SAND2012-9663C

Hands-On Criticality Safety Training at Sandia National Laboratories

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SAND2012-XXXX

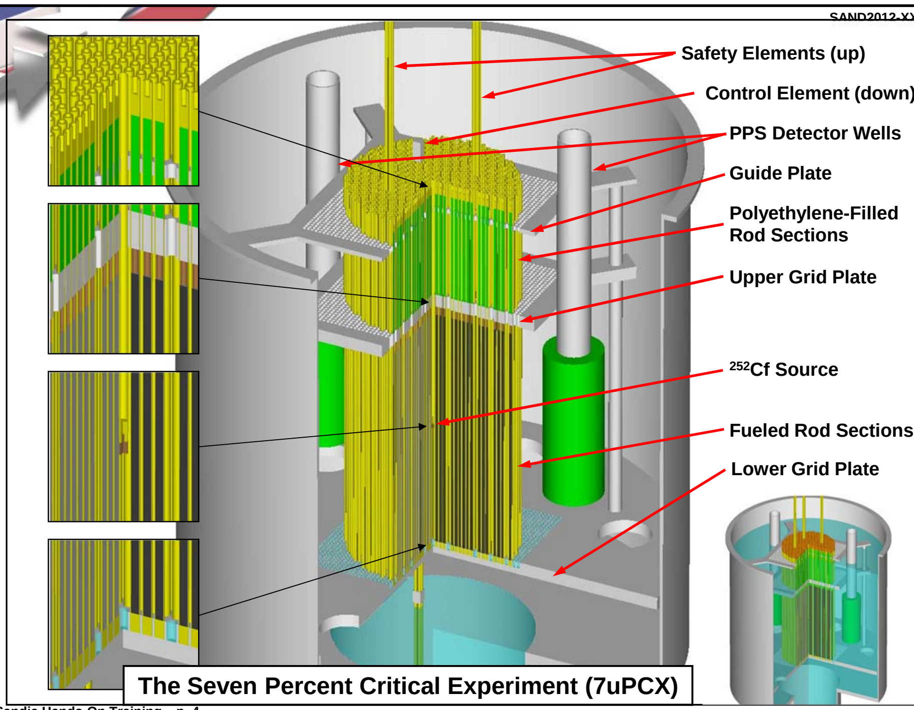
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

What is ahead

- We have developed a hands-on criticality experiments class
- It is part of the US DOE Nuclear Criticality Safety Program (NCSP) Training and Education Program for Nuclear Criticality Safety Engineers
- Sign up at http://ncsp.llnl.gov/classMain.html
- The Sandia part of the class is a series of four experiments
  - Approach on fuel
  - Approach on moderator height
  - "Split table" approach
  - Fuel removal approach
- Lectures on various subjects are integrated with the experiments

Classroom discussions are interspersed through the experiments

- The basics of criticality safety
- Criticality safety data and limits
- Historic critical experiments
- Subcritical multiplication
- Reactor theory and kinetics
- Identify lessons from historic critical-assembly accidents
- The design and operation of critical experiments at Sandia
- Radiation detection in the experiments
- Results of Sandia critical experiments
- The development and use of critical experiment benchmarks
- Light water reactor concepts as applied to the Sandia experiments



The Seven Percent Critical Experiment (7uPCX)

The Approach-to-Critical Process

Subcritical Multiplication

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

This goes to infinity as k_{eff} approaches 1

The count rates in detectors near or in the assembly behave *similarly* to the subcritical multiplication

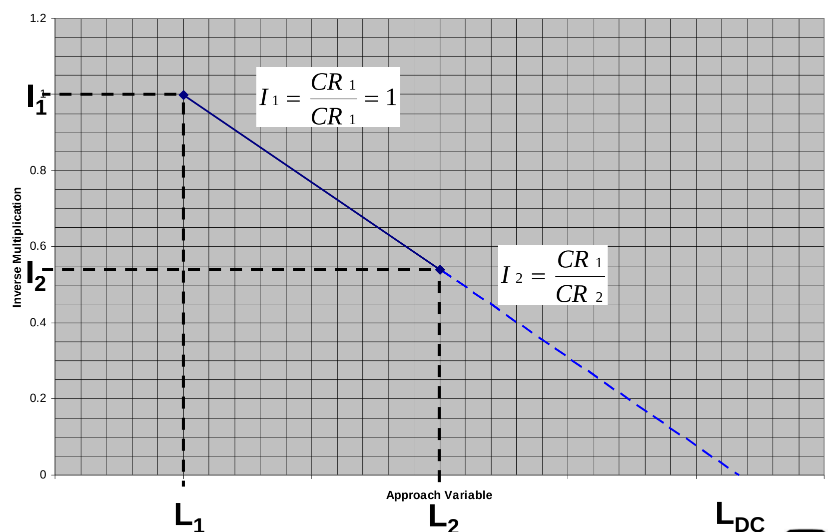
Inverse Multiplication

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

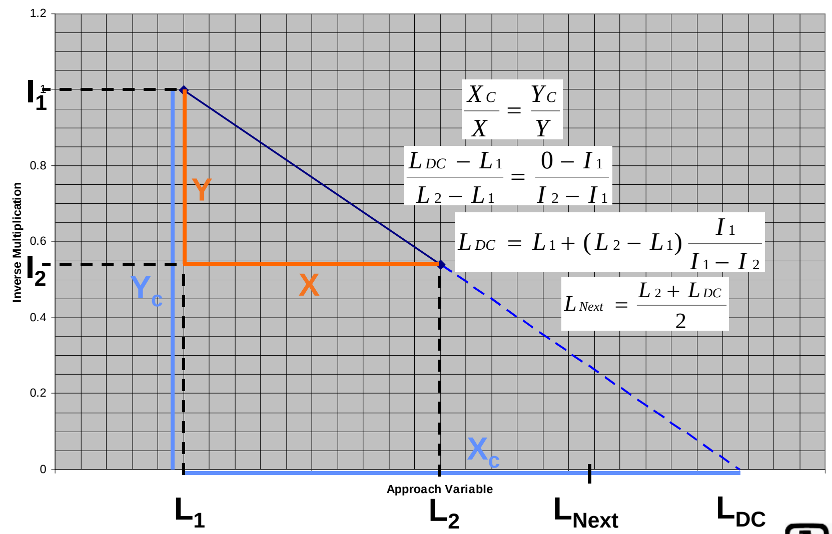
This goes to zero as k_{eff} approaches 1

