SAND2016-5037PE

Sandia National Laboratories

Exceptional Service in the National Intererst

Seven Percent Critical Experiment (7uPCX)

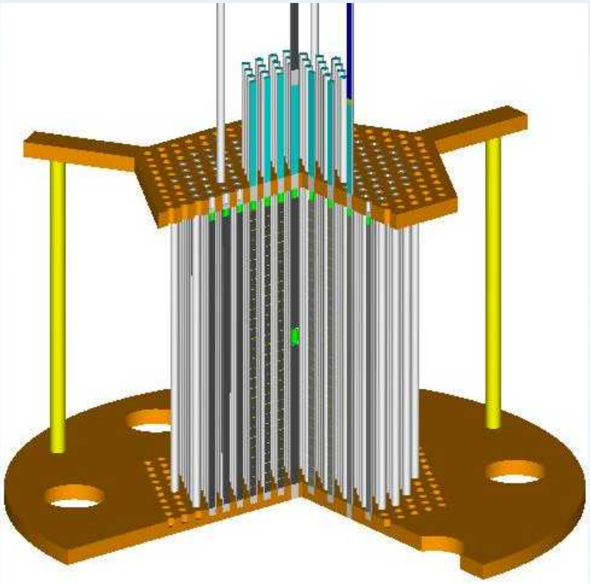
Allison D. Miller

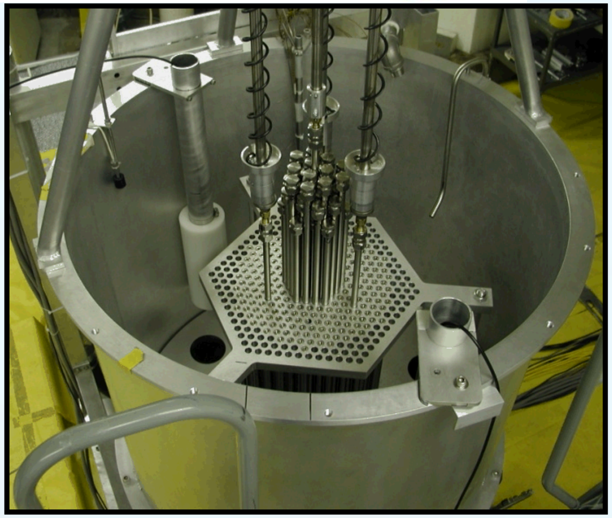
Nuclear Engineer, Sandia National Laboratories

Outline

- A description of recent Sandia critical experiments
  - BUCCX
  - 7uPCX
- A description of the critical assembly
- A description of how we operate the 7uPCX
- An introduction to the approach-to-critical experiment process
- Nuclear Criticality Safety Hands-On Training Course
- Future for SCX

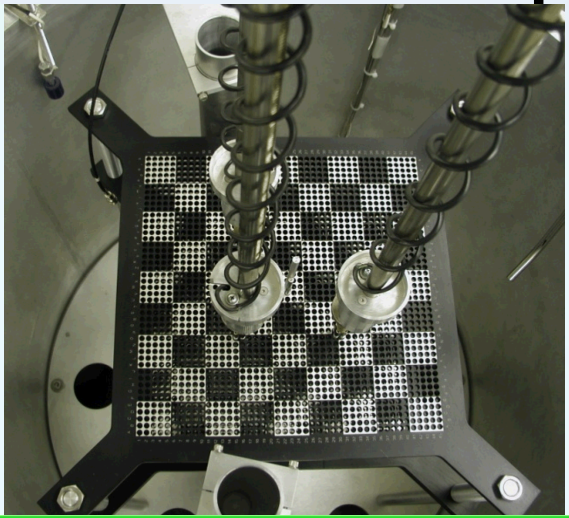
In 2002, we performed some critical experiments with rhodium

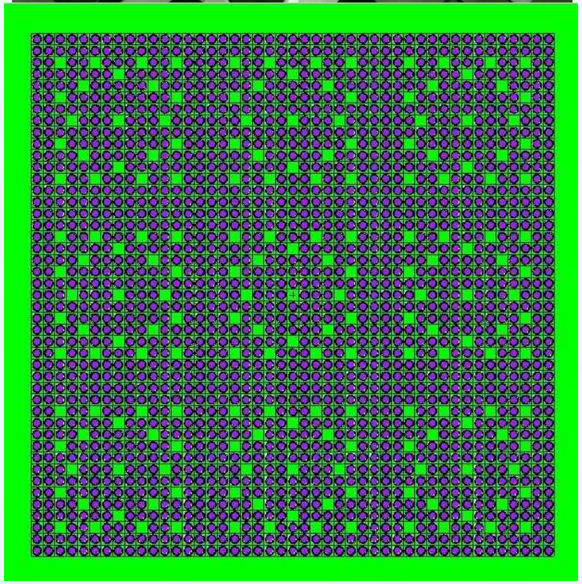




- The Burnup Credit Critical Experiment (BUCCX) was funded by the Nuclear Energy Research Initiative (NERI)
- We built a critical assembly in which we could insert fission product materials to measure reactivity effects
- The NERI funding was used to bring the experiment capability up and perform the first set of experiments
- We completed a set of experiments with rhodium
- The experiment is documented as LEU-COMP-THERM-079 in the International Handbook of Evaluated Criticality Safety Benchmark Experiments

The Seven Percent Critical Experiment (7uPCX) is our current experiment





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**
  - **Soluble poison worth**

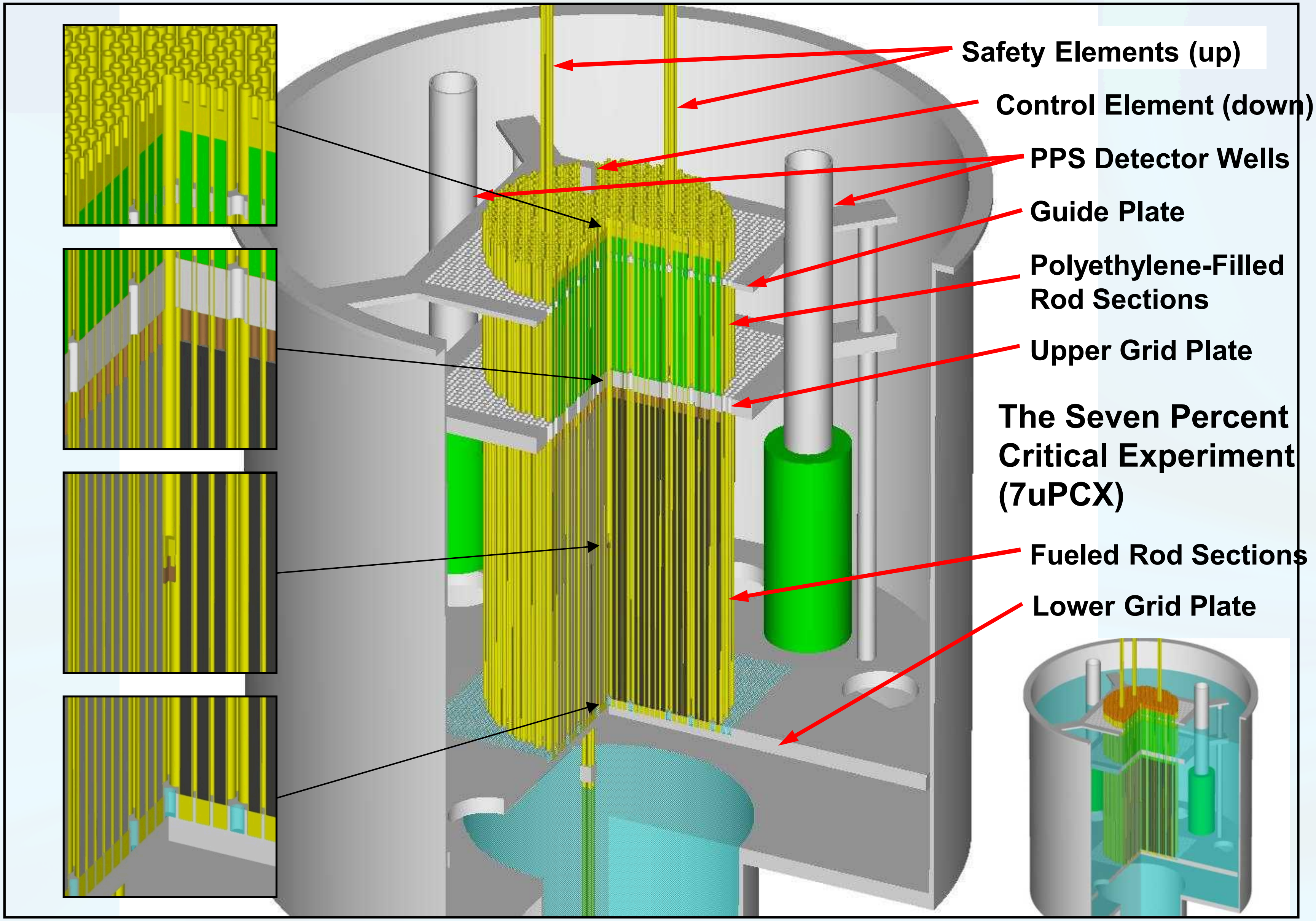
The 7uPCX experiment matrix

- **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 have completed a set of fully-reflected benchmark critical experiments with each grid plate set**

  Full reflection: Adding a thicker reflector does not change k_{eff} appreciably – about 6 inches of water on all sides

  - We loaded fuel into the assembly in an "approach-to-critical" experiment
  - We loaded fuel until the assembly became supercritical
- We are preparing for experiments with larger fuel arrays
  - We will find the water level that makes the larger arrays critical
  - The arrays will not be fully reflected

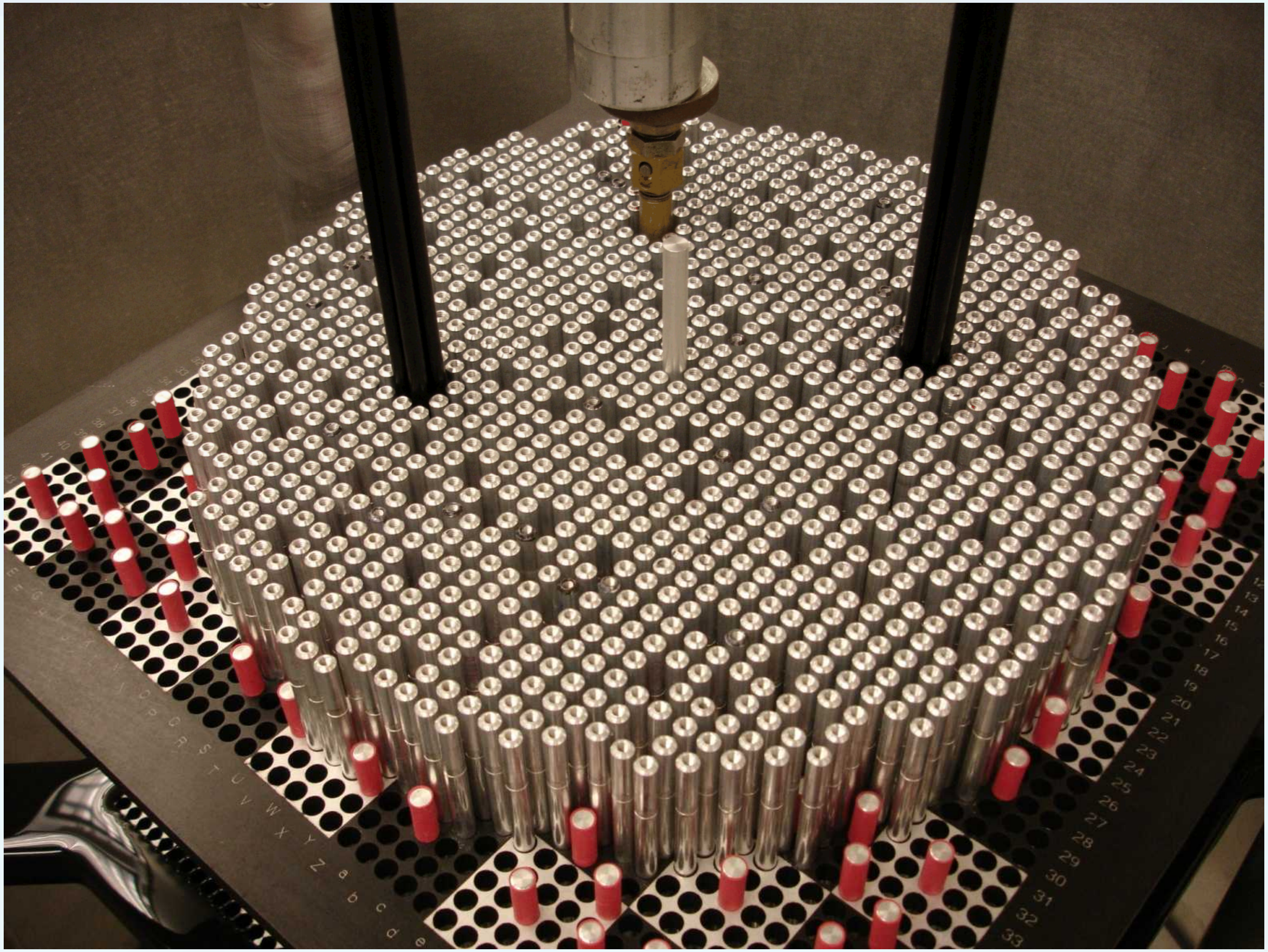
The critical assembly


Safety Elements (up)
Control Element (down)
PPS Detector Wells
Guide Plate
Polyethylene-Filled Rod Sections
Upper Grid Plate
The Seven Percent Critical Experiment (7uPCX)
Fueled Rod Sections
Lower Grid Plate

Characteristics of the Sandia Critical Experiments

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

The first 7uPCX core at the end of the approach



How is a critical assembly different from a reactor?

- A critical experiment looks like a reactor from the outside

Except:

- ***The reactor is the experiment***
  - The core may undergo significant configuration changes

  "Critical assemblies are special nuclear devices designed and used to sustain nuclear reactions. Critical Assemblies may be subject to frequent core and lattice configuration change and are used frequently as mockups of reactor configurations." [DOE Order 5480.30 Chg 1 – *Nuclear Reactor Safety Design Criteria*, Attachment 2, p. 4]

- The fission product inventory is low
  - This limits the potential consequences of an accident

  "critical assembly. *a device or physical system for performing critical experiments. In a critical assembly, the energy produced by fission is insufficient to require auxiliary cooling and the power history is such that the inventory of long-lived fission products is insignificant."*

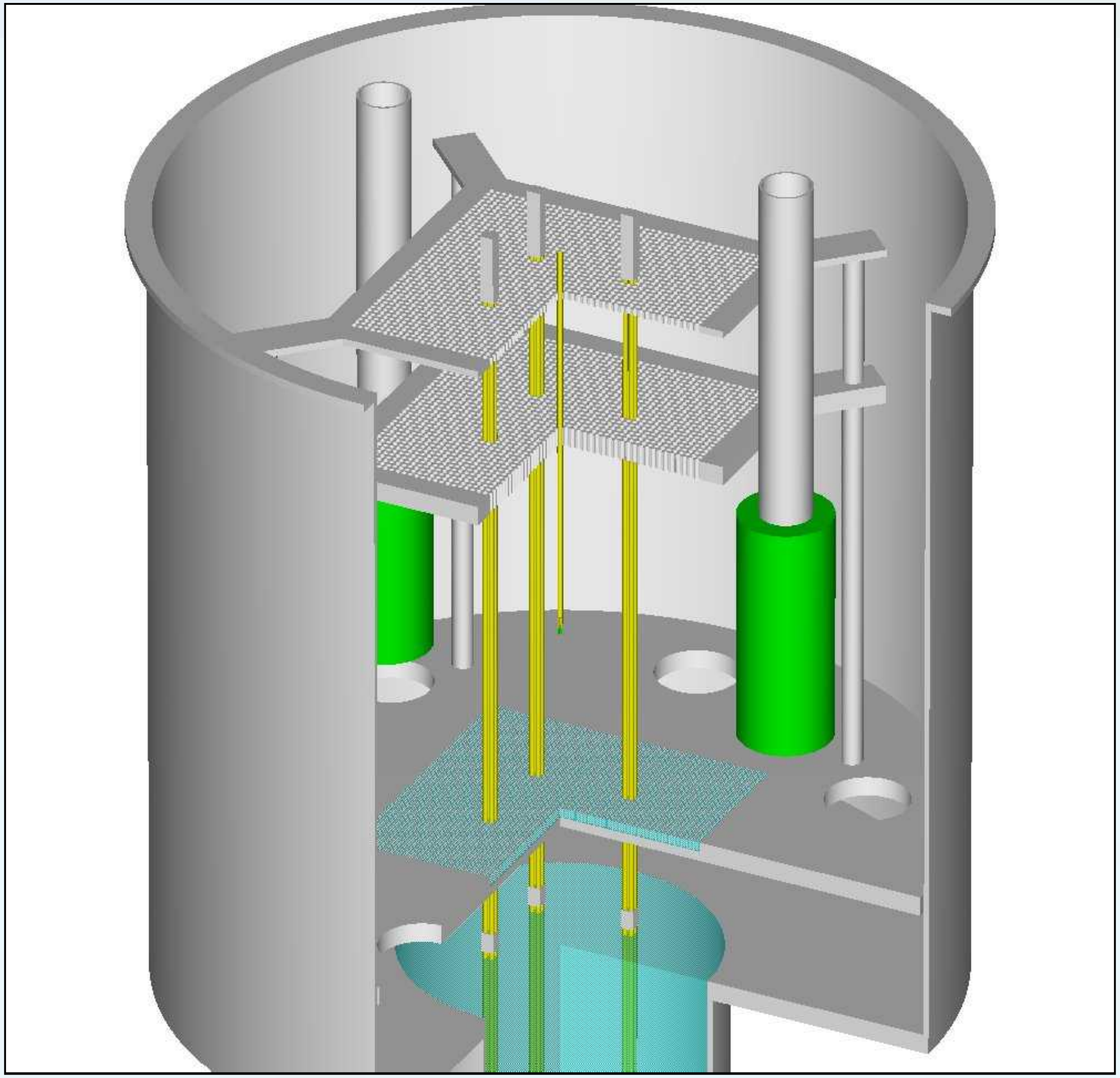
  [ANSI/ANS-1-2000 – *Conduct of Critical Experiments*, Section 2.3]

Sandia National Laboratories

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**
- **When out of storage, the fuel is in the core tank that is connected to the dump tank through two large-diameter normally-open dump valves**
  - **Water cannot collect in the core tank if the dump valves are open**
- **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**

The Shut-Down Configuration of the Assembly



Fuel: 12 - CE/SE only

$k_{eff} \approx 0.139$

Safety Elements: Down

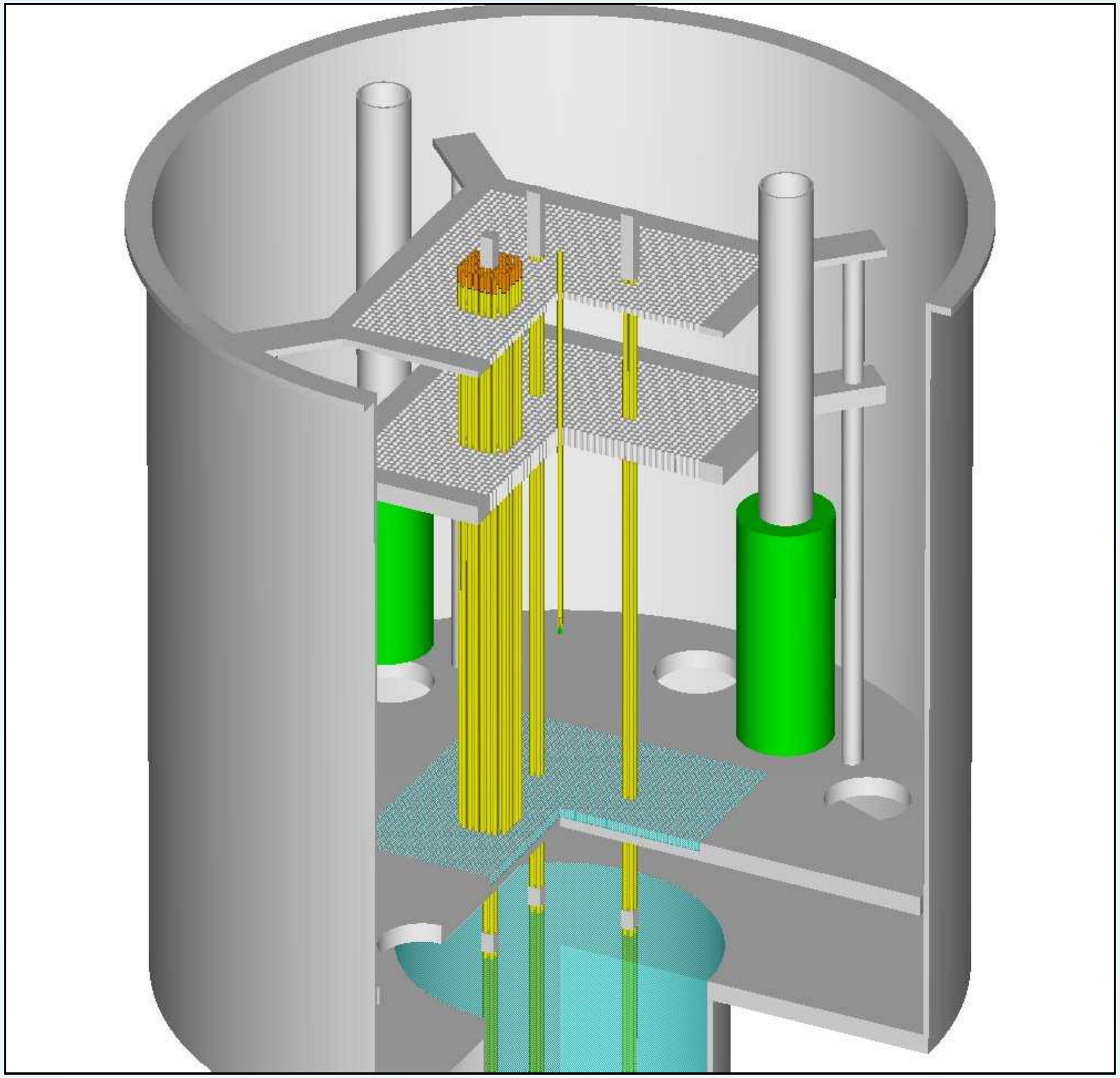
Control Element: Down

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.

