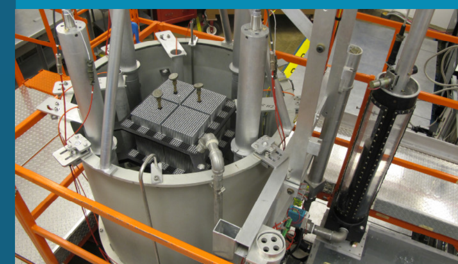
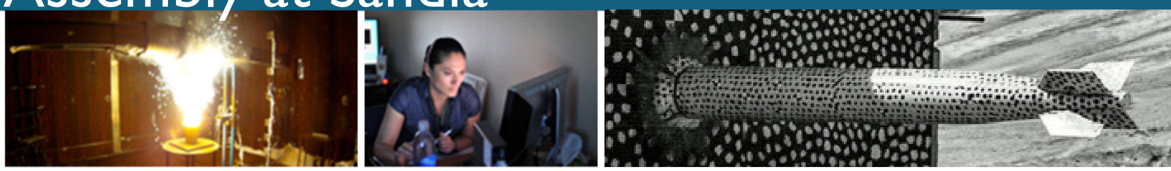
This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

Sandia National Laboratories

Experiments to Measure the Inversion Point of the Isothermal Reactivity Coefficient in a Water-Moderated Pin-Fueled Critical Assembly at Sandia





Gary A. Harms and David E. Ames

Nuclear Criticality Safety Division Topical Meeting (NCSD 2022)
Anaheim, CA
June 12-16, 2022

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Experiments to measure temperature effects

Two experiment series are planned to measure temperature effects in the Sandia Critical Experiments

The first series (IER-304) will measure the critical size of a fuel rod configuration at several temperatures

- The temperature of the critical assembly will be set and an approach-to-critical experiment on the number of fuel rods in the critical assembly or the water depth in the core tank will be done
- This series was requested and designed by Oak Ridge National Laboratory
- Sandia now leads the execution phase of the experiment

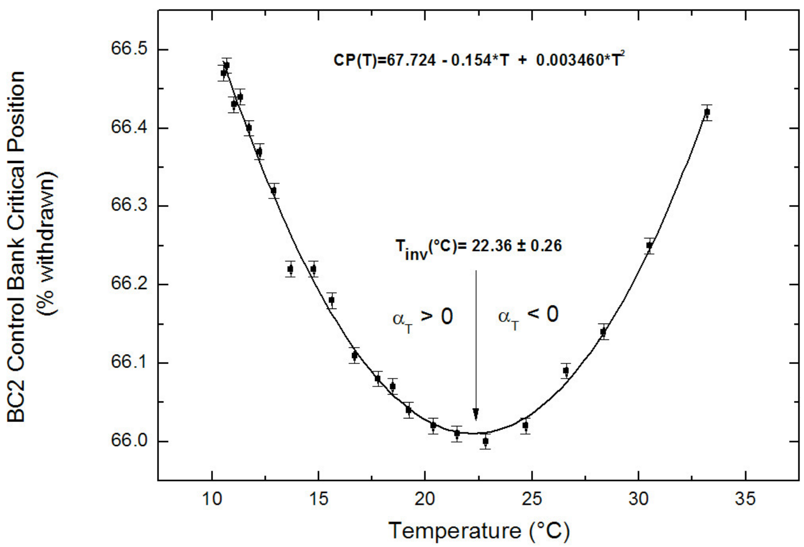
The second series (IER-452) will measure the inversion temperature of the isothermal reactivity coefficient in the Sandia critical assembly

- The fuel rod array will be set and the temperature of the critical assembly will be varied to determine the temperature that yields the highest reactivity of the system
- This series is in preliminary design and is lead by Sandia

Each experiment in the second series will be preceded by one or more experiments in the first series

This paper addresses the conceptual design of the inversion temperature experiments

IPEN(MB01)-LWR-RESR-017 – Inversion Point of the Isothermal Reactivity Coefficient of the IPEN/MB-01 Reactor



Control Rod Position vs Temperature
IPEN Configuration C

The beauty of this experiment is that very little physics information is needed about the target system

One just has to be able to make relative reactivity measurements as a function of temperature

International Reactor Physics Experiment Evaluation Project: International Handbook of Evaluated Reactor Physics Benchmark Experiments

IPEN(MB01)-LWR-RESR-017
THE INVERSION POINT OF THE ISOTHERMAL REACTIVITY COEFFICIENT OF THE IPEN/MB-01 REACTOR
Adimir dos Santos et al.