An approach-to-critical experiment is done by determining where the inverse count rates pass through zero

Using Inverse Multiplication



Determining the Next Reactivity Increment



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

$$\frac{L_{DC} - L_1}{L_2 - L_1} = \frac{0 - I_1}{I_2 - I_1}$$

$$L_{DC} = L_1 + (L_2 - L_1)\frac{I_1}{I_1 - I_2}$$

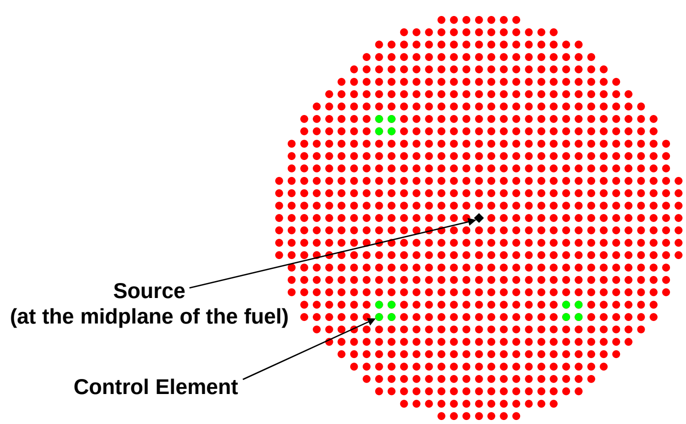
$$L_{Next} = \frac{L_2 + L_{DC}}{2}$$

Experiment 1
Approach to Critical on Fuel Loading

Experiment 1 Overview

- We perform an approach-to-critical experiment by loading fuel into the fully-reflected assembly
- This is the way we normally perform experiments
- The primary criticality safety parameter investigated is the fissile MASS
- Other parameters in play are:
  - Moderation
  - Reflection
  - Absorption
- Application to criticality safety:
  - What happens when the number of fuel lumps in an array increases?

