Restart of the Sandia Pulsed Reactor Facility Critical Experiments

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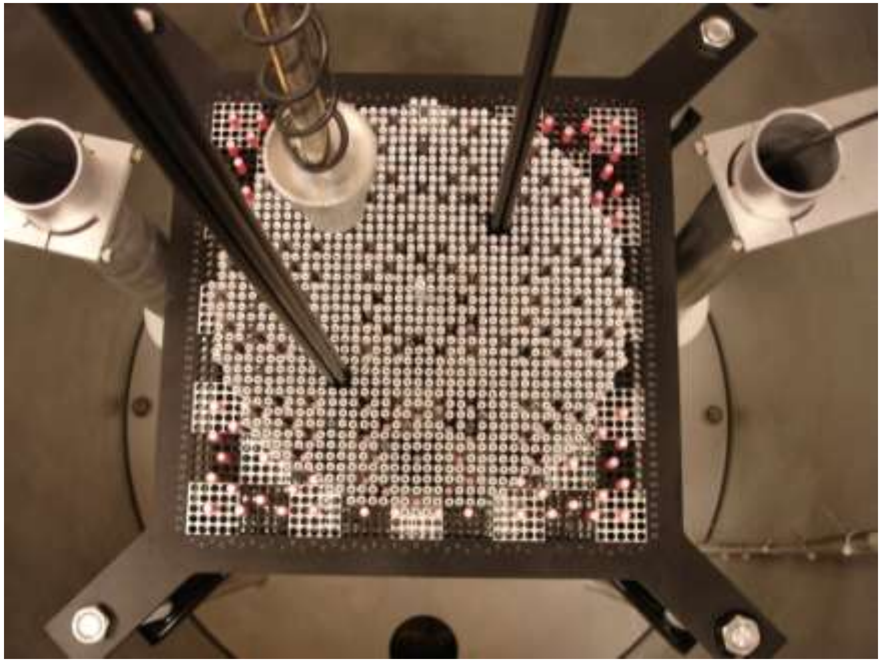
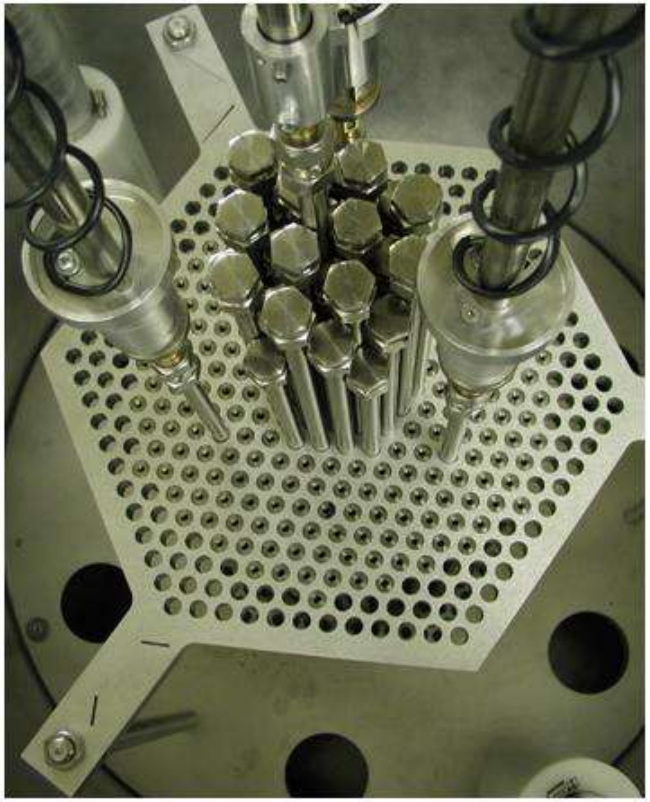
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

We have restarted our critical experiment capability



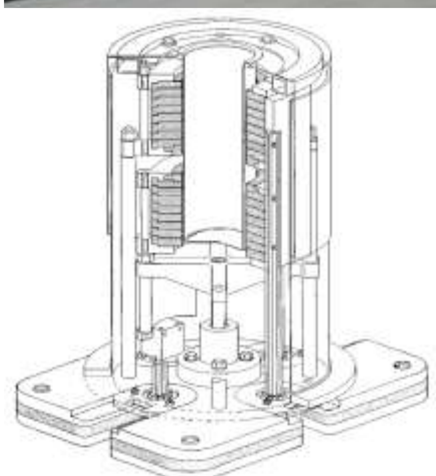
BUCCX – fission product effects



7uPCX – physics of higher-enrichment cores (5-10%)

This is the first core investigated after the restart

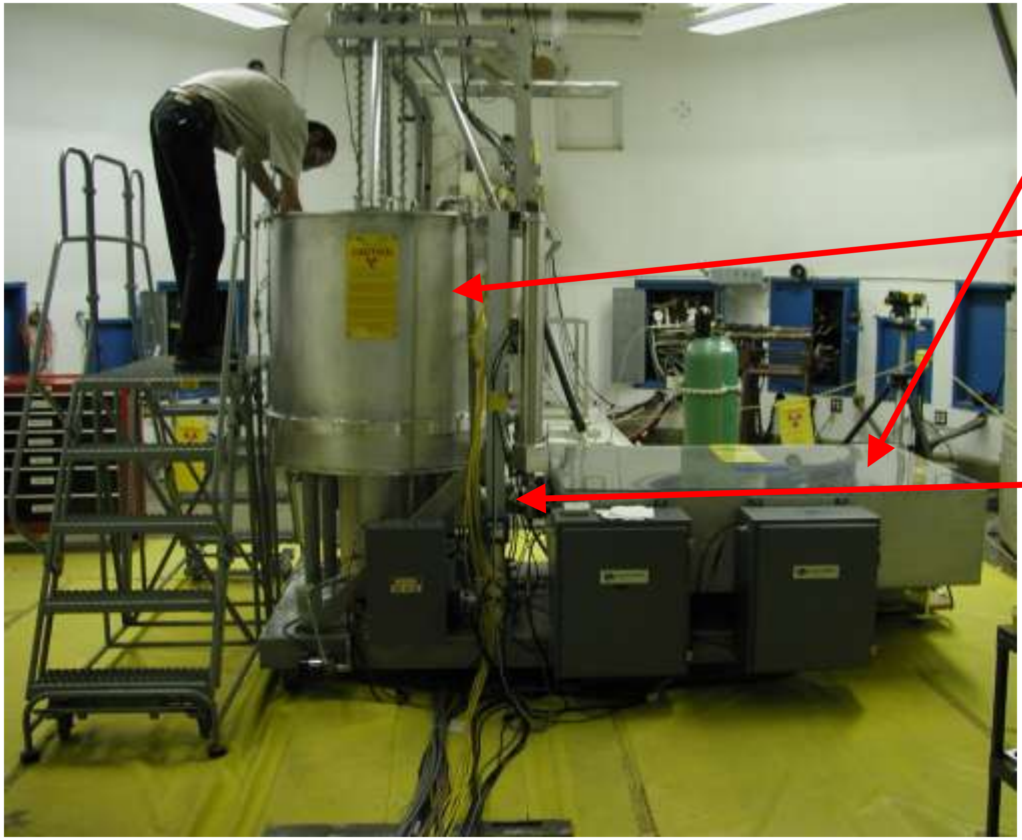
We operate our critical experiments in the Sandia Pulsed Reactor Facility



Sandia Pulsed Reactor III (SPR-III)

- The SPRF is an operating Nuclear Facility
- The SPRF has:
  - ✓ a professional operating staff and supporting infrastructure
  - ✓ an existing Authorization Basis (AB)
  - ✓ room in its schedule – the HEU SPR fuel has been removed
- We modify the AB as needed for the critical experiments
- The AB is current – SER 1/18/08, annual update is in the works
- We restarted our critical experiments capability in May, 2009

The critical assembly safety systems are gravity-driven



- The water moderator is normally stored in the dump tank
- The fuel array is in the elevated core tank
- The core tank is connected to the dump tank by two 4” lines with normally-open remotely-controlled dump valves
- To close the dump valves, a key must be inserted into the console and turned – the key cannot be removed if activated

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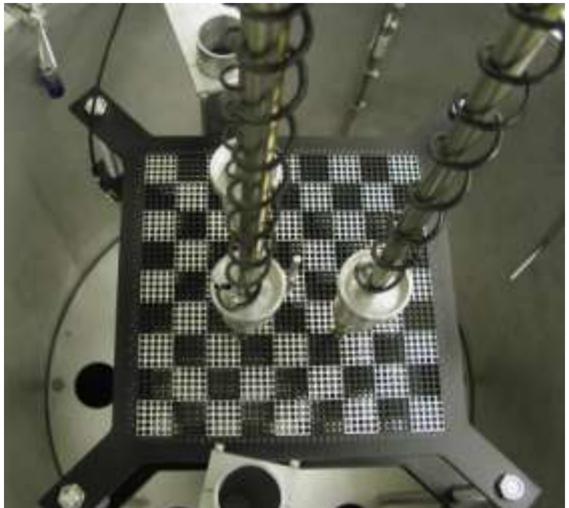
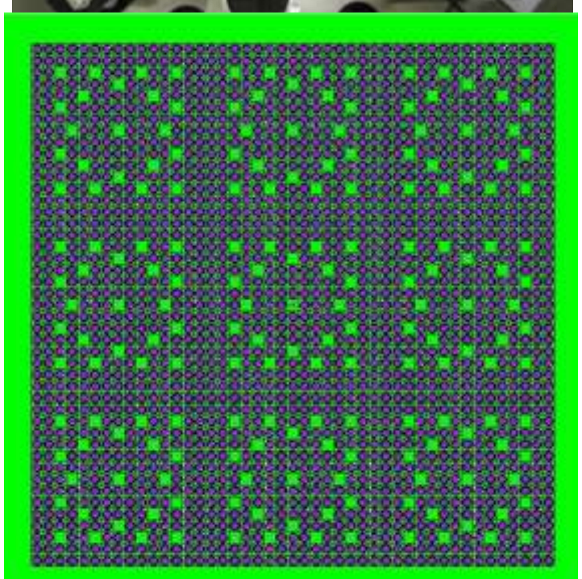
The safety case is simple

- **Low-enriched (<20%) fuel is used**
  - **1000 kg of the fuel is subcritical without water moderator**
  - **Reactor room is limited to 500 kg of fuel**
- **Access controls ensure personnel safety – 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 fission product inventory is kept low by limiting the energy deposition in the fuel (15 MJ fission energy per year)**

  15 MJ is less than 3 SPR-III pulses
  - **Limits accident source term**
  - **Allows manual handling of fuel during 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 will be made**
  - **Fission density profiles**
  - **Soluble poison worth**

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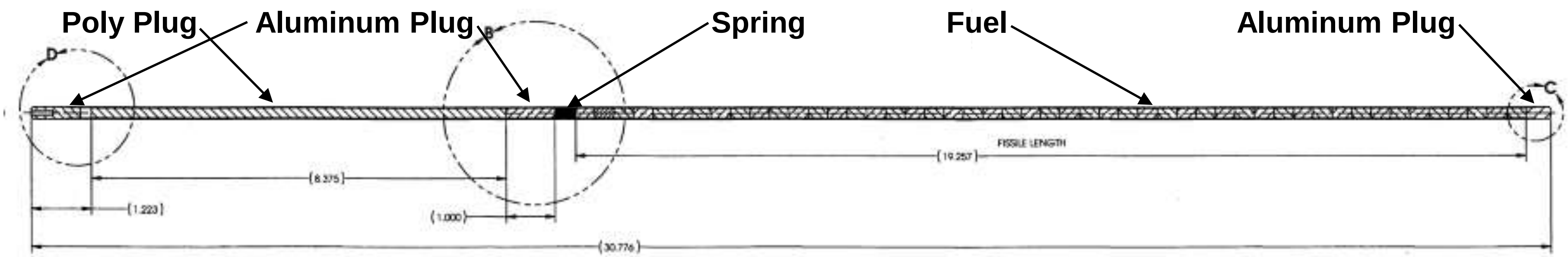
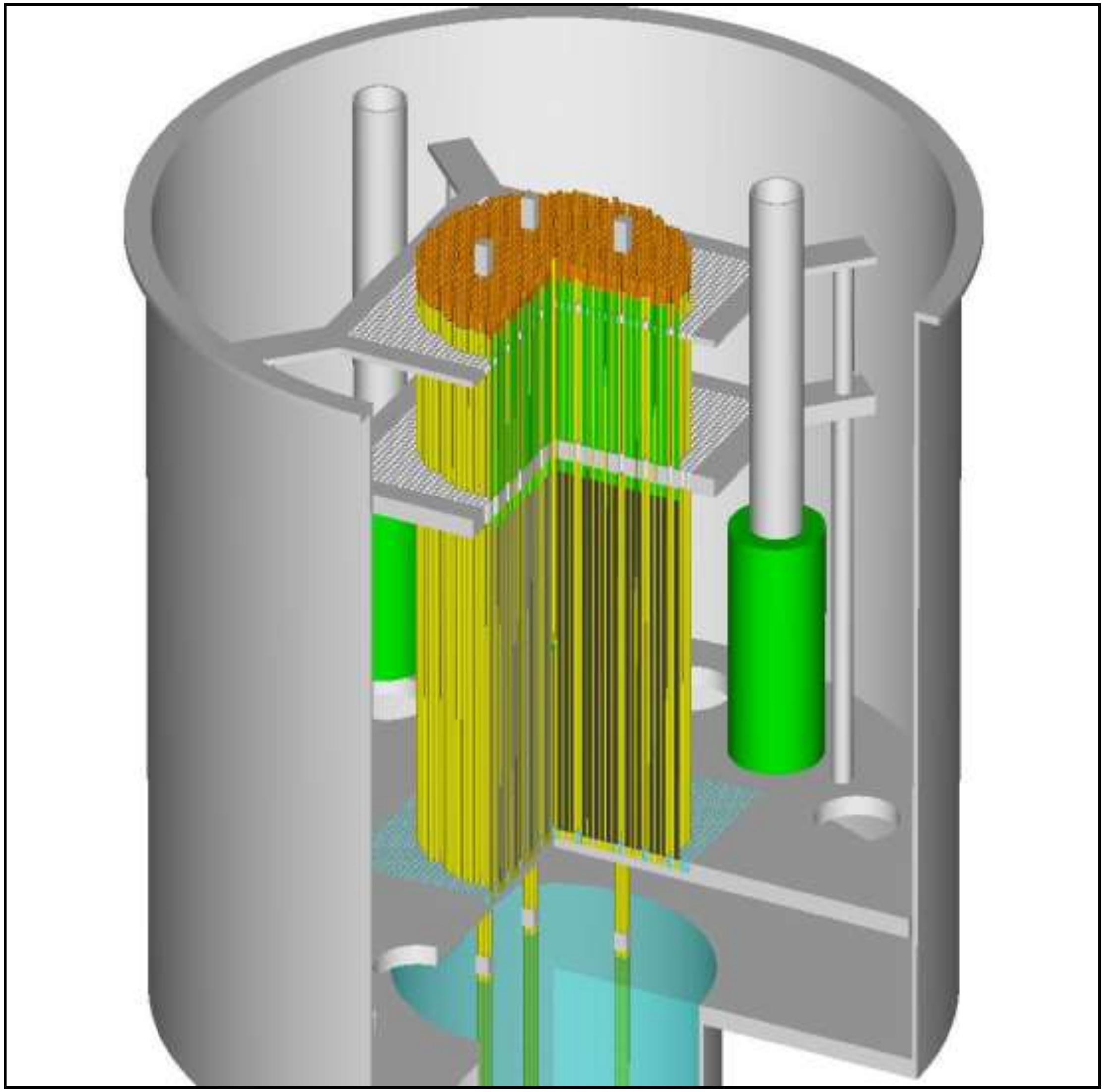
The 7uPCX core uses a new set of fuel rods



- 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 plugs are aluminum
- The fuel rods extend above the upper grid plate – the upper plug is above the highest level of the moderator
- A polyethylene plug above the upper grid plate replaces the water

The shut-down configuration of the assembly



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 removed or added but a "new" configuration may not be built.