The experiment was done by measuring the critical control rod position as a function of reactor temperature

The inversion temperature is the temperature that yields the maximum system reactivity

It coincides with the temperature that yields the minimum critical control rod position

Adimir and his colleagues measured three systems with T_{inv} between 14.99 and 22.36 ^{0}C and published a benchmark in the 2016 edition of the handbook

A different way to measure the inversion temperature

The IPEN experiments were done by measuring the critical control rod height as a function of temperature

- The inversion temperature was the temperature with the lowest control rod height (maximum reactivity) at delayed critical

We propose to perform similar experiments by measuring detector count rates as a function of temperature in an otherwise static system

The subcritical multiplication and reactivity of a configuration are given by

$$M = \frac{1}{1-k_{eff}} \quad \text{and} \quad \rho = \frac{k_{eff}-1}{k_{eff}}$$

Combine to get

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

When a system is near critical, the count rates in detectors near the system are proportional to the subcritical multiplication of the system.

If the count rates of a subcritical system are measured as a function of temperature, the inversion temperature will be the temperature with the highest count rate

Calculating k_{eff} as a function of temperature in water-moderated critical experiments

Estimating temperature effects in a water-moderated critical experiment is done by

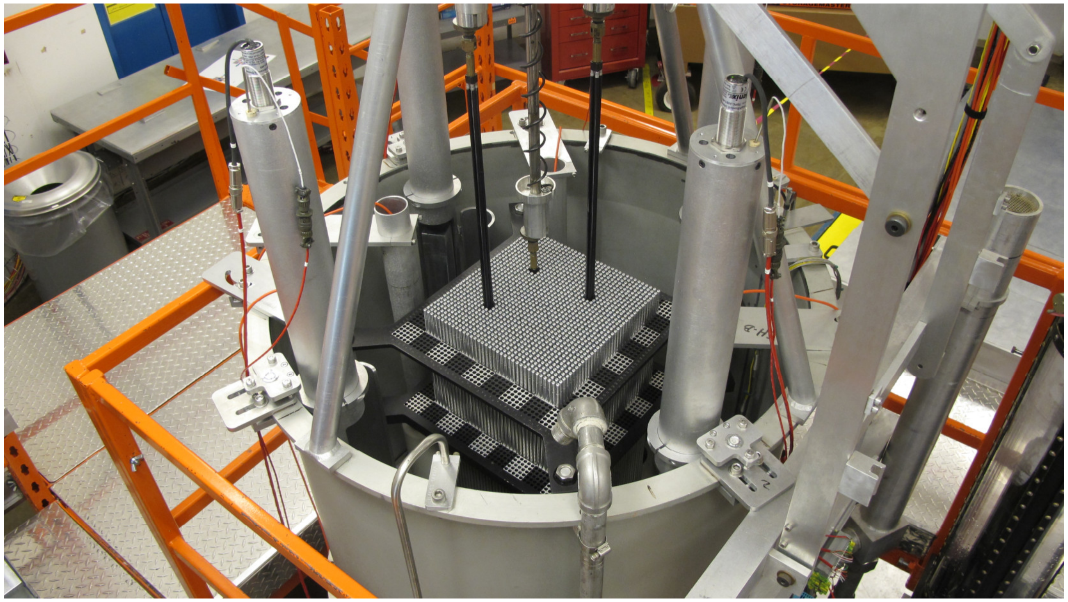
1. Assuming the temperature effects are separable into contributions from the fuel and the water
2. Calculating k_{eff} as a function of fuel temperature while holding the water temperature constant
3. Calculating k_{eff} as a function of water temperature while holding the fuel temperature constant
4. Convert the k_{eff} results to reactivity and add the two temperature-dependent reactivities

The fuel calculation is done by calculating the system k_{eff} at several **fuel** temperatures accounting for thermal expansion of the fuel and doppler broadening of the cross section resonances

The water calculation is done by calculating the system k_{eff} at several **water** temperatures accounting for the changes in the water density with temperature and the temperature dependence of the thermal scattering in the water

The two reactivities are combined to obtain the total reactivity of the experiment as a function of temperature