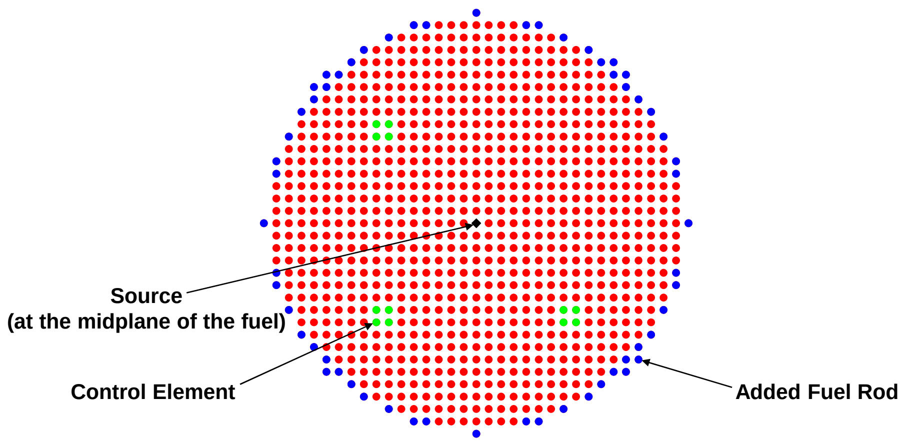
Core Loading Experiment Configuration 1



Fuel Rods: 836

k ~ 0.950

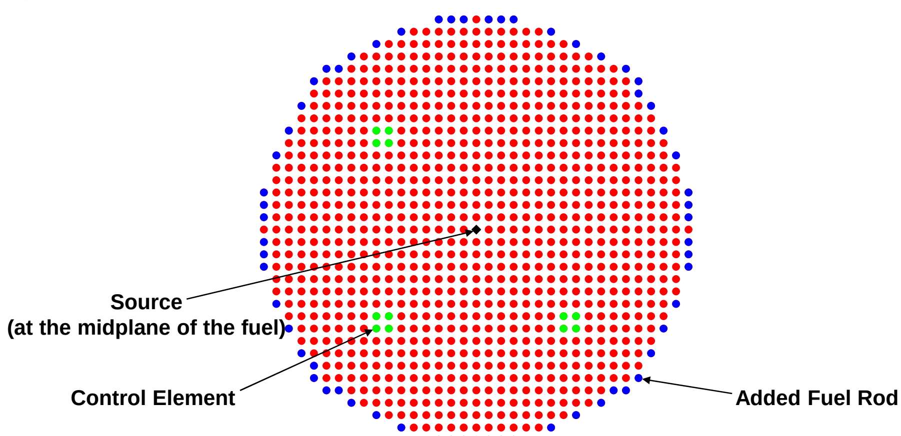
Core Loading Experiment Configuration 2



Fuel Rods: 895

k ~ 0.965

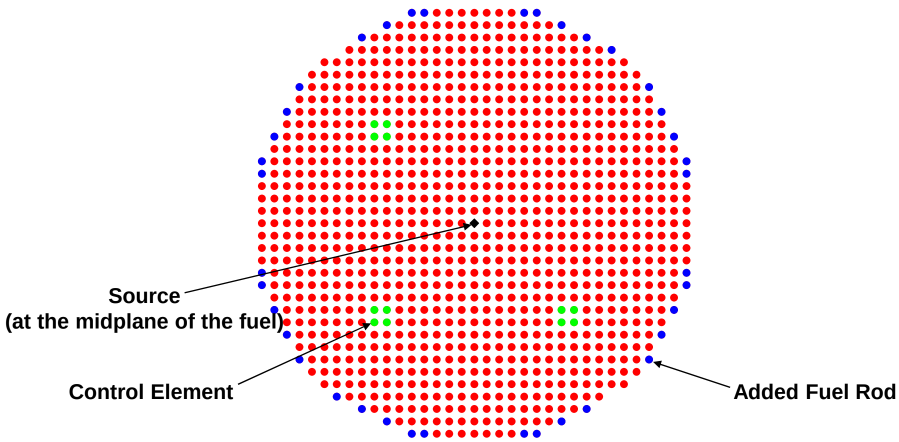
Core Loading Experiment Configuration 3



Fuel Rods: 956

k ~ 0.979

Core Loading Experiment Configuration 4



Fuel Rods: 994

k ~ 0.988

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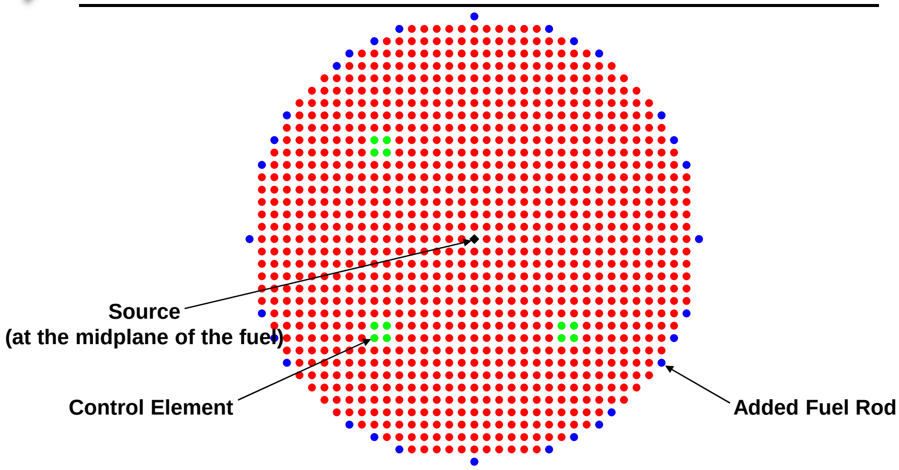
Core Loading Experiment Configuration 5



Fuel Rods: 1024

k ~ 0.994

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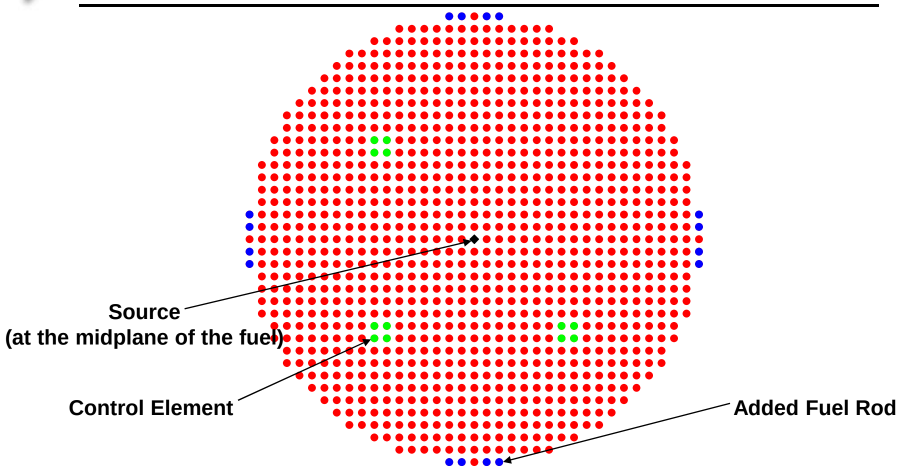
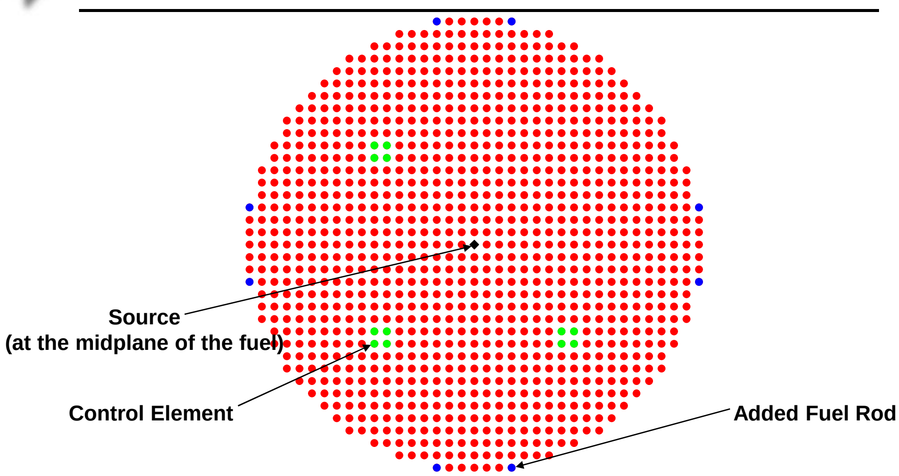
Core Loading Experiment Configuration 6