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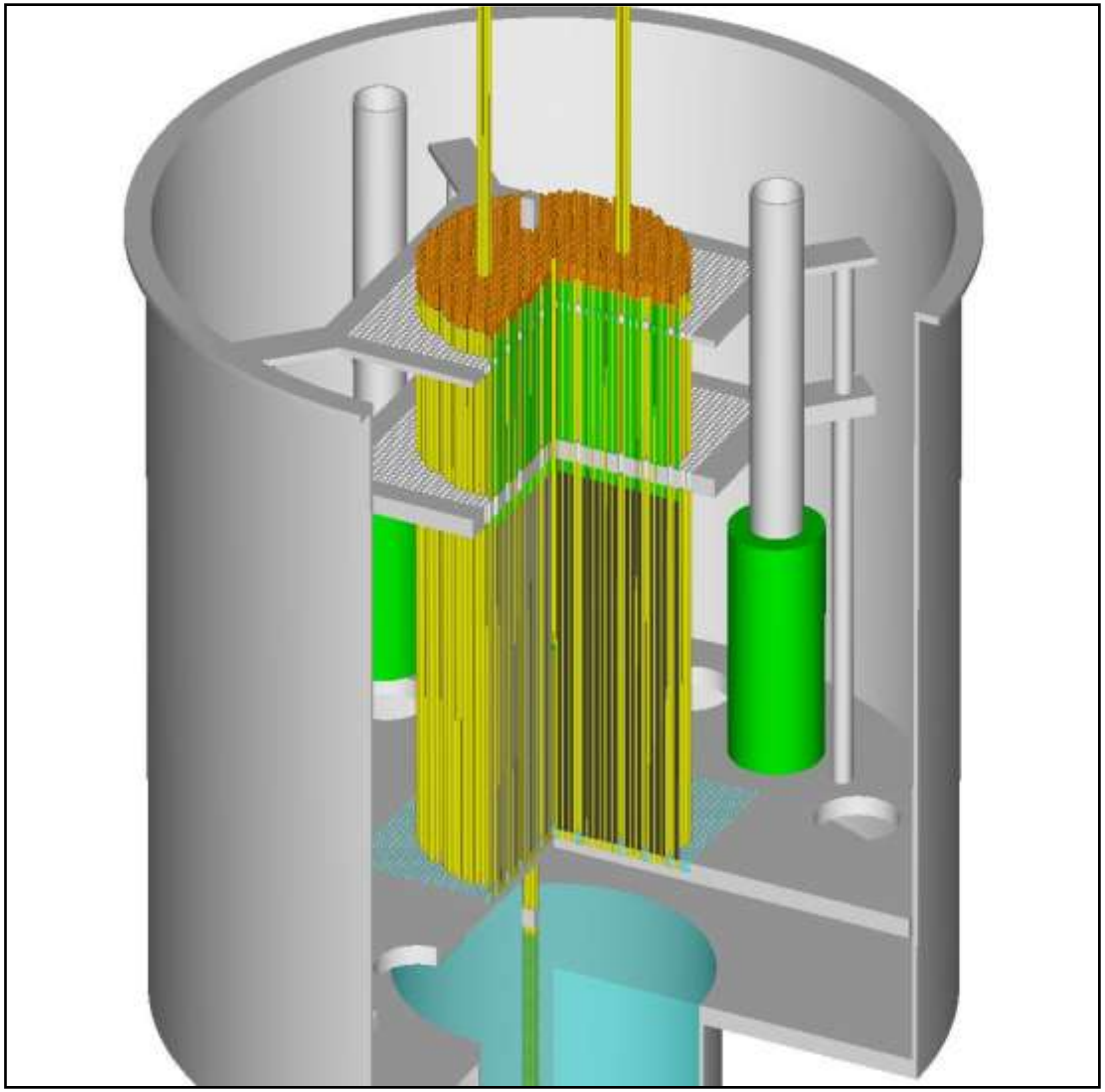
Raise the safety elements



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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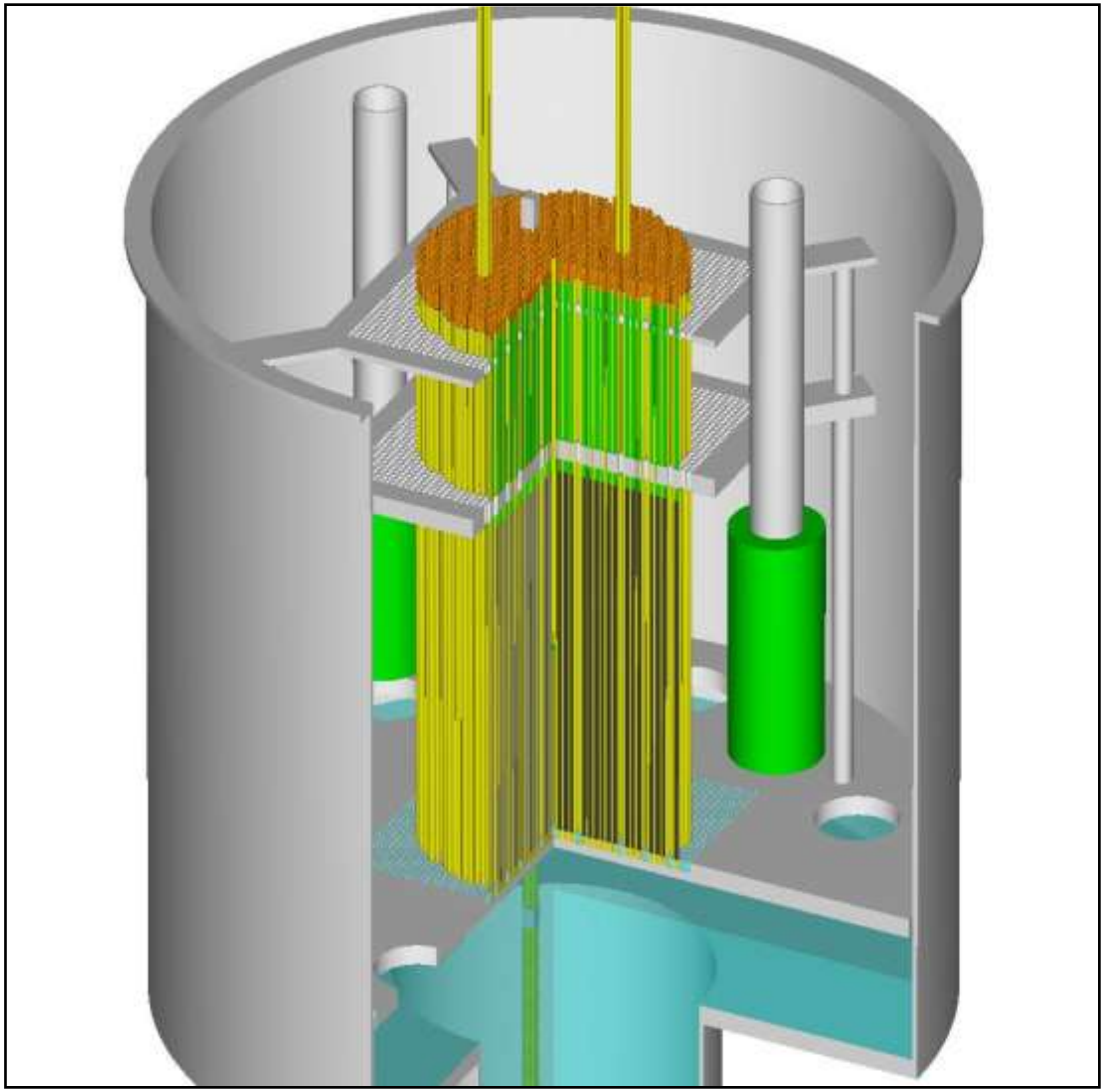
Fill the core tank



Safety Elements: Up

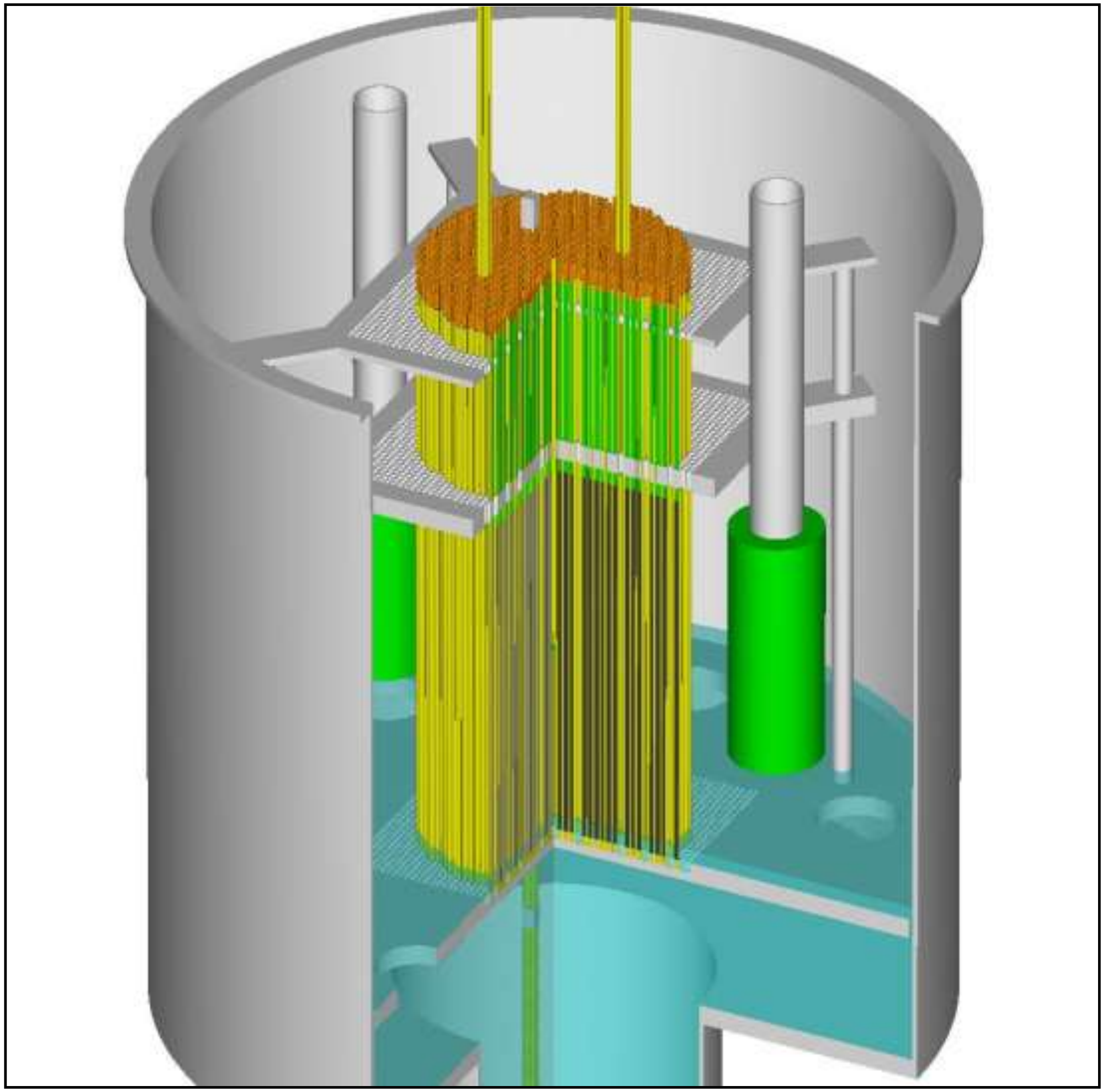
Control Element: Down

Core Tank: Filling

Personnel: Excluded

Filling the core tank requires about 15 minutes.

Fill the core tank



Safety Elements: Up

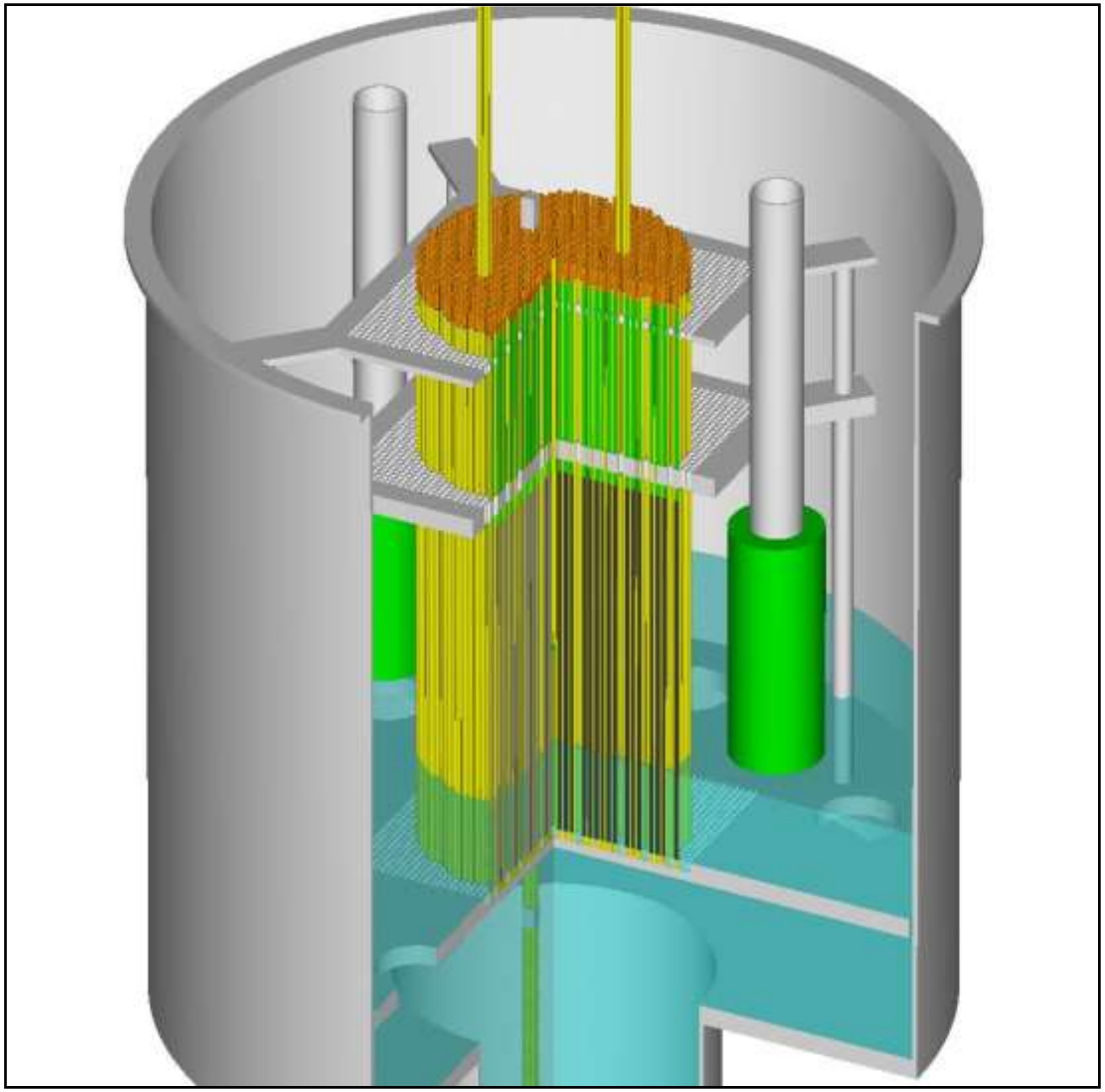
Control Element: Down

Core Tank: Filling

Personnel: Excluded

Filling the core tank requires about 15 minutes.

Fill the core tank



Safety Elements: Up

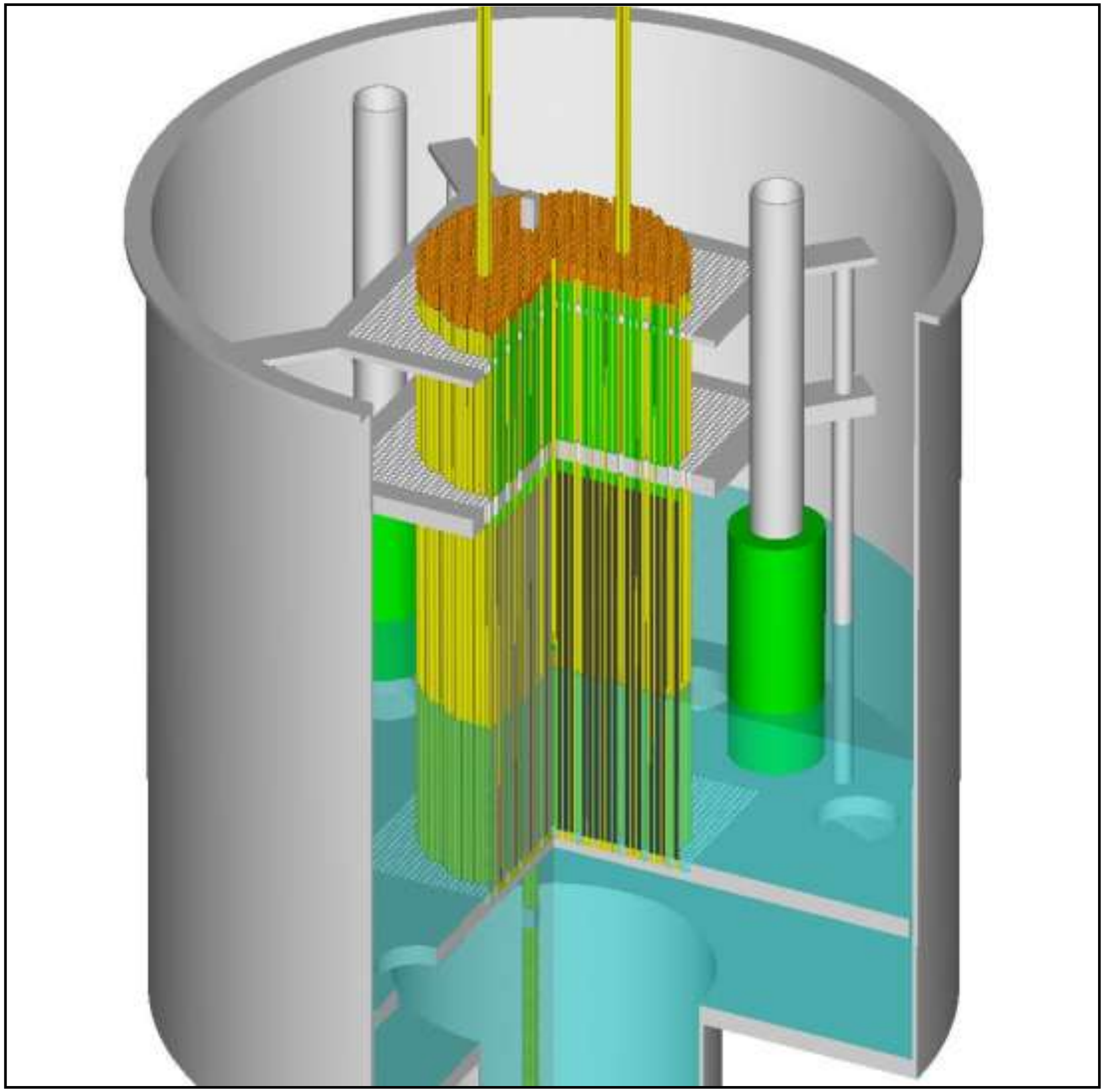
Control Element: Down

Core Tank: Filling

Personnel: Excluded

Filling the core tank requires about 15 minutes.

Fill the core tank



Safety Elements: Up

Control Element: Down

Core Tank: Filling

Personnel: Excluded

Filling the core tank requires about 15 minutes.

