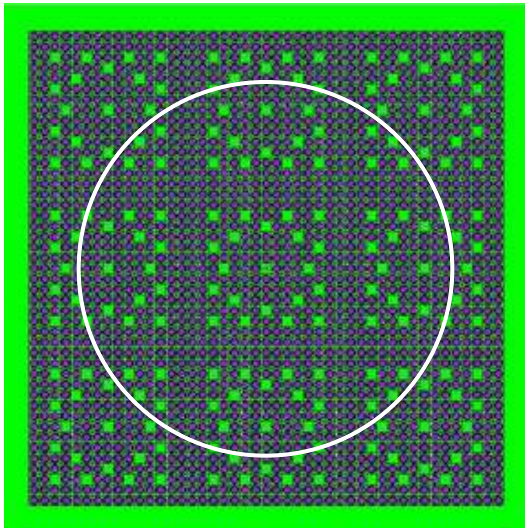
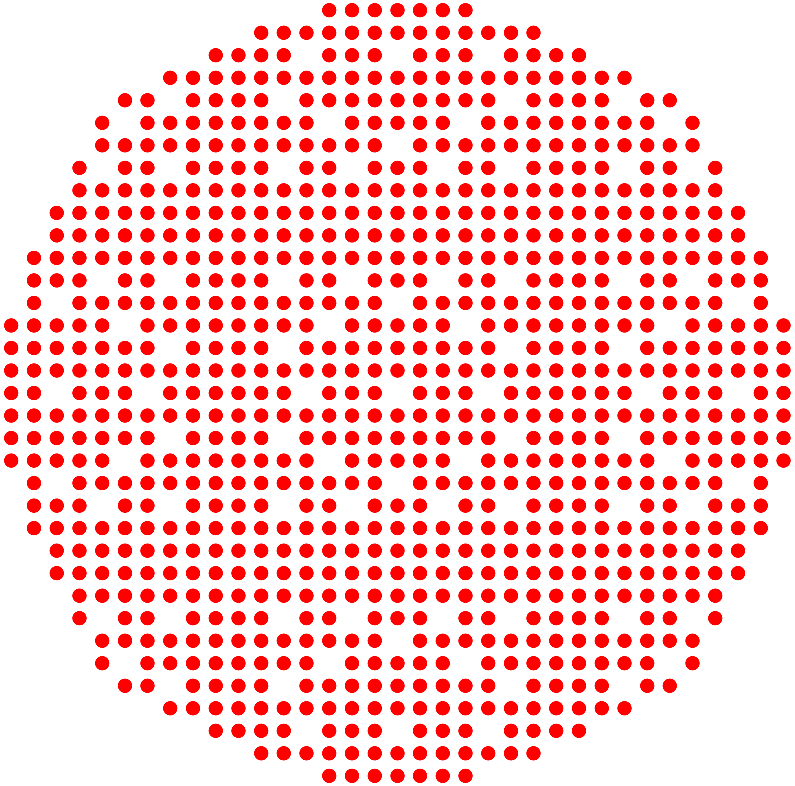
LEU-COMP-THERM-078 Case 15