Fuel Rods: 1040

k ~ 0.997

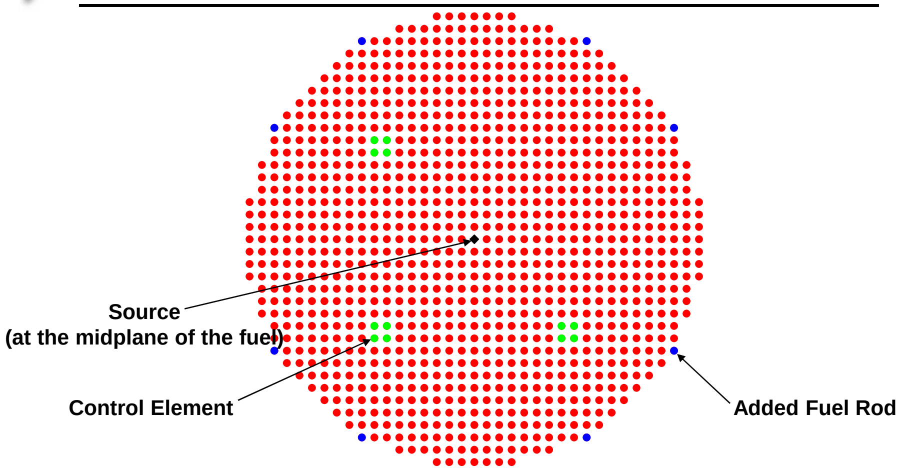
Core Loading Experiment Configuration 7



Fuel Rods: 1048

k ~ 0.998

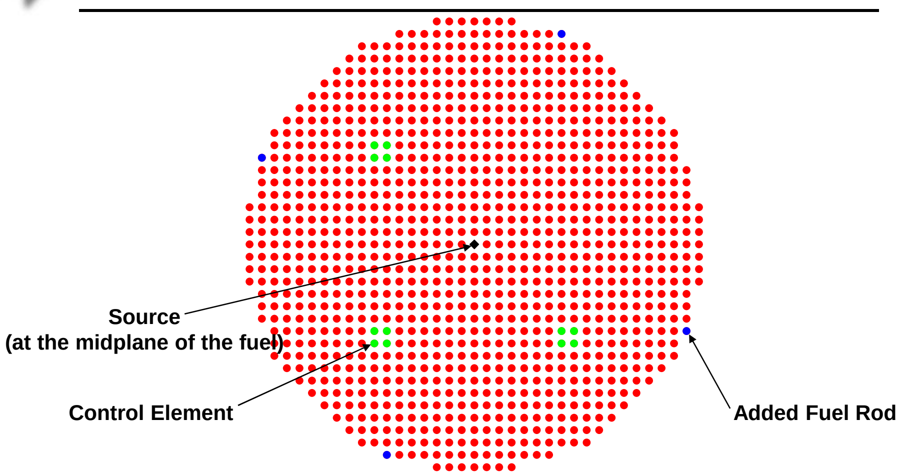
Core Loading Experiment Configuration 8



Fuel Rods: 1056

k ~ 0.999

Supercritical Core Loading



Fuel Rods: 1060

k > 1.00

Mechanics of the Experiment

- The number of fuel rods in the core changes
- The fuel configurations are guided by the count rates
- The class sorts the fuel rods and passes them to the operations staff
- The operations staff places fuel rods in the core
- The minimum fuel increment is eight rods

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The Experiment Process

- The desired fuel rod array is loaded
- The safety rods are “cocked”
- The reactor room is cleared
- The core tank is filled with water
- The control rod is raised – this puts the assembly in its most reactive condition in this operational mode
- Counts are taken
- The core tank is drained
- The control rod is lowered
- The safety rods are dropped
- The next fuel increment is determined from the count rates
- The reactor room is opened
- Loop back to the first step on this page

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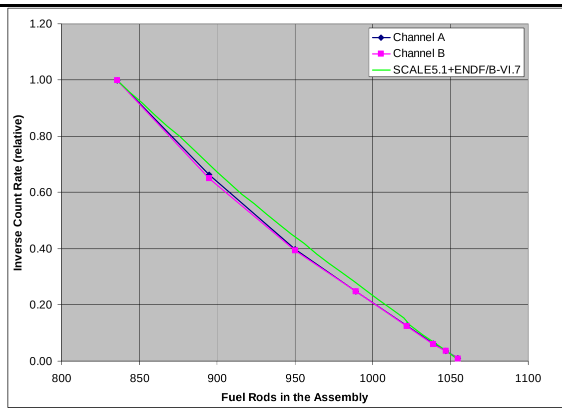
Approach on Fuel Loading



	Count Rate		Inverse Count Rate		**Channel A**		**Channel B**	
Rods	Ch. A	Ch. B	Ch. A	Ch. B	Projected	Next	Projected	Next
836	6130	5632	1.0000	1.0000				
895	9237	8655	0.6636	0.6507	1011.40	953.20	1004.92	949.96
950	15377	14292	0.3986	0.3941	1032.74	991.37	1034.45	992.22
989	24647	22716	0.2487	0.2479	1053.69	1021.35	1055.17	1022.08
1022	48744	45195	0.1258	0.1246	1055.75	1038.88	1055.35	1038.67
1039	98406	93457	0.0623	0.0603	1055.69	1047.34	1054.92	1046.96
1047	165607	156219	0.0370	0.0361	1058.71	1052.86	1058.91	1052.96
1055	626813	596754	0.0098	0.0094	1057.87	1056.44	1057.84	1056.42

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NCSP HANDS-ON TRAINING

Experiment 2
Approach to Critical on Moderator Height

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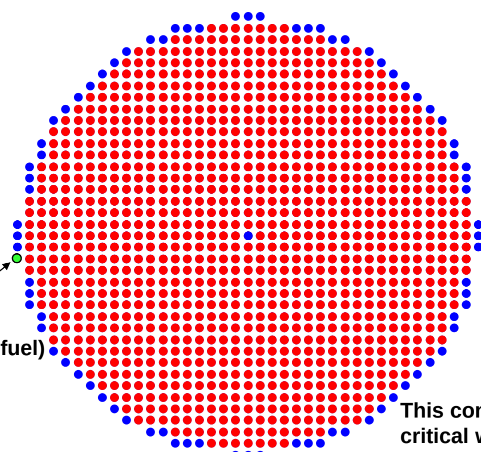
Experiment 2 Overview

- We perform an approach-to-critical experiment by increasing the moderator height in the assembly with a constant fuel loading
- The primary criticality safety parameter investigated is MODERATION
- Other parameters that are in play:
  - Geometry
  - Mass
- Application to criticality safety:
  - What happens to an array that becomes flooded?