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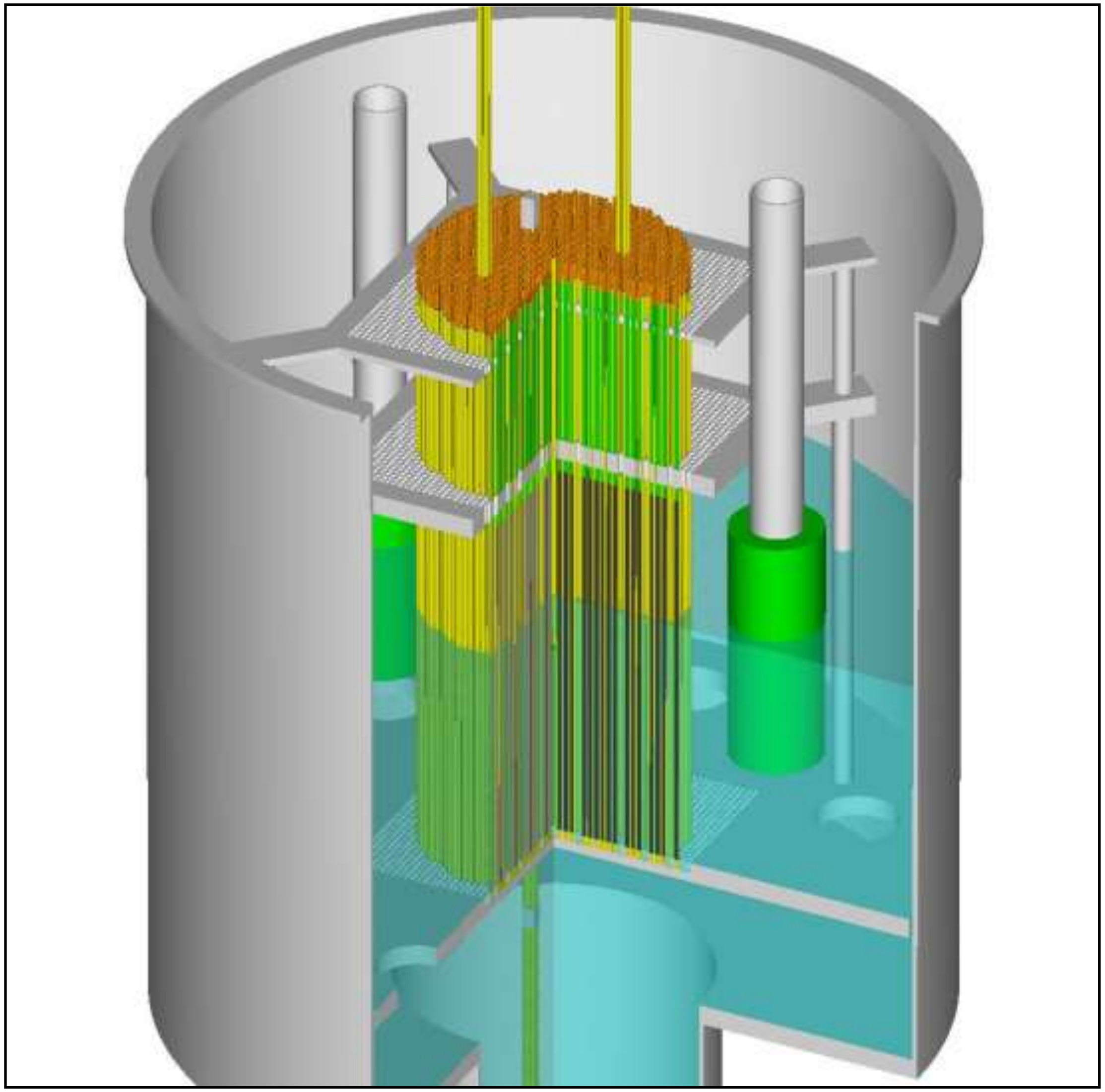
Fill the core tank



Safety Elements: Up

Control Element: Down

Core Tank: Filling

Personnel: Excluded

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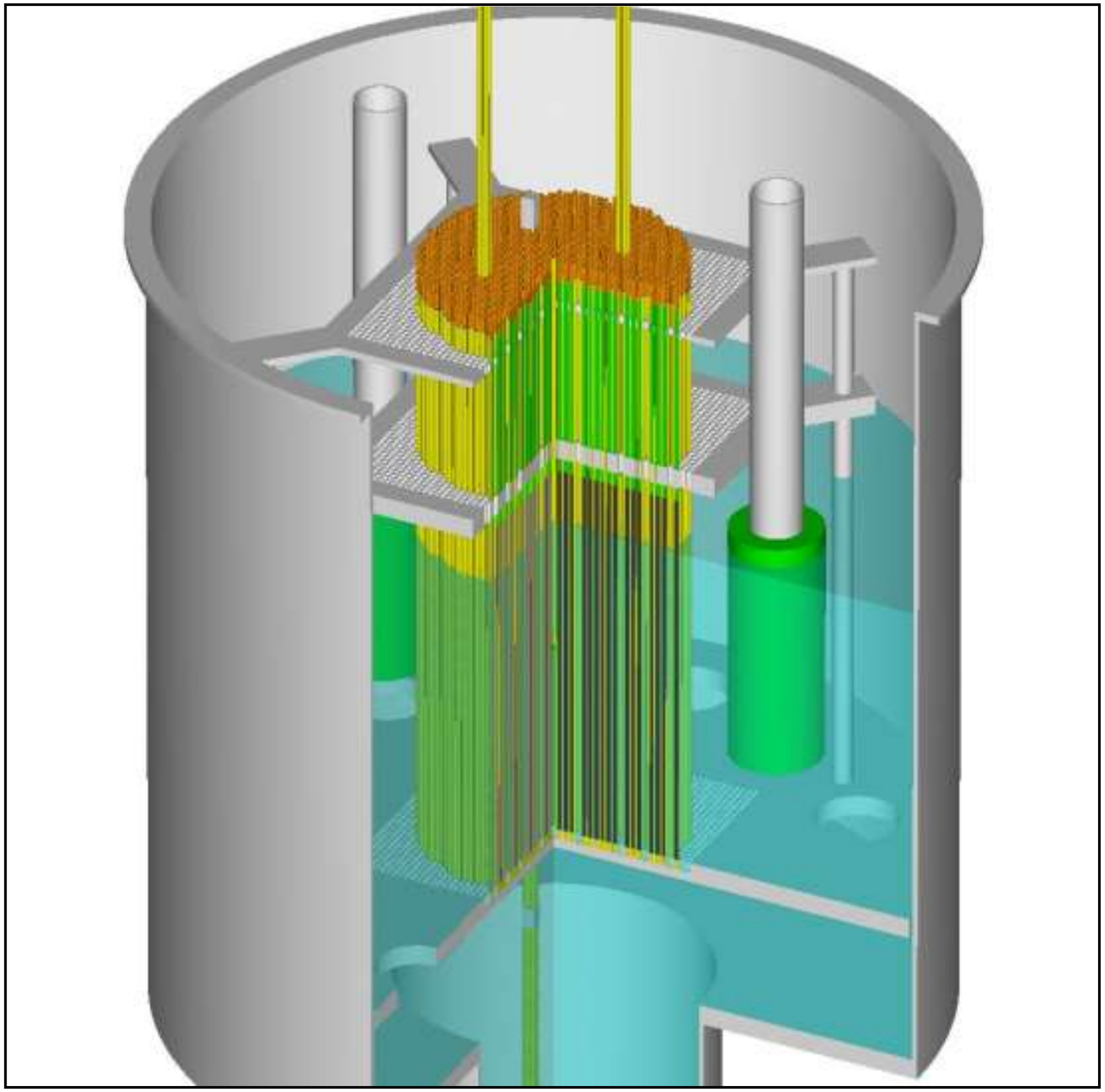
Fill the core tank



Safety Elements: Up

Control Element: Down

Core Tank: Filling

Personnel: Excluded

Filling the core tank requires about 15 minutes.

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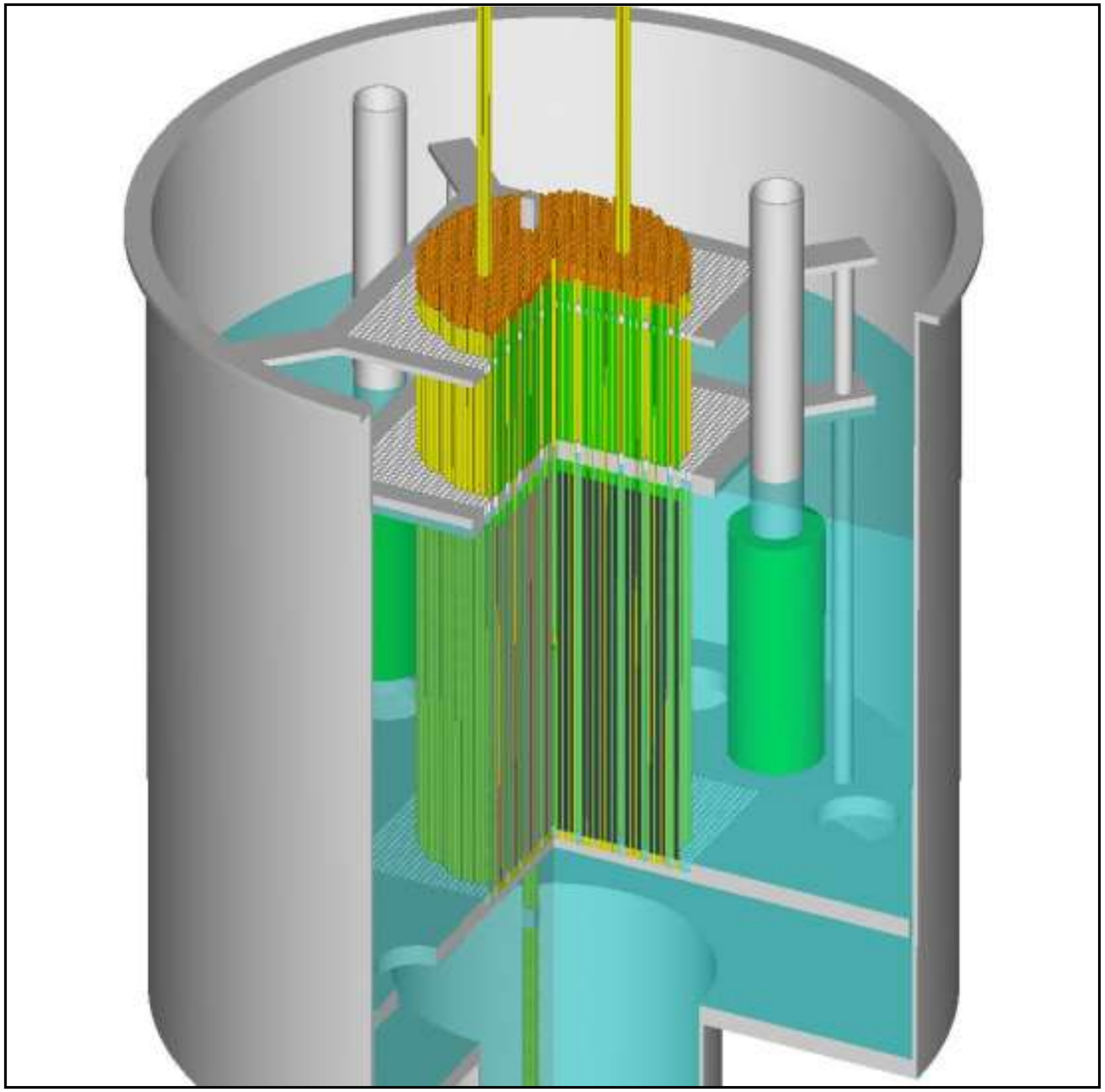
Fill the core tank



Safety Elements: Up

Control Element: Down

Core Tank: Filling

Personnel: Excluded

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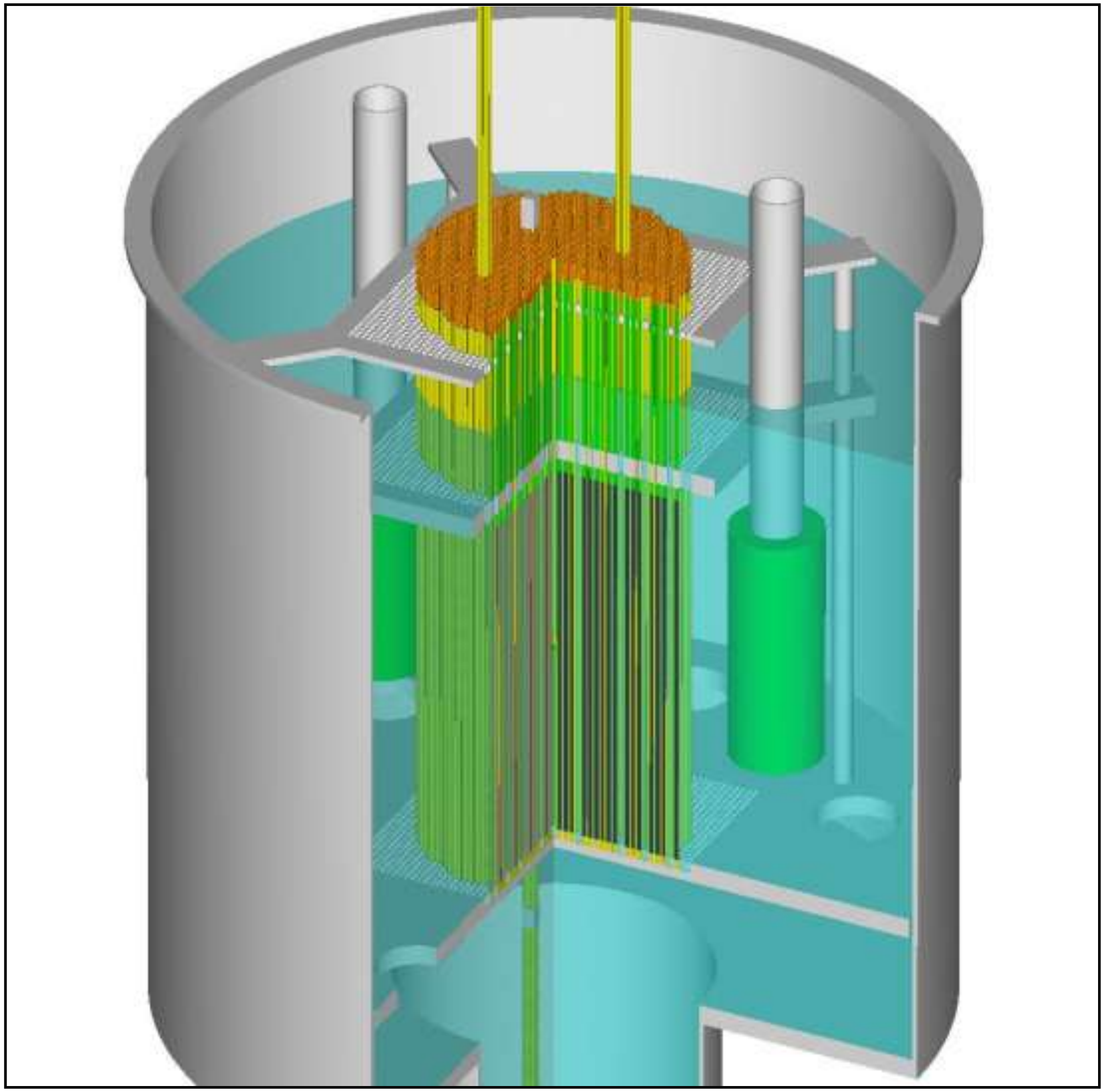
Fill the core tank



Safety Elements: Up

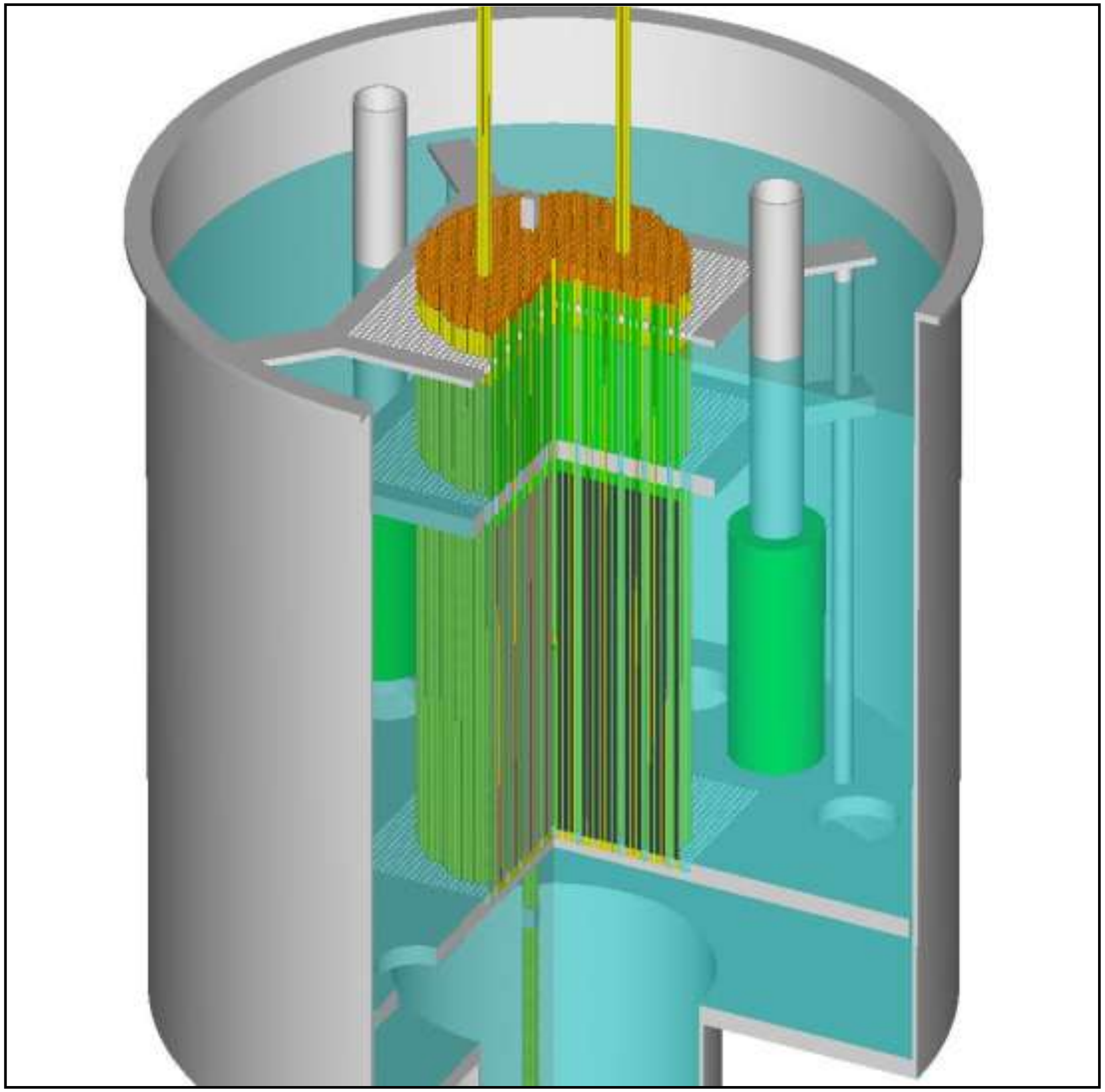
Control Element: Down

Core Tank: Filling

Personnel: Excluded

Filling the core tank requires about 15 minutes.

Fill the core tank



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 stand pipe.