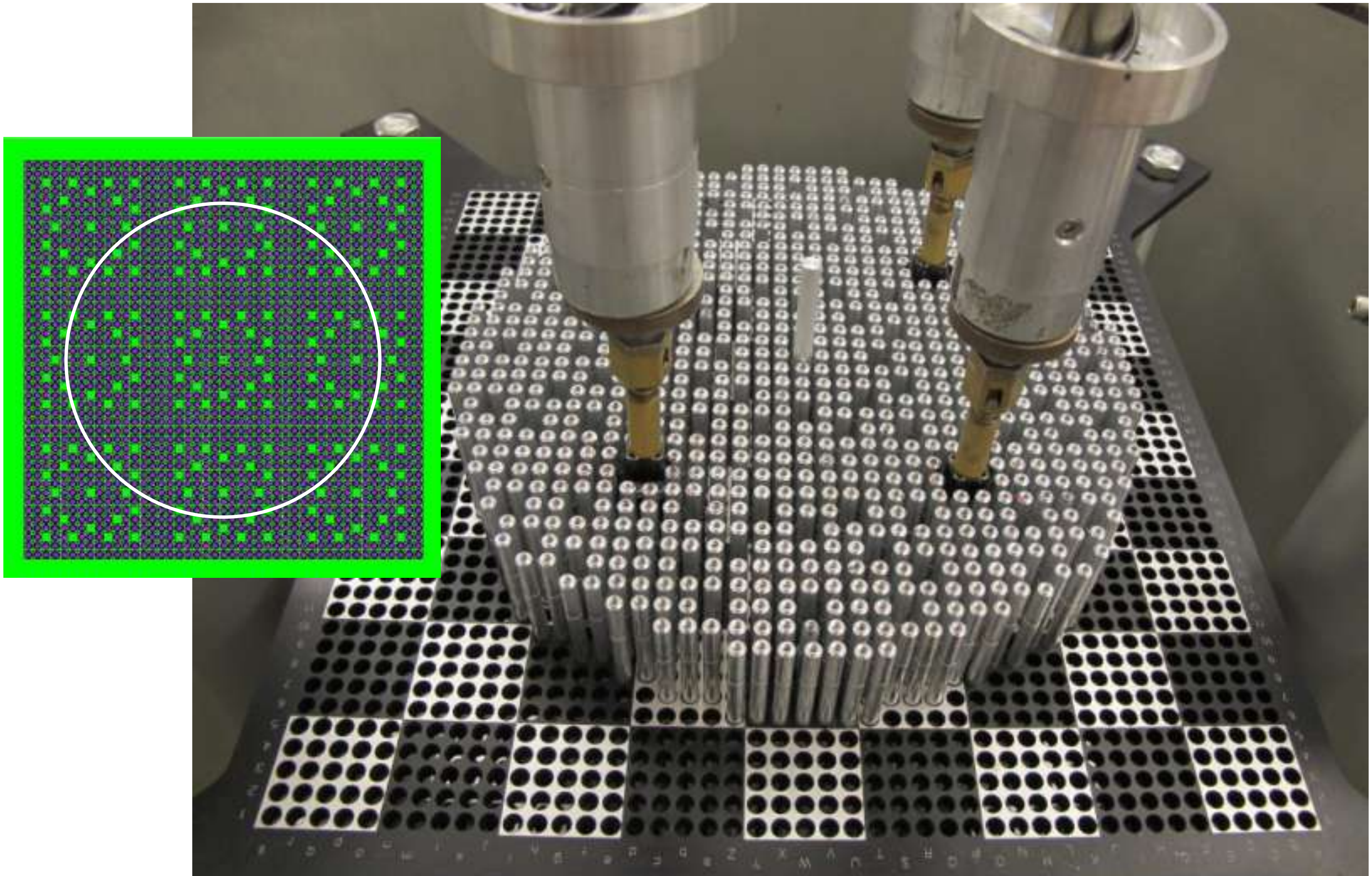




872 rods

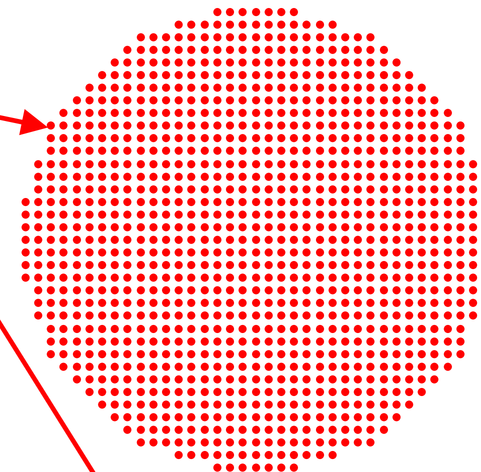
k_{eff} = 0.9996

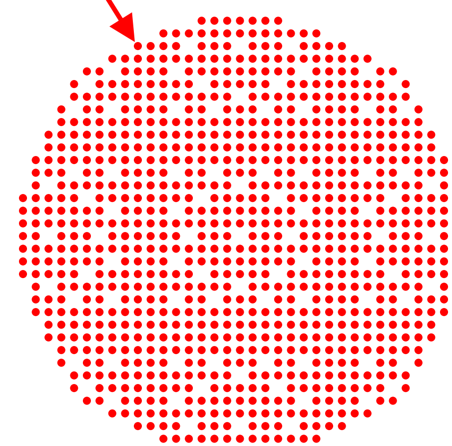
The 7uPCX core at the end of an approach – LCT078 Case 15