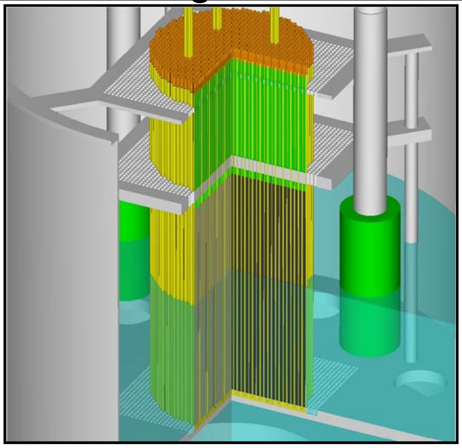
The Fuel Rod Configuration



1137 fuel rods

The blue rods are the difference from the fully-reflected critical array in the first experiment

Moderator Height Experiment Configuration 1

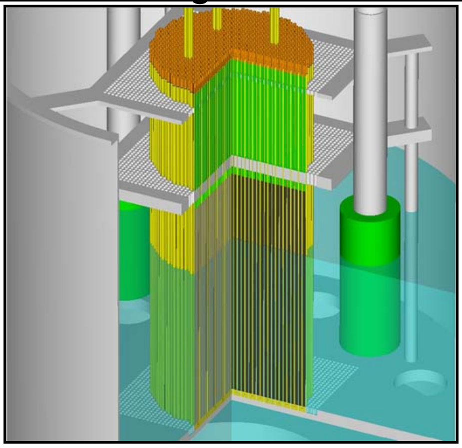


Fuel Rods: 1137

k_{eff}: ~0.90

Water Depth: 271.6 mm

Moderator Height Experiment Configuration 2

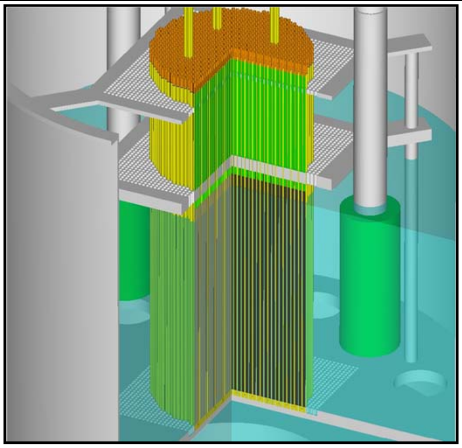


Fuel Rods: 1137

k_{eff}: ~0.95

Water Depth: 341.3 mm

Moderator Height Experiment at DC



Fuel Rods: 1137

k_{eff}: ~1.0

Water Depth: 461 mm

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Mechanics of the Experiment

- **The number of fuel rods in the core is constant**
- **The approach-to-critical is done with the depth of the moderator in the core tank as the free parameter**
- **The choice of water depth is guided by the count rates**
- **This approach is done remotely (we don't go into the reactor room)**
- **The minimum water height increment is 5 mm**

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The Experiment Process

- The desired fuel rod array is loaded
- The safety rods are “cocked”
- The reactor room is cleared
- The core tank is filled with water to the height that gives a calculated k_{eff} of about 0.90
- The control rod is raised
- The slow pump is turned on – the water height in the core is controlled by the setting of the overflow standpipe
- When the water level in the core tank reaches the standpipe, counts were taken [A]
- The next water level is determined from the previous two counts
- The standpipe is set for the new water level
- Loop back to the step marked [A]

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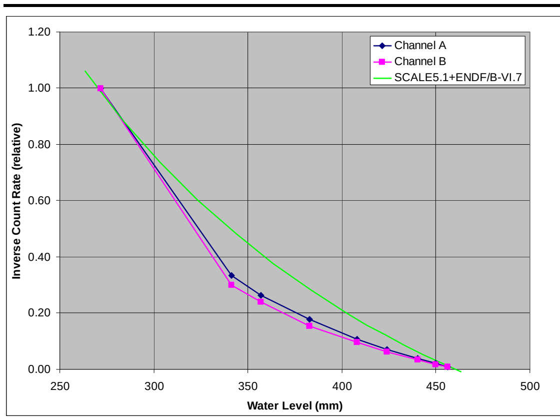
Approach on Moderator Level



$$M_1 = \frac{1}{1-0.9} = 10$$

$$I_1 = \frac{M_1}{M_1} = 1$$

The relative inverse multiplication

$$M_2 = \frac{1}{1-0.95} = 20$$

$$I_2 = \frac{M_1}{M_2} = \frac{10}{20} = 0.5$$

	Count Rate		Inverse Count Rate		Channel A		Channel B	
Water Level	Ch. A	Ch. B	Ch. A	Ch. B	Projected	Next	Projected	Next
271.7	1034	853	1.0000	1.0000				
341.4	3108	2847	0.3327	0.2996	376.15	358.77	371.22	356.31
357	3917	3565	0.2640	0.2393	416.93	386.97	418.86	387.93
382.9	5826	5521	0.1775	0.1545	436.04	409.47	430.11	406.50
408	9687	8939	0.1067	0.0954	445.87	426.94	448.54	428.27
424.1	14600	13547	0.0708	0.0630	455.84	439.97	455.33	439.72
440.2	26853	25241	0.0385	0.0338	459.38	449.79	458.85	449.53
450	50723	48777	0.0204	0.0175	461.02	455.51	460.51	455.25
456.1	113530	108681	0.0091	0.0078	461.03	458.56	461.07	458.58

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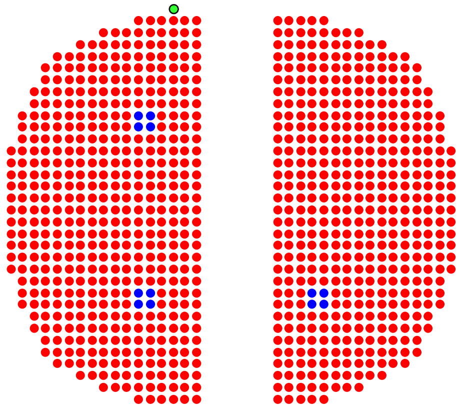
Experiment 3
Approach to Critical on Fuel Lump Separation

Experiment 3 Overview

- We perform an approach-to-critical experiment by moving two roughly equal (and unchanging) fuel lumps toward each other
- This simulates experiments done with a horizontal split table machine
- The primary criticality safety parameter that is investigated is INTERACTION
- Moderation is also in play

- Application to criticality safety:
  - What happens as two fuel masses are moved progressively closer to one another?
  - What happens when two neighboring fuel masses are moved apart?
  - This experiment is applicable to many accident configurations.