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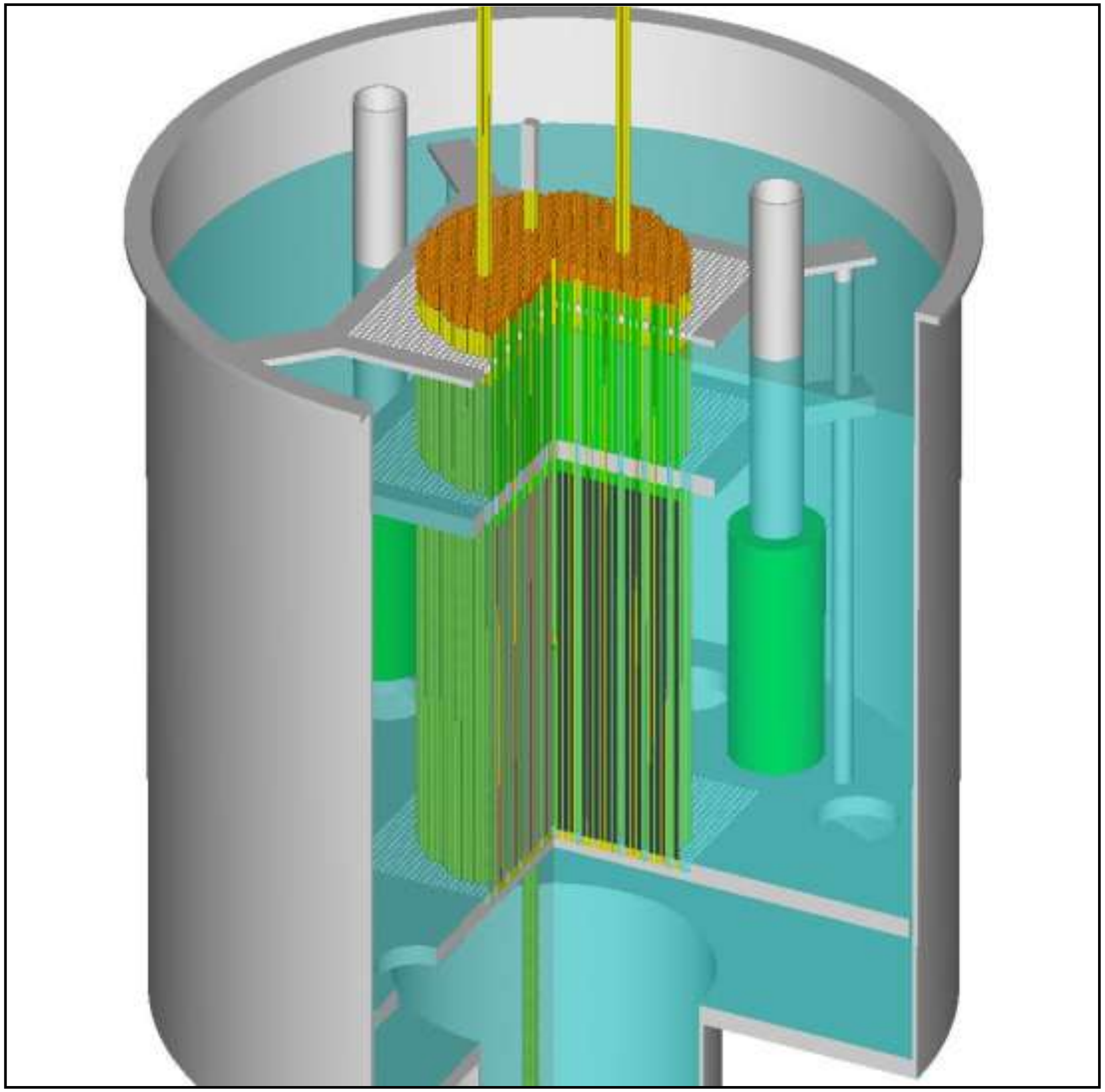
Raise the control element



Safety Elements: Up

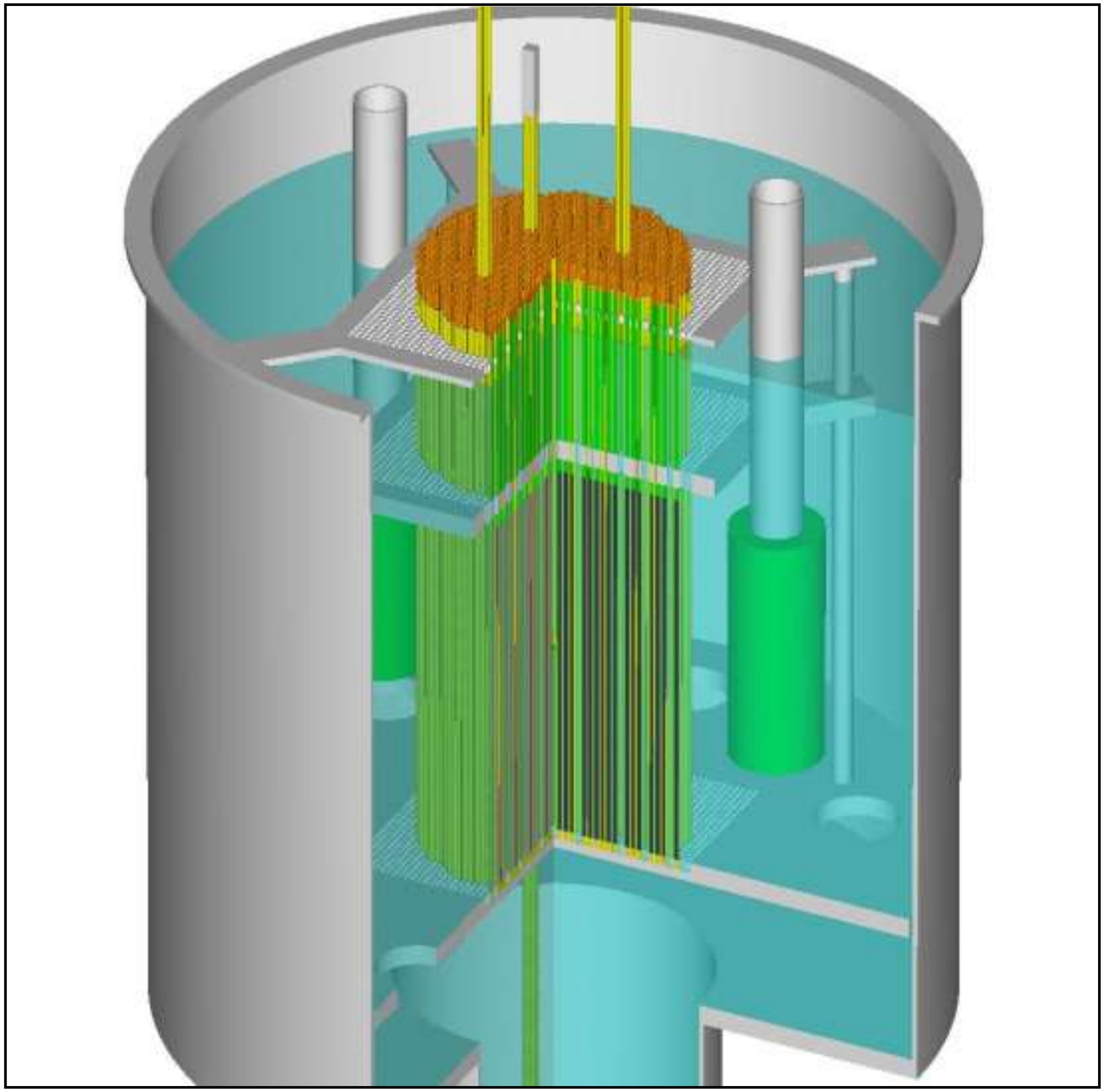
Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

Raise the control element



Safety Elements: Up

Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

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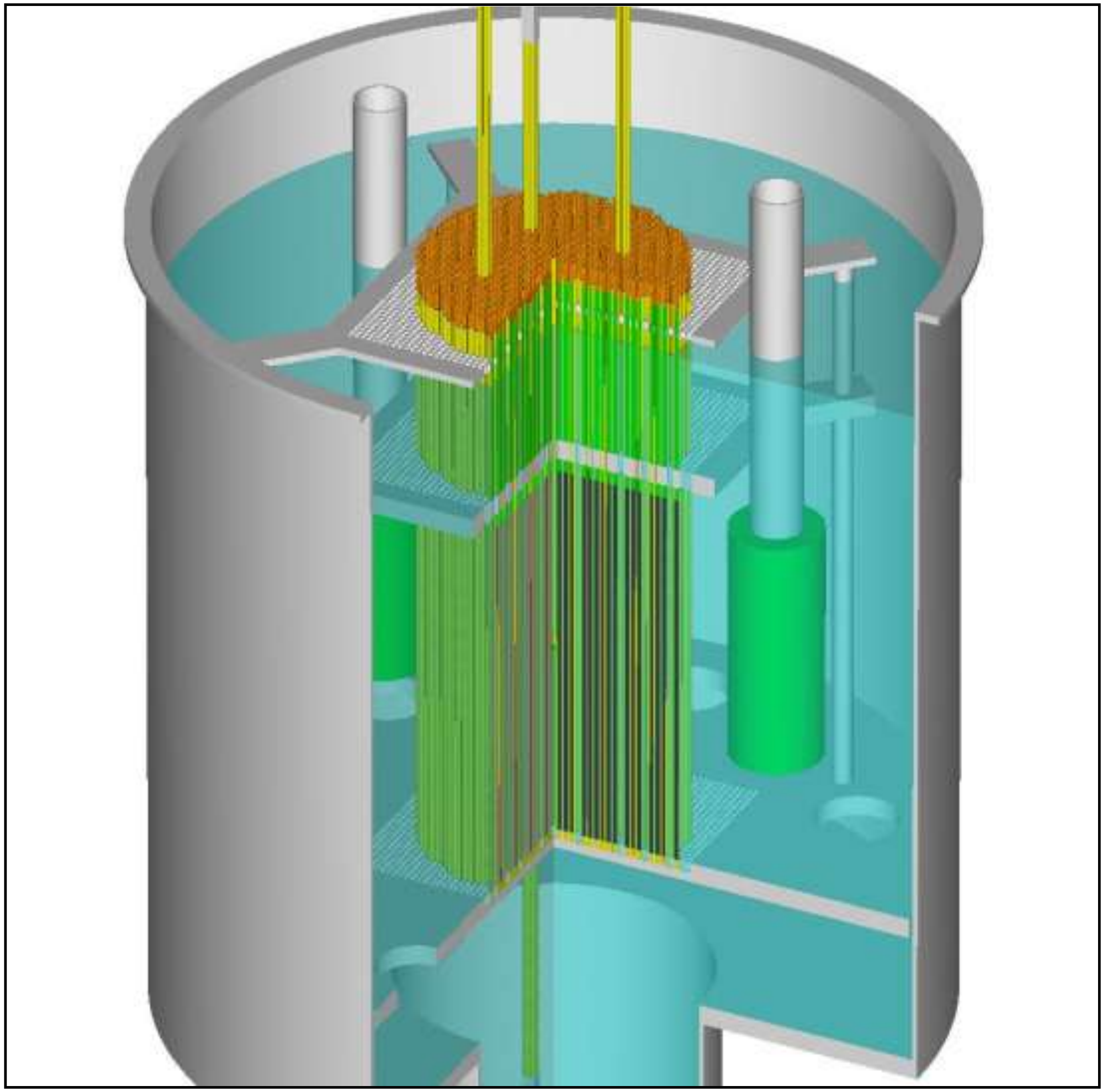
Raise the control element



Safety Elements: Up

Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

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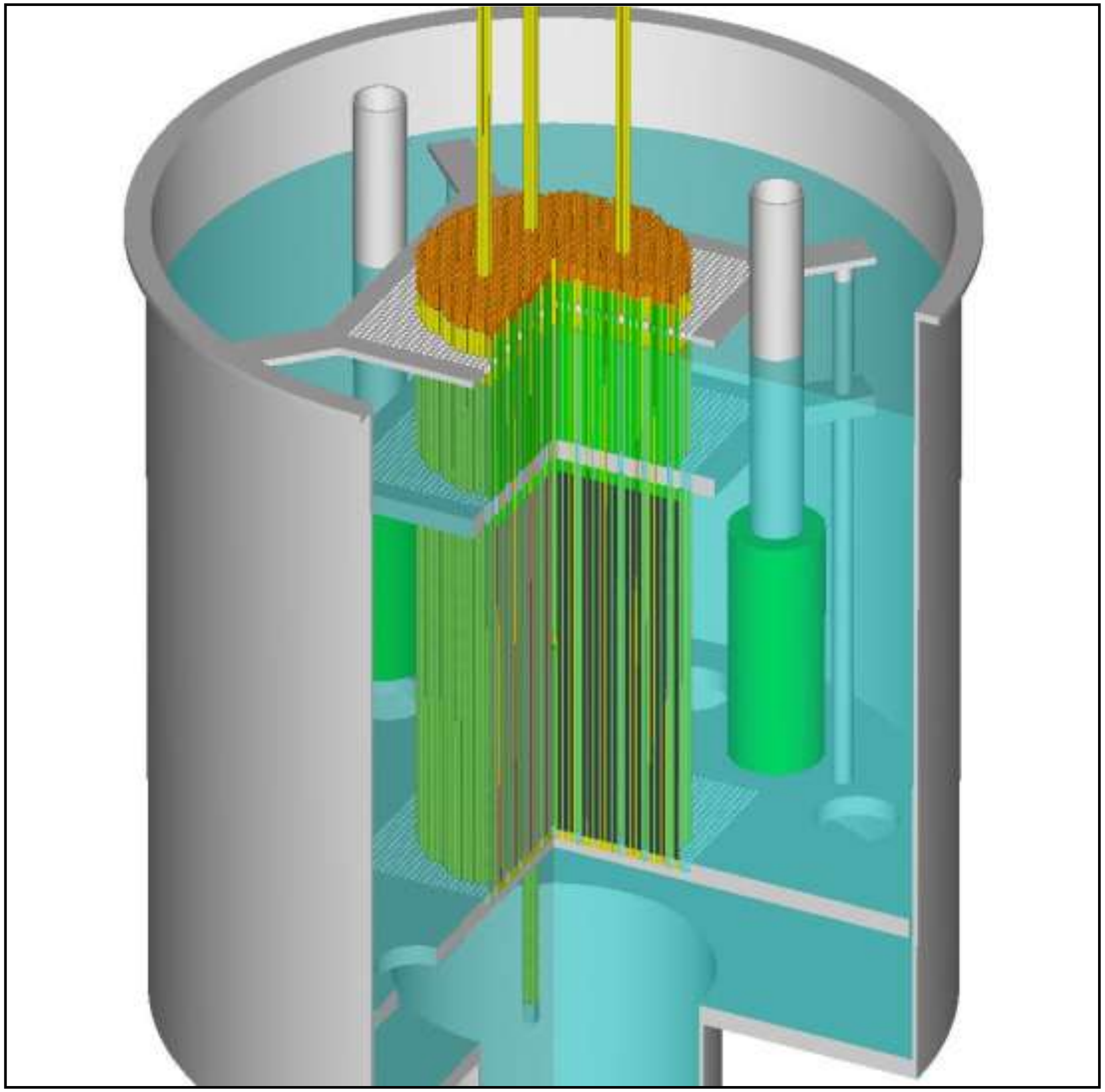
Raise the control element



Safety Elements: Up

Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

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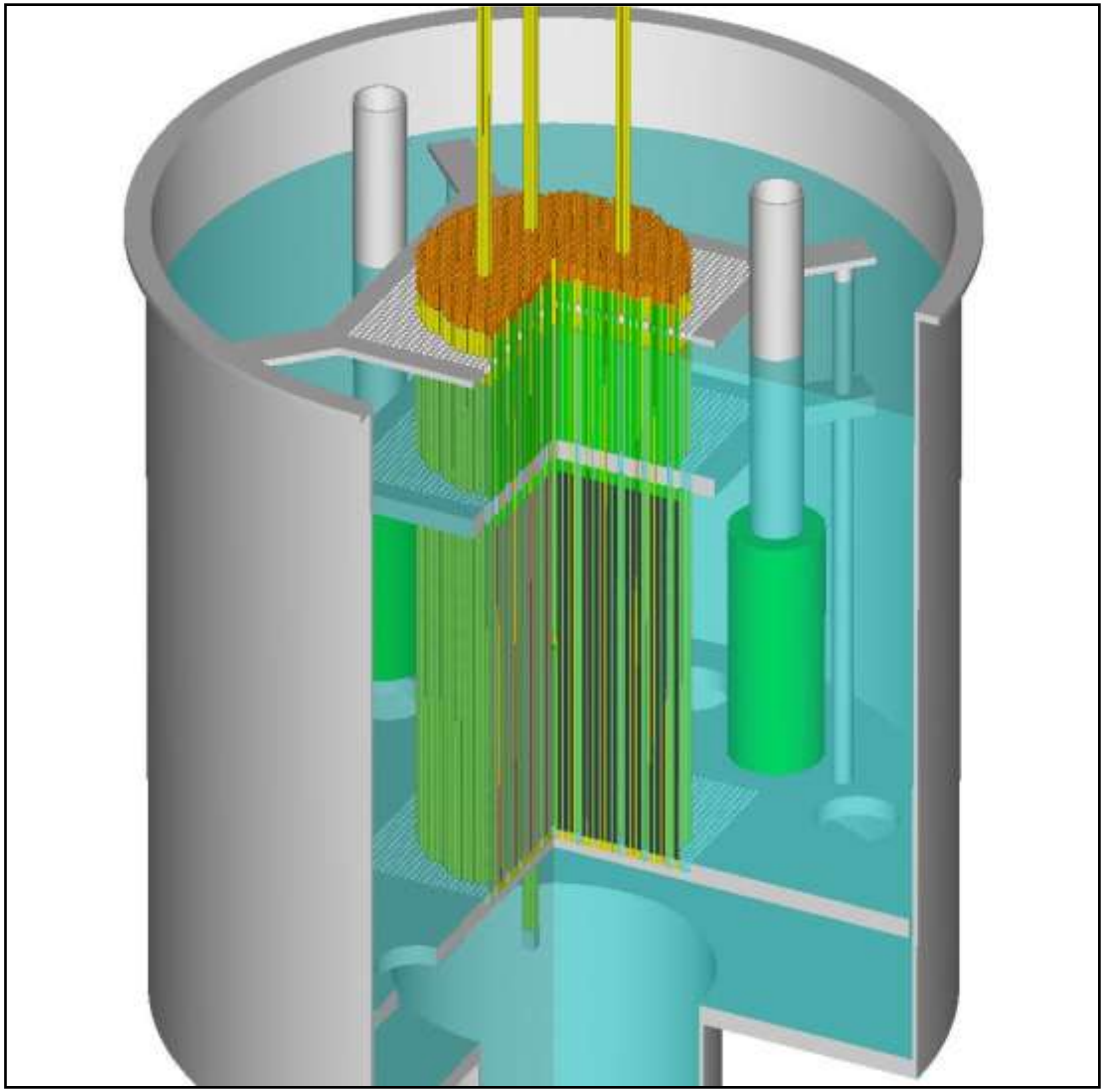
Raise the control element