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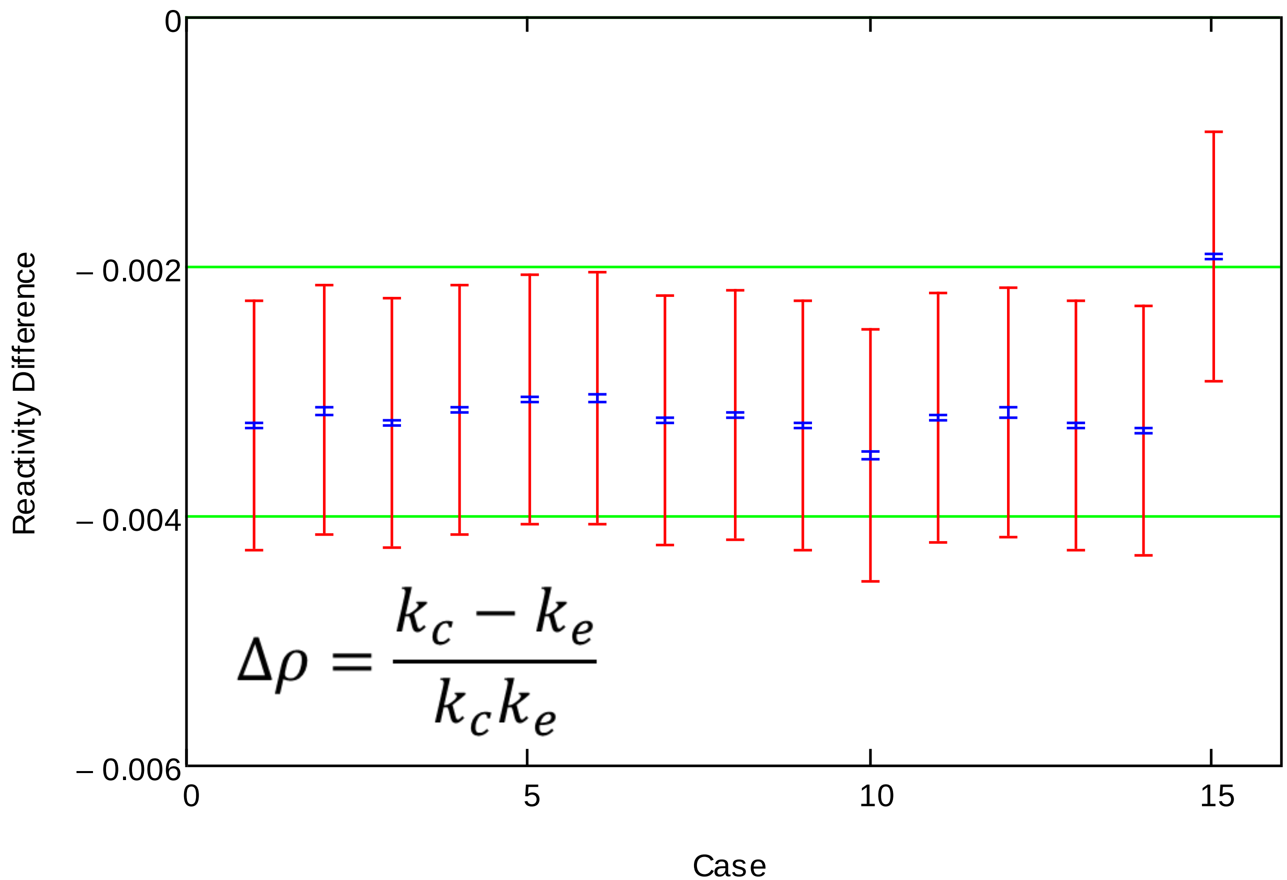