Core Separation Experiment Configurations



Fuel Rods: 477 (left) + 444 (right) = 921 (total)

Separation: 5.130 cm

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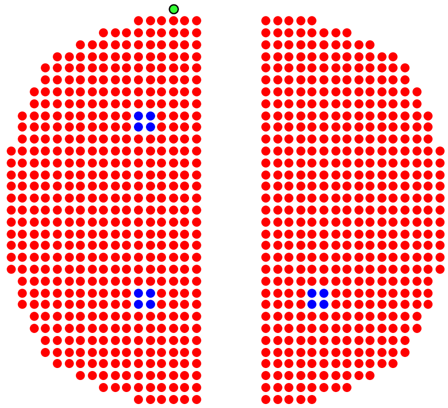
Core Separation Experiment Configurations



Fuel Rods: 477 (left) + 444 (right) = 921 (total)

Separation: 4.275 cm

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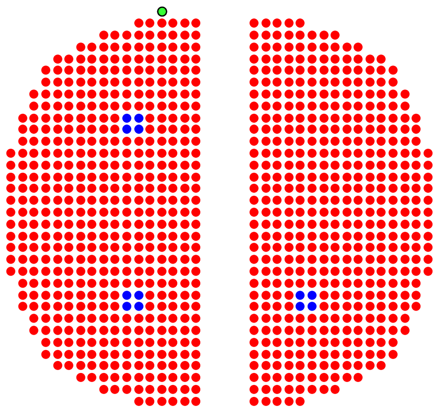
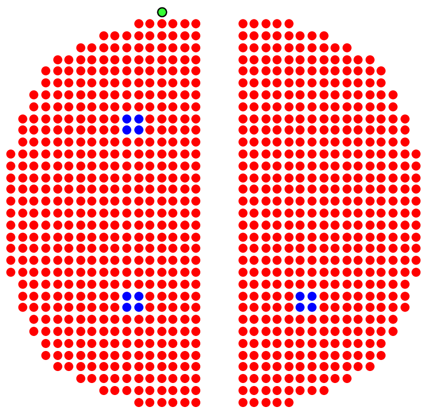
Core Separation Experiment Configurations



Fuel Rods: 477 (left) + 444 (right) = 921 (total)

Separation: 3.420 cm

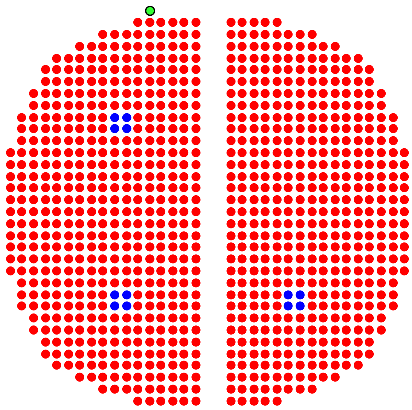
Core Separation Experiment Configurations



Fuel Rods: 477 (left) + 444 (right) = 921 (total)

Separation: 2.565 cm

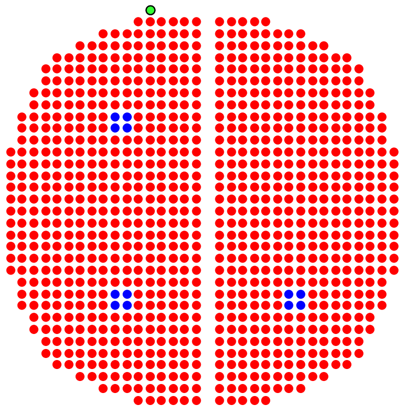
Core Separation Experiment Configurations



Fuel Rods: 477 (left) + 444 (right) = 921 (total)

Separation: 1.710 cm

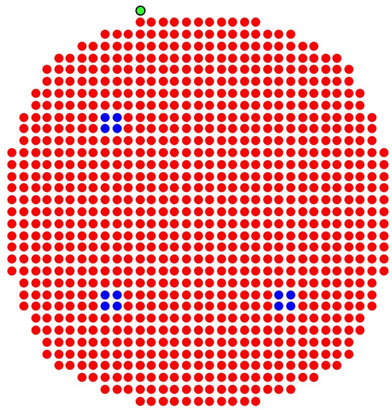
Core Separation Experiment Configurations



Fuel Rods: 477 (left) + 444 (right) = 921 (total)

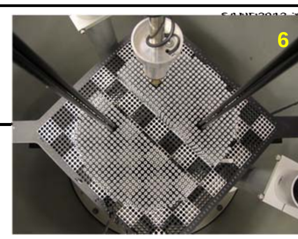
Separation: 0.855 cm

Core Separation Experiment Configurations

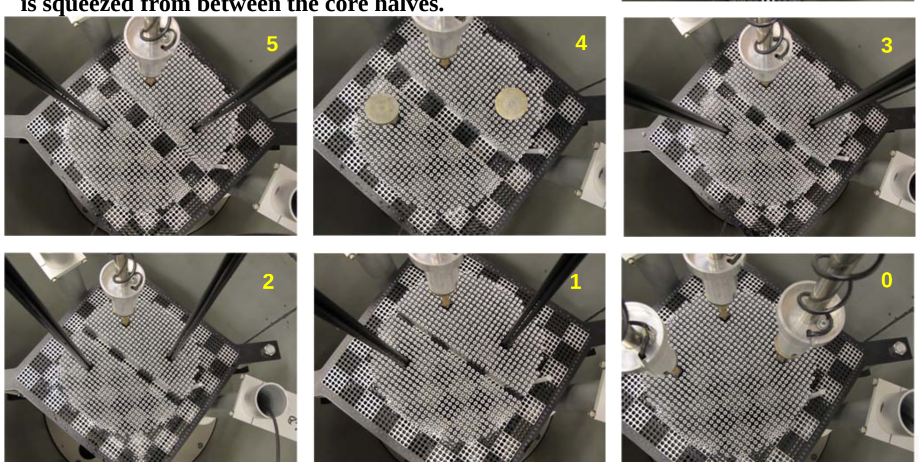


Fuel Rods: 921

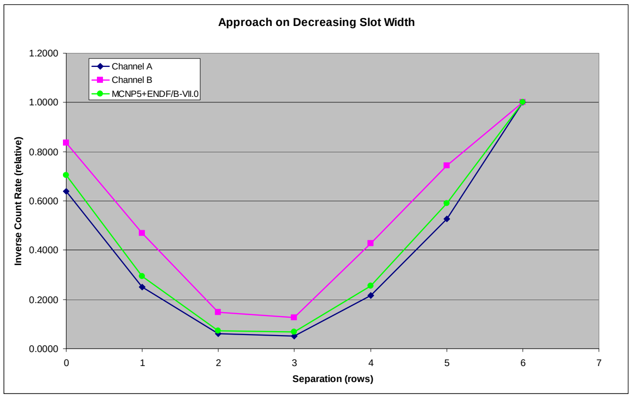
Fuel Separation Experiment



This experiment demonstrates the trade-off between increasing interaction between the core halves as they come together and decreasing moderation as the water is squeezed from between the core halves.