First, the configuration of the critical assembly to be discussed



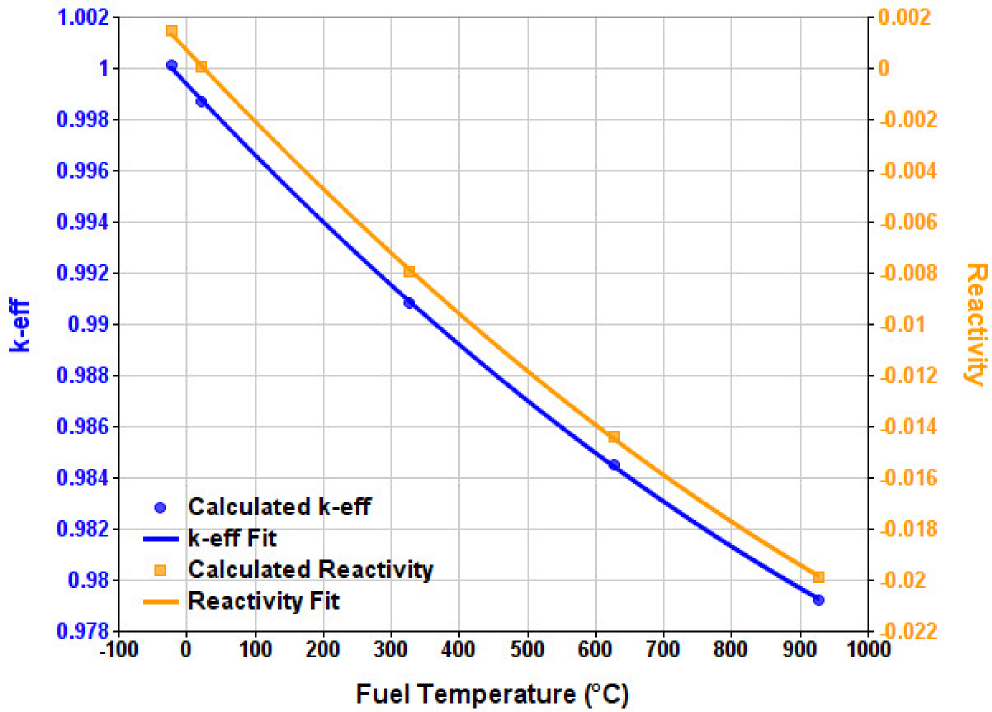
LEU-COMP-THERM-101 reported on 22 partially-reflected fuel rod arrays

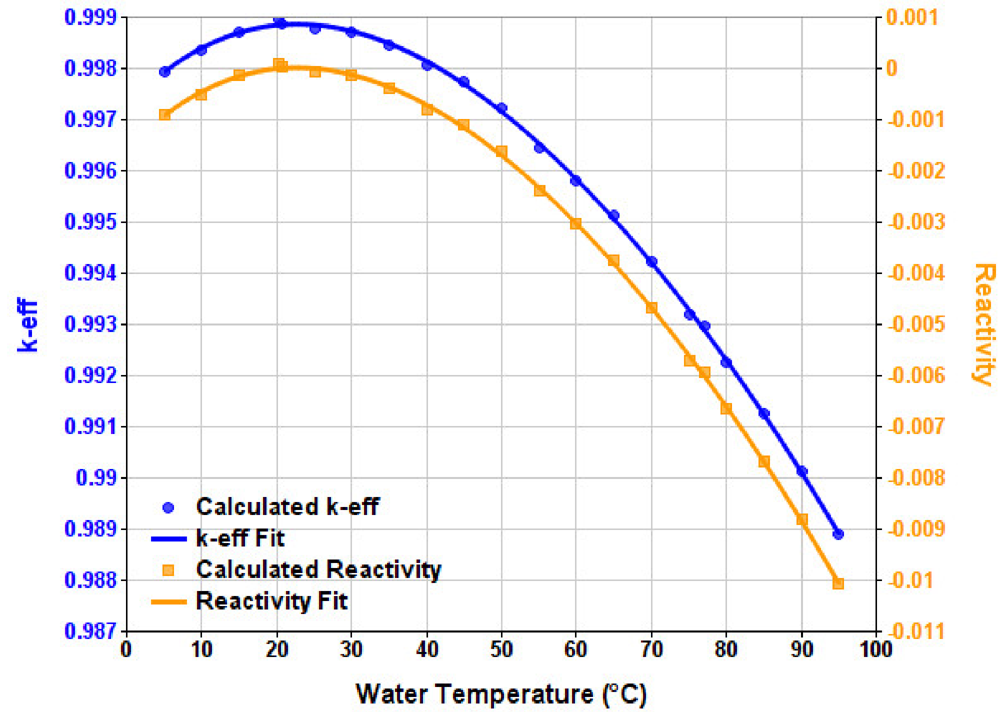
The critical water height was measured for each configuration

This is a photograph of the fuel array measured in LEU-COMP-THERM-101 Case 10

The fuel is in a square 36x36 array of 1296 fuel rods with no holes in the approximate center of the critical assembly