Safety Elements: Up

Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

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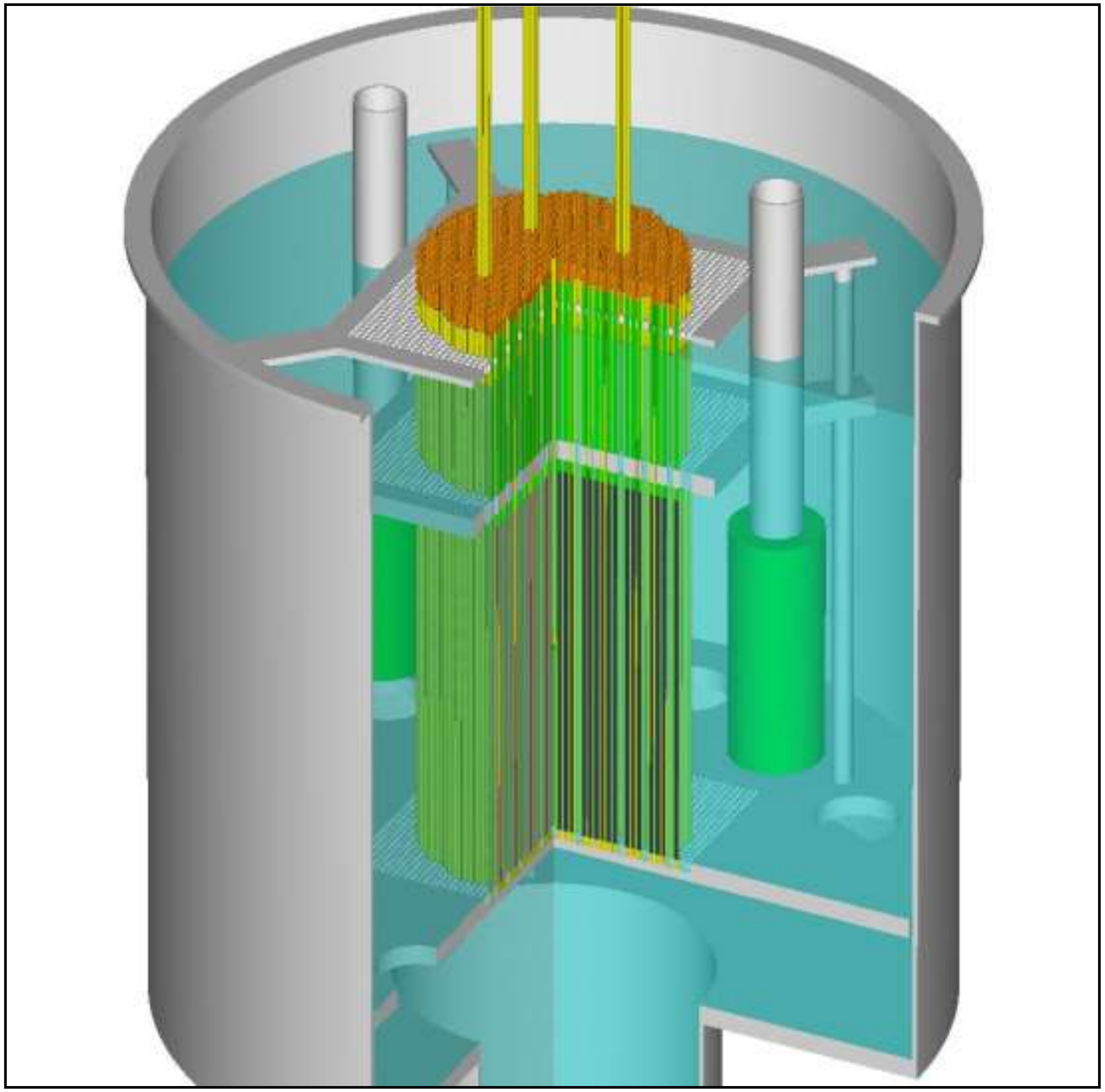
Raise the control element



Safety Elements: Up

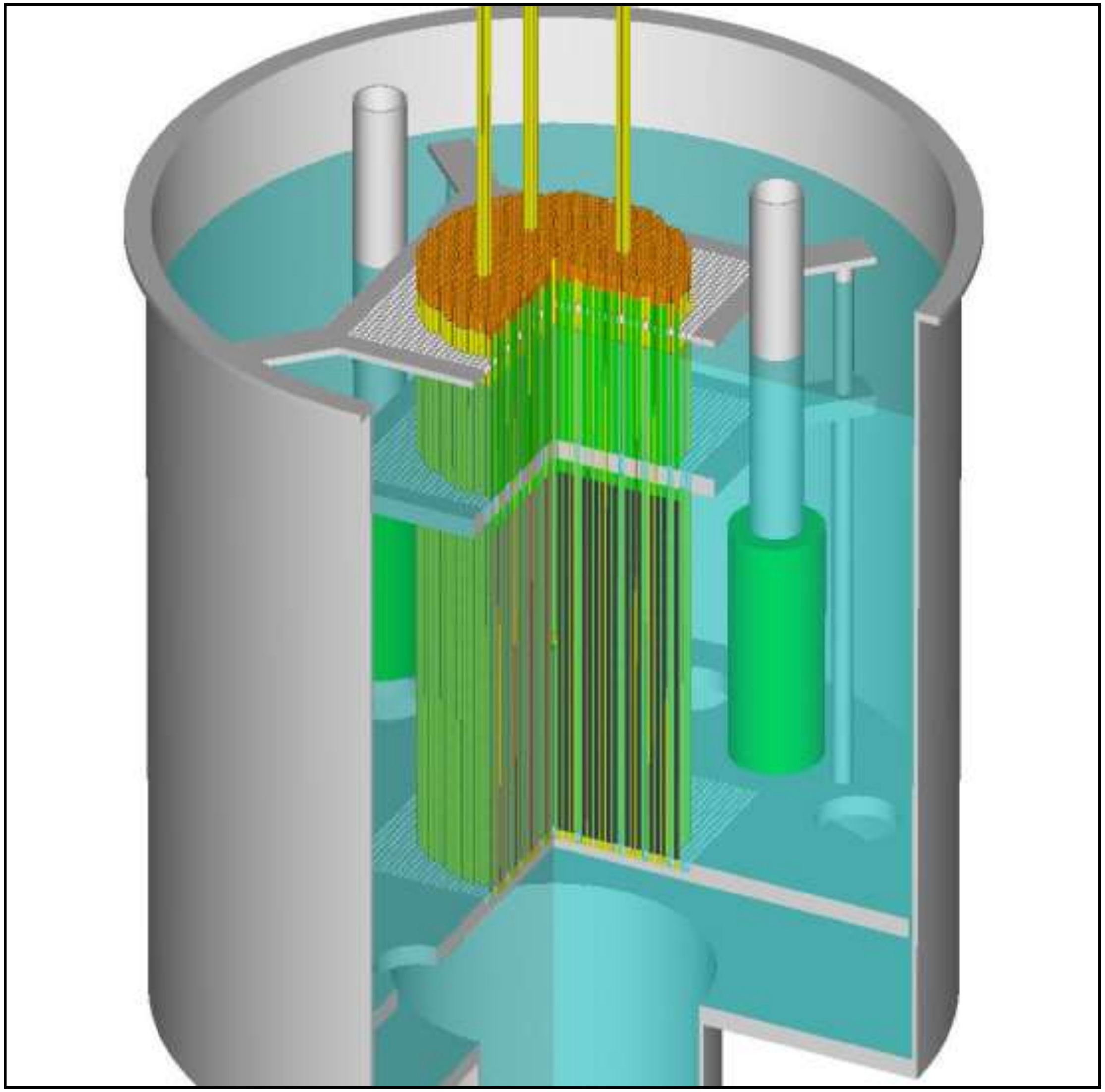
Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

The assembly reaches its most reactive state



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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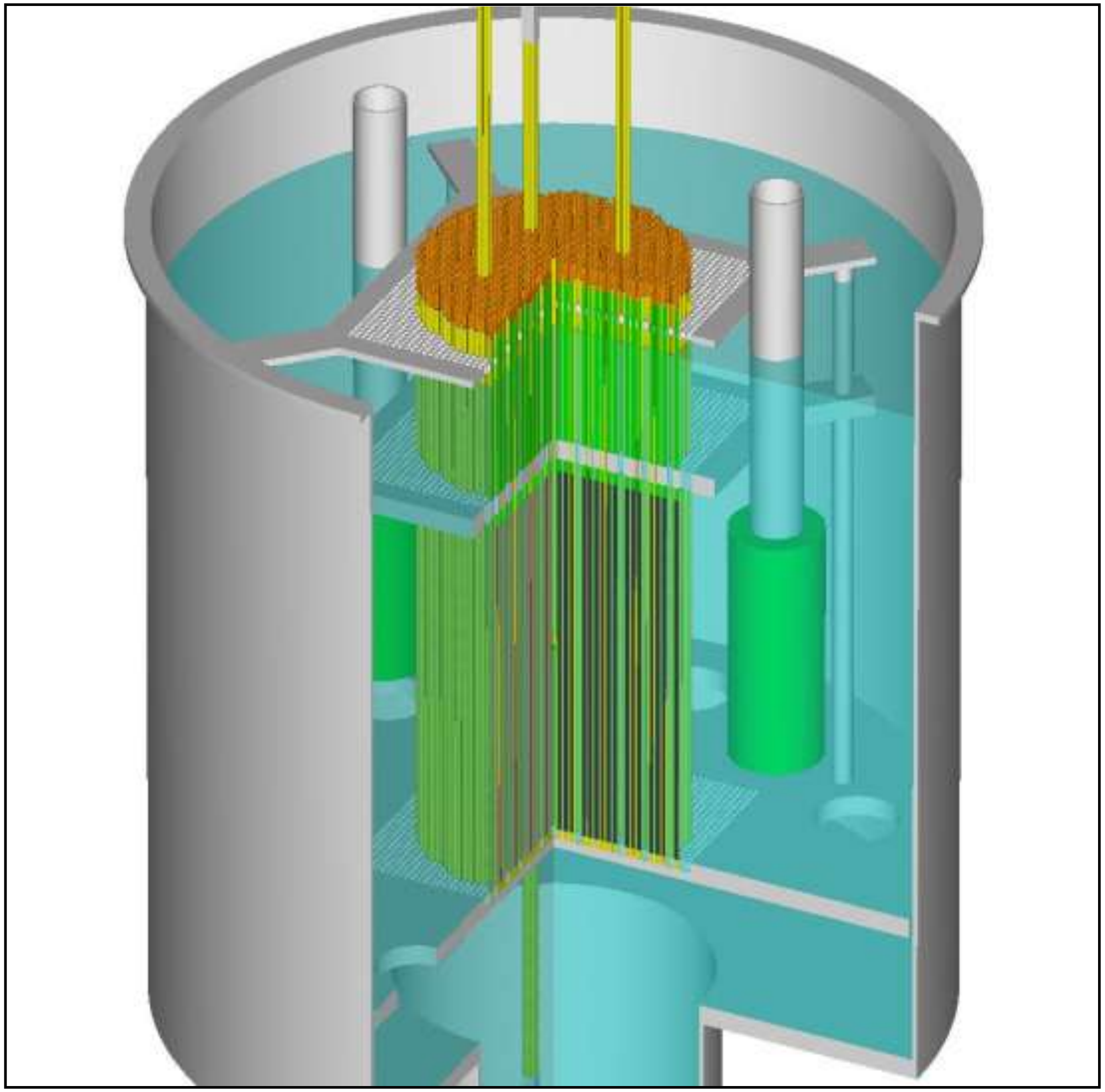
Lower the control element



Safety Elements: Up

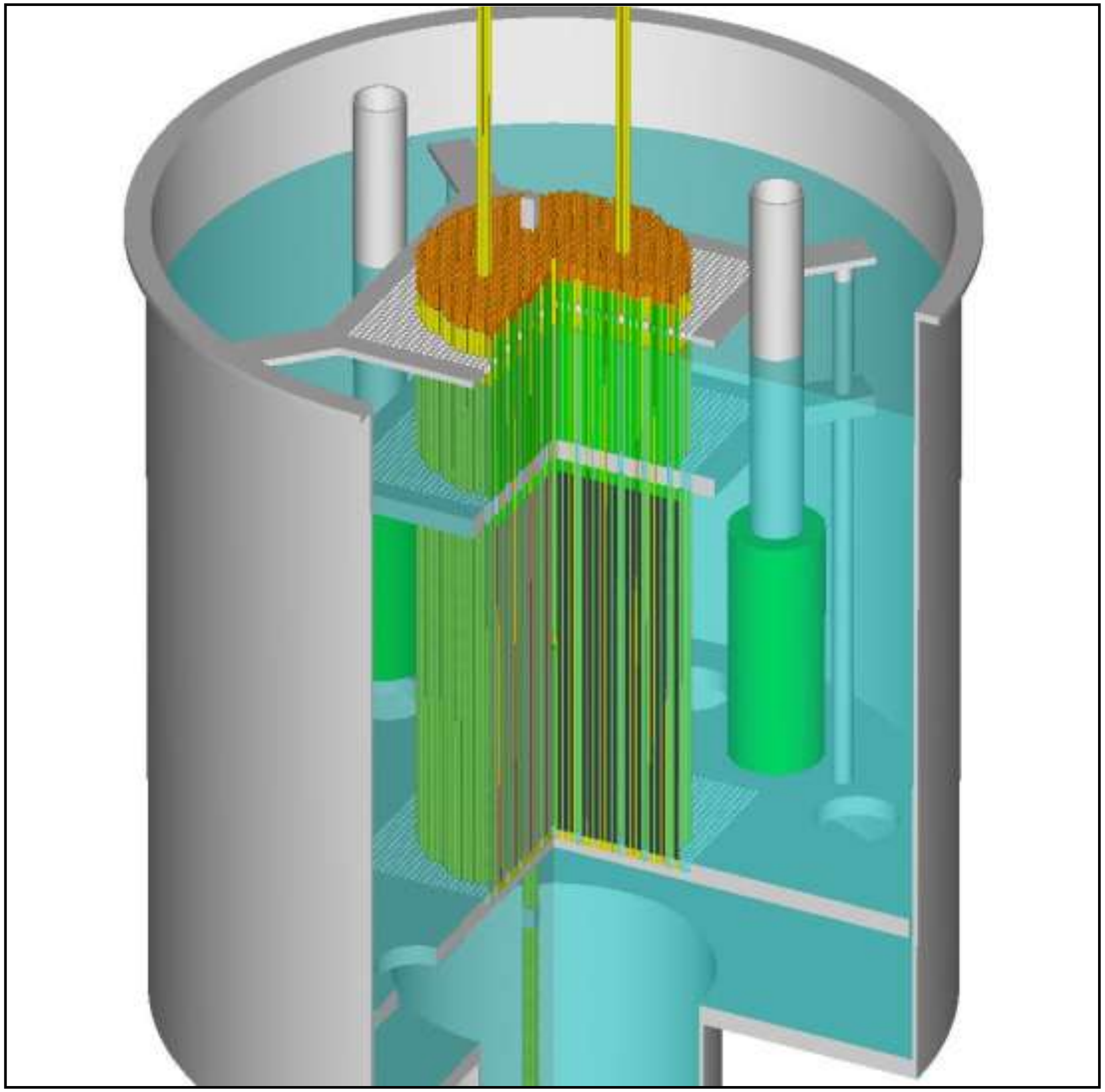
Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element.