Approach on Fuel Separation



		Count Rate		Inverse Count Rate		Channel A		Channel B	
Rows	Holes	Ch. A	Ch. B	Ch. A	Ch. B	Projected	Next	Projected	Next
6	198	17957	45453	1.0000	1.0000				
5	165	34035	61171	0.5276	0.7430	3.88	4.44	2.11	3.55
4	132	82682	106178	0.2172	0.4281	3.30	3.65	2.64	3.32
3	99	346693	360622	0.0518	0.1260	2.69	2.84	2.58	2.79
2	66	290713	305421	0.0618	0.1488	8.19	5.10	8.53	5.27
1	33	71572	96942	0.2509	0.4689	2.33	1.66	2.46	1.73
0	0	28105	54327	0.6389	0.8367	1.65	0.82	2.27	1.14

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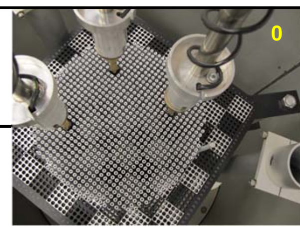
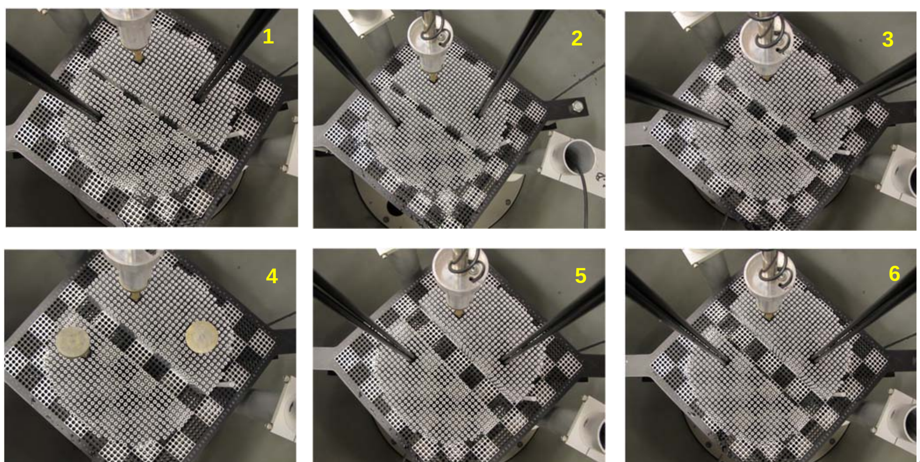
Fuel Separation (2)



The reverse order demonstrates increasing moderation first and the decrease in reactivity as the core halves move "to far" apart.



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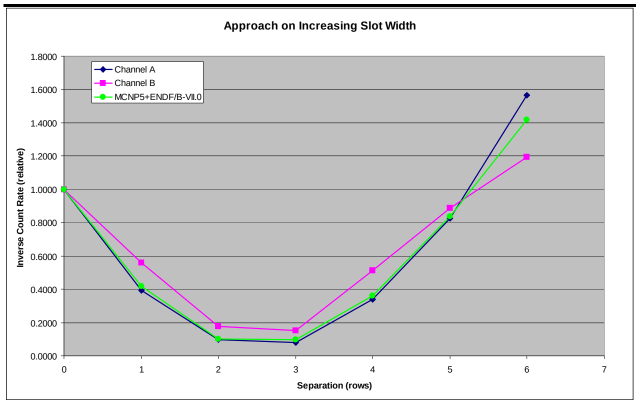
Approach on Fuel Separation (2)



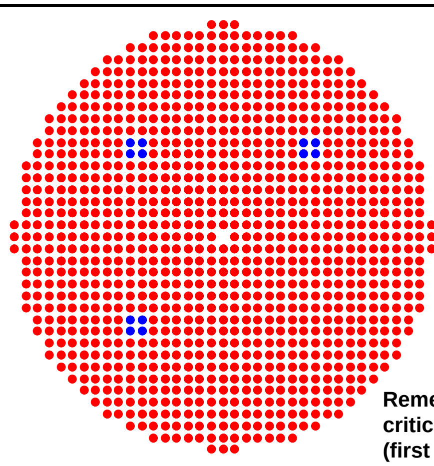
		Count Rate		Inverse Count Rate		Channel A		Channel B	
Rows	Holes	Ch. A	Ch. B	Ch. A	Ch. B	Projected	Next	Projected	Next
0	0	28105	54327	1.0000	1.0000				
1	33	71572	96942	0.3927	0.5604	1.65	1.32	2.27	1.64
2	66	290713	305421	0.0967	0.1779	2.33	2.16	2.46	2.23
3	99	346693	360622	0.0811	0.1506	8.19	5.60	8.53	5.77
4	132	82682	106178	0.3399	0.5117	2.69	3.34	2.58	3.29
5	165	34035	61171	0.8258	0.8881	3.30	4.15	2.64	3.82
6	198	17957	45453	1.5651	1.1952	3.88	4.94	2.11	4.05

Experiment 4
Interior Fuel Rod Removal

Experiment 4 Overview

- We determine the effect of removing fuel rods from the interior of the fuel array
- We are actually replacing fuel rods with water
- The primary criticality safety parameters that are investigated are fissile MASS and MODERATION
- Other parameters that are in play:
  - Reflection
  - Absorption
- Application to criticality safety:
  - What happens to a compact array of fuel lumps if the array becomes more spread out?