Load Fuel



Fuel: 64

$k_{eff} \approx 0.139$

Safety Elements: Down

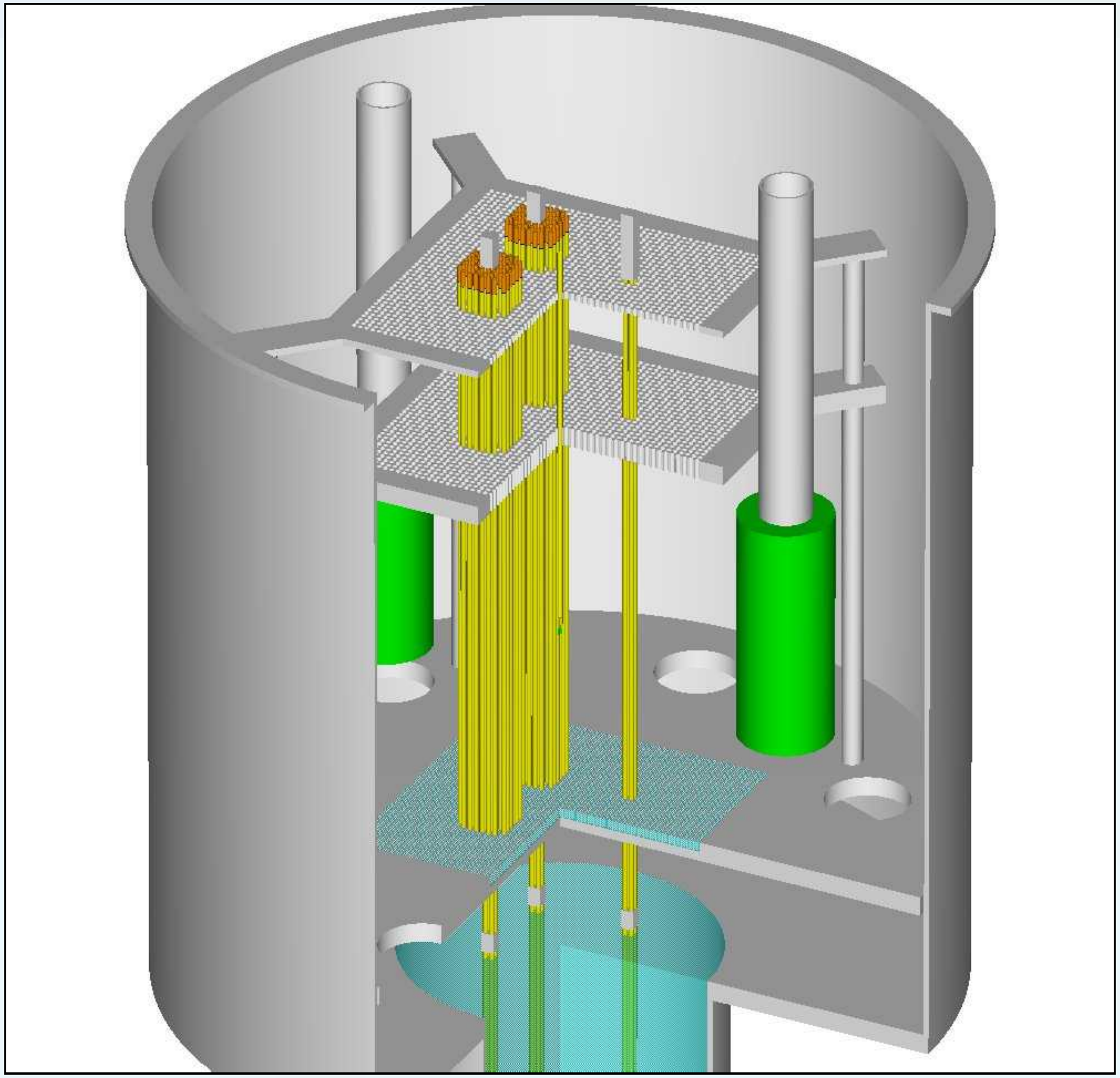
Control Element: Down

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

$k_{eff} \approx 0.139$

Safety Elements: Down

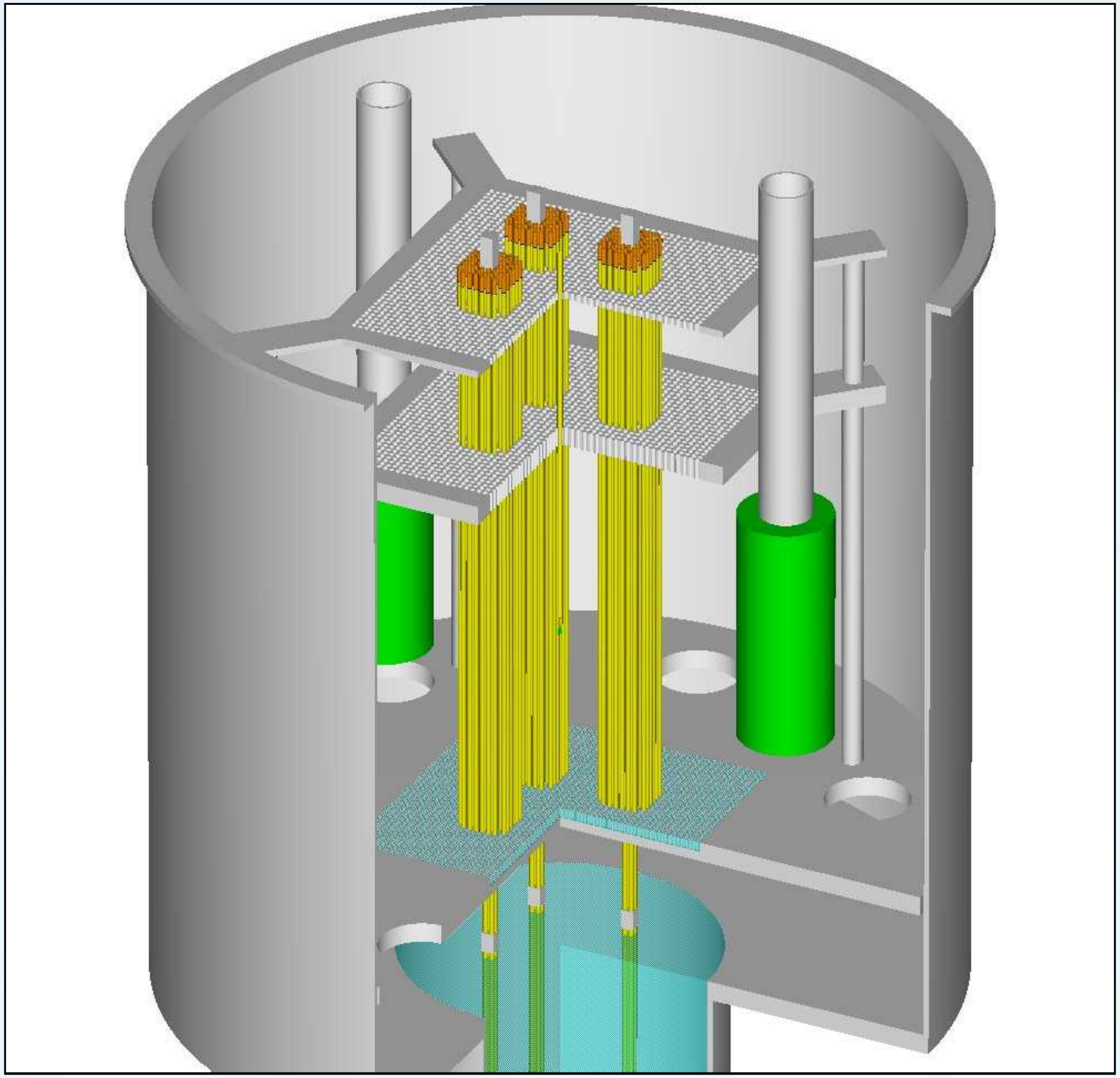
Control Element: Down

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: 168

$k_{eff} \approx 0.139$

Safety Elements: Down

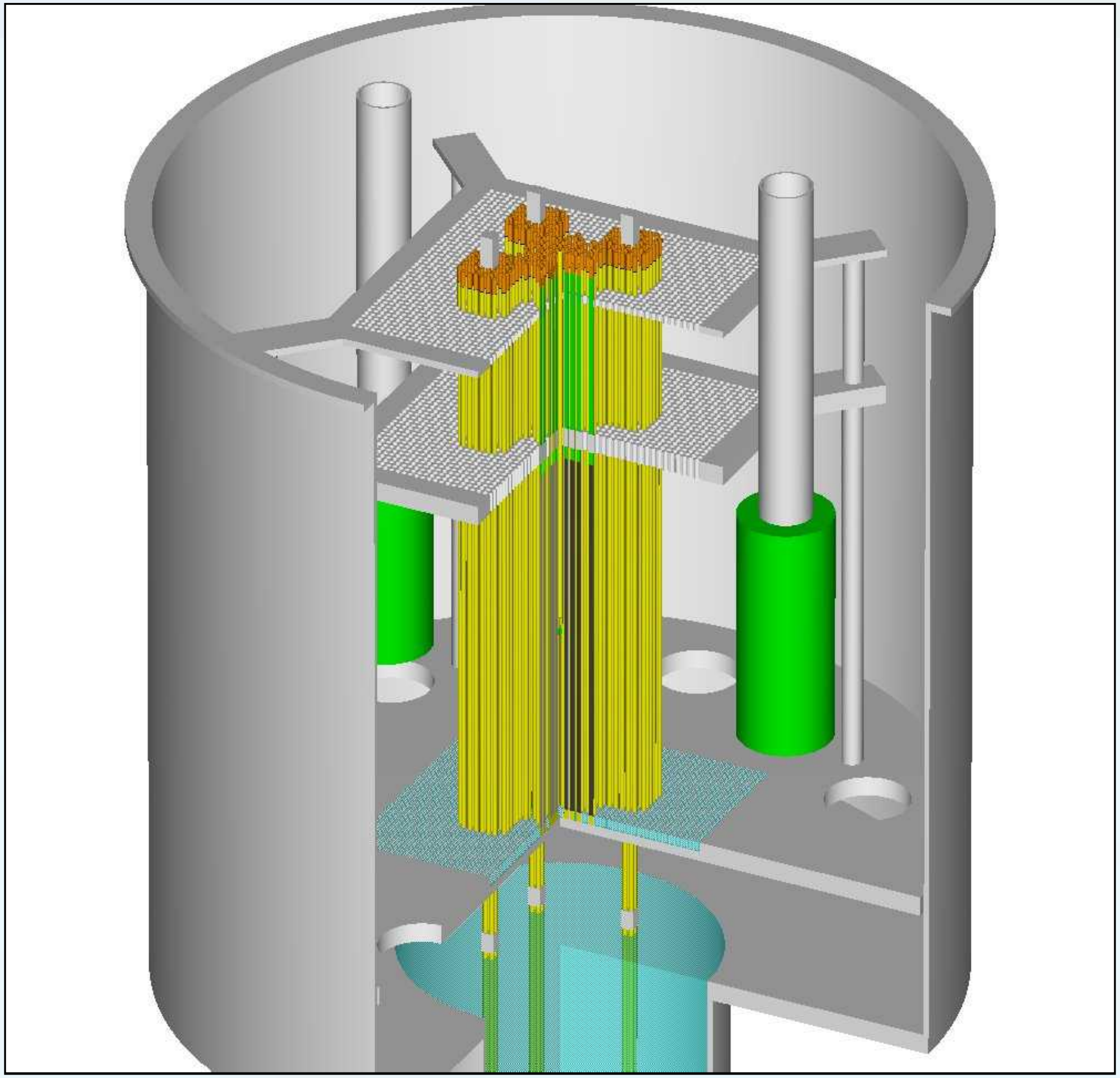
Control Element: Down

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: 318

$k_{eff} \approx 0.140$

Safety Elements: Down

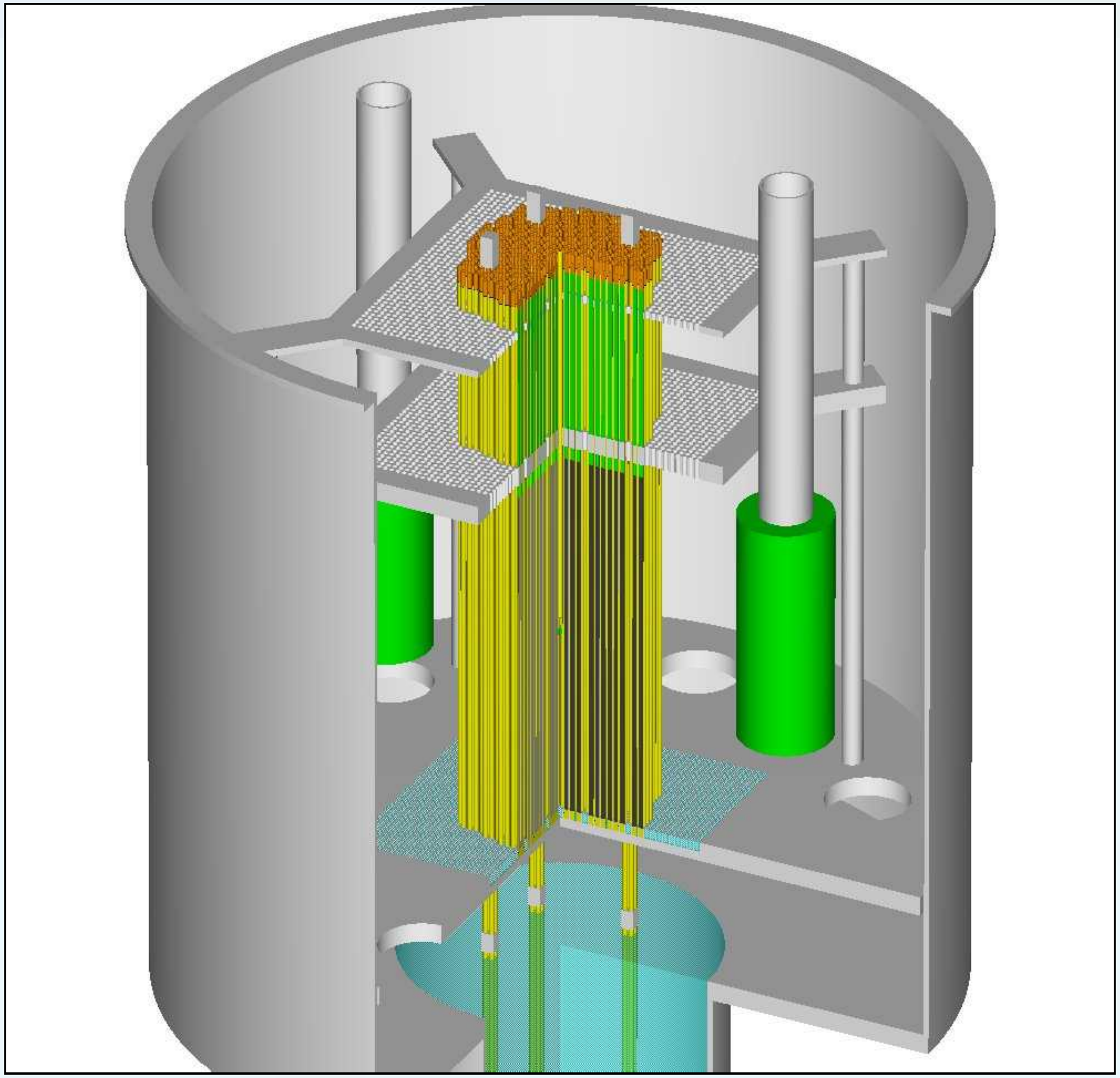
Control Element: Down

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.

Load Fuel



Fuel: 548

$k_{eff} \approx 0.140$

Safety Elements: Down

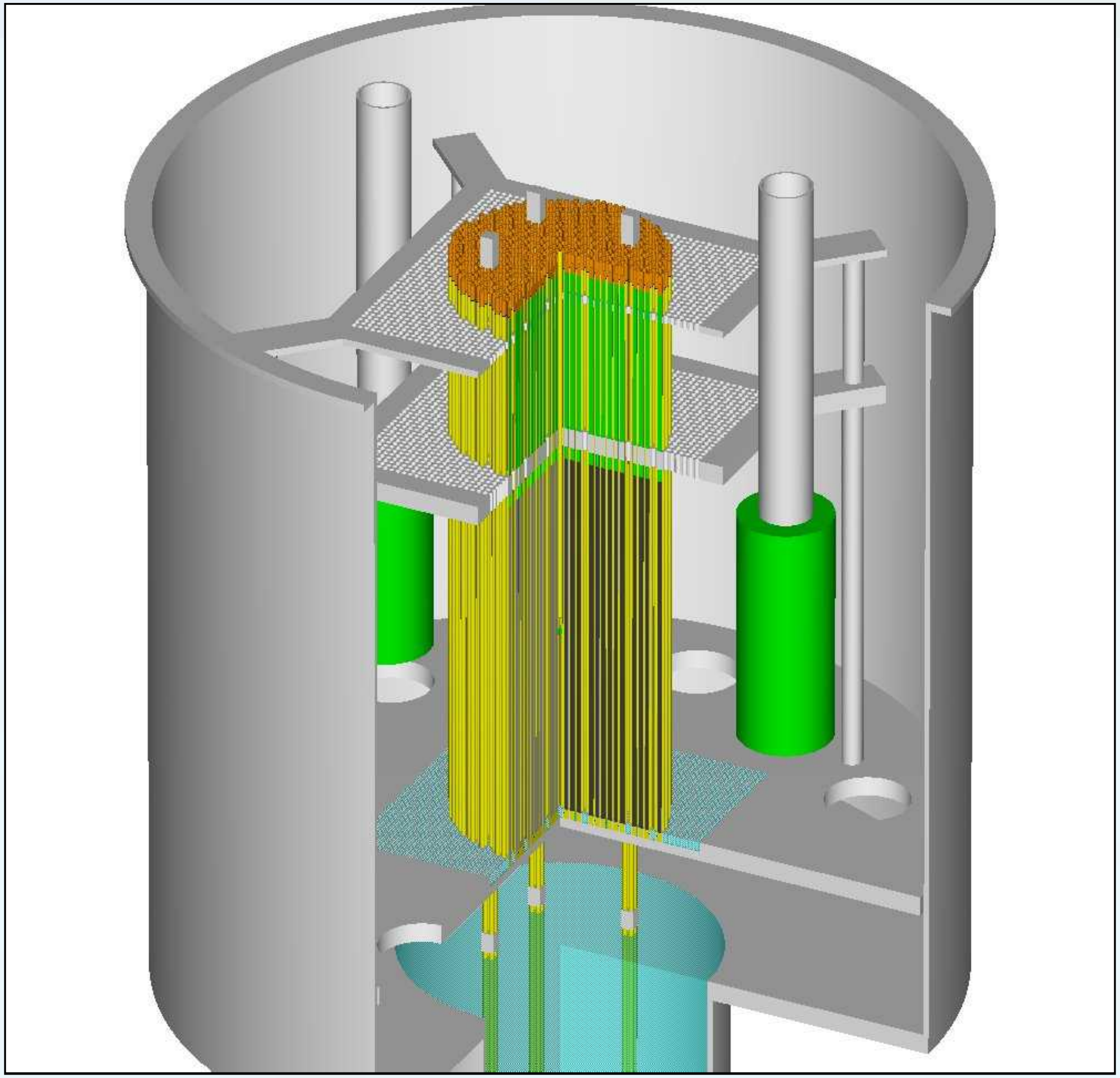
Control Element: Down

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.

Load Fuel



Fuel: 740

$k_{eff} \approx 0.140$

Safety Elements: Down

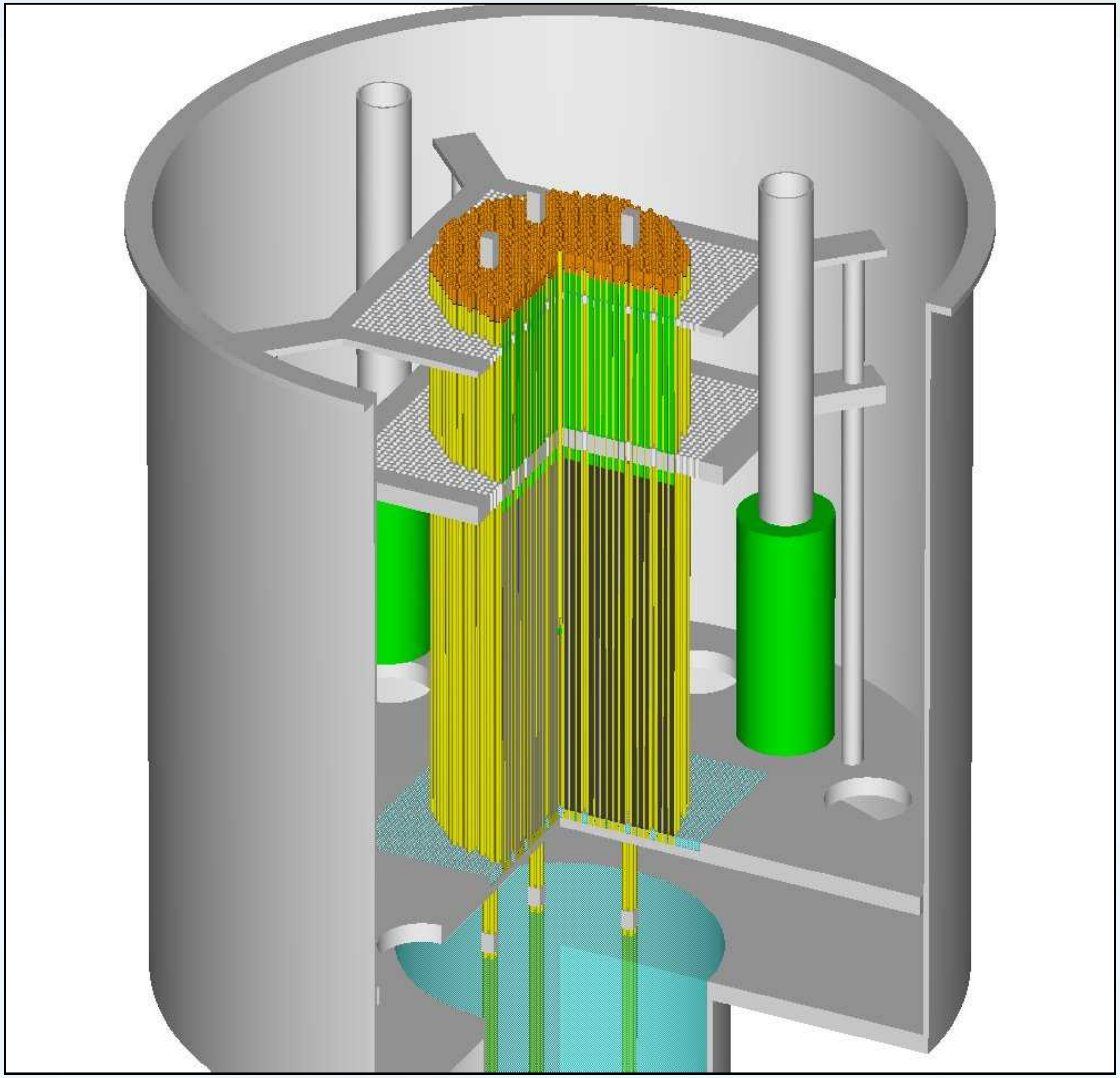
Control Element: Down

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.