Lower the control element



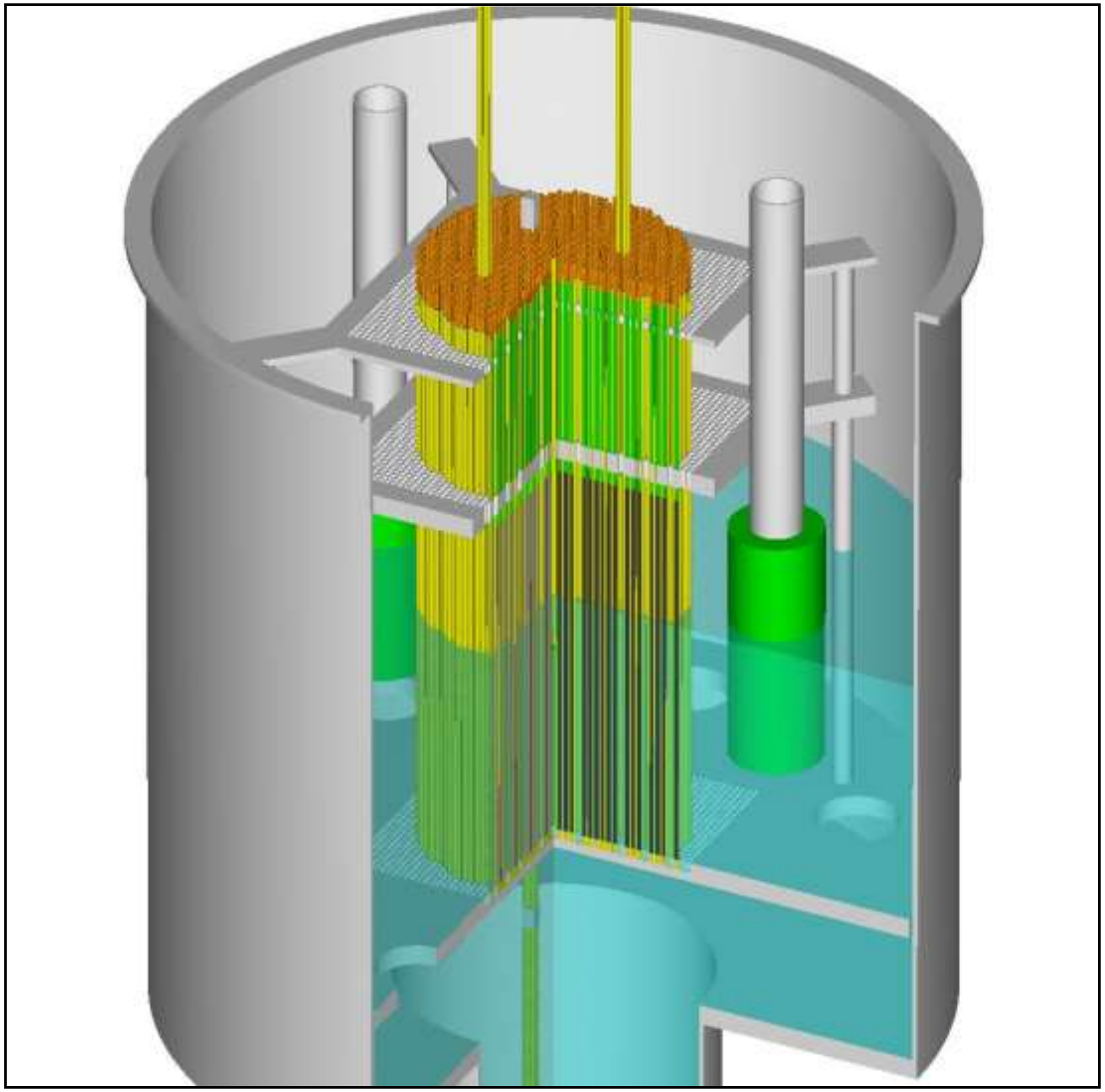
Safety Elements: Up

Control Element: Down

Core Tank: Full

Personnel: Excluded

Drain the core tank



Safety Elements: Up

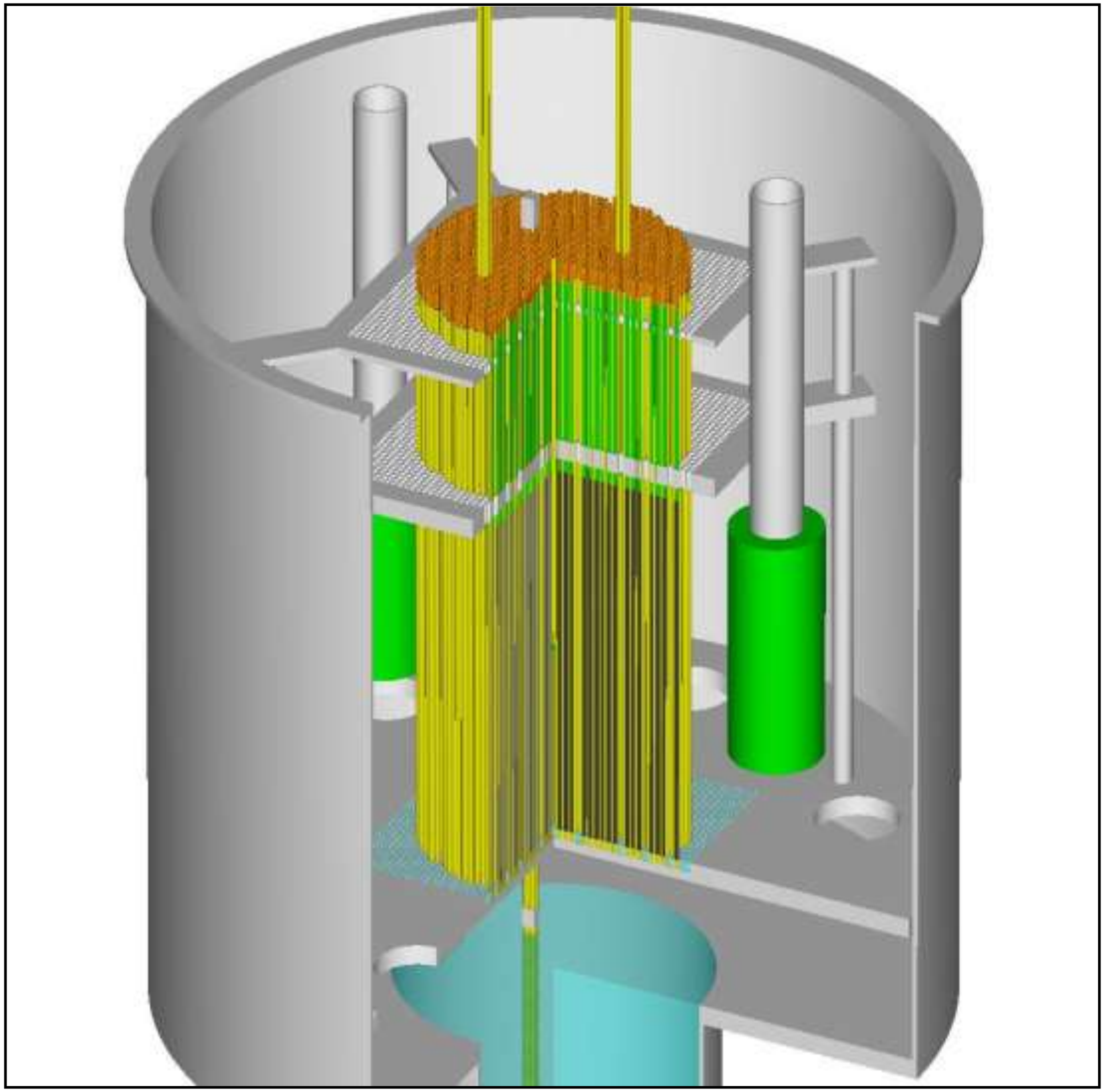
Control Element: Down

Core Tank: Draining

Personnel: Excluded

Draining the core tank requires only a few seconds.

Drain the core tank



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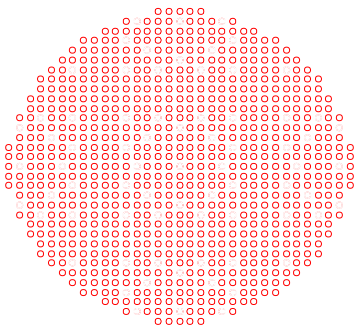
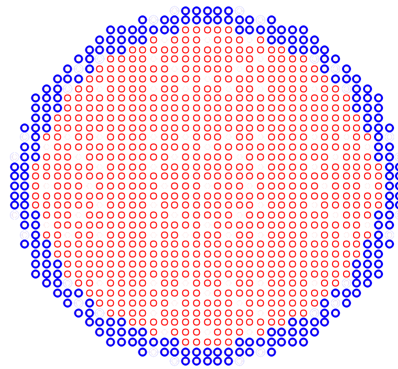
Core configurations during the first approach-to-critical experiment (1)



740

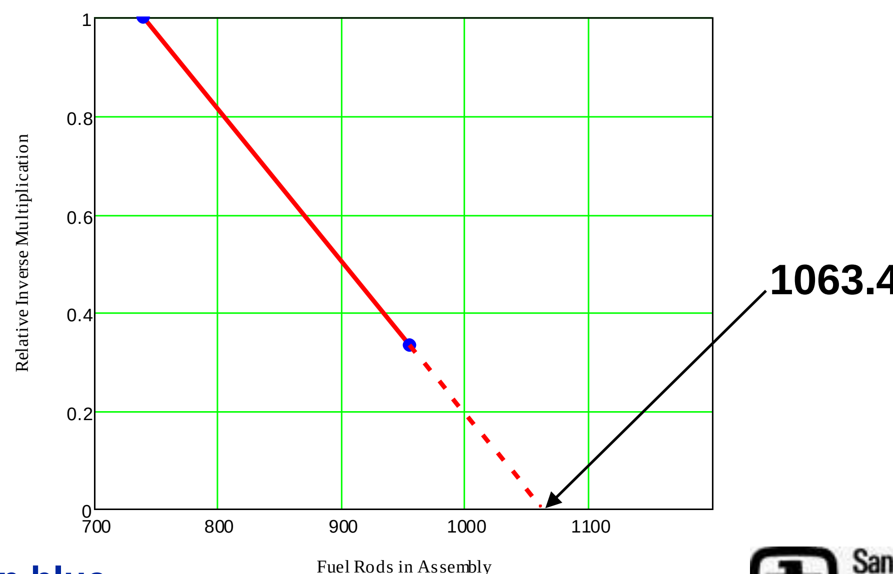


956

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

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

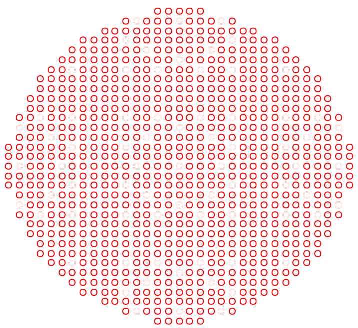
$$\frac{1}{M} = 1 - k_{eff}$$



Project the two inverse multiplication measurements to zero and add half the increment to get the next array – in this case 1009 elements

The incremental fuel elements are shown in blue

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



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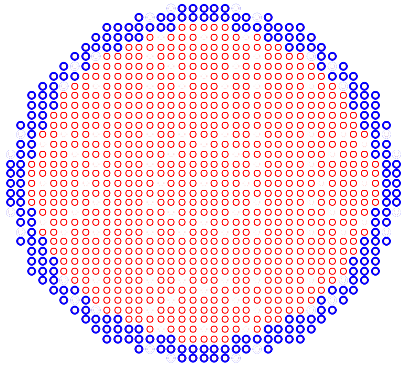

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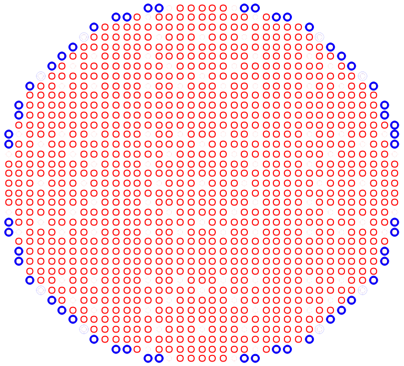
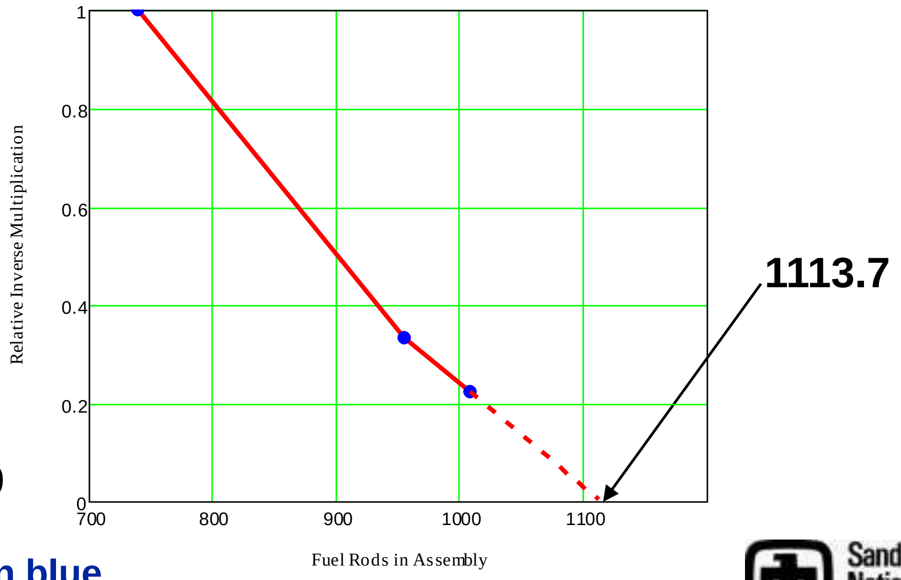


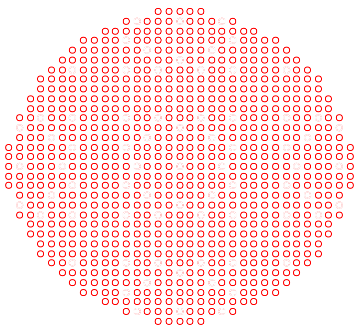
1009



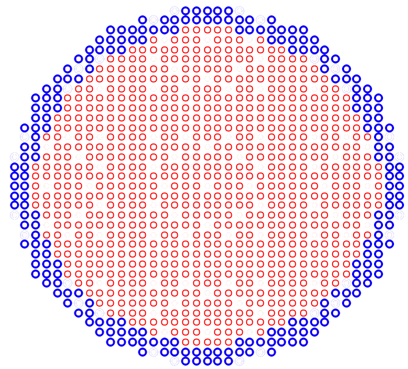
The next array: 1059

The incremental fuel elements are shown in blue

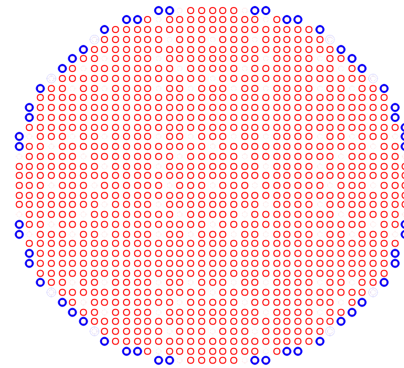
Core configurations during the first approach-to-critical experiment (3)



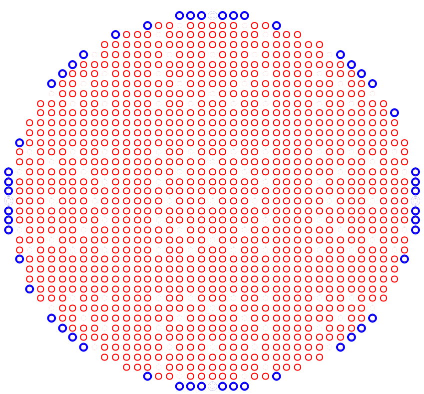
740



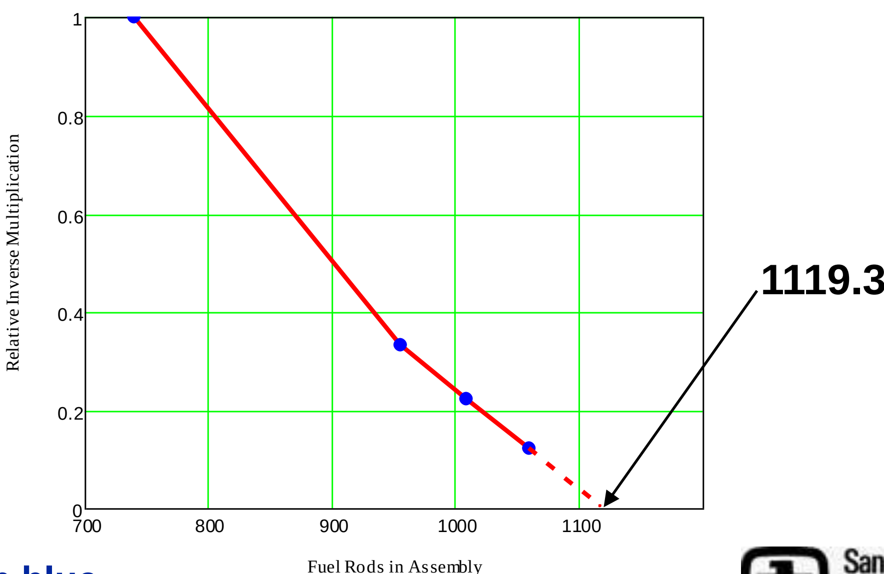
956



1009

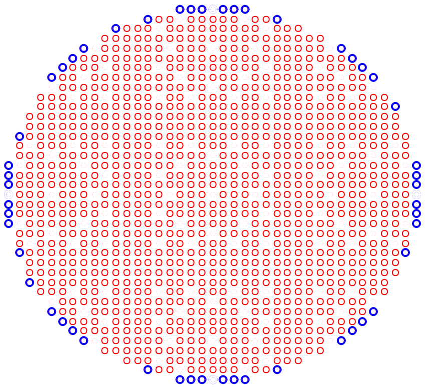


1059 **The next array: 1089**

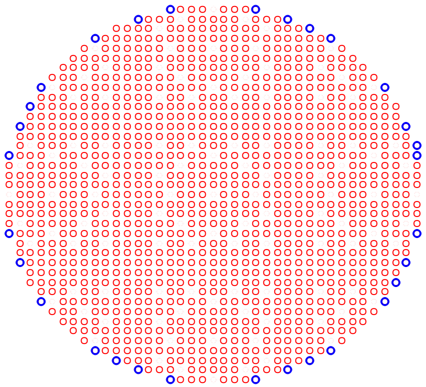


The incremental fuel elements are shown in blue

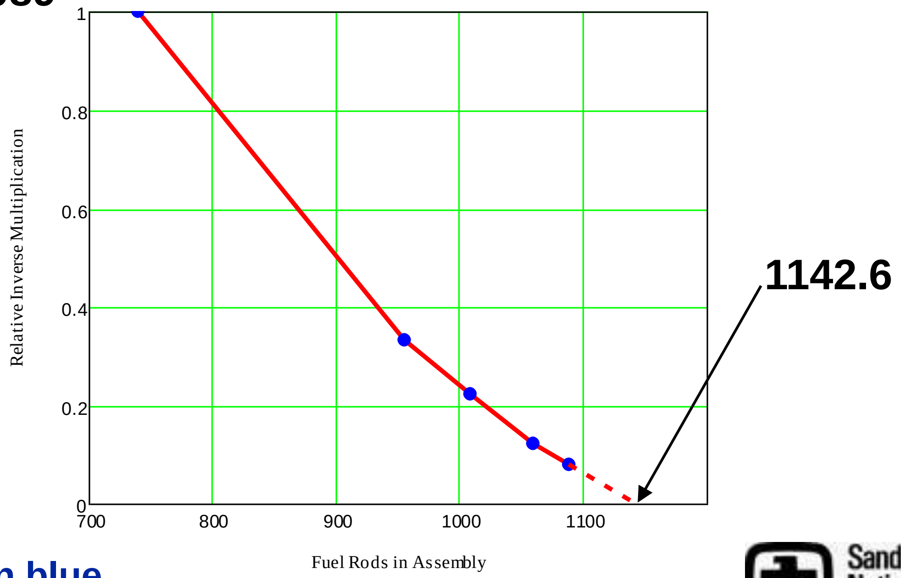
Core configurations during the first approach-to-critical experiment (4)



1059



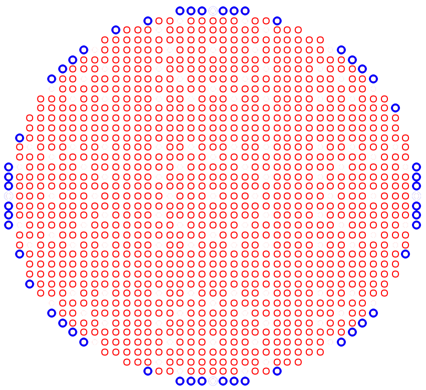
1089



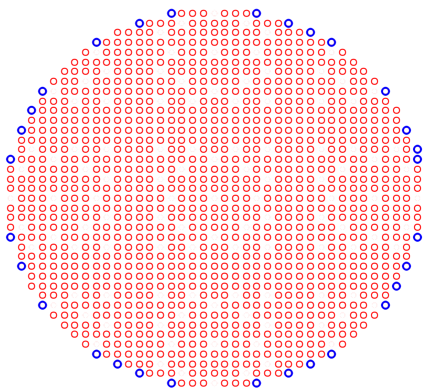
The next array: 1115

The incremental fuel elements are shown in blue

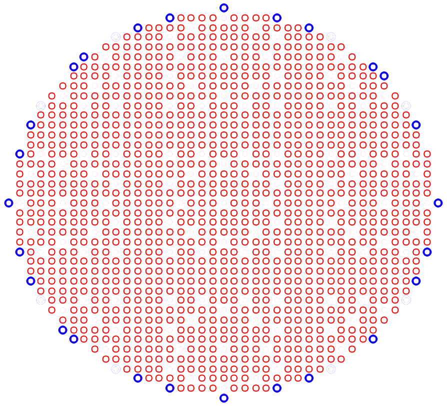
Core configurations during the first approach-to-critical experiment (4)