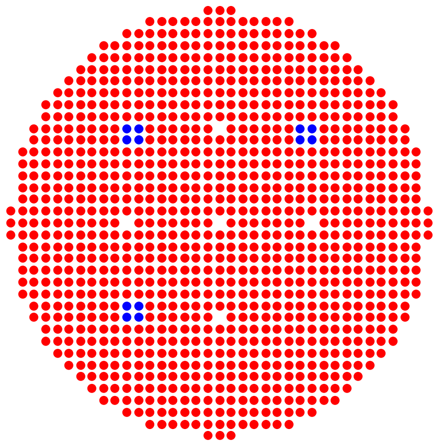
. Fuel Replacement with Water Configuration 0



Remember that this core is critical with about 1060 rods (first experiment)

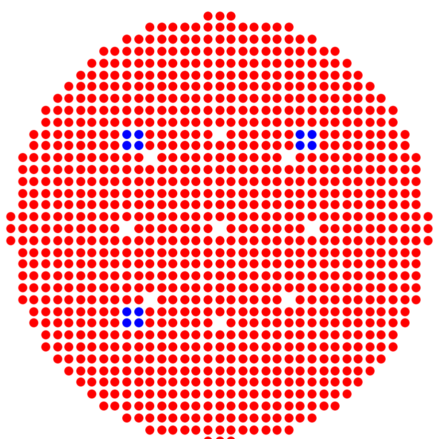
1032 Fuel Rods
0 Water Holes (the source doesn't count)

Fuel Replacement with Water Configuration 1



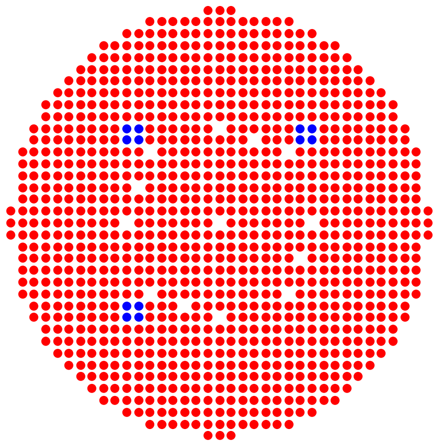
1028 Fuel Rods
4 Water Holes

Fuel Replacement with Water Configuration 2



1024 Fuel Rods
8 Water Holes

Fuel Replacement with Water Configuration 3



1020 Fuel Rods
12 Water Holes

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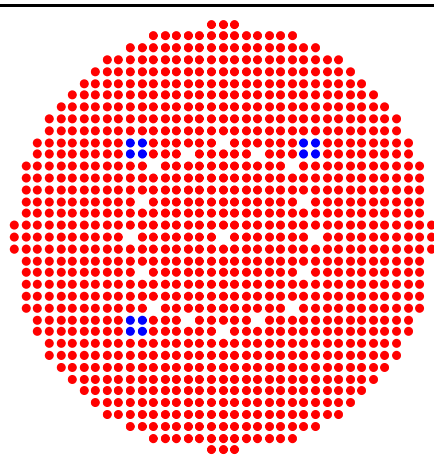
Fuel Replacement with Water Configuration 4



1016 Fuel Rods
16 Water Holes

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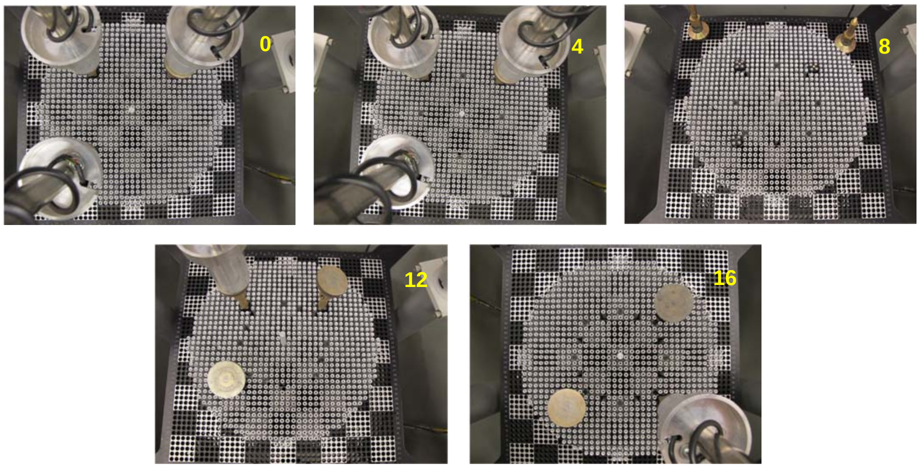
Approach on Water Holes



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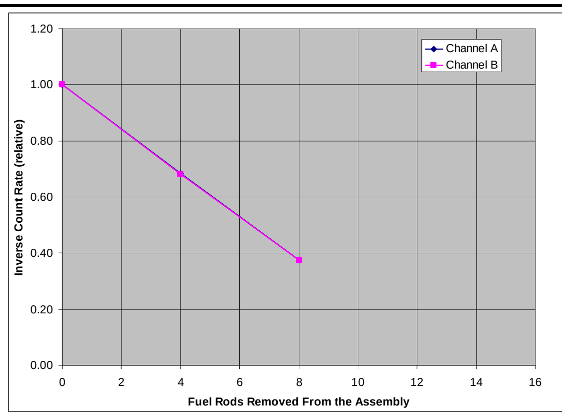
Approach on Water Holes



	Count Rate		Inverse Multiplication		Channel A		Channel B	
Rods	Ch. A	Ch. B	Ch. A	Ch. B	Projected	Next	Projected	Next
0	73697	69113	1.0000	1.0000				
4	107895	101371	0.6830	0.6818	12.62	8.31	12.57	8.29
8	196099	184739	0.3758	0.3741	12.89	10.45	12.86	10.43

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Concluding Remarks

- We are now offering a hands-on criticality experiments class as the second week in the NCSP T&EP course for Nuclear Criticality Safety Engineers
- The class focuses on four experiments, all using a different approach variable
- The experiments are accompanied by a series of lectures intended to supplement the experiments
- Sign up at http://ncsp.llnl.gov/classMain.html
  - 2-week (LANL/NCERC or LANL/Sandia) starting 1/28/13
  - 1-week NCERC experiments only starting 3/11/13
  - 2-week (LANL/NCERC or LANL/Sandia) starting 5/6/13
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