Load Fuel



Fuel: 956

$k_{eff} \approx 0.140$

Safety Elements: Down

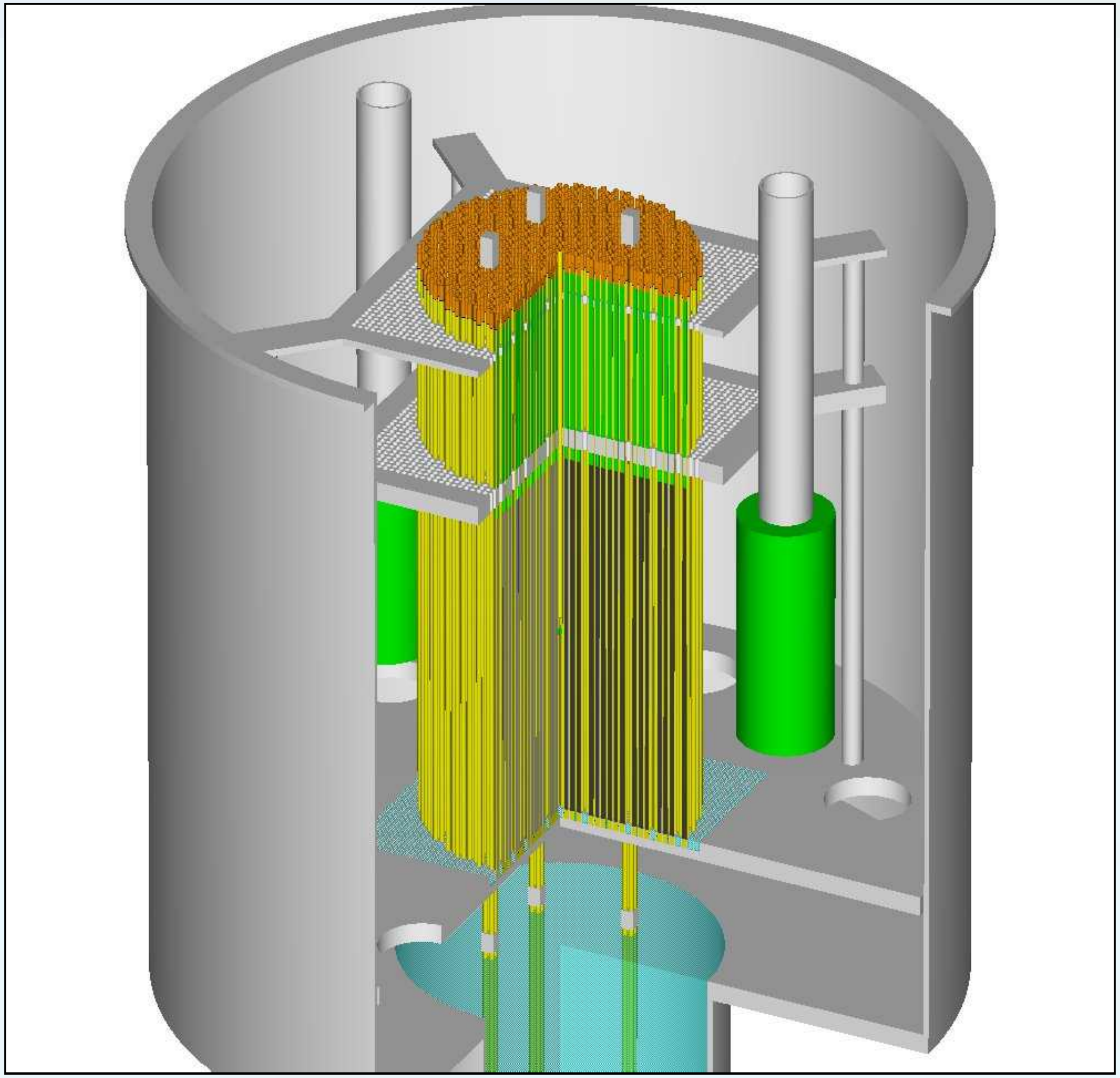
Control Element: Down

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.

The Desired Fuel Array is Complete



Fuel: 1136

$k_{eff} \approx 0.140$

Safety Elements: Down

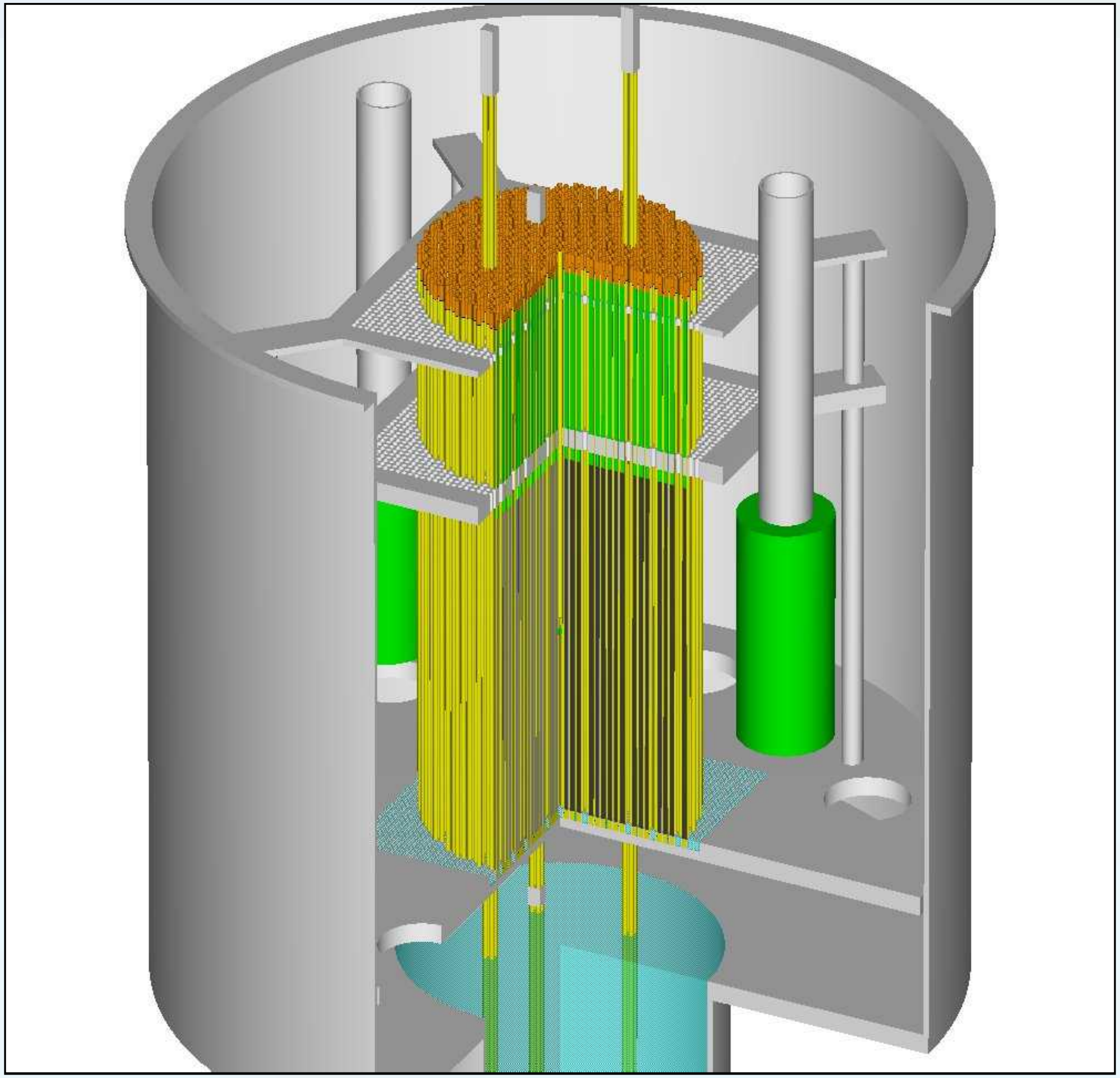
Control Element: Down

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

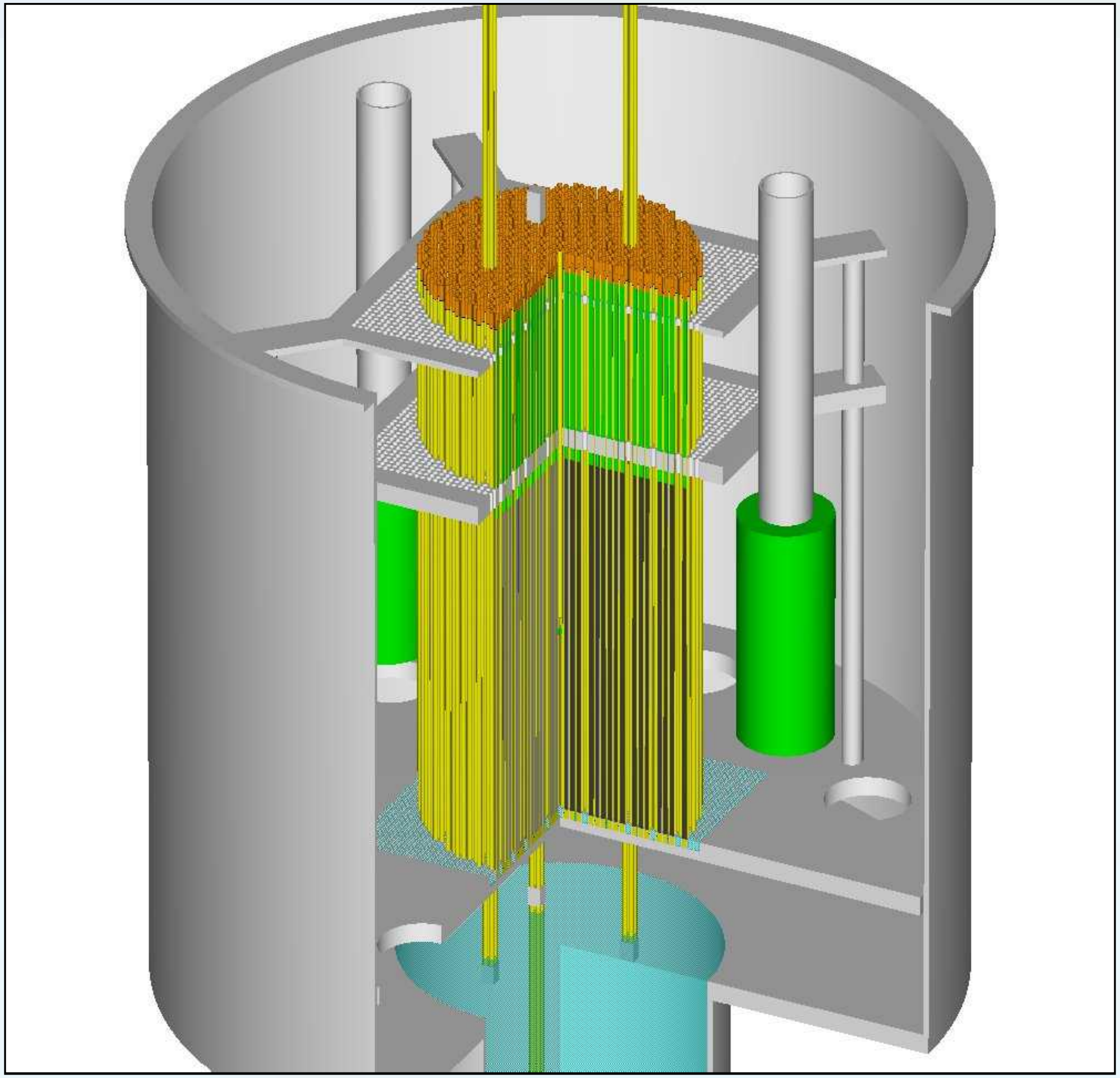
Control Element: Down

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

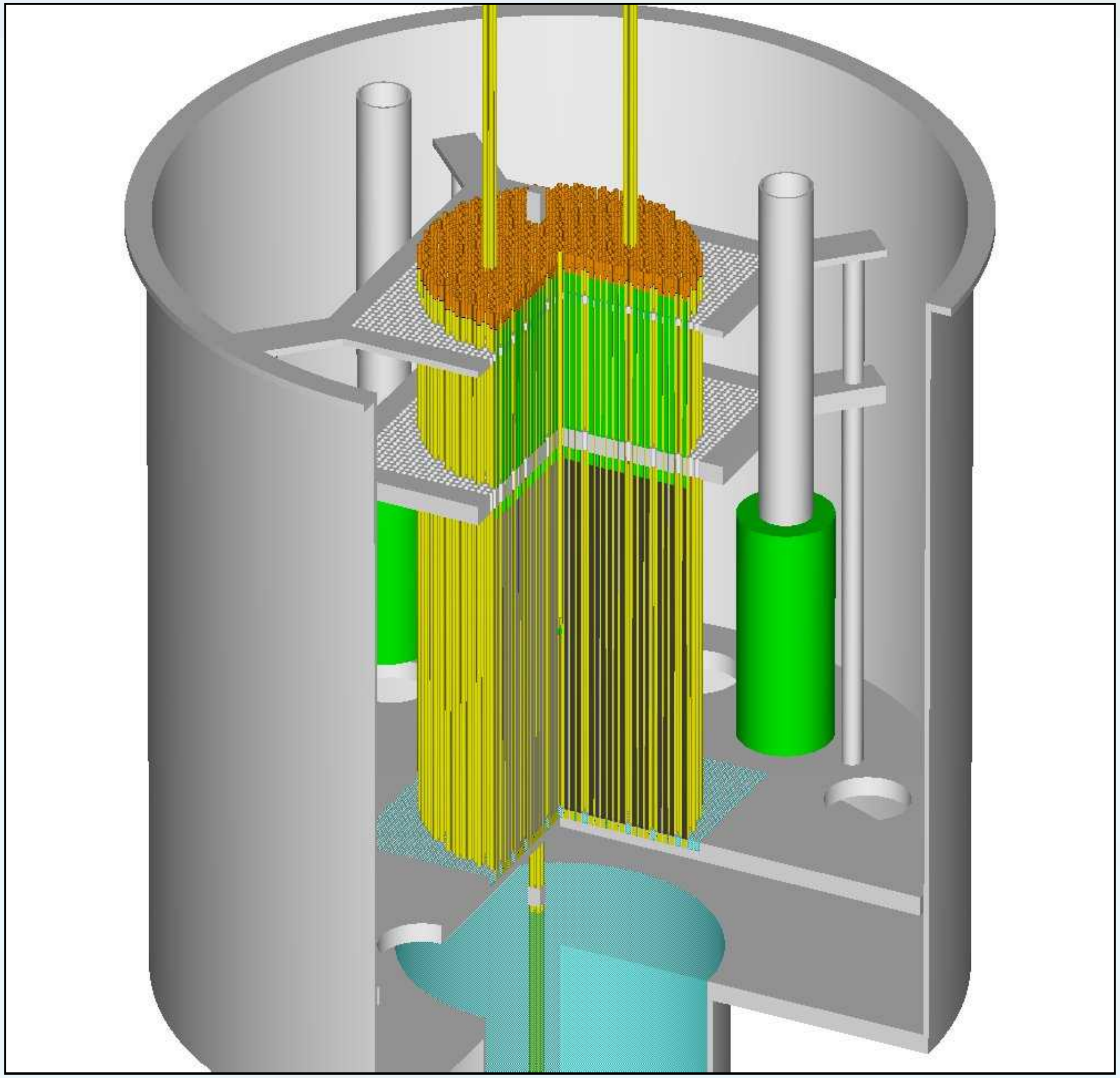
Control Element: Down

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.

The Safety Elements are Up



Fuel: 1136

$k_{eff} \approx 0.128$

Safety Elements: Up

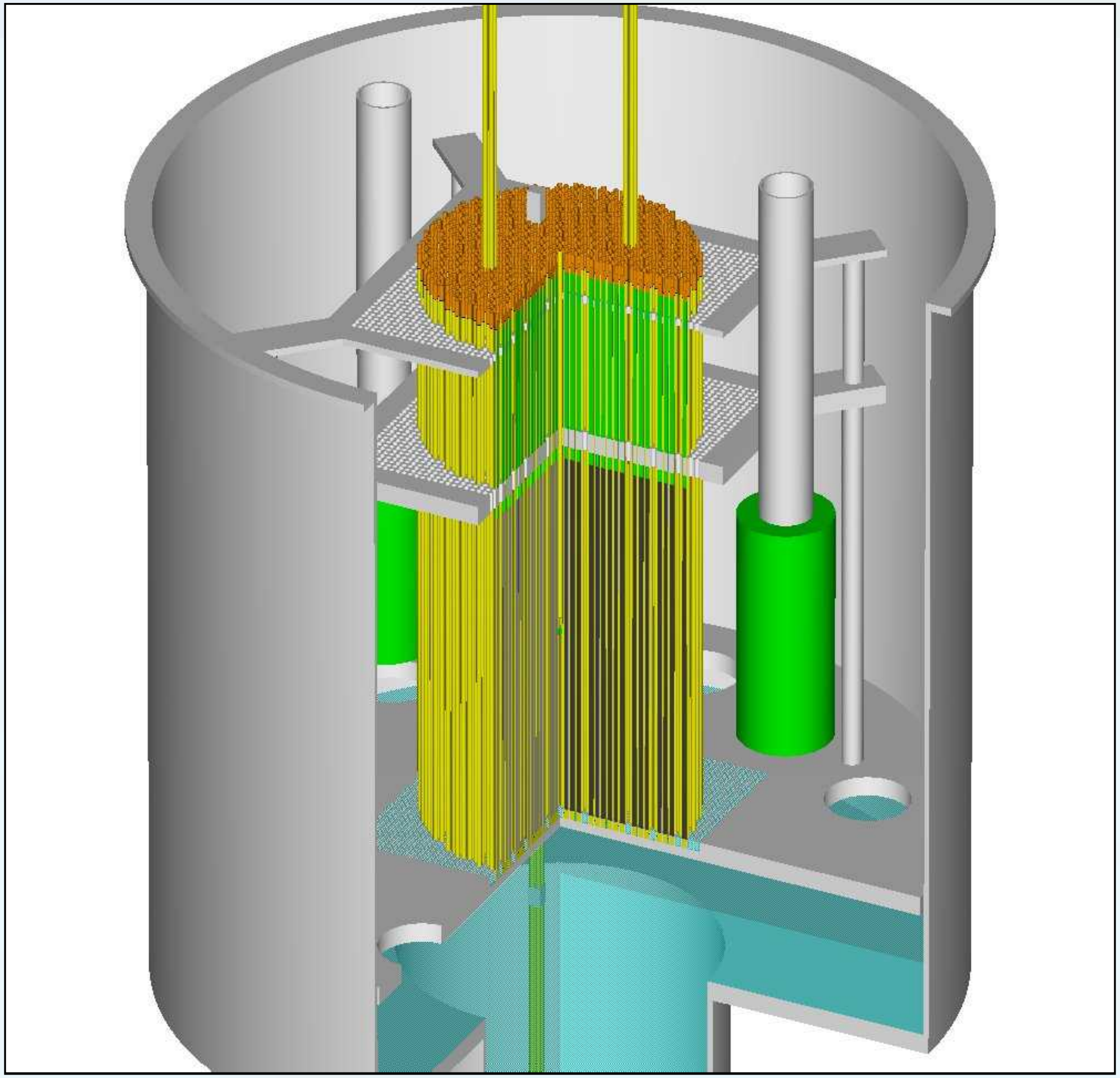
Control Element: Down

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.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.139$