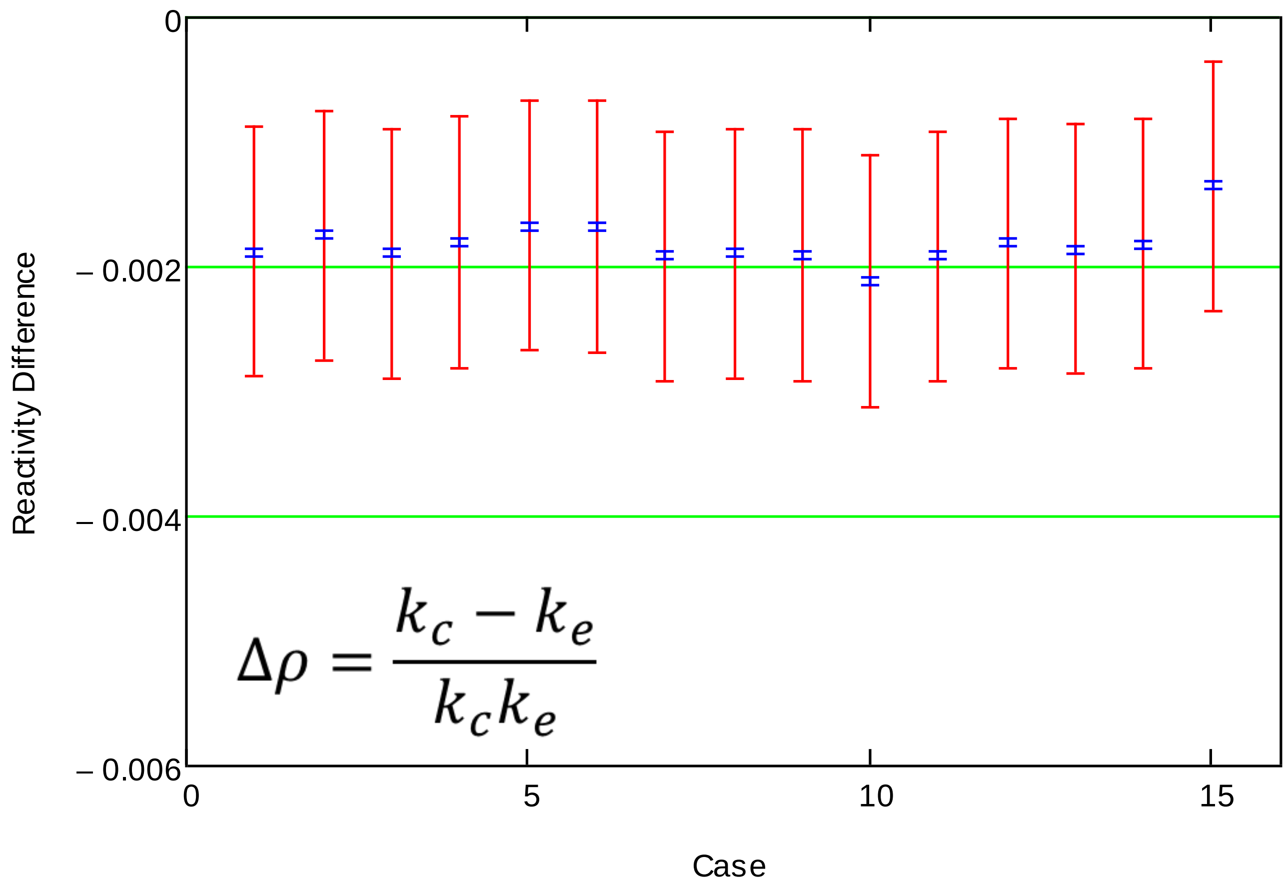
Reactivity Difference – KENO V.a + ENDF/B-VII.0 (MG) vs Benchmark Model k_{eff}