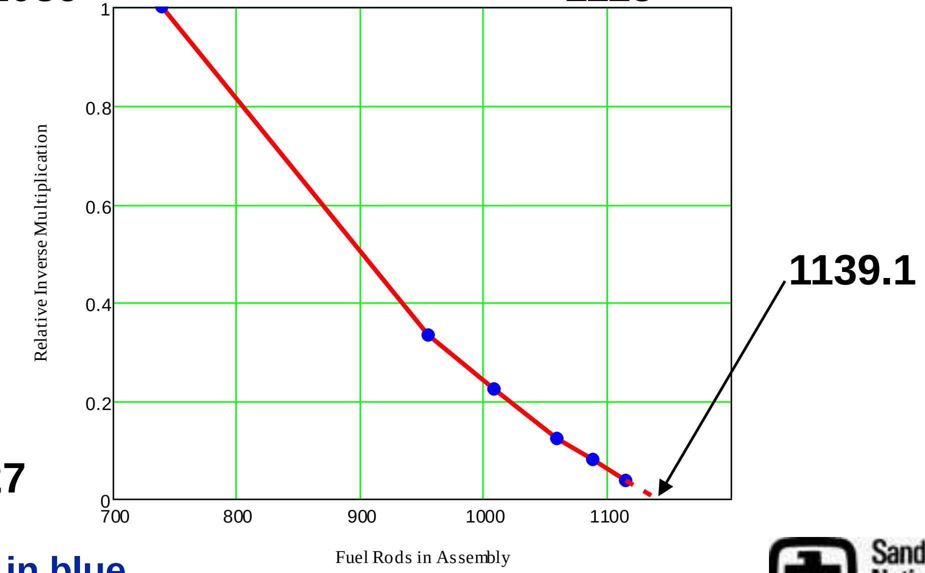
1059



1089



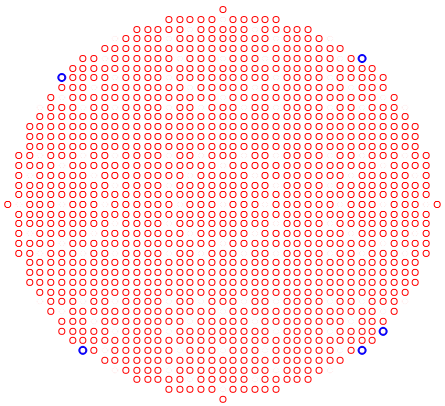
1115



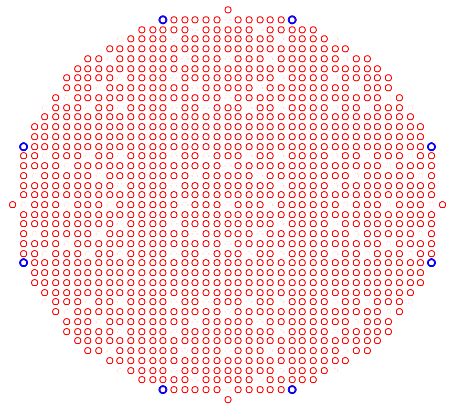
The next array: 1127

The incremental fuel elements are shown in blue

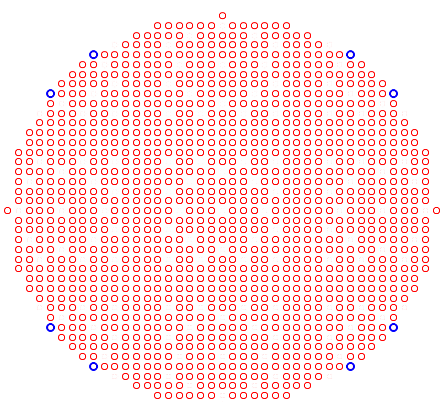
Core configurations during the first approach-to-critical experiment (5)



1120

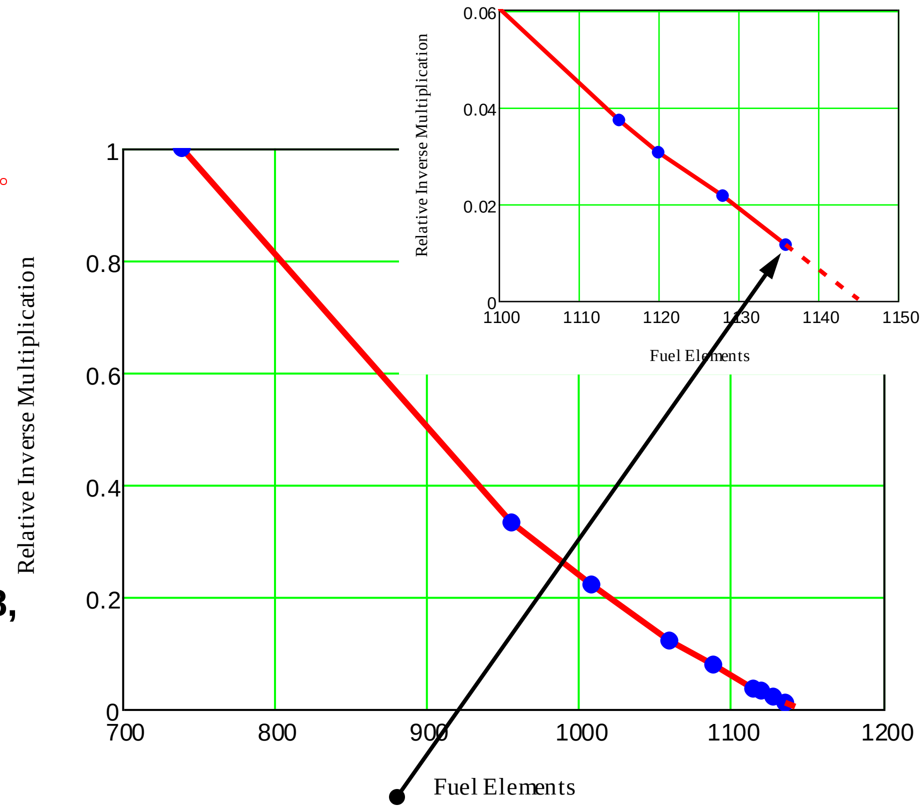


1128



1136

We also made measurements with 1138, 1140, and 1144 elements (all subcritical). A core with 1148 elements was supercritical.



At 1136 fuel elements:

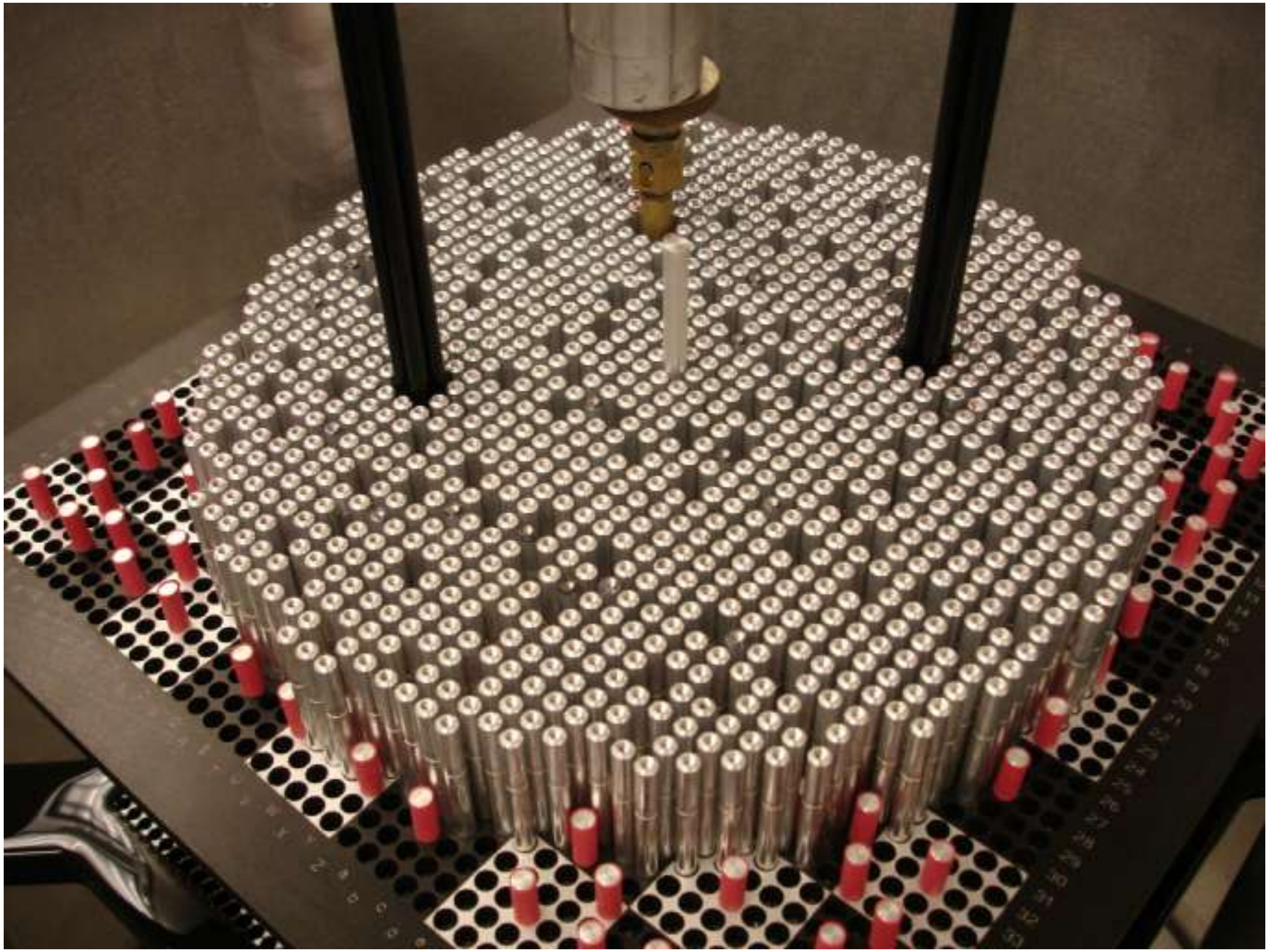
N_{crit} = 1145.3

k_{eff} = 0.9984

M ~ 610

The incremental fuel elements are shown in blue

The first 7uPCX core at the end of the approach



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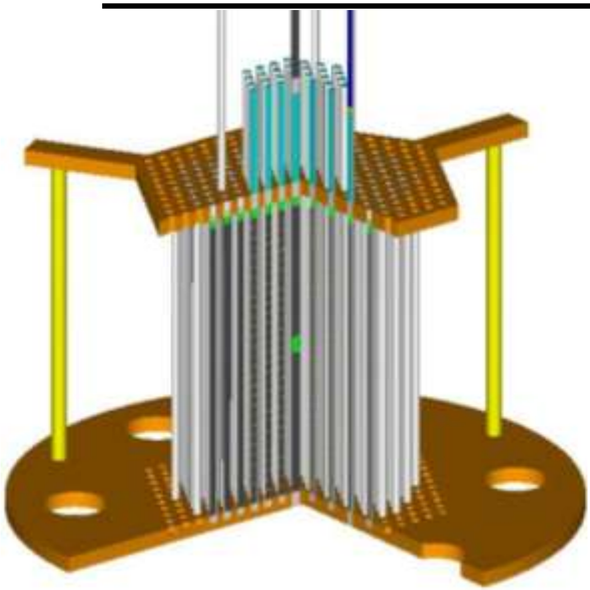
The 7uPCX experiment matrix

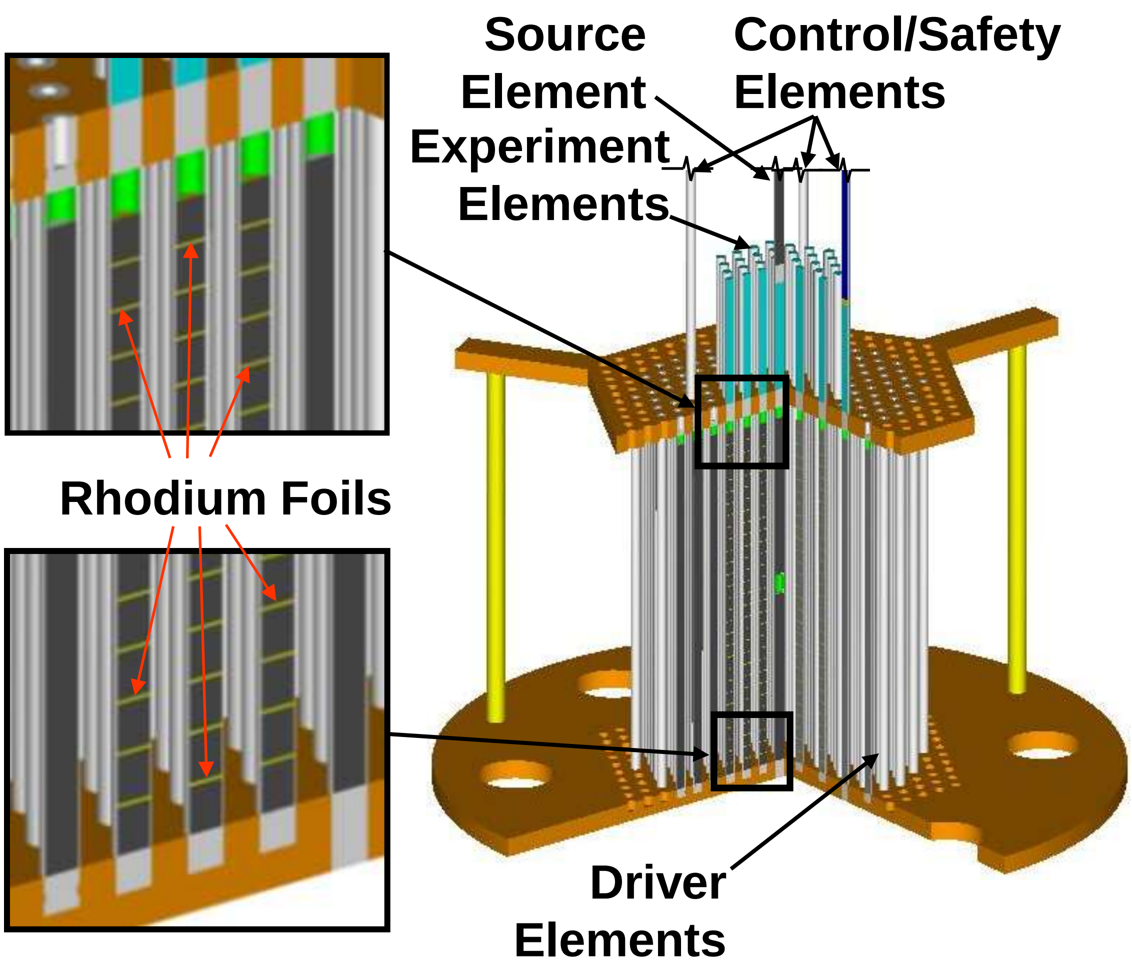
- We have two grid plate sets
  - The sets were chosen to bound the fuel-to-water ratio of commercial PWRs
  - A full set of experiments will be done at each pitch
- We will find the array that is critical with pure water moderator
- We will search for the boric acid concentration in the moderator that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

In 2002, we performed some critical experiments with rhodium



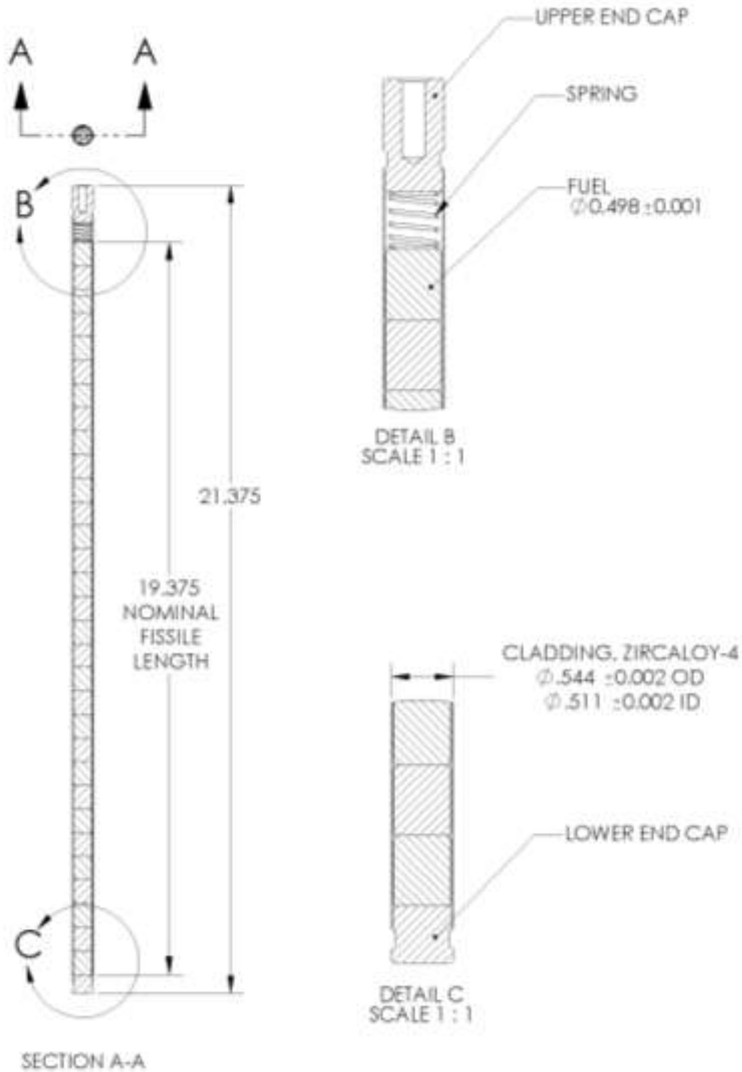
- The Burnup Credit Critical Experiment (BUCCX) was funded by the Nuclear Energy Research Initiative (NERI)
- We built a critical assembly in which we could insert fission product materials to measure reactivity effects
- The NERI funding was used to bring the experiment capability up and perform the 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 BUCCX core was designed to be easy to model



- The assembly is a triangular-pitched array of Zircaloy-4 clad U(4.31%)O_2 fuel (driver) elements
- Test materials are placed between the fuel pellets in "experiment elements"
- The assembly has 3 control/safety elements
  - the B_4C absorber is decoupled from the assembly by a polyethylene spacer
  - the absorber is followed by a fuel rod
- The source is in the central fuel element
- The grid plates are aluminum
- The pitch of the array is modified by replacing the grid plates

We used driver fuel rods that were fabricated for an earlier critical experiment



The fuel was built for an earlier critical experiment. The UO_2 pellets come from fuel that was used in experiments at the Critical Mass Laboratory at Pacific Northwest Laboratories (now PNNL) documented in the *__International Handbook of Evaluated Criticality Safety Benchmark Experiments__*, NEA/NSC/DOC/95 (experiment LEU-COMP-THERM-002 and others). The uranium is 4.31% enriched and was well characterized at PNNL. Originally in aluminum tubes, the pellets were rebuilt into Zircaloy-4 tubes.