Safety Elements: Up

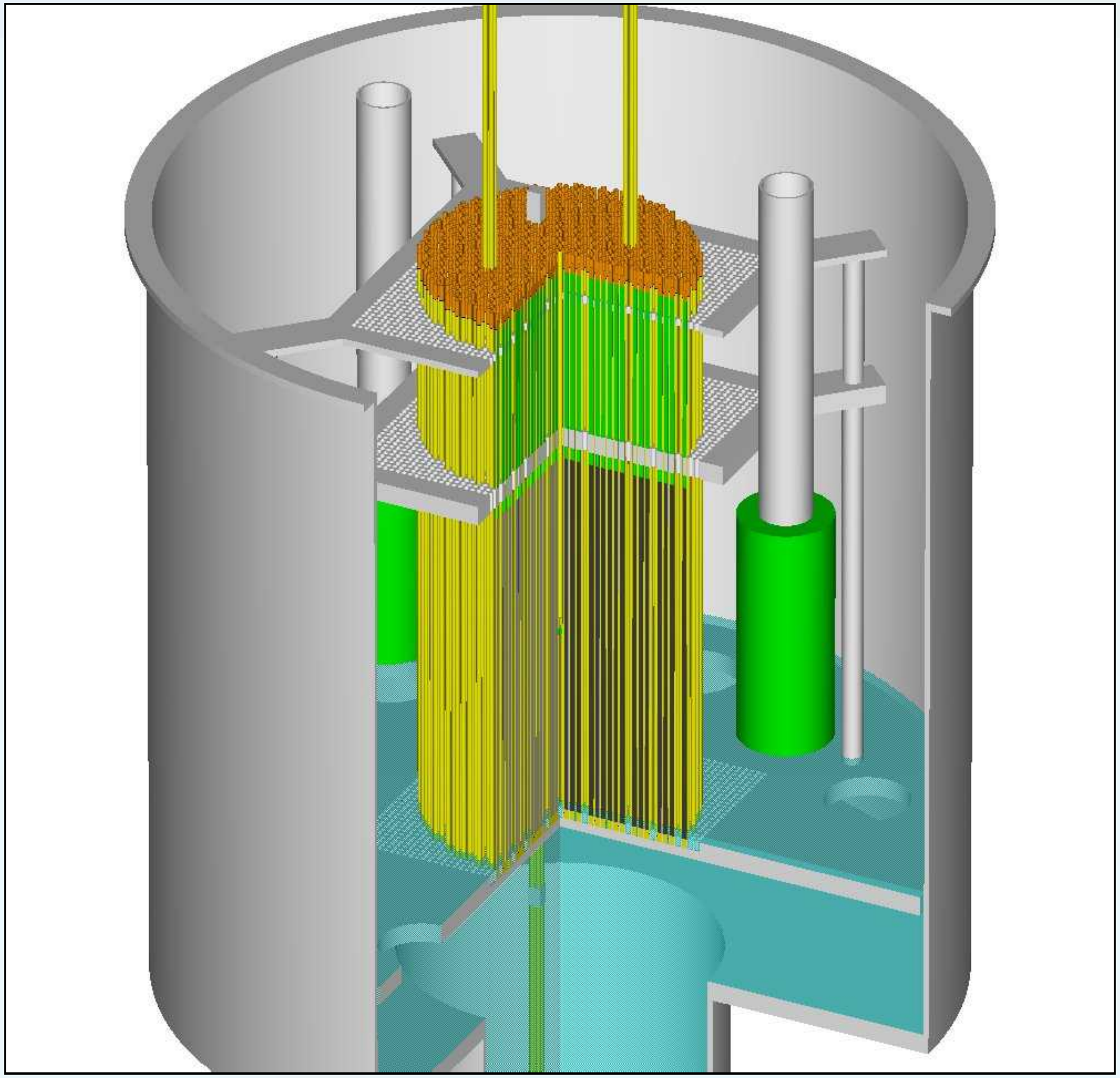
Control Element: Down

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

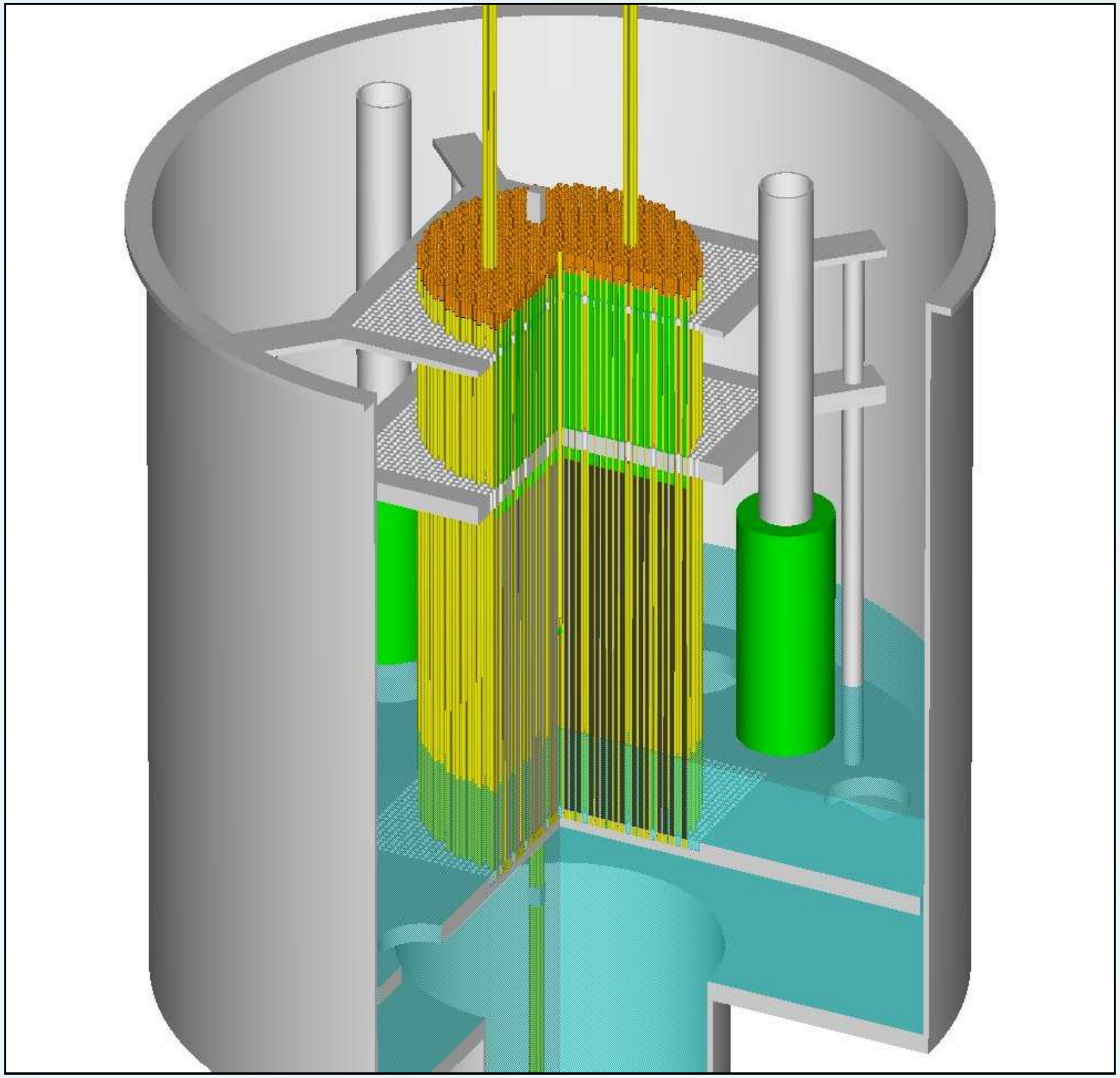
Control Element: Down

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

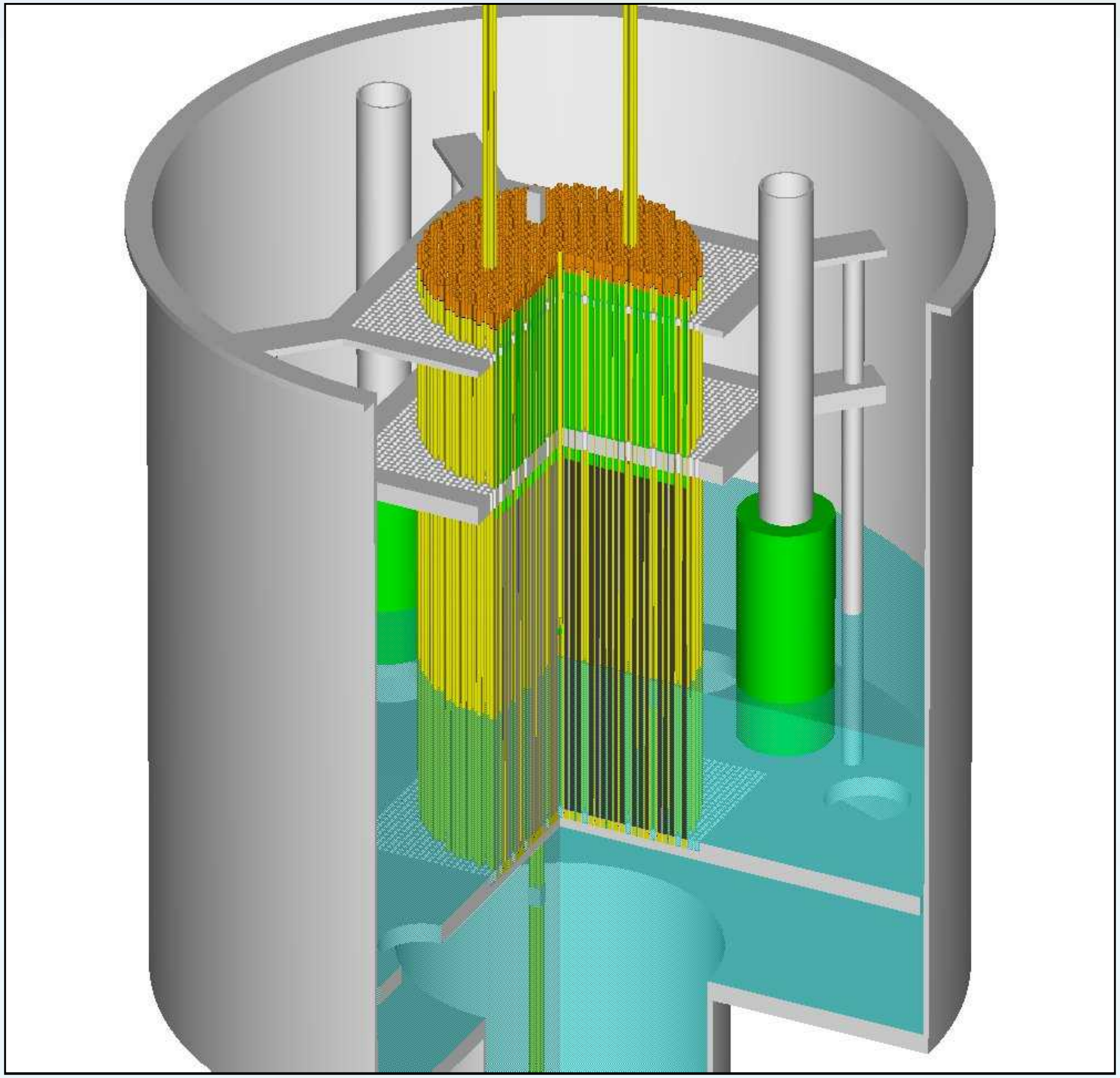
Control Element: Down

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

$k_{eff} \approx 0.804$

Safety Elements: Up

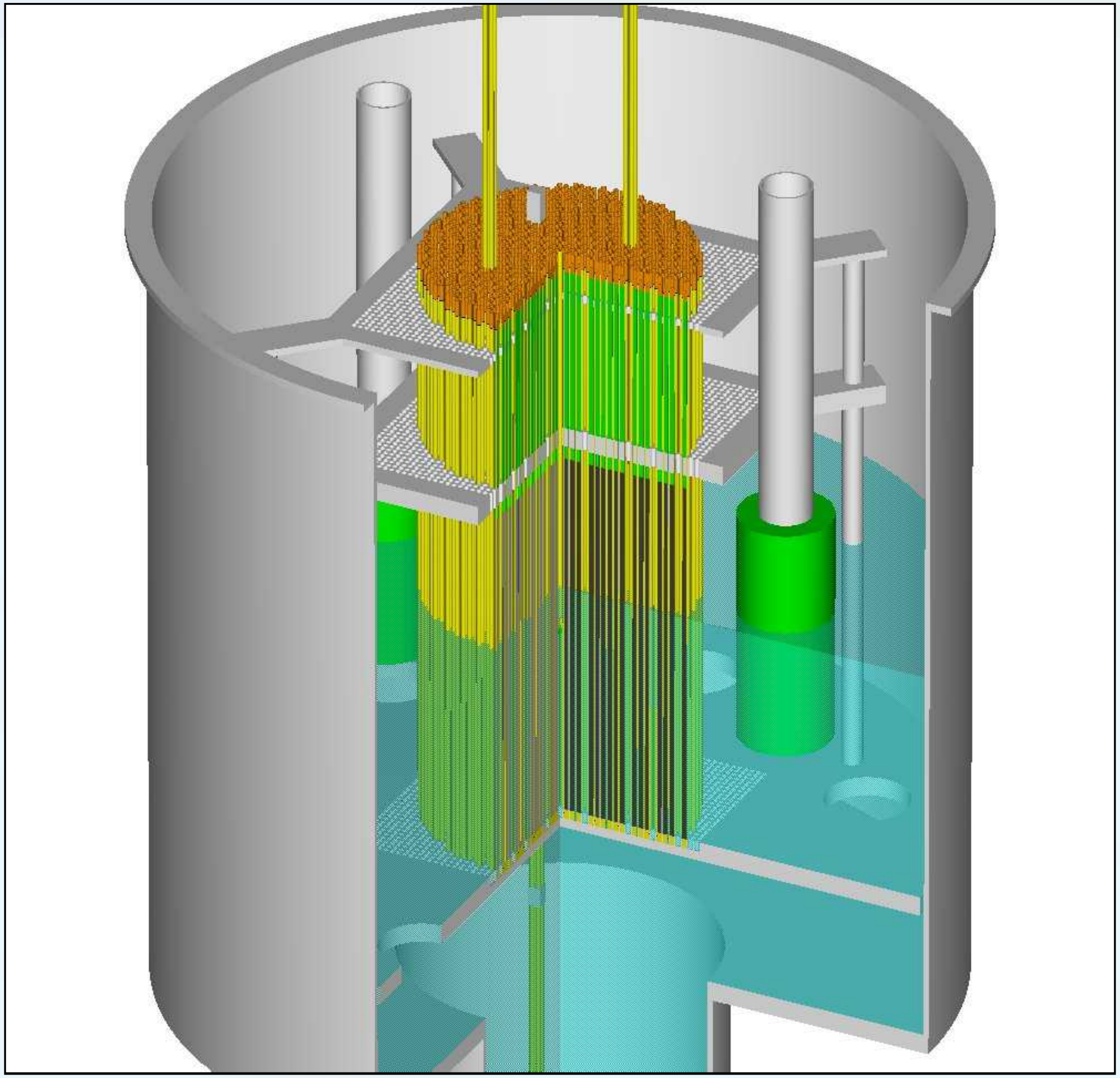
Control Element: Down

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

$k_{eff} \approx 0.901$

Safety Elements: Up

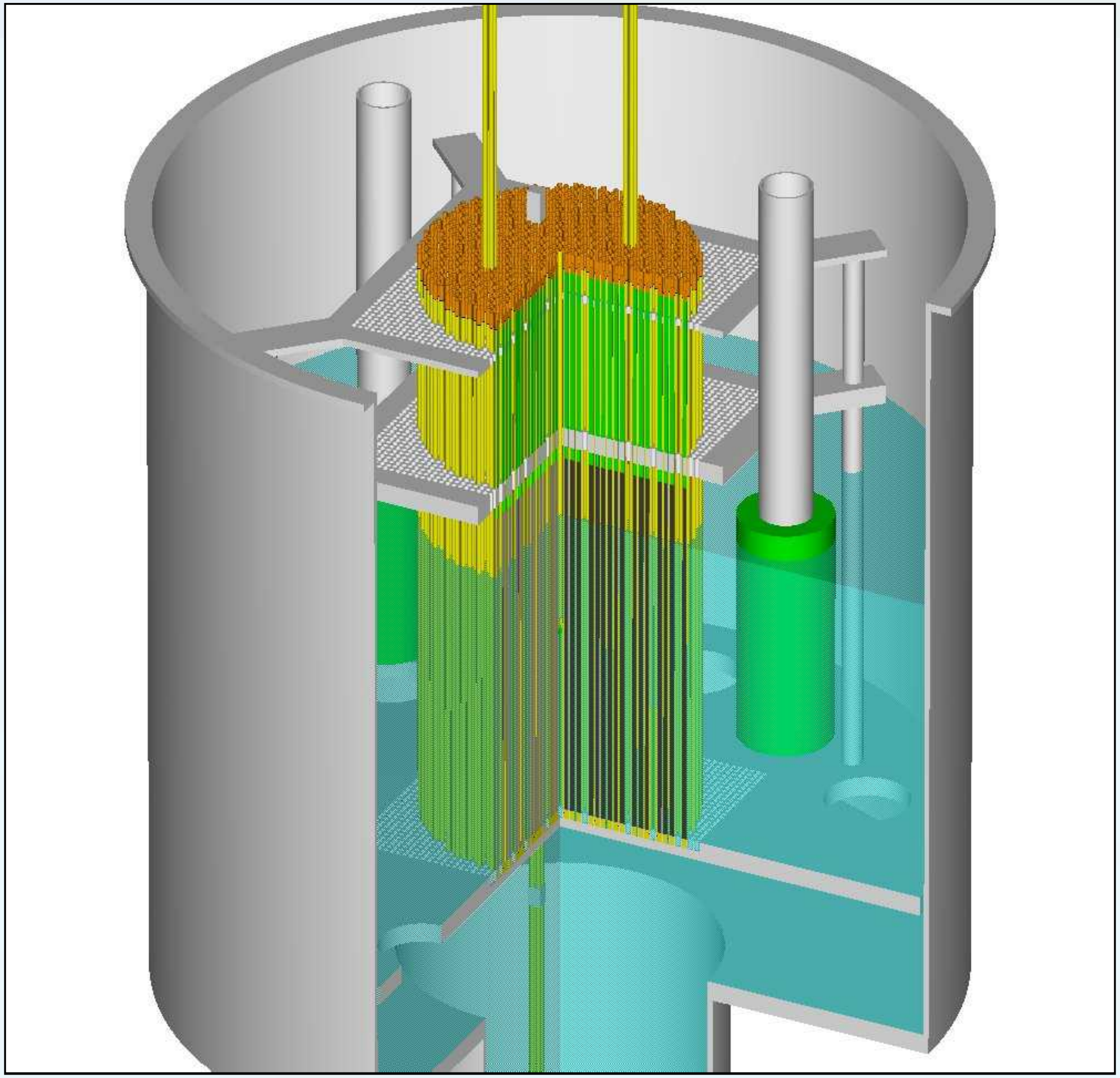
Control Element: Down

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

$k_{eff} \approx 0.953$

Safety Elements: Up

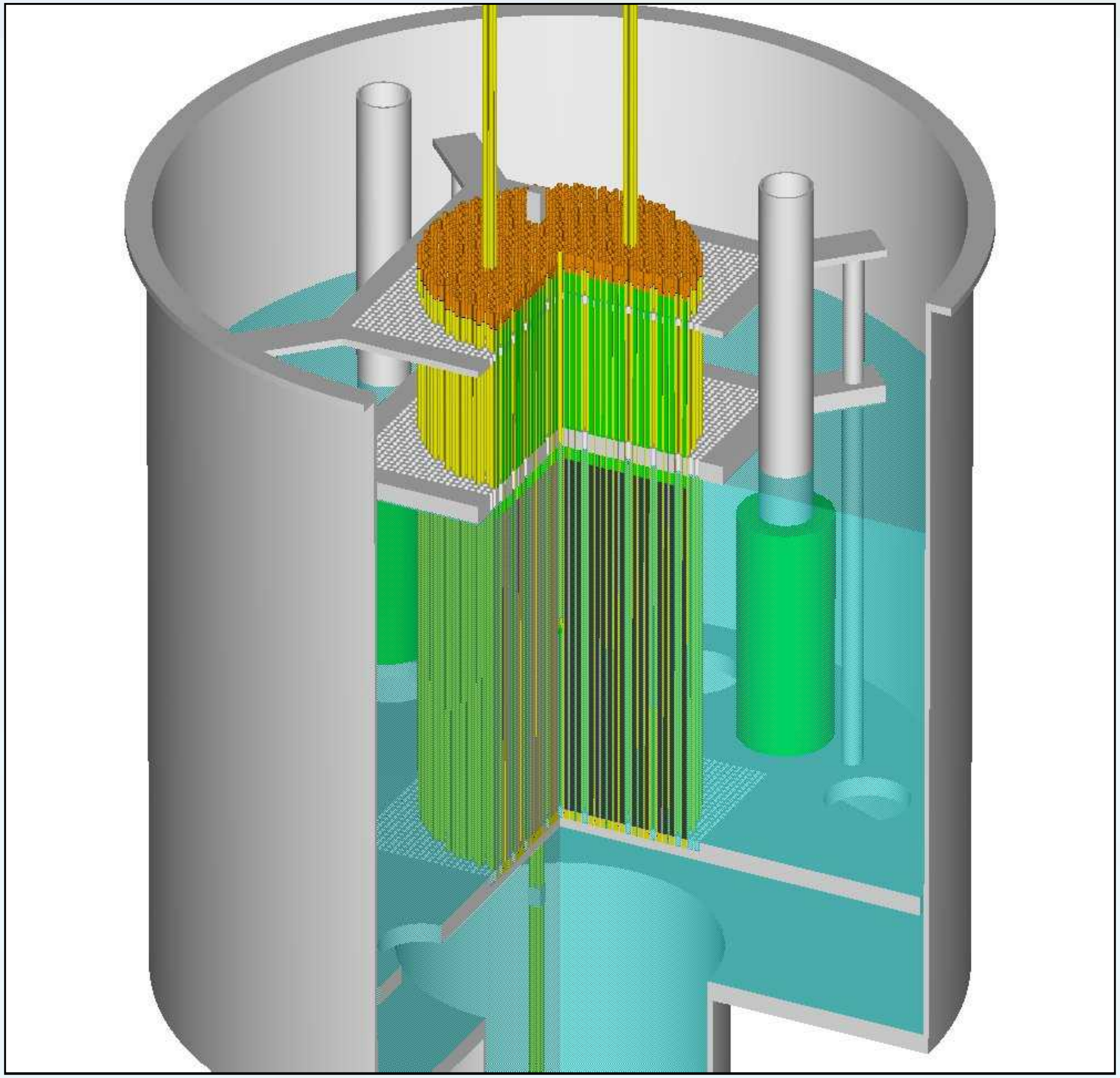
Control Element: Down

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

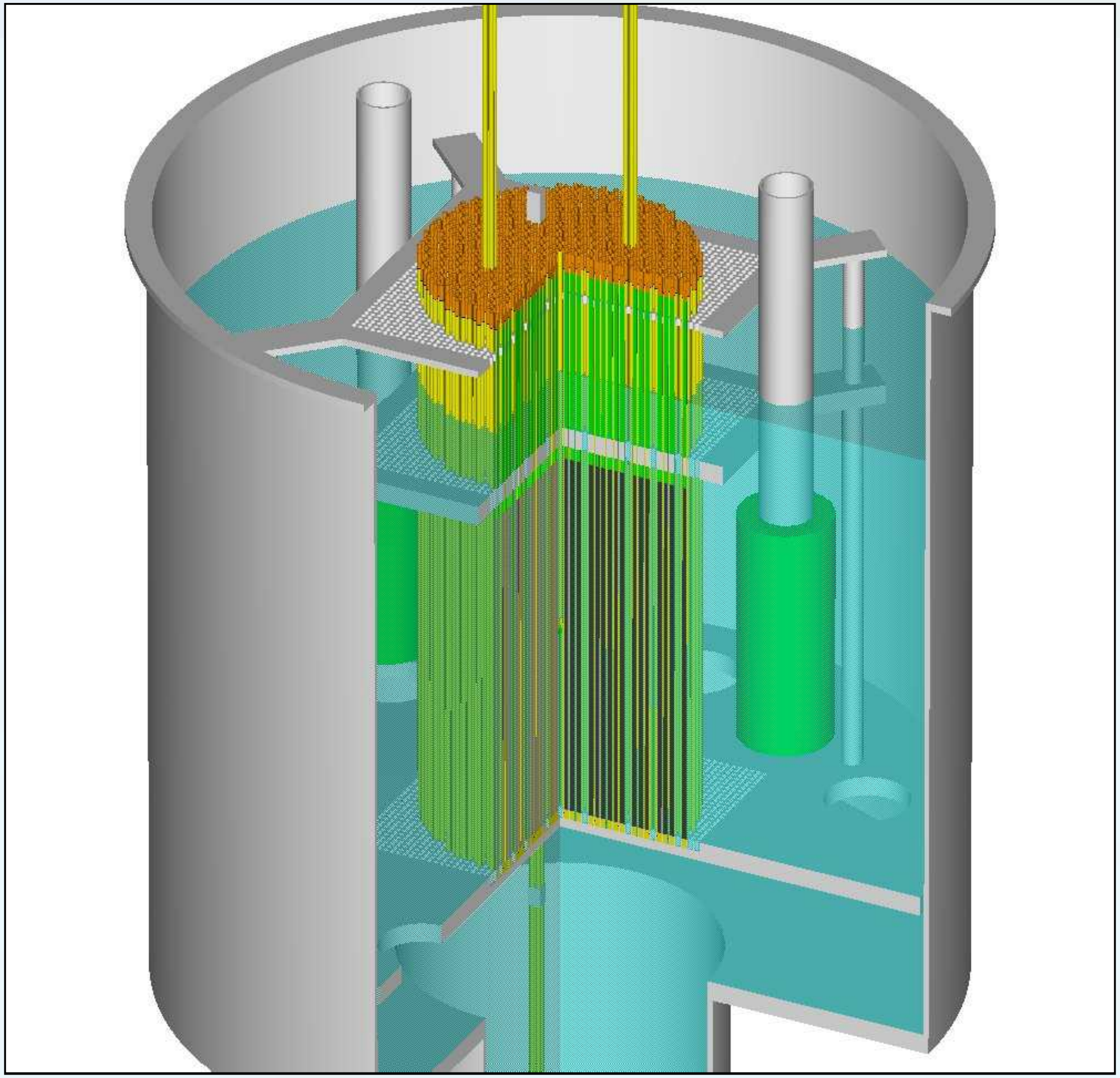
Control Element: Down

Core Tank: Filling

Personnel: Excluded

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

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.986$

Safety Elements: Up

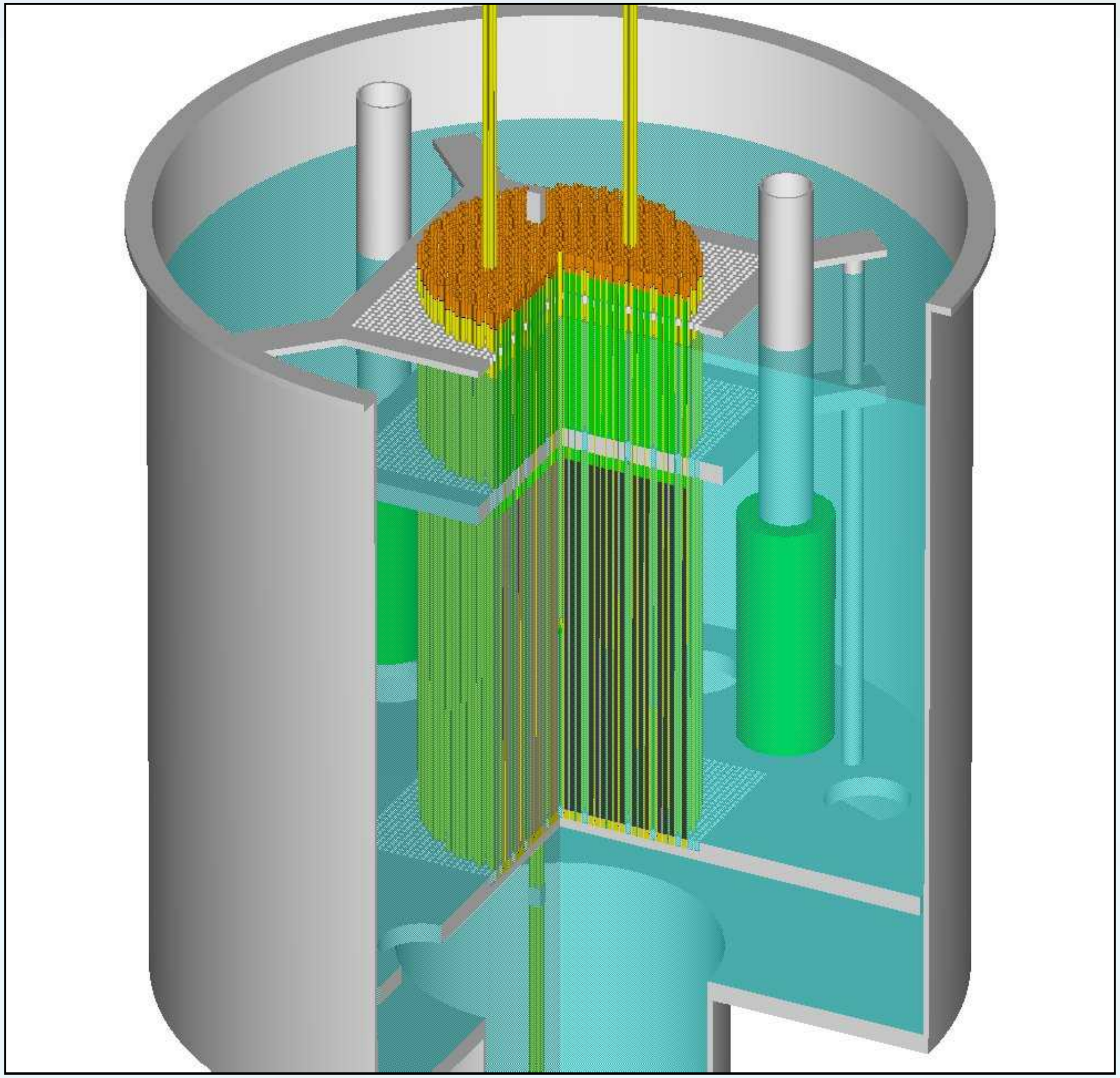