$$\Delta\rho = \frac{k_c - k_e}{k_c k_e}$$

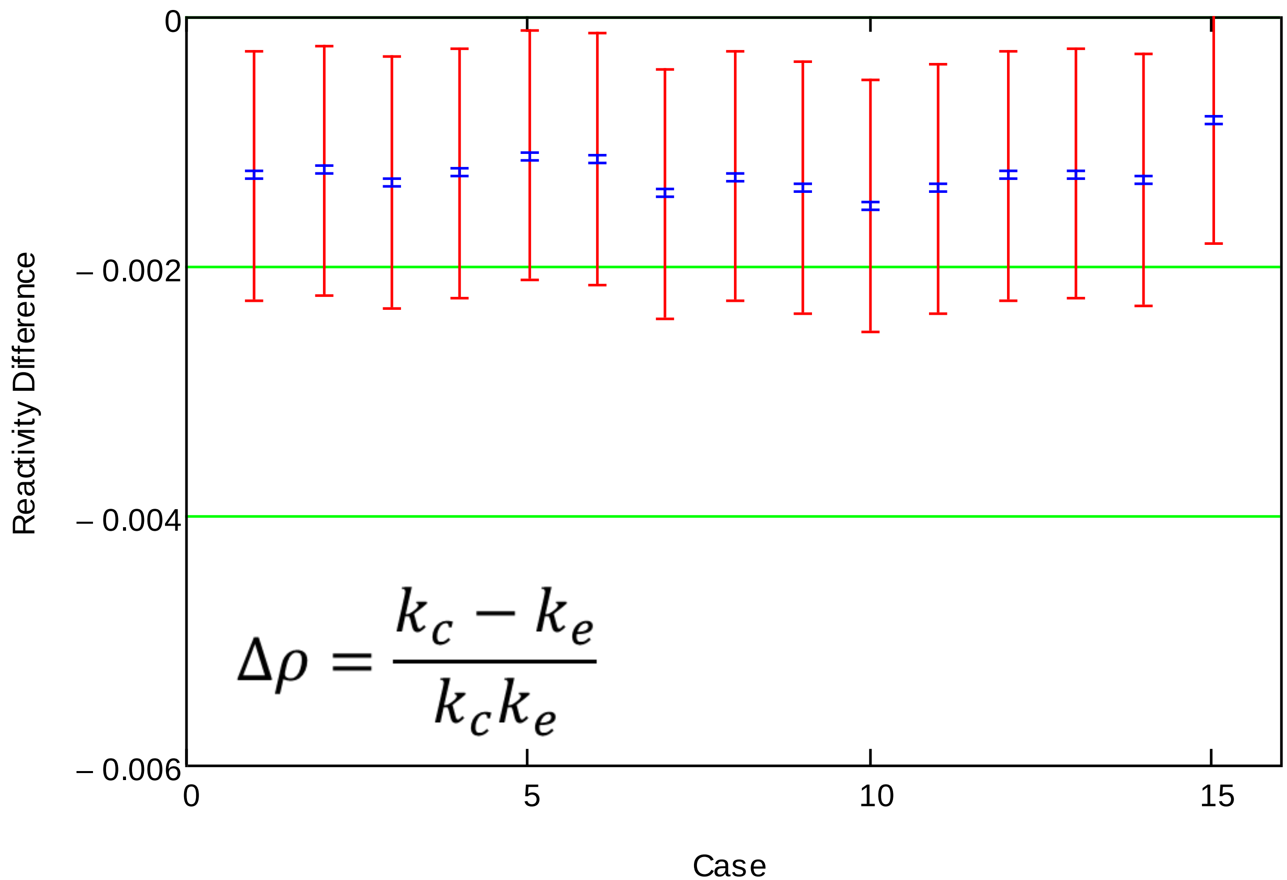
The mean reactivity difference is about 3.2 × experiment uncertainty.
The red error bars show the benchmark uncertainties.
The blue error bars show the stochastic uncertainties in the calculations.

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.

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.

Conclusion

- **We measured 15 7uPCX configurations with fuel-to-water ratios of 0.52 (0.855 cm pitch)**
- **The 15 configurations are evaluated in LEU-COMP-THERM-078 in the forthcoming 2013 edition of *The International Handbook of Evaluated Criticality Safety Benchmark Experiments***

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Critical Experiments at Sandia