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

We completed ten critical experiments

- We used two grid plate sets
  - 2.0 cm pitch – gives fuel-to-water ratio about the same as a PWR fuel element
  - 2.8 cm pitch – gives a softer spectrum (nearly optimum moderation)
- We did five experiments at each pitch
  - Driver fuel only
  - 36 experiment elements with no foils
  - 36 experiment elements each with 31 Rh foils (25 micron) between the 32 fuel pellets (1116 foils total)
  - 36 experiment elements each with 31 Rh foils (50 micron)
  - 36 experiment elements each with 31 Rh foils (100 micron)
- The critical fuel array size was determined at the highest reactivity state of the assembly (fully reflected)

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The details of the experiment are given in the “benchmark book”

International Handbook of Evaluated Criticality Safety Benchmark Experiments

NEA/NSC/DOC/(95)03 – updated annually in September

LEU-COMP-THERM-079

These experiments first appeared in September, 2005

Our plans for the critical experiments

We are now funded by the DOE Nuclear Criticality Safety Program

- Restarted the critical experiment capability in May, 2009
- Maintain the capability in FY10 and beyond
  - Perform at least four approach-to-critical experiments per year
  - We have considerable excess capability for other experiments
- Develop a hands-on nuclear criticality safety engineer training course using our CX capability in FY10
- Begin offering the hands-on class in later years
  - DOE security clearance NOT required
  - Available to both DOE- and NRC-regulated entities

Critical Experiments at Sandia

The safety case is simple

- **Access controls ensure personnel safety – 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**
- **Low-enriched (<20%) fuel is used**
  - **1000 kg of the fuel is subcritical without water moderator**
  - **Reactor room is limited to 500 kg of fuel**
- **The fission product inventory is kept low by limiting the energy deposition in the fuel (15 MJ fission energy per year)**

  15 MJ is less than 3 SPR-III pulses
  - **Limits accident source term**
  - **Allows manual handling of fuel during experiments**
- **The control system includes power and period scrams for asset protection**

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  - Allows manual handling of fuel during experiments
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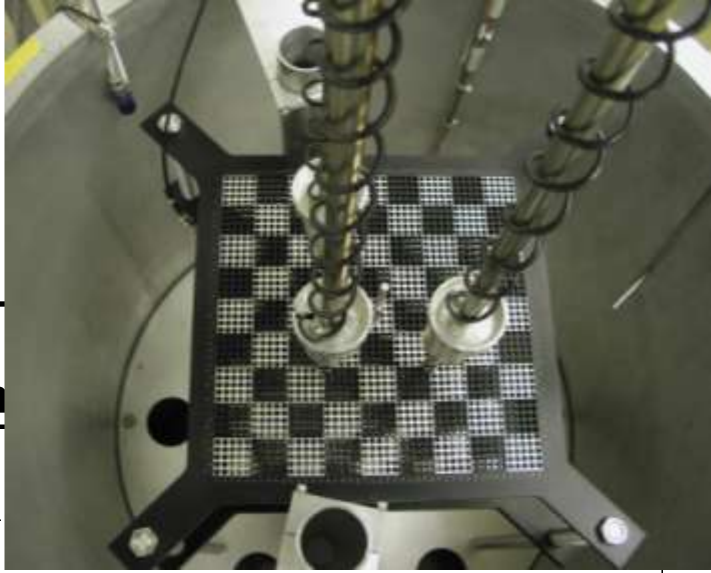
The fission product inventory and the excess reactivity in the assembly are controlled

- **Fission Product Inventory**
  - Limit the duration of operations at or above delayed critical
  - Limit the power of the assembly
  - The SPRF/CX limit imposed by the AB is 15 MJ per year of fission energy
    - *The SPRF/CX yield for a full year is less than 3 SPR-III pulses*
- **Excess Reactivity**
  - Approach-to-critical done in a controlled manner
  - Analyze incremental reactivities and limit additions when near delayed critical
  - The SPRF/CX self-imposed limit is $0.80 maximum excess reactivity
    - *The maximum excess reactivity during the 2002 BUCCX experiments was less than $0.25*

Starting a core load



The first fuel addition

Step	Fuel Elements	SE	CE	Water in Core?	People Allowed?	Action
1	0	Down	Down	No	Yes	Start new core load here.
2	0	Up	Down	No	Yes	Raise the safety elements.
3	0	Up	Up	No	Yes	Raise the control element.
4	N_1	Up	Up	No	Yes	Add the first fuel increment.
5, 6*	N_1	Up	Up	No	No	Leave and lock the reactor room.
	N_1	Up	Down	No	No	Lower the control element.
7	N_1	Up	Down	Yes	No	Close dump valves and fill the core tank.
8	N_1	Up	Up	Yes	No	Raise control element, measure count rates.
9, 10*	N_1	Up	Down	Yes	No	Lower the control element.
	N_1	Up	Down	No	Yes	Open the dump valves.
11	N_1	Up	Down	No	Yes	Jump to “C” below for the next fuel increment.

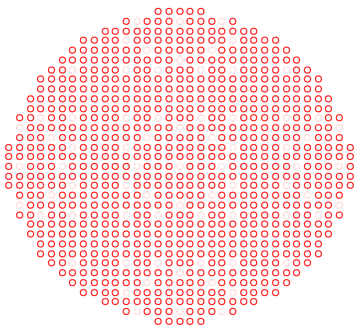
* Steps can be done in any order.

Loading to critical is a repetitive process

All fuel additions after the first

Step	Fuel Elements	SE	CE	Water in Core?	People Allowed?	Action
A	N_1	Down	Down	No	Yes	Perform the necessary startup actions.
B	N_1	Up	Down	No	Yes	Condition after startup actions.
C	N_2	Up	Down	No	Yes	Add fuel increment.
D	N_2	Up	Down	No	No	Leave and lock the reactor room.
E	N_2	Up	Down	Yes	No	Close dump valves and fill the core tank.
F	N_2	Up	Up	Yes	No	Raise control element, measure count rates.
G, H, I*	N_2	Up	Down	Yes	No	Lower the control element.
	N_2	Up	Down	No	Yes	Open the dump valves.
	N_2	Up	Down	No	Yes	Determine the next fuel increment. Loop to "C" unless done.
* Steps can be done in any order.						

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



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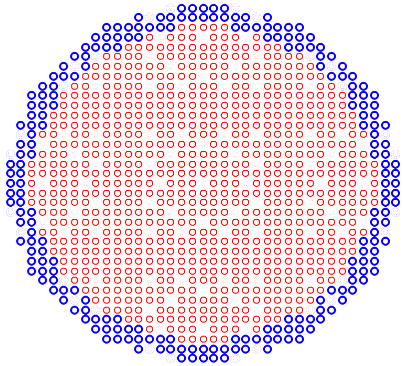

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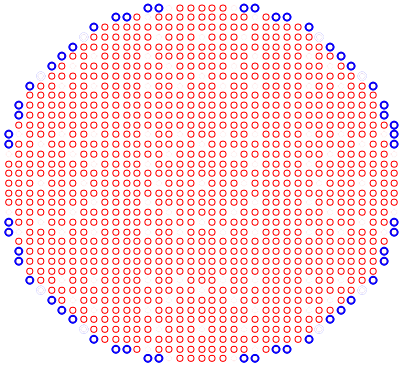

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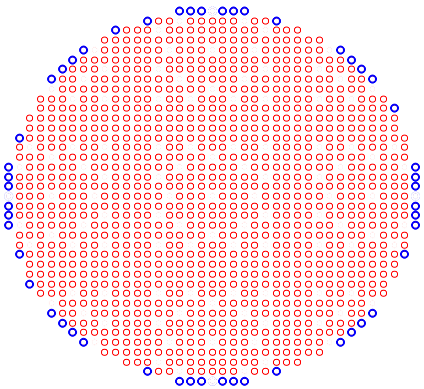

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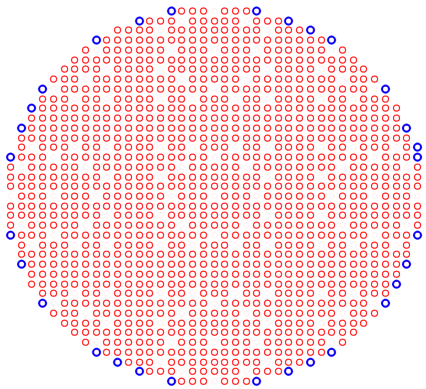

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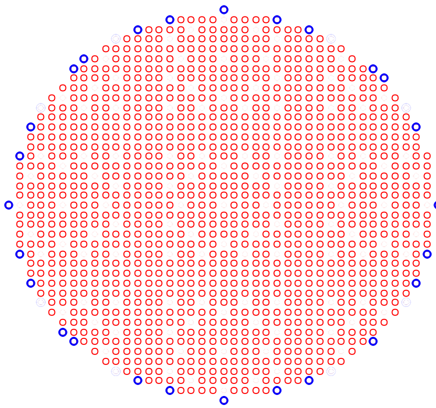

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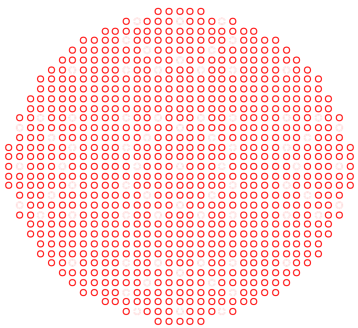
The incremental fuel elements are shown in blue

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



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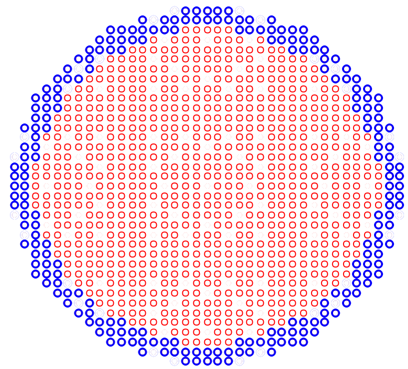

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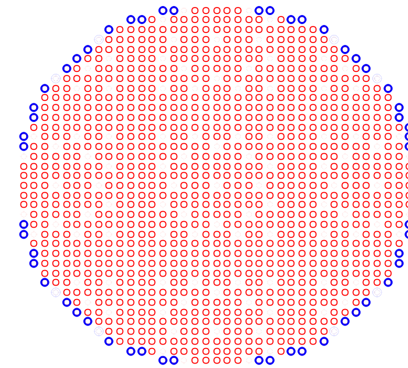

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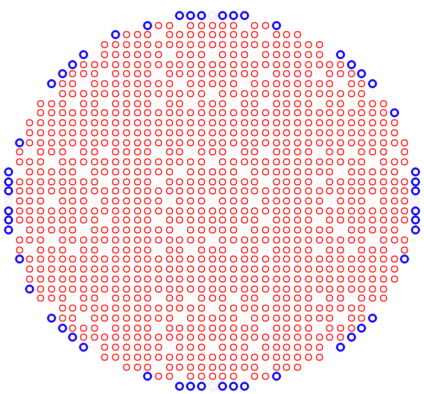

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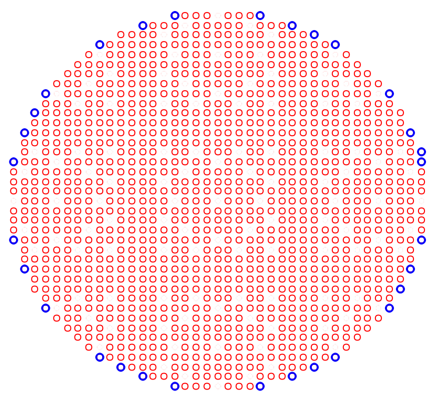

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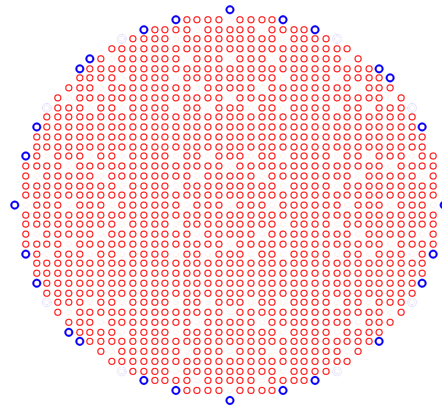

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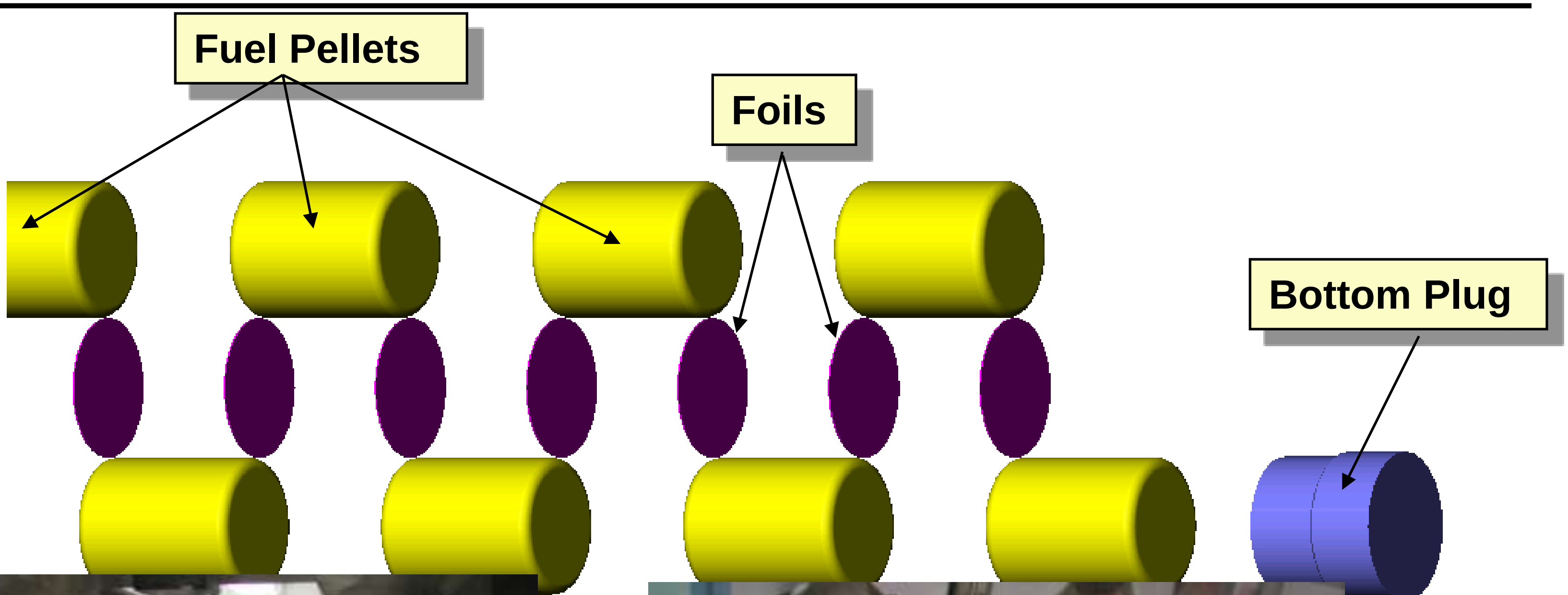
We built special experiment fuel rods that give us access to the fuel pellets



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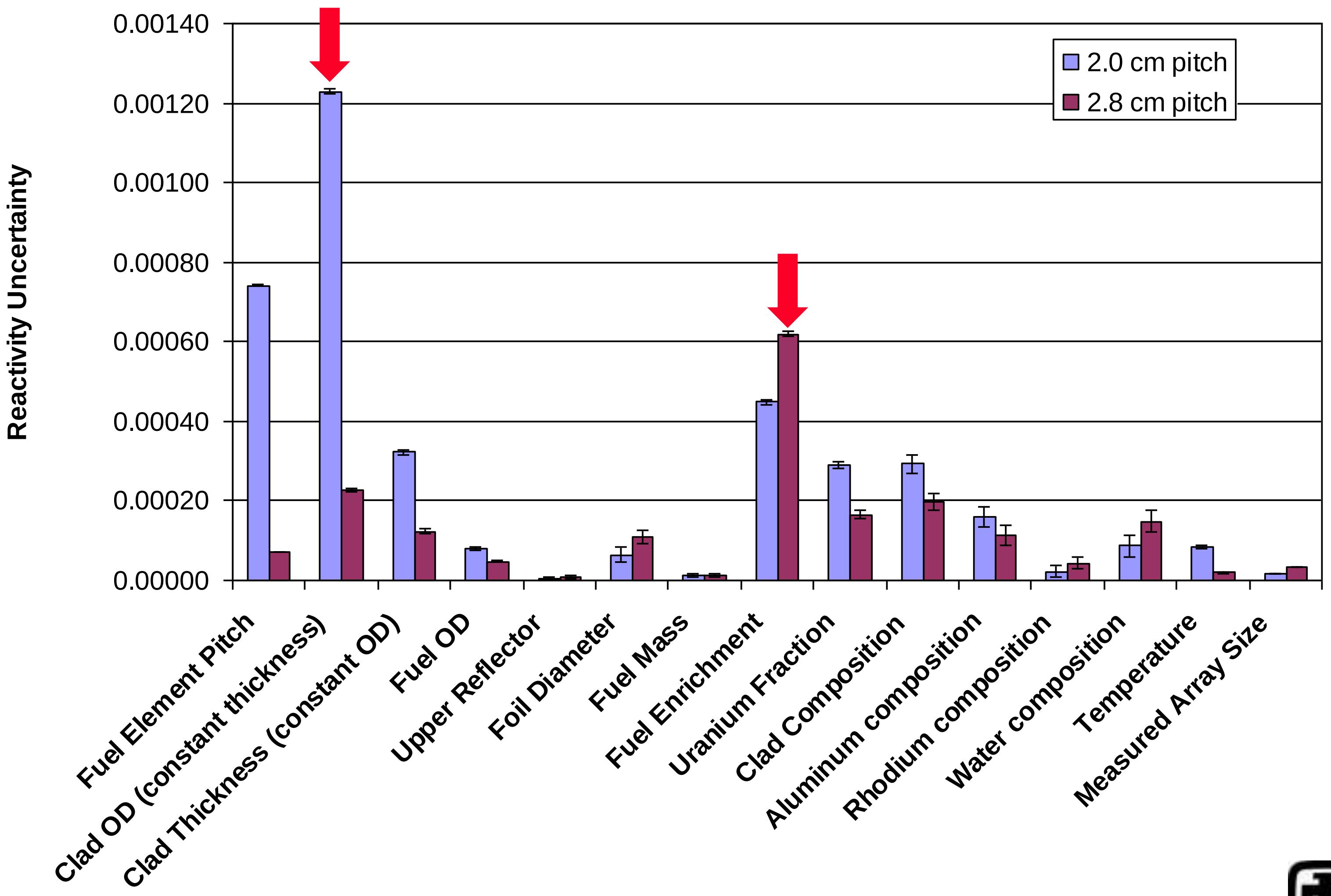
The experimental uncertainties are relatively small

Uncertainty	2.0 cm Pitch (under-moderated)	2.8 cm Pitch (~optimum moderation)
Assembly Dimensions	0.00147	0.00029
Fuel Effects	0.00054	0.00064
Composition Effects	0.00034	0.00028
Assembly Temperature	0.00008	0.00002
Sum in Quadrature	**0.0016**	**0.0008**

The experimental uncertainties are relatively small



Status of the Sandia critical experiments capability

- First approach-to-critical experiment started May 11
- First supercritical core measured on May 15
- We will perform one critical experiment per quarter to maintain the capability of the facility and the proficiency of the staff