Control Element: Down

Core Tank: Filling

Personnel: Excluded

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

The Core Tank is Full



Fuel: 1136

k_{eff} ≈ 0.986

Safety Elements: Up

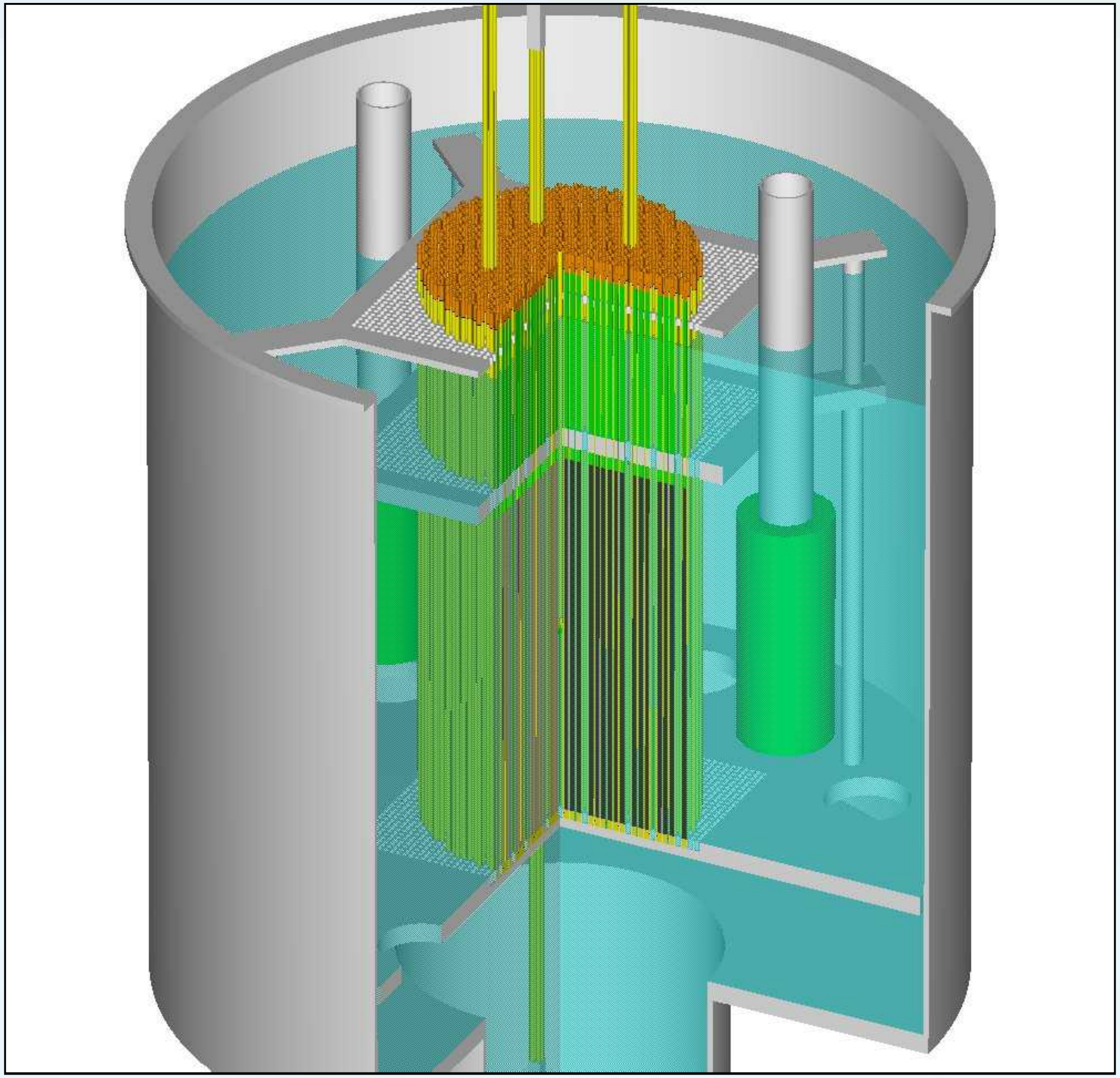
Control Element: Down

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.

Raise the Control Element



Fuel: 1136

$k_{eff} \approx 0.992$

Safety Elements: Up

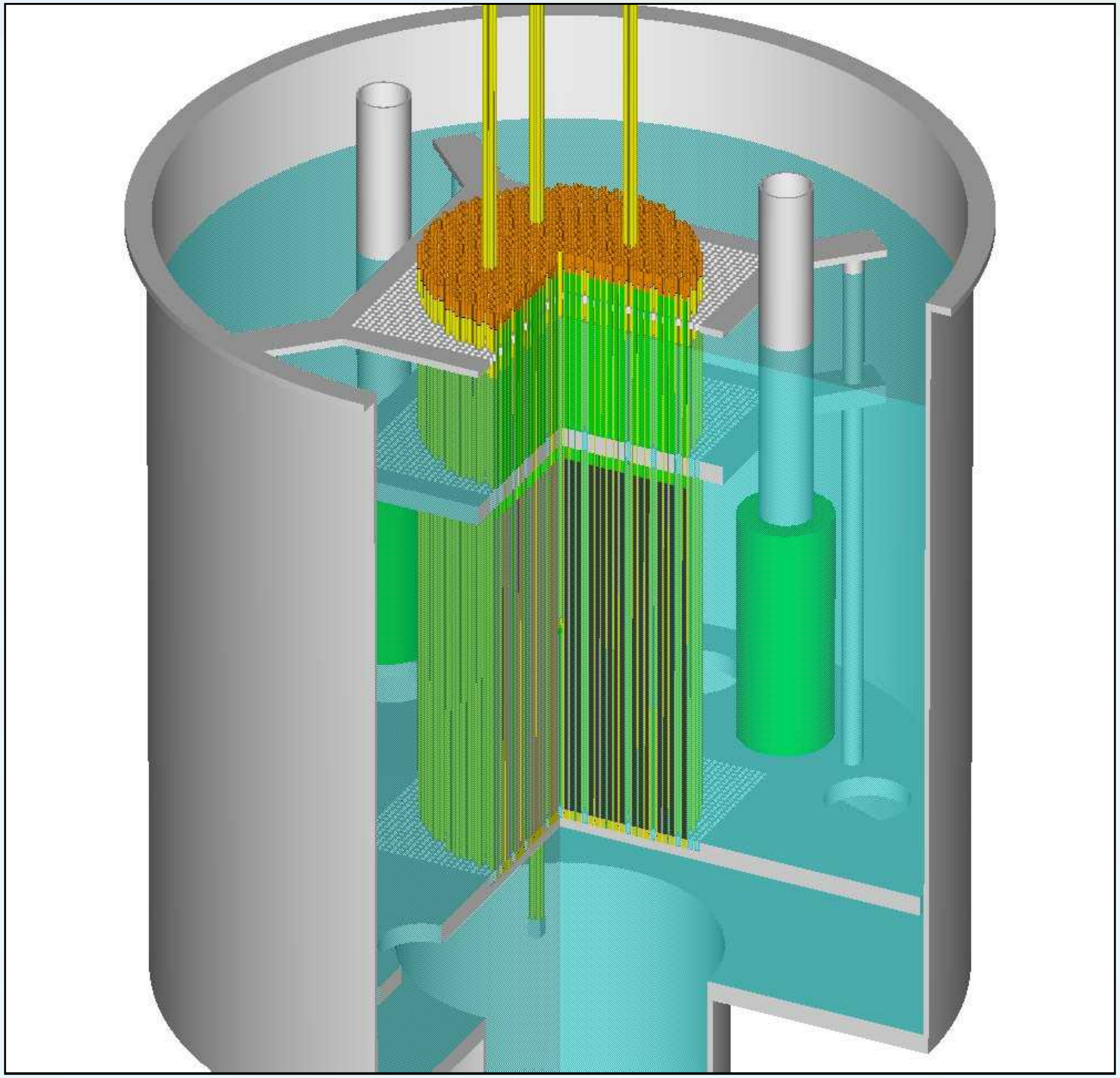
Control Element: Raising

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.

Raise the Control Element



Fuel: 1136

$k_{eff} \approx 0.998$

Safety Elements: Up

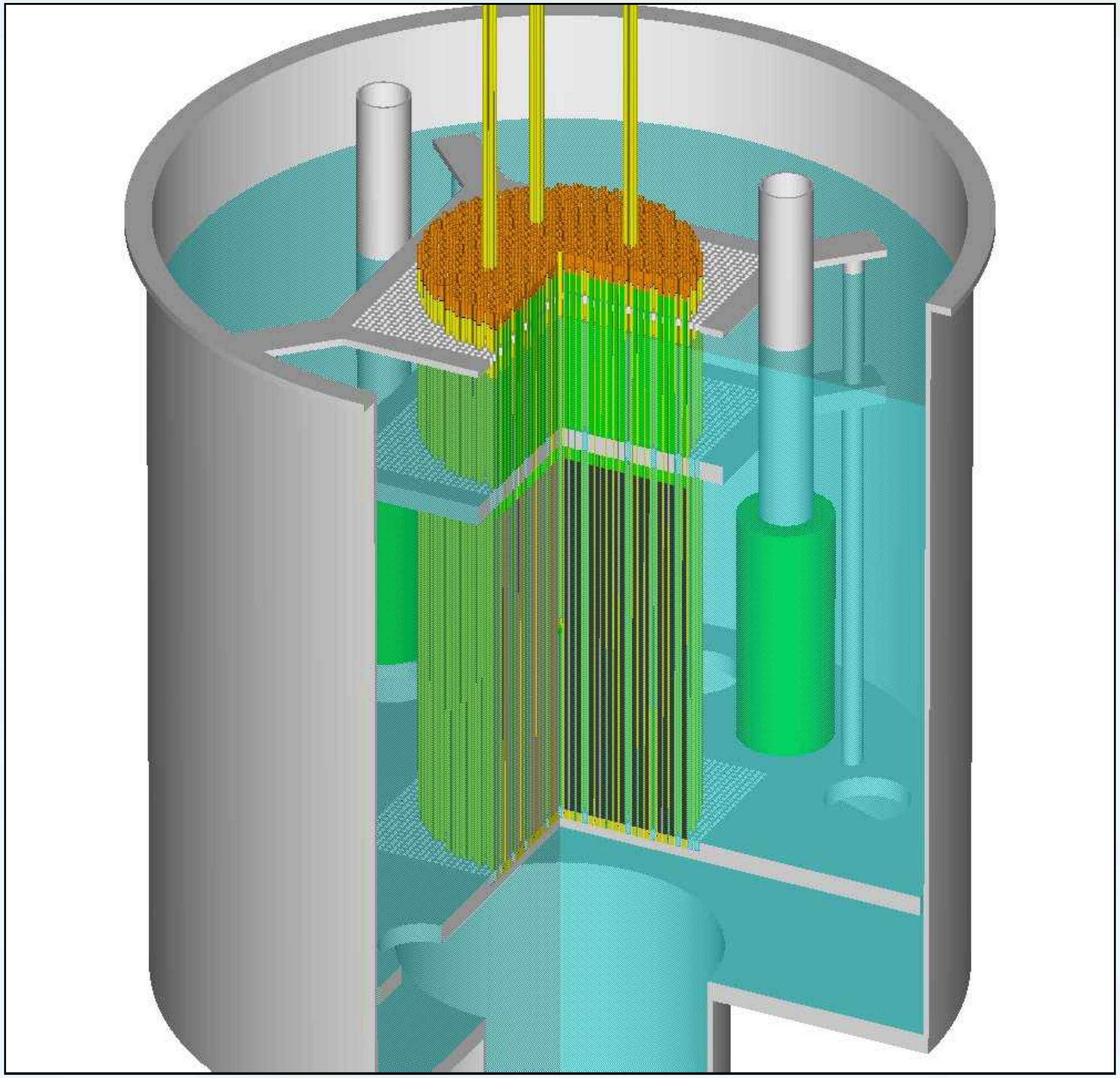
Control Element: Raising

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.

The Assembly Reaches Its Most Reactive State



Fuel: 1136

k_{eff} ≈ 0.999

Safety Elements: Up

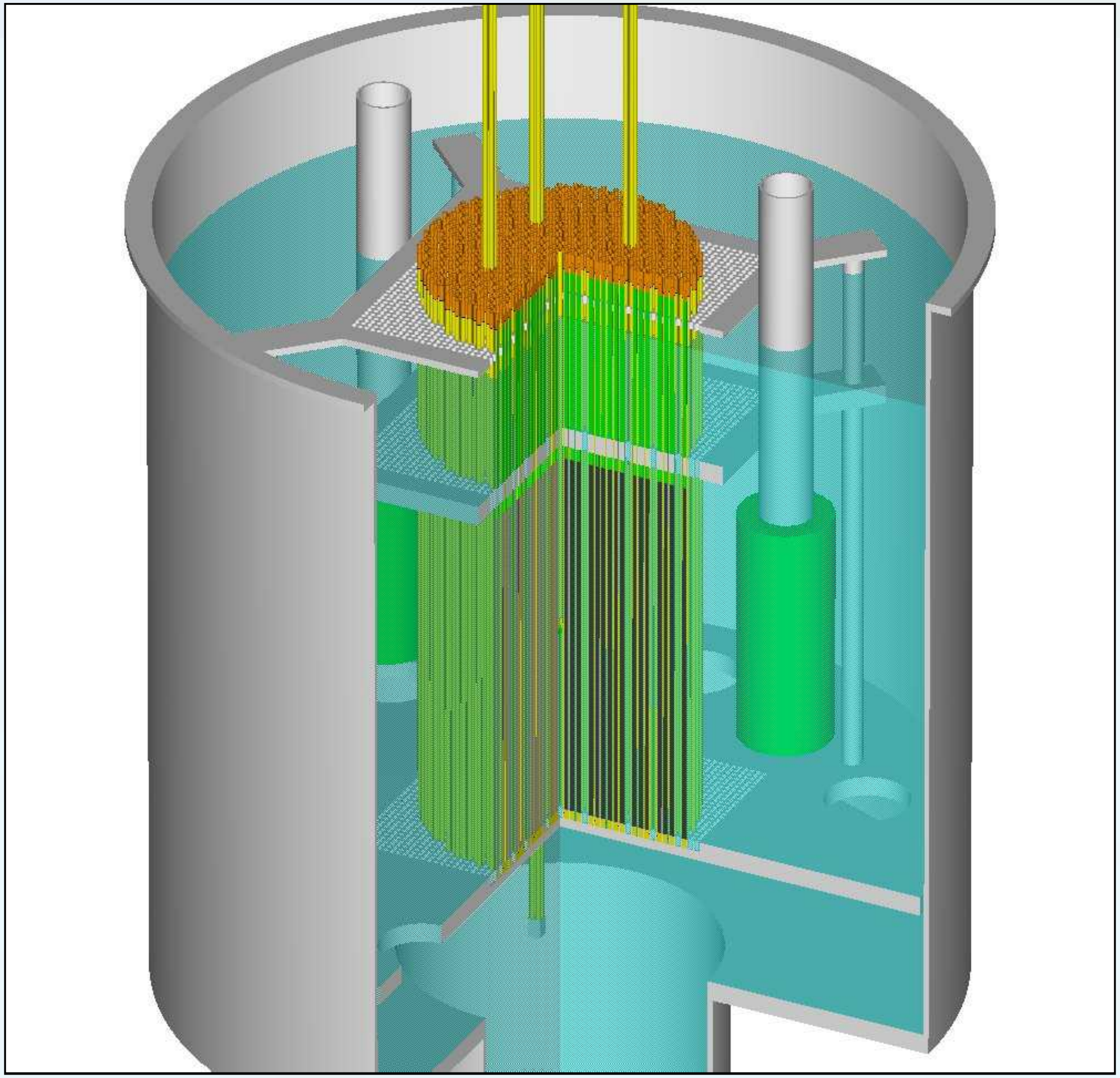
Control Element: Up

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.

Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.998$

Safety Elements: Up

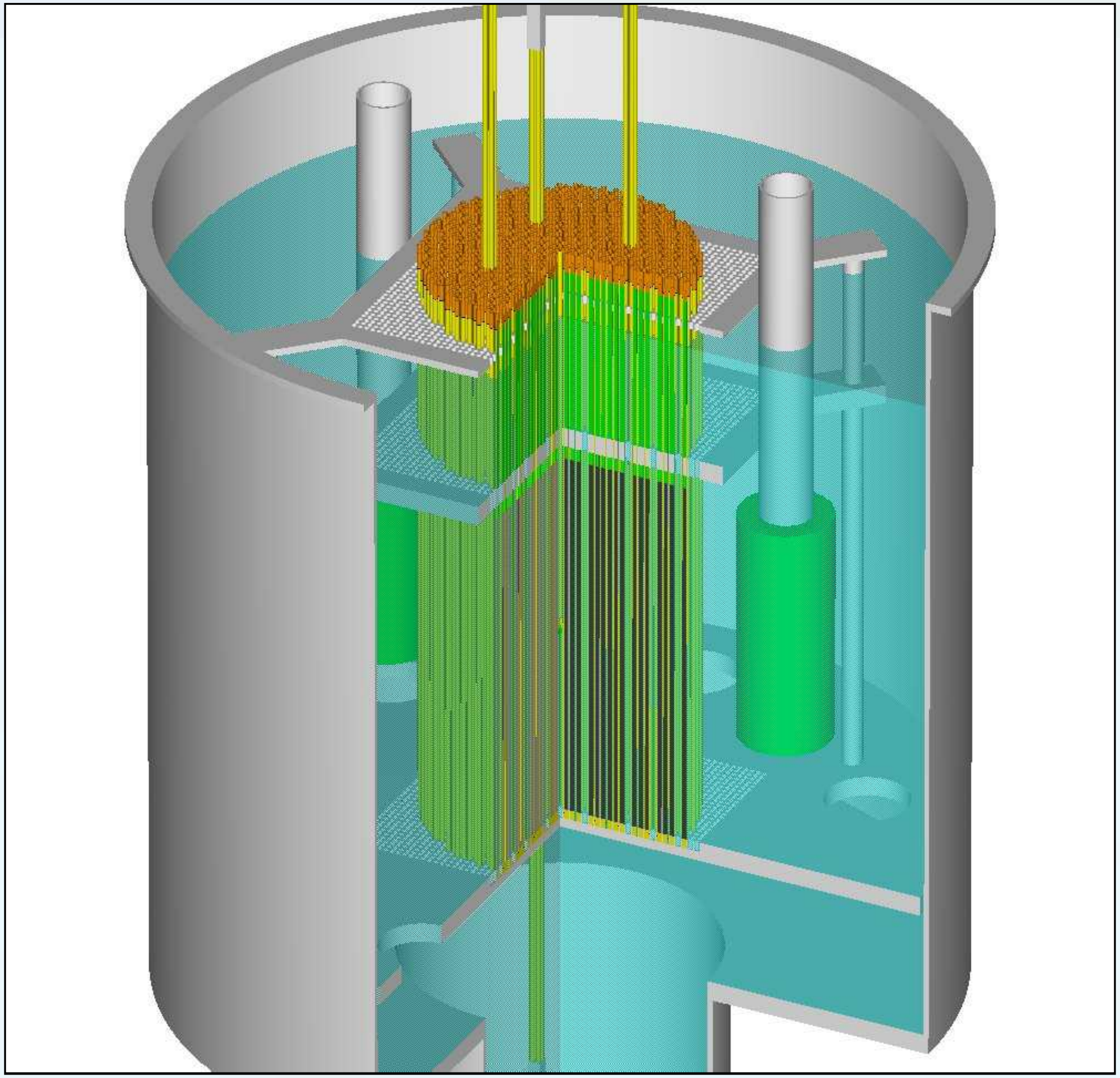
Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to lower the control element.

Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.992$

Safety Elements: Up

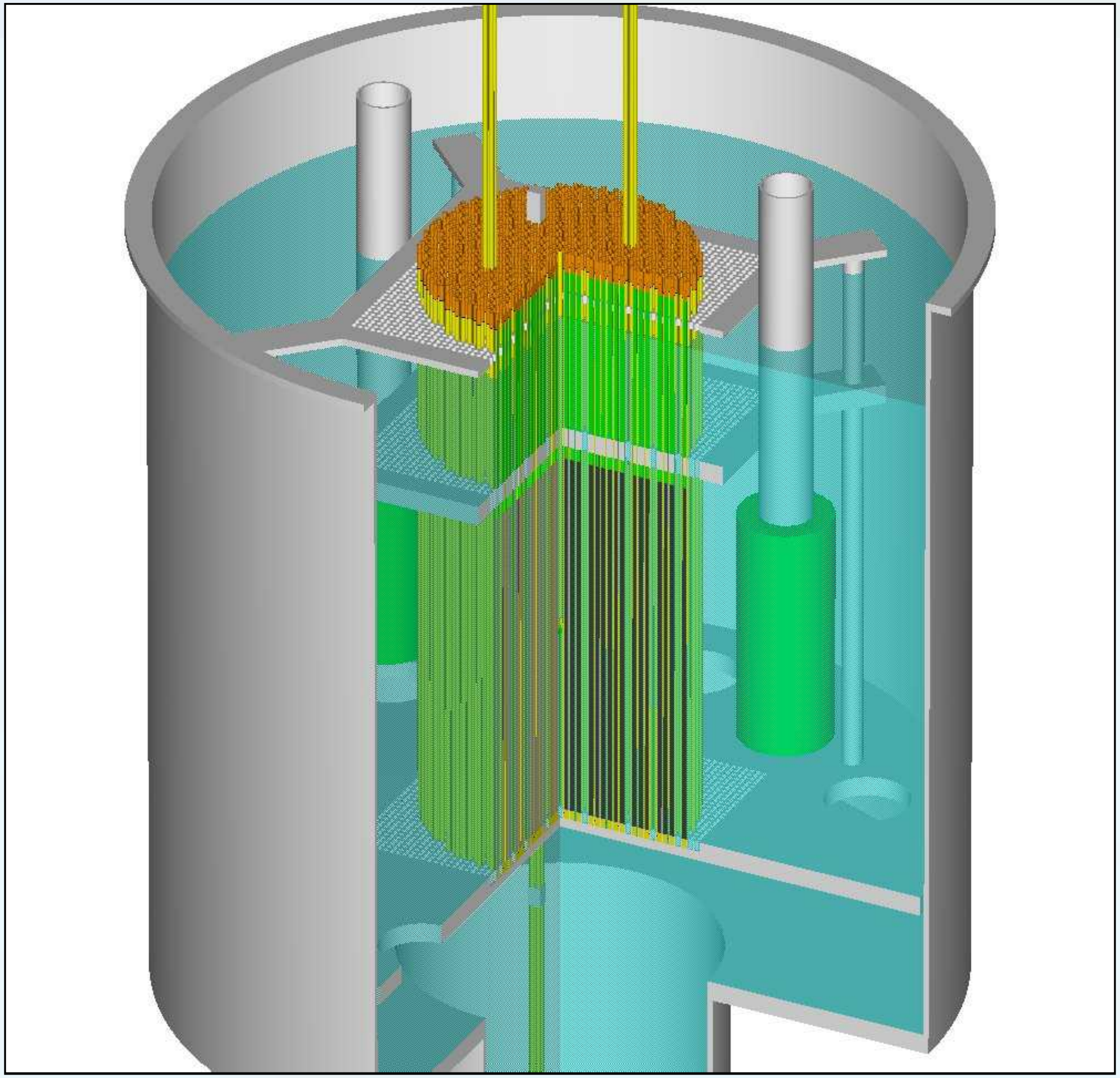
Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to lower the control element.

Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.986$

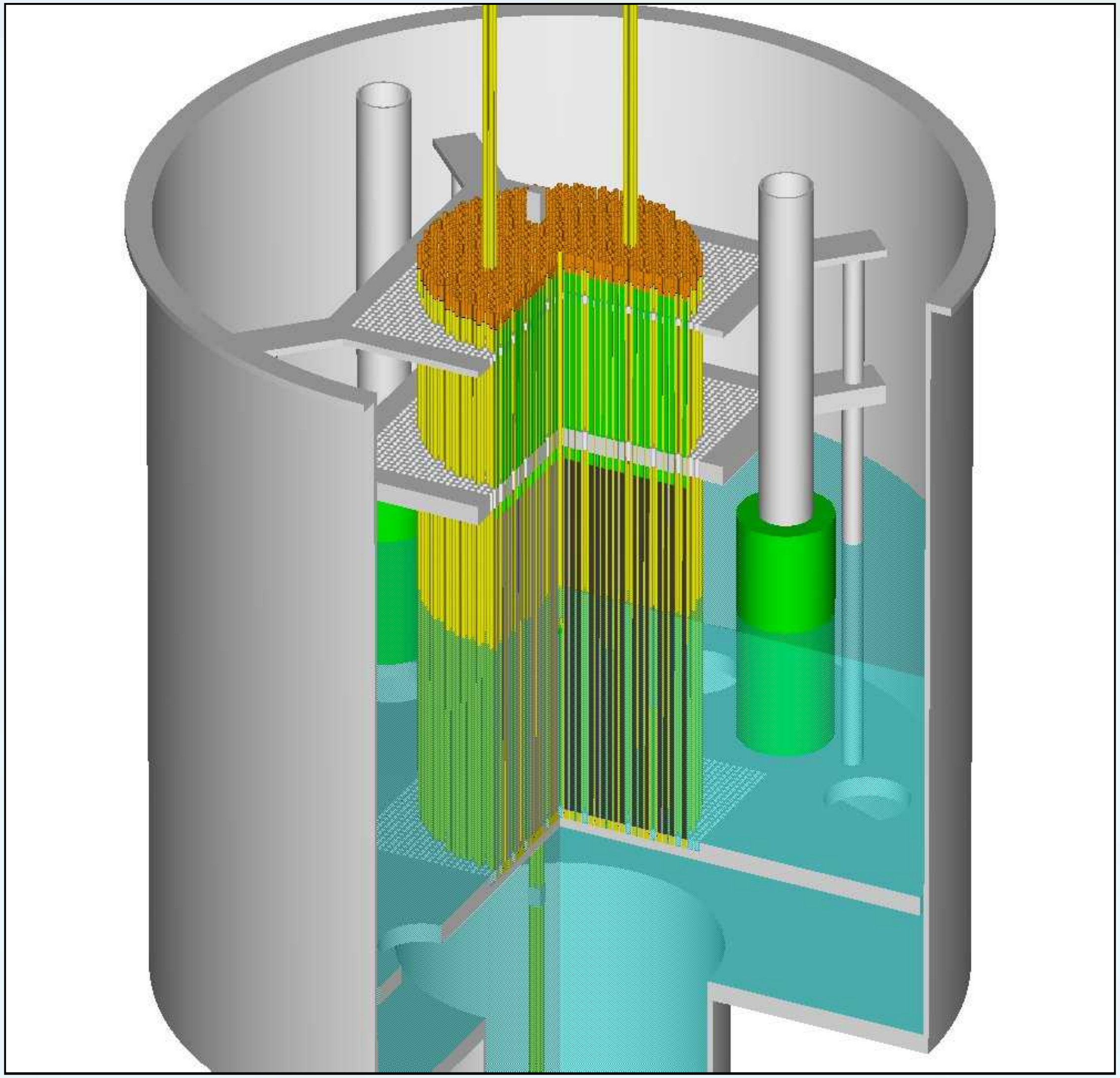
Safety Elements: Up

Control Element: Down

Core Tank: Full

Personnel: Excluded

Drain the Core Tank



Fuel: 1136

$k_{eff} \approx 0.901$

Safety Elements: Up

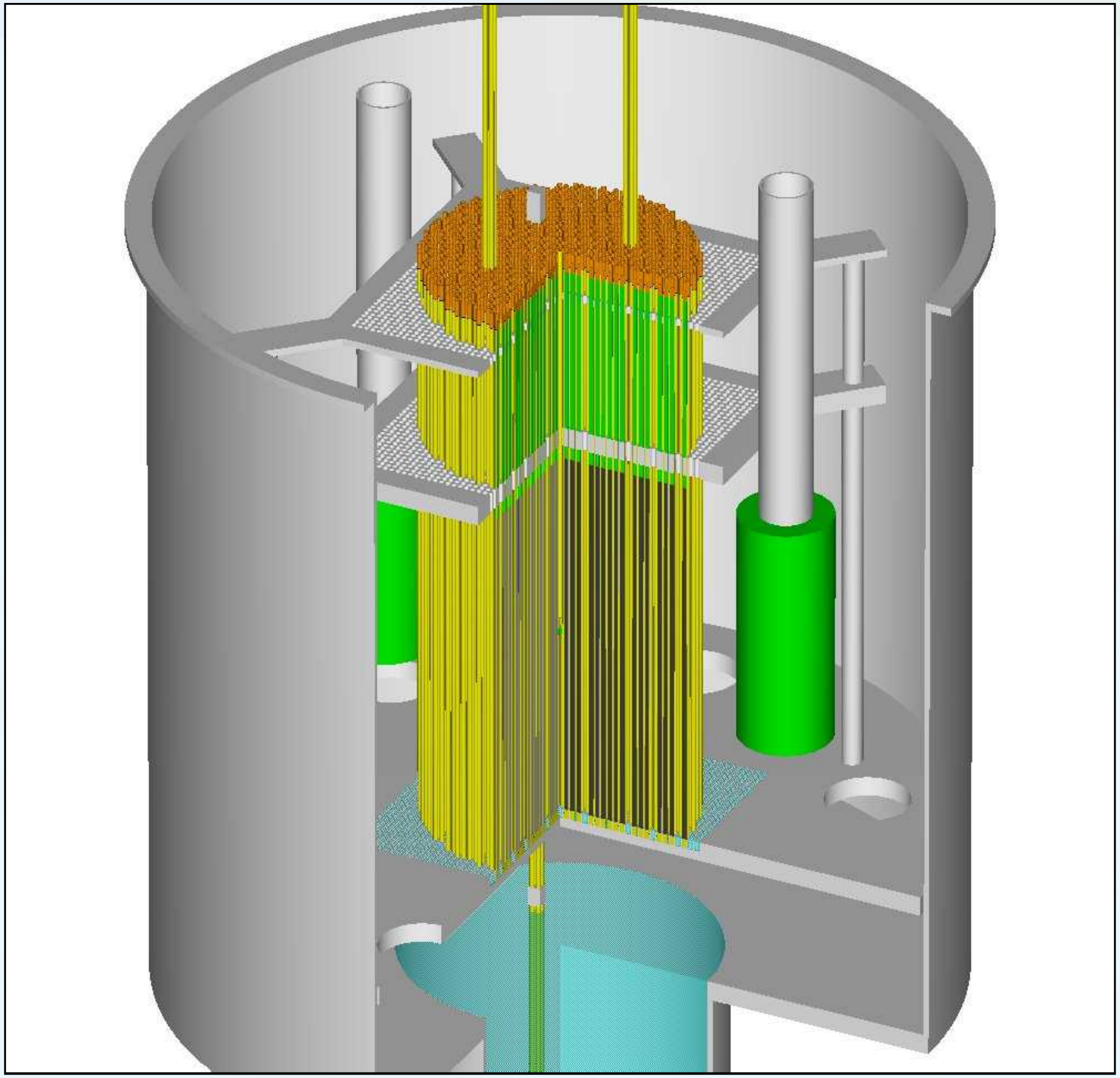
Control Element: Down

Core Tank: Draining

Personnel: Excluded

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

Drain the Core Tank



Fuel: 1136

$k_{eff} \approx 0.128$

Safety Elements: Up

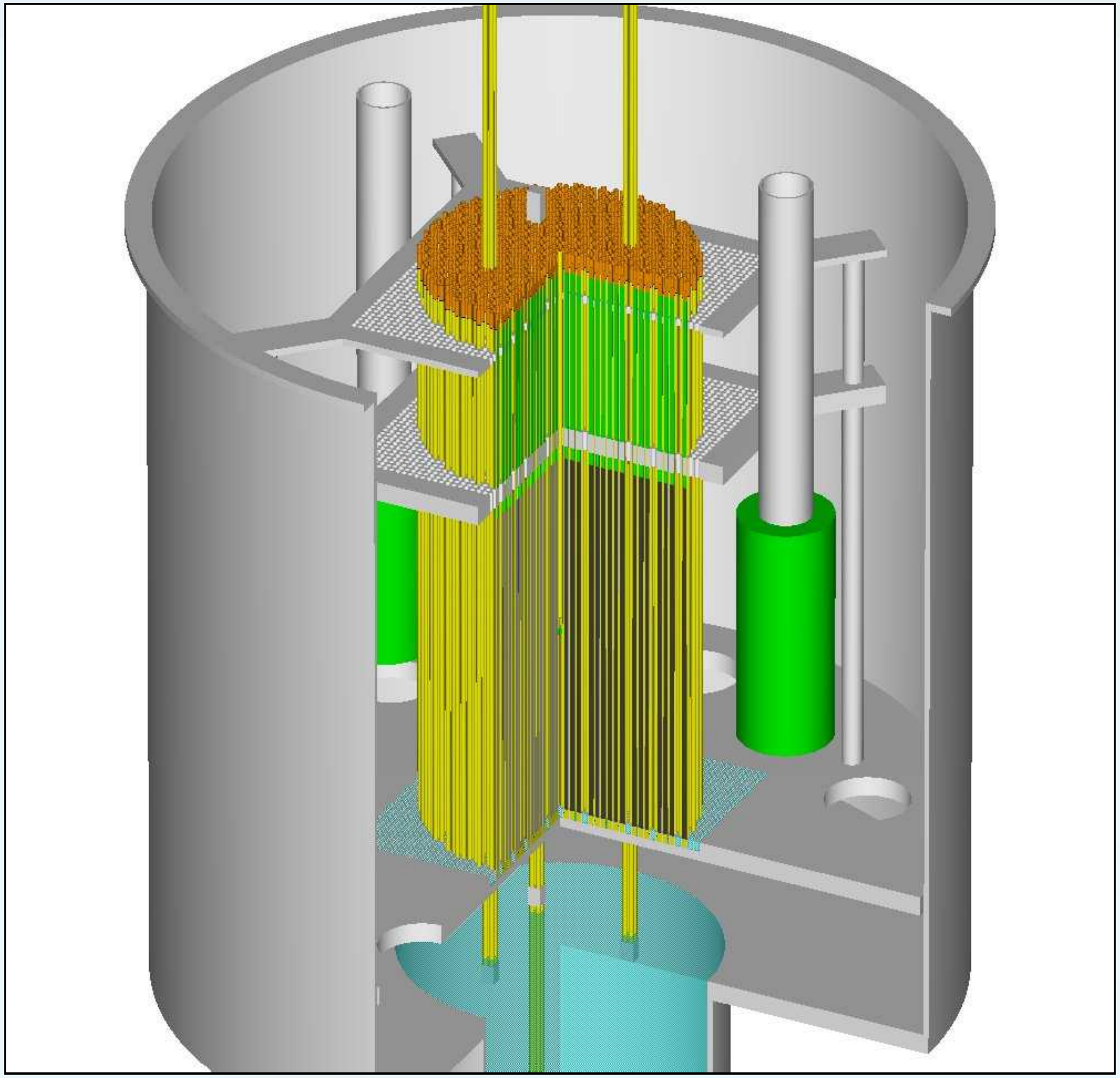
Control Element: Down

Core Tank: Empty

Personnel: Allowed

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

Lower the Safety Elements



Fuel: 1136

$k_{eff} \approx 0.127$

Safety Elements: Lowering

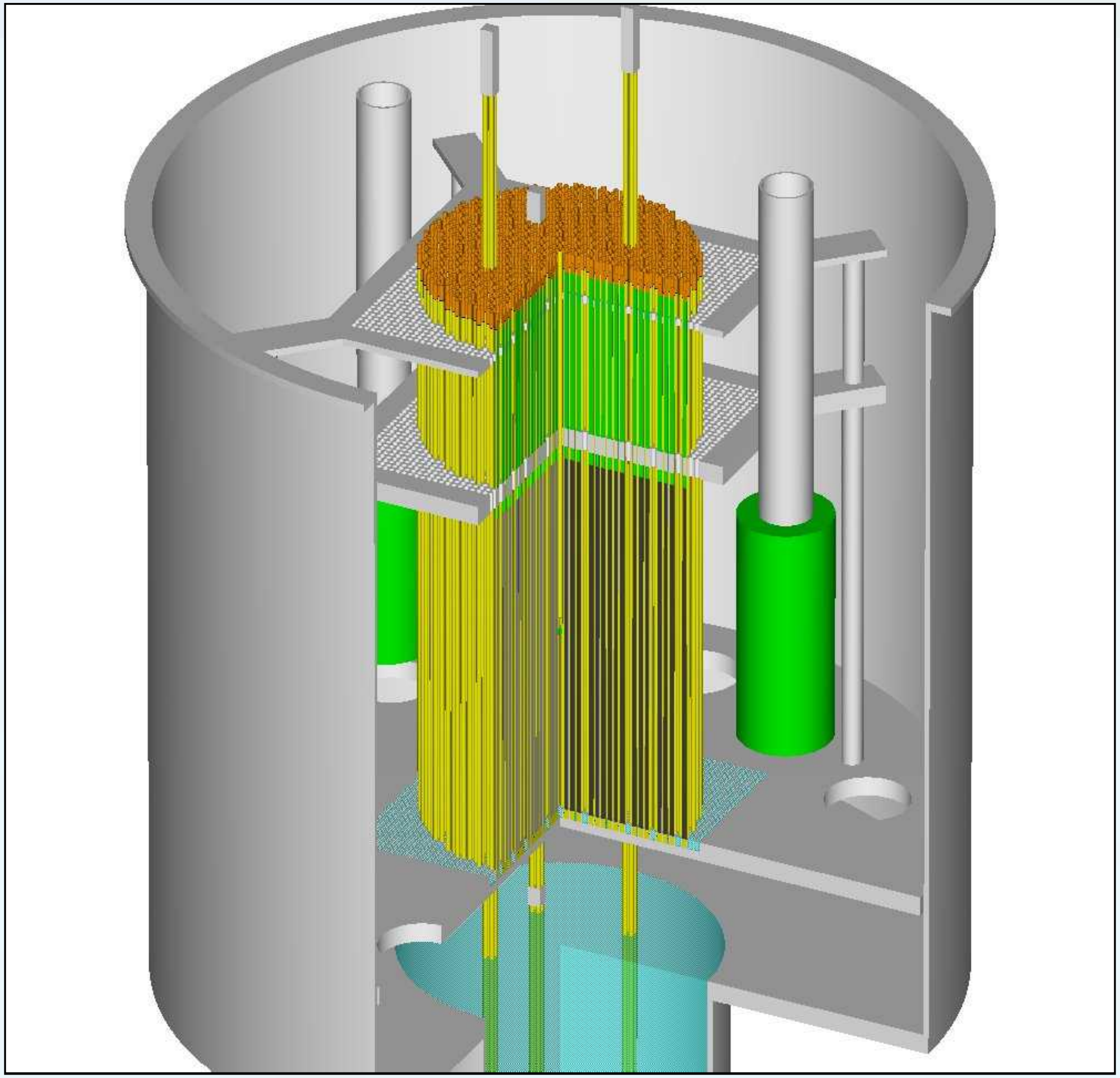
Control Element: Down

Core Tank: Empty

Personnel: Allowed

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

Lower the Safety Elements



Fuel: 1136

k_{eff} ≈ 0.132

Safety Elements: Lowering

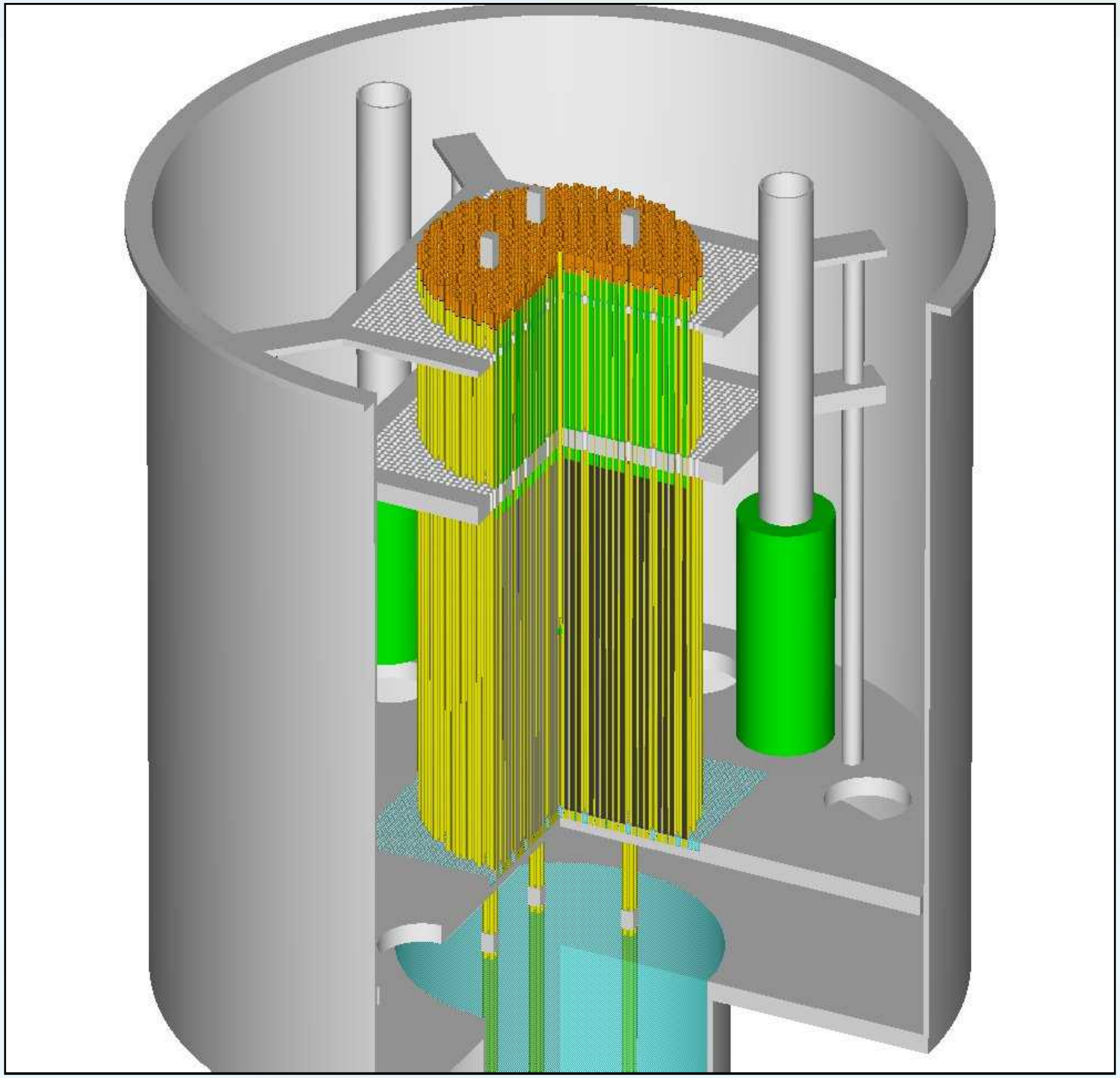
Control Element: Down

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

$k_{eff} \approx 0.140$

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.

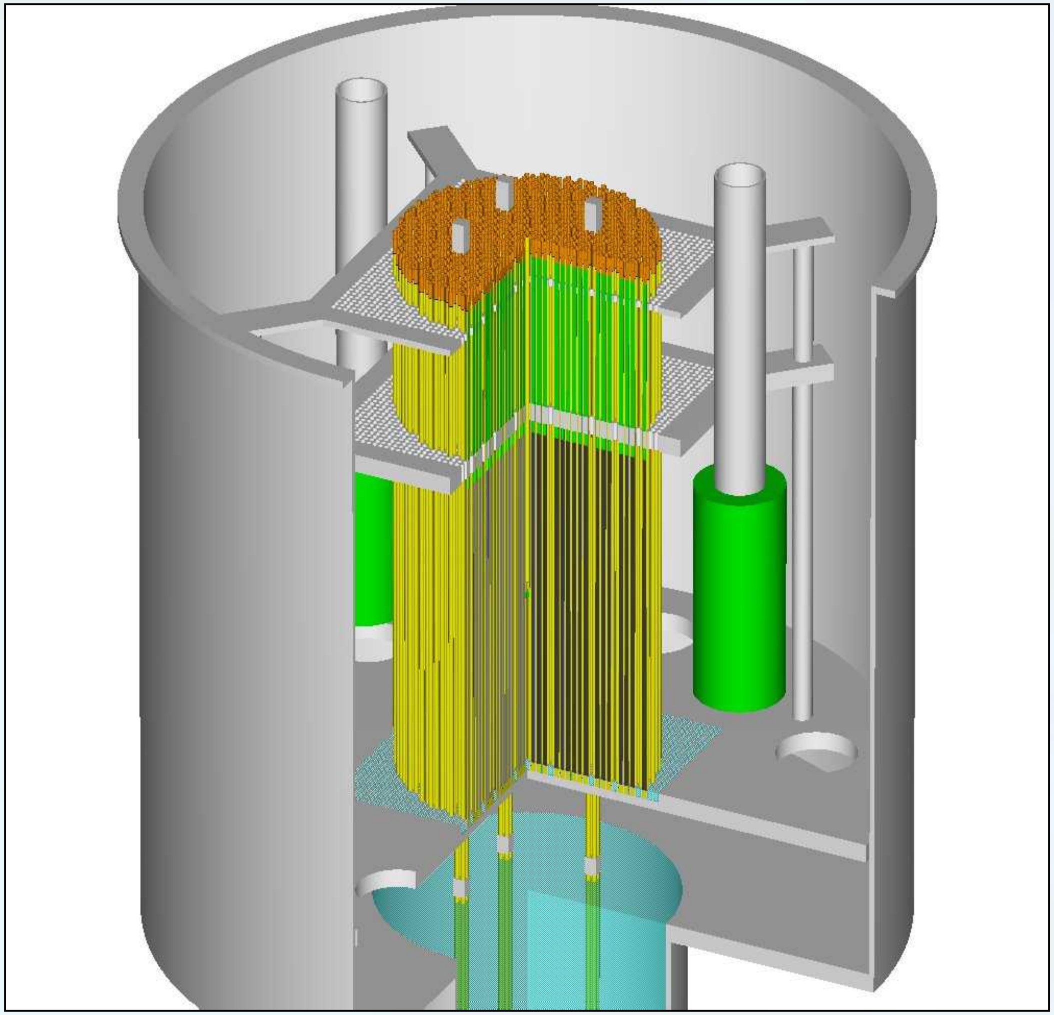
Some interesting physics . . .

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

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

Subcritical Multiplication

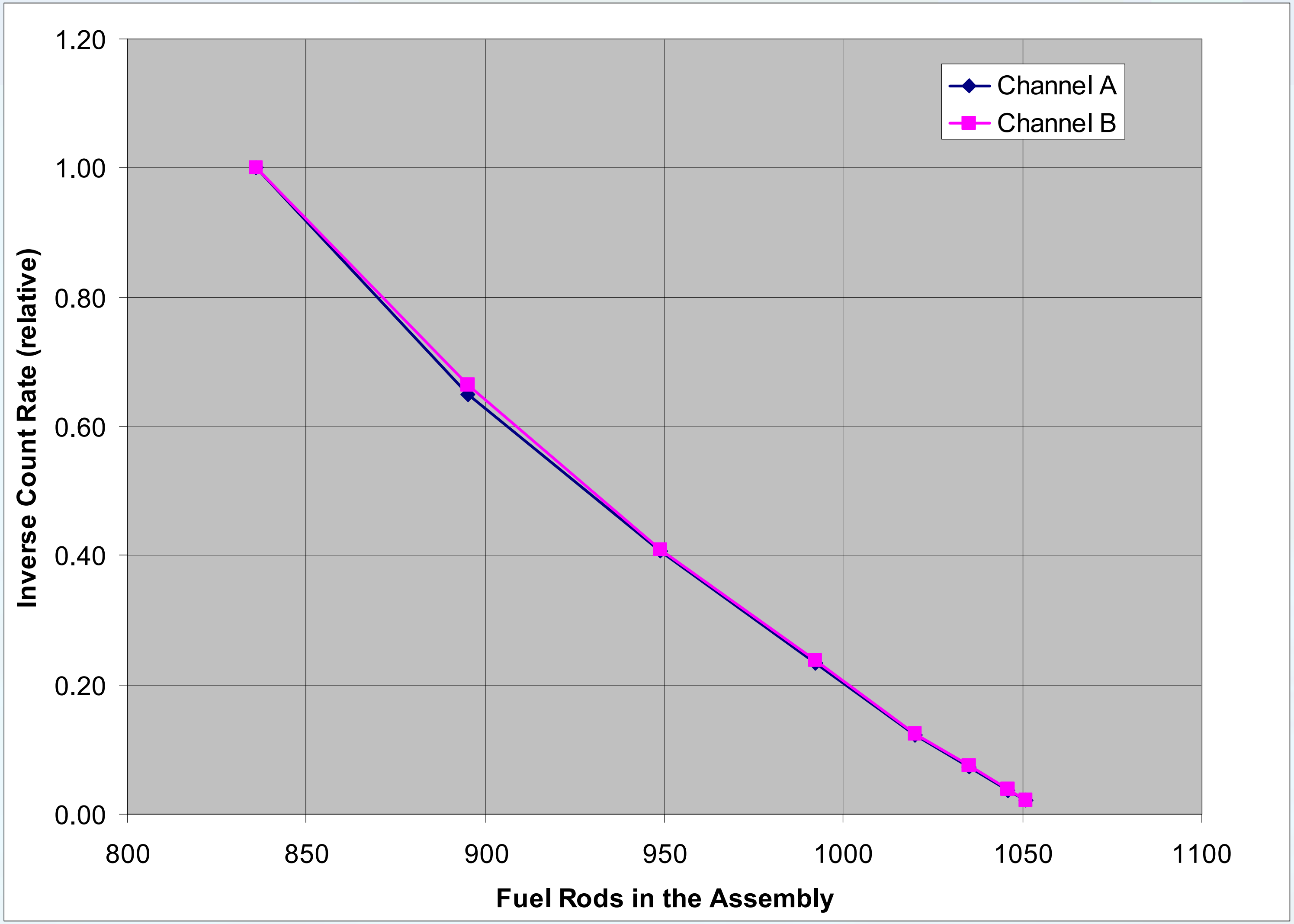
$$\frac{1}{M} = 1 - k_{eff}$$

Inverse Subcritical Multiplication

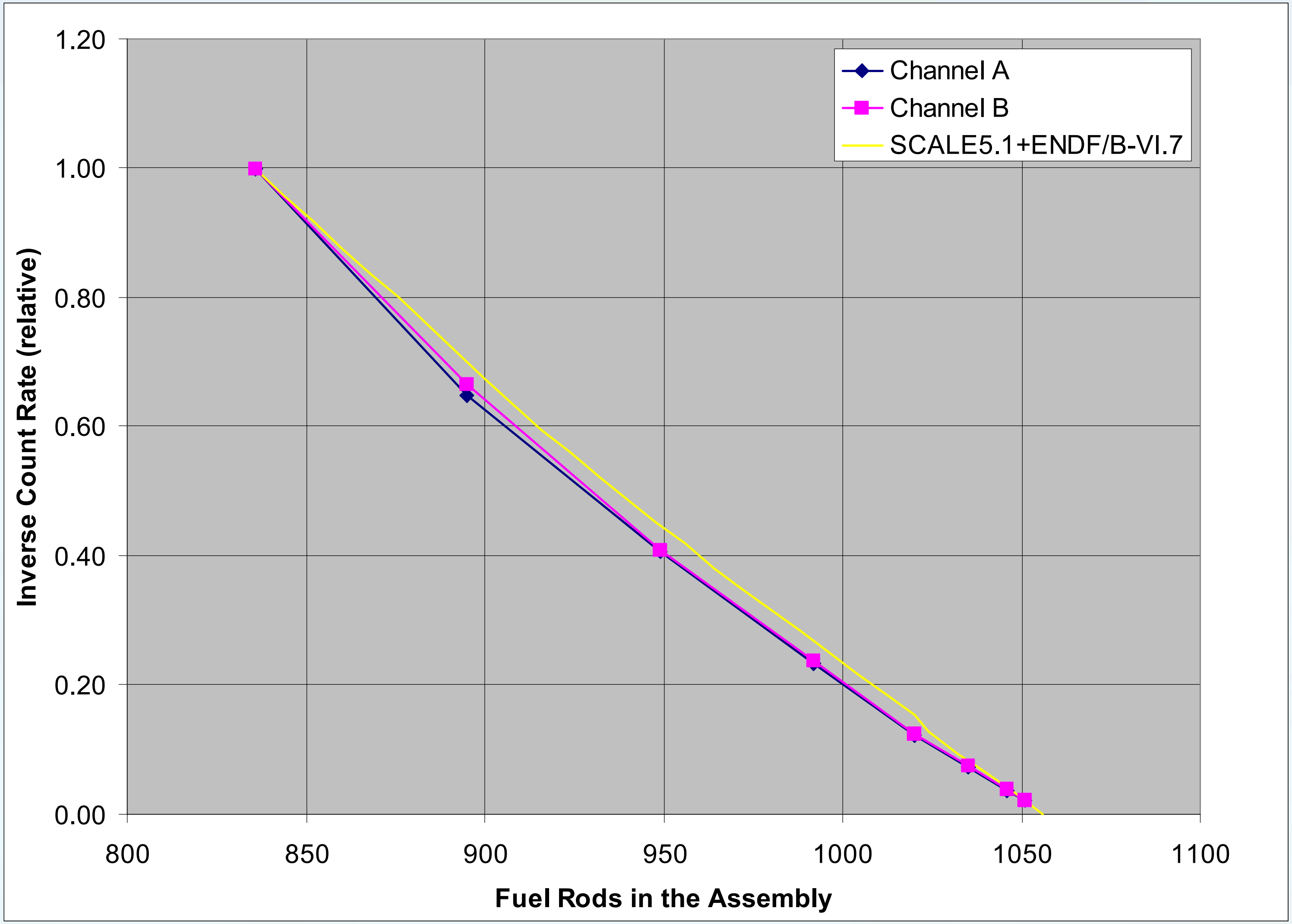
$$I_n = \frac{Constant}{CR_n}$$

Inverse Count Rate

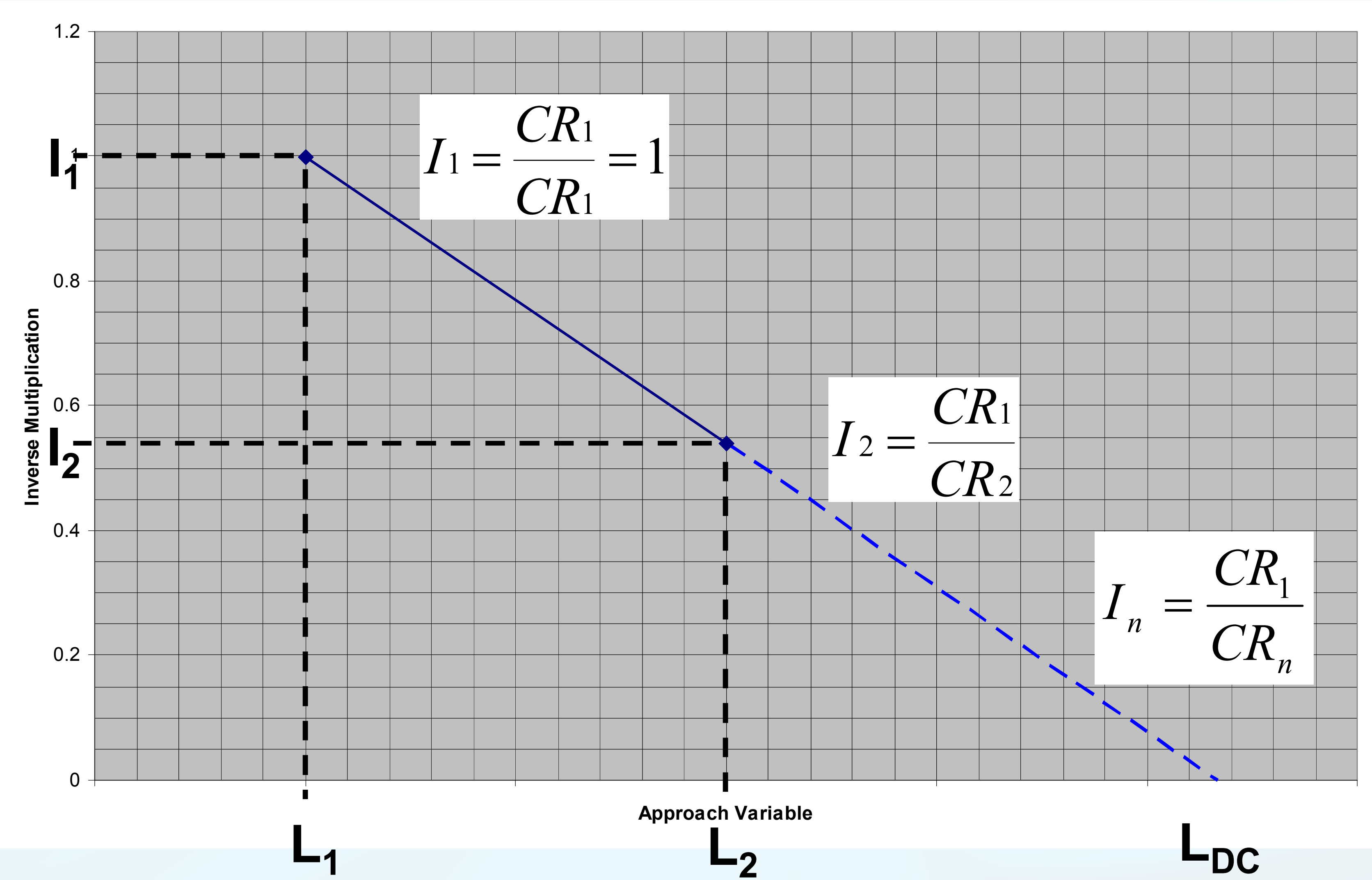
Inverse Count Rate Plot



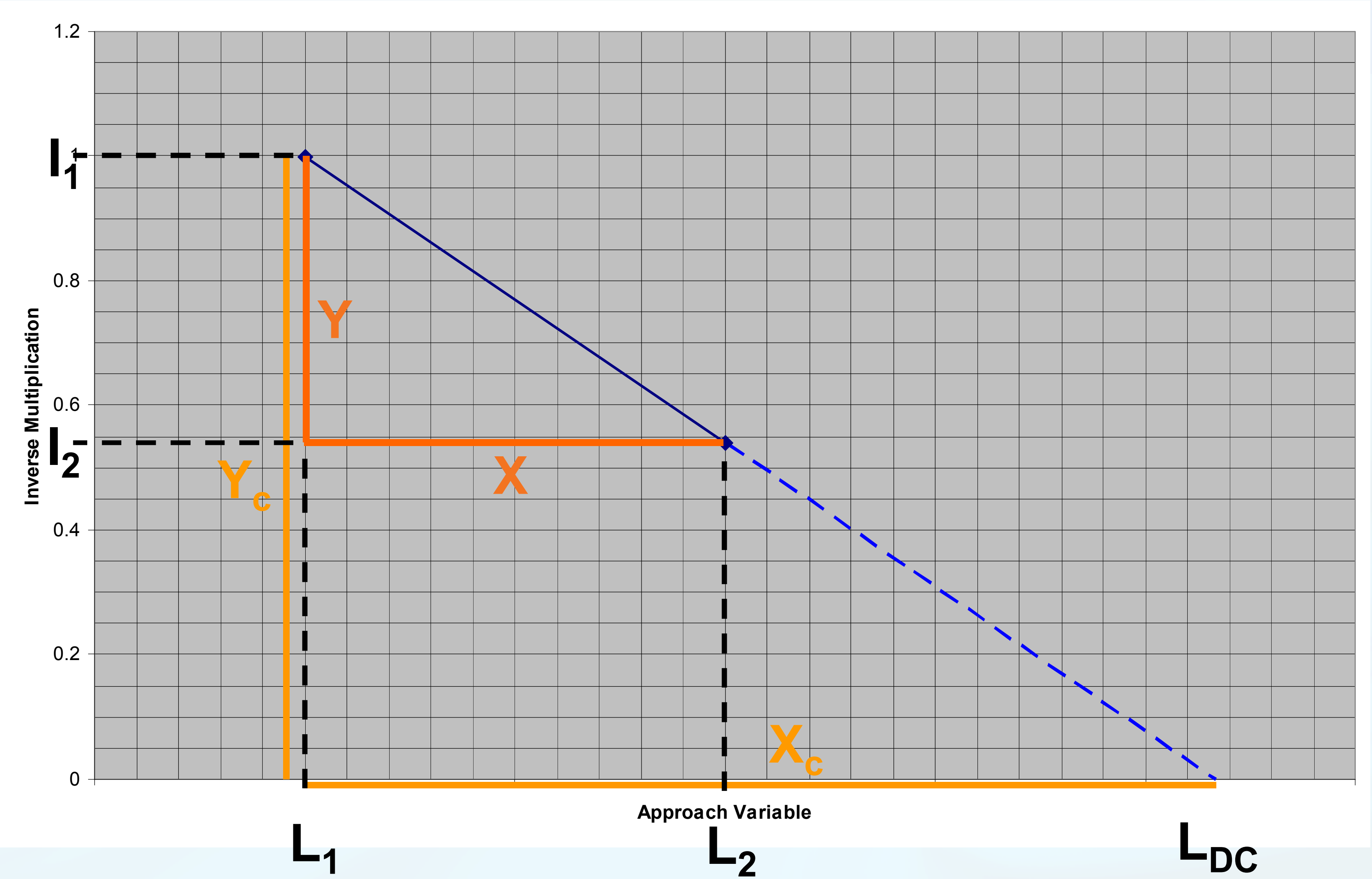
Inverse Count Rate Plot



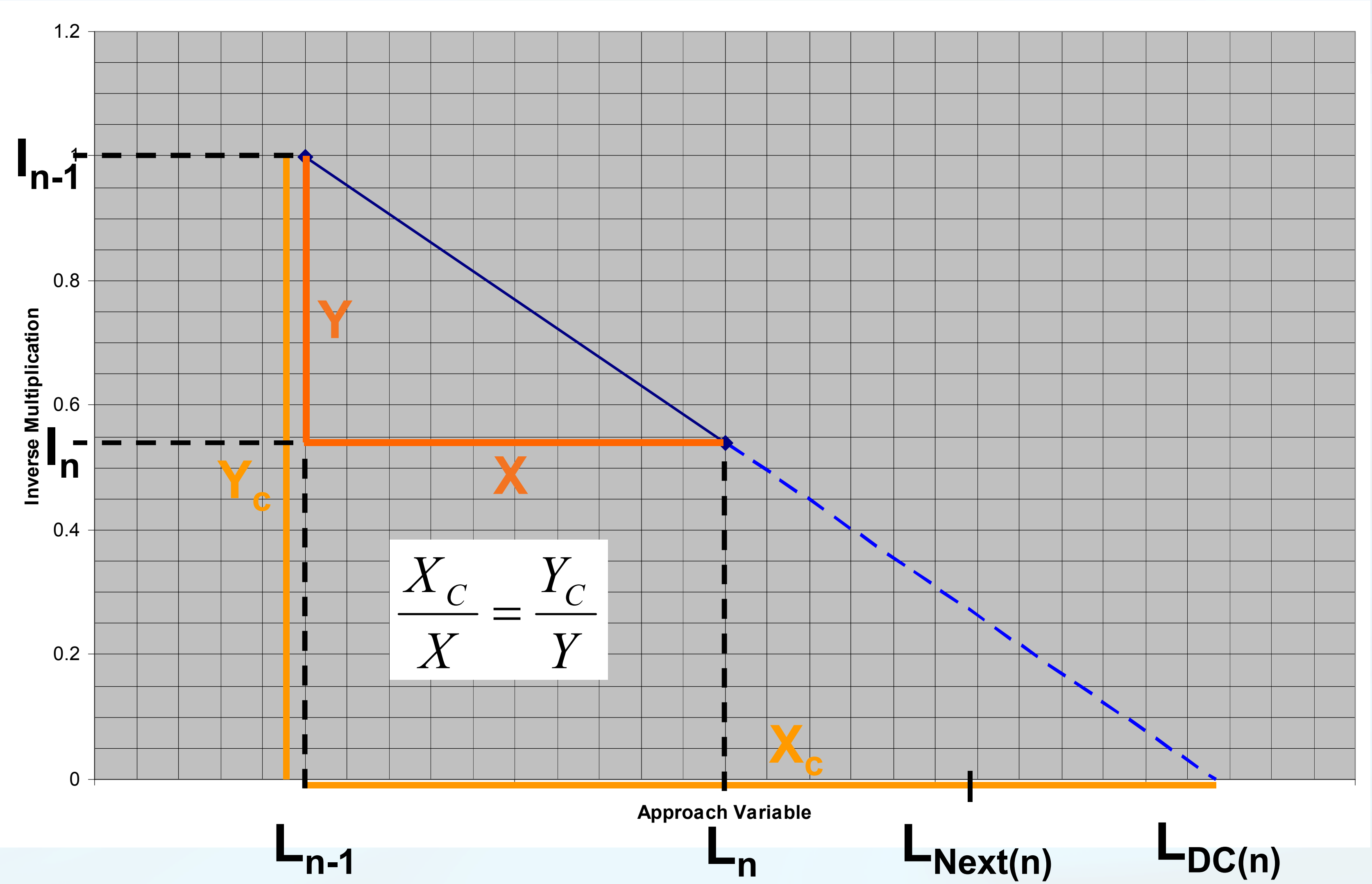
Determining the Next Fuel Increment



Determining the Next Fuel Increment

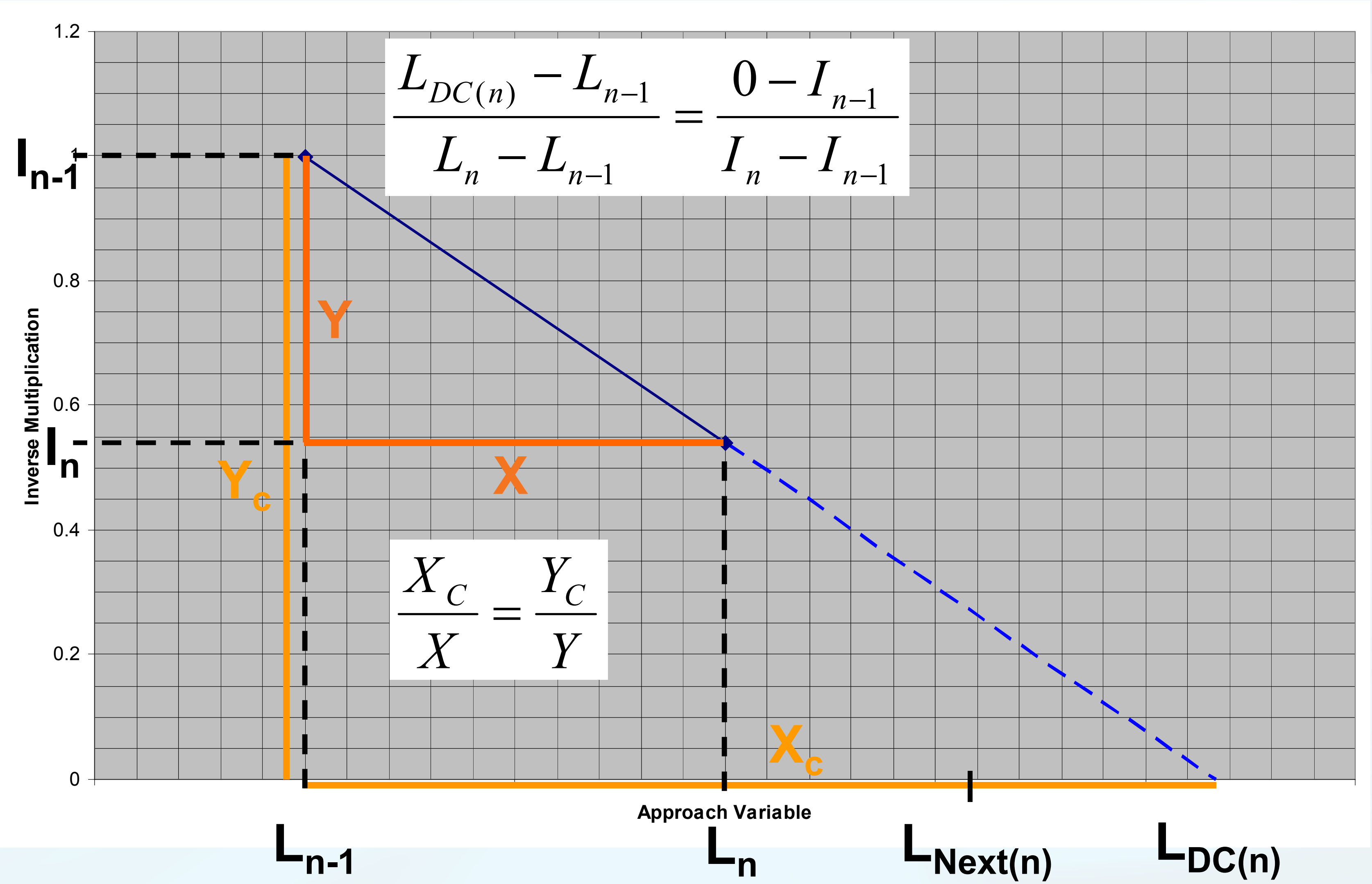


Determining the Next Fuel Increment

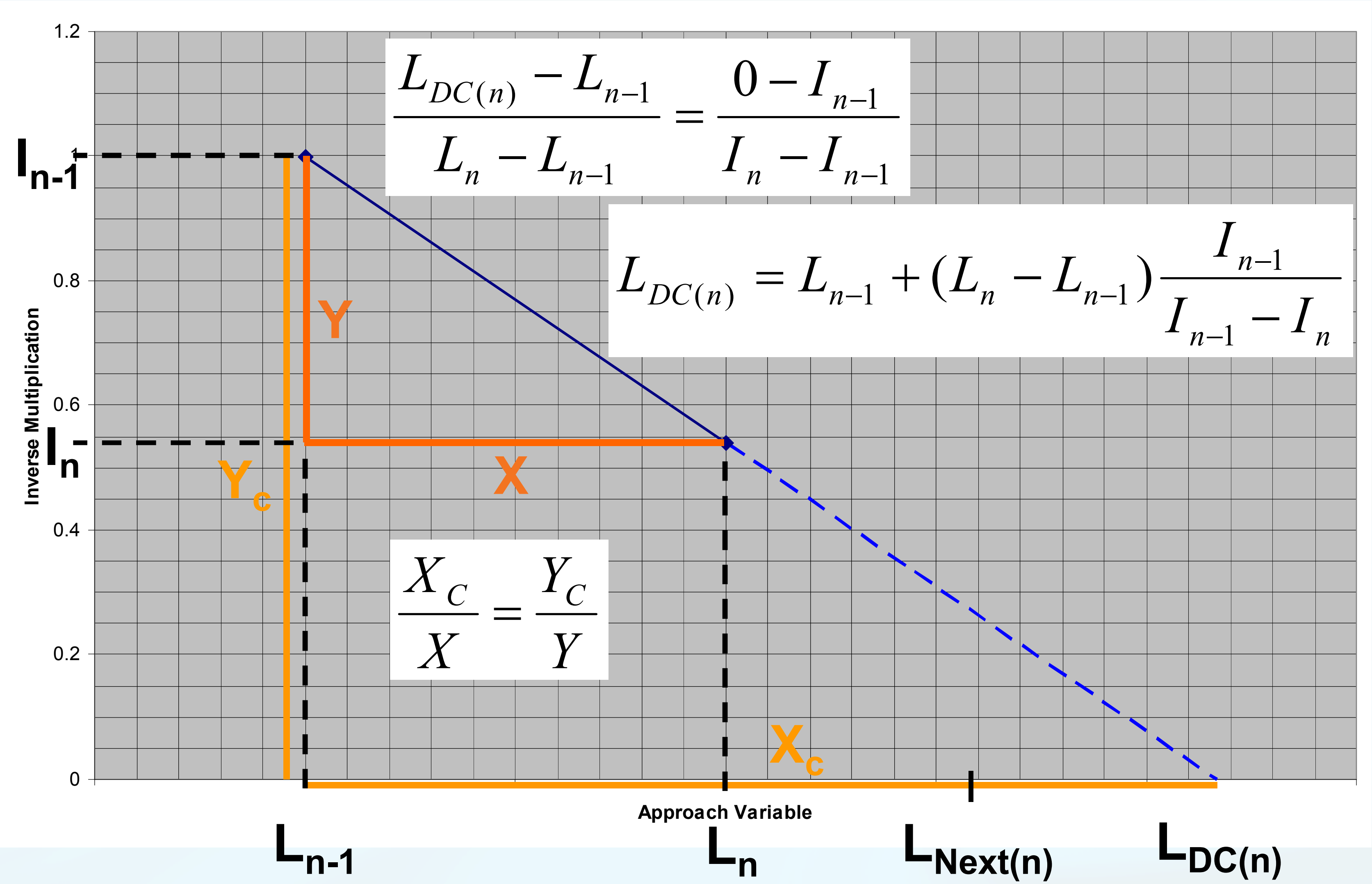


$$\frac{X_C}{X} = \frac{Y_C}{Y}$$

Determining the Next Fuel Increment



Determining the Next Fuel Increment



How Do We Know if the Assembly is Critical?

What do we expect?

- **Neutrons are fed into the assembly by a constant source**
  - About 10^6 neutrons per second in our experiments

How Do We Know if the Assembly is Critical?

What do we expect?

- **Neutrons are fed into the assembly by a constant source**
  - About 10^6 neutrons per second in our experiments
- **If the assembly is subcritical – the count rate becomes constant**
  - The level is determined by the strength of the neutron source and the conditions in the assembly

How Do We Know if the Assembly is Critical?

What do we expect?

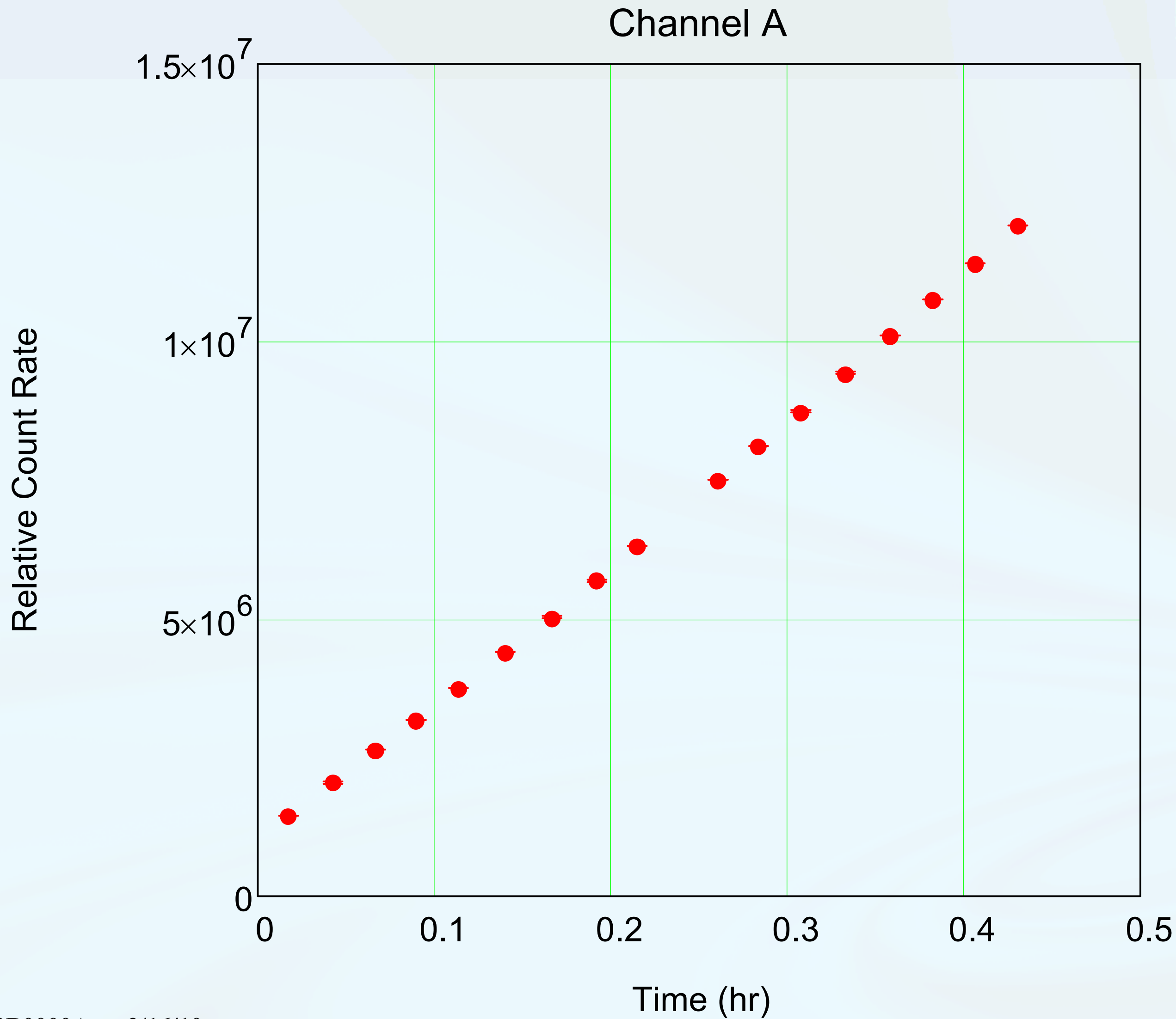
- **Neutrons are fed into the assembly by a constant source**
  - About 10^6 neutrons per second in our experiments
- **If the assembly is subcritical – the count rate becomes constant**
  - The level is determined by the strength of the neutron source and the conditions in the assembly
- **If the assembly is supercritical – the count rate increases at an increasing rate**
  - The time behavior of the neutron level is determined by the conditions in the assembly

How Do We Know if the Assembly is Critical?

What do we expect?

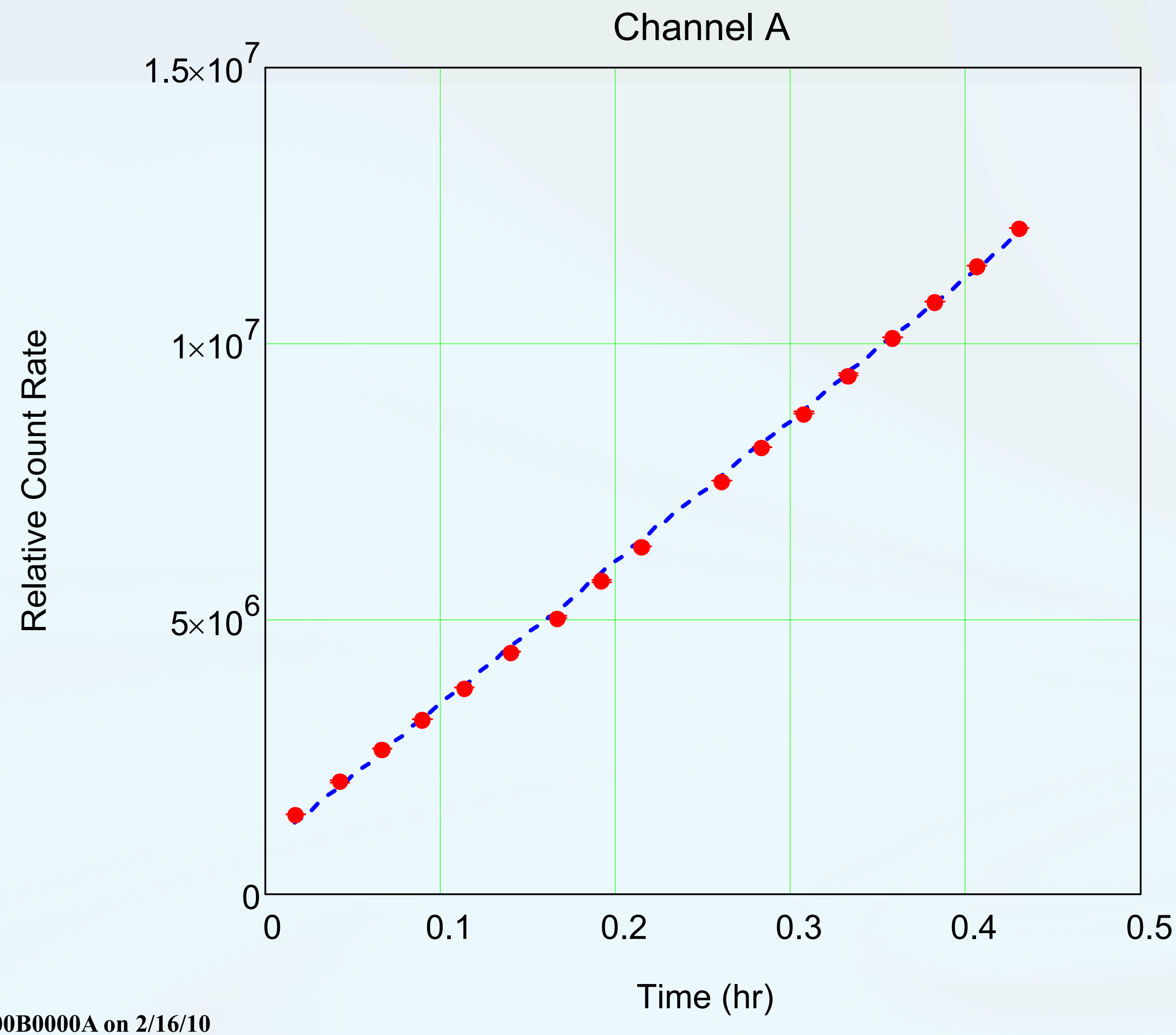
- **Neutrons are fed into the assembly by a constant source**
  - About 10^6 neutrons per second in our experiments
- **If the assembly is subcritical – the count rate becomes constant**
  - The level is determined by the strength of the neutron source and the conditions in the assembly
- **If the assembly is supercritical – the count rate increases at an increasing rate**
  - The time behavior of the neutron level is determined by the conditions in the assembly
- **If the assembly is exactly at delayed critical – the count rate increases linearly**
  - On average, every neutron produces another in the next generation – in effect, each neutron lives forever
  - The fixed source is continually adding neutrons to the assembly
  - So the number of neutrons in the assembly increases linearly

A Configuration Very Close to Critical



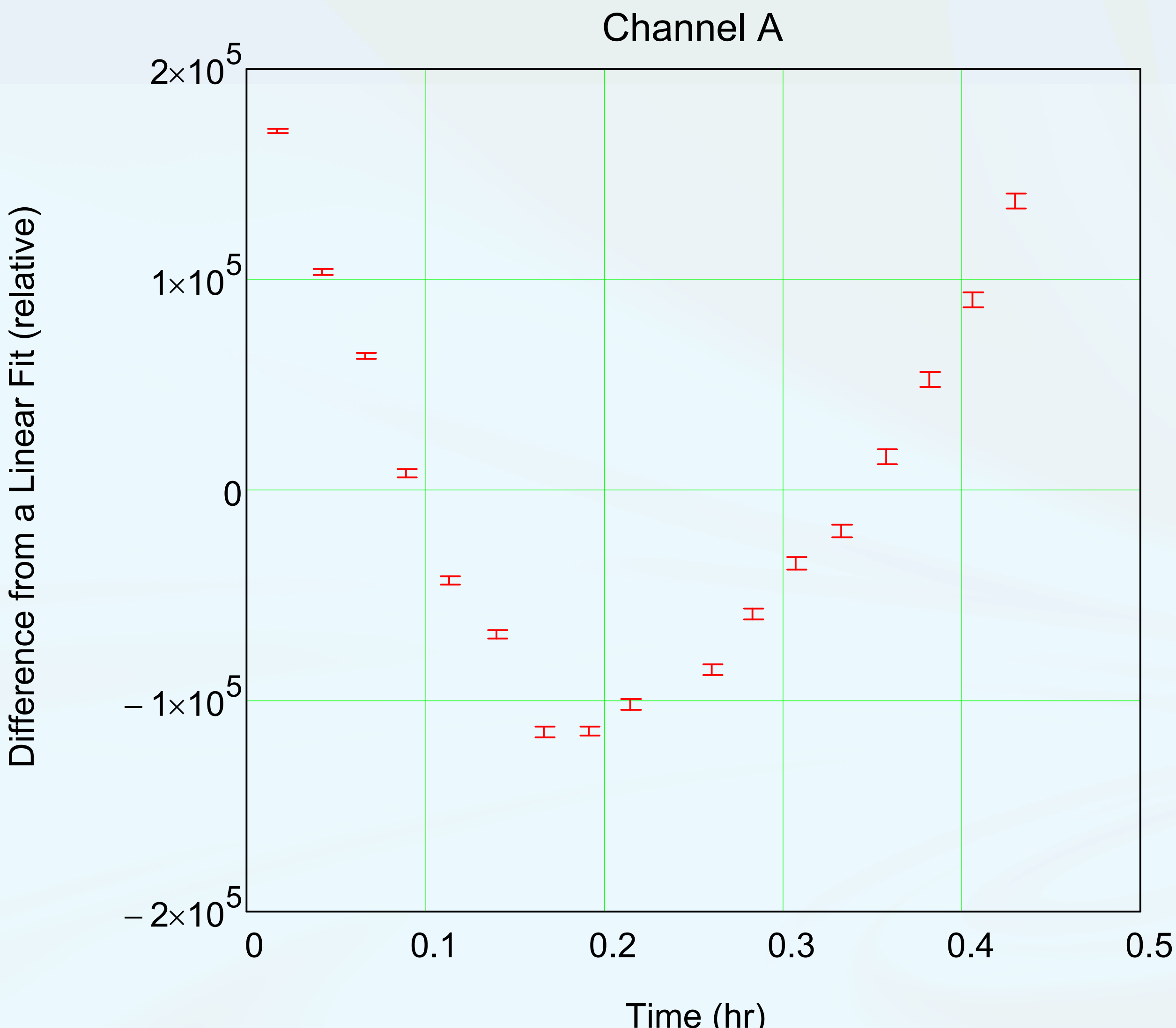
1460 rods in core 800B0000A on 2/16/10

A Configuration Very Close to Critical



1460 rods in core 800B0000A on 2/16/10

A Configuration Very Close to Critical



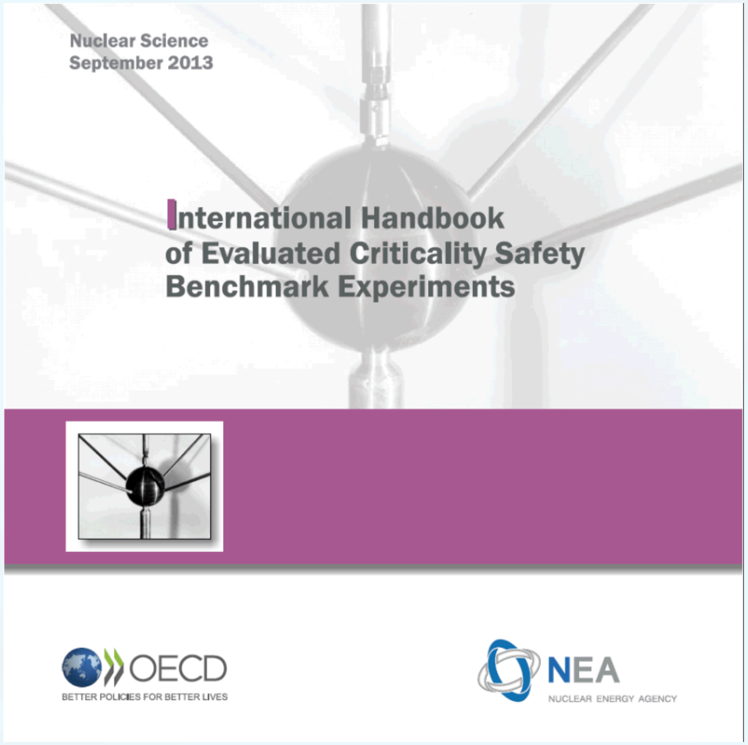
1460 rods in core 800B0000A on 2/16/10

Nuclear Criticality Safety Hands-On Training Course

- **Perspective Criticality Safety Engineers**
  - DOE National Labs and Contractors, University, Nuclear Industry, Federal Employees, International
  - One Week Lecture and Criticality Safety Evaluation Training at Los Alamos
- **Supervisors/Managers and Fissile Material Managers/Handlers**
  - Condensed One-Week Training Course

Sandia National Laboratories

International Criticality Safety Benchmark Evaluation Project



The purpose of the ICSBEP is to:

- **Identify a comprehensive set of critical benchmark data and, to the extent possible, verify the data by reviewing original and subsequently revised documentation, and by talking with the experimenters or individuals who are familiar with the experimenters or the experimental facility.**
- **Evaluate the data and quantify overall uncertainties through various types of sensitivity analysis.**
- **Compile the data into a standardized format.**
- **Perform calculations of each experiment with standard criticality safety codes.**
- **Formally document the work into a single source of verified benchmark critical data.**

Benchmark Evaluations

- **LEU-COMP-THERM-078**
  - 7uPCX 0.855 cm pitch
- **LEU-COMP-THERM-079**
  - BUCCX – Rhodium Experiments
- **LEU-COMP-THERM-080**
  - 7uPCX 0.800 cm pitch

Questions