Calculate k_{eff} as a function of temperature

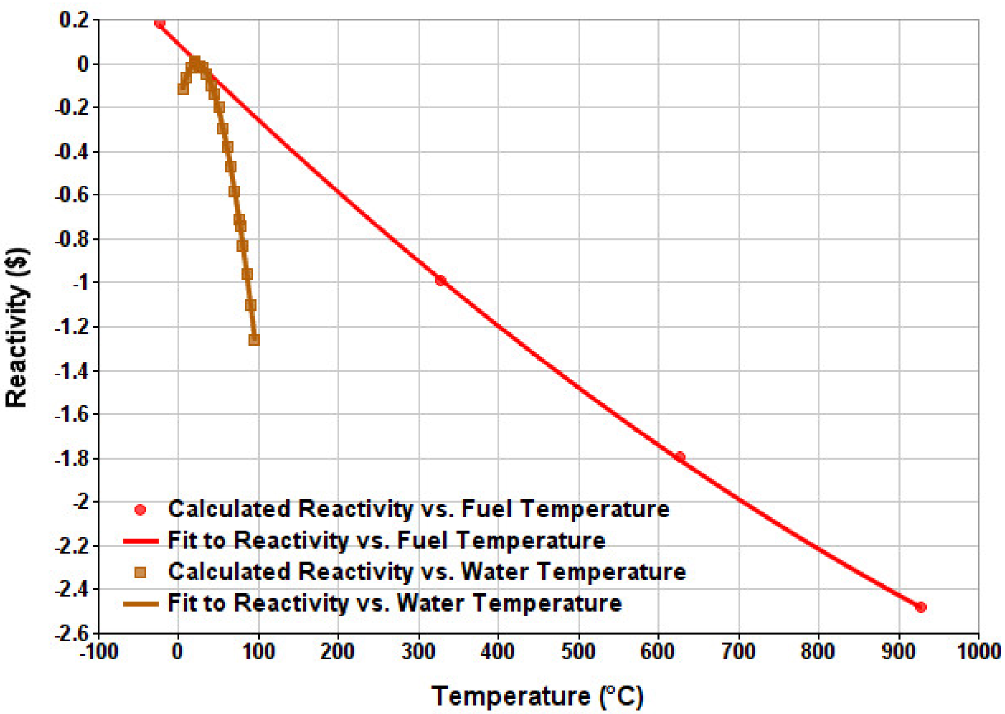


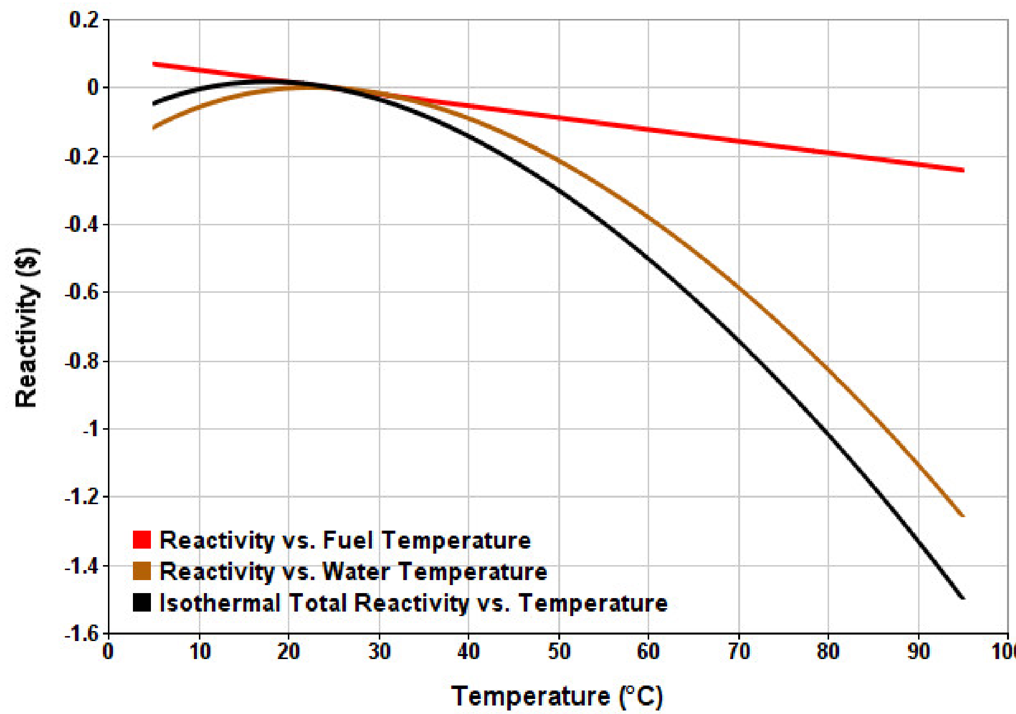


- **Hold water temperature at 298.15 K (25 ºC)**
- **Vary fuel temperature from 250 K to 1200 K**
  - **Use fuel cross sections appropriate for the temperature**
  - **Match fuel dimensions to temperature**
- **The curve is a second-order fit**

- **Hold fuel temperature at 293.6 K**
- **Vary water temperature from 5 ºC to 95 ºC**
  - **Vary water density with temperature**
  - **Use water scattering data [S(α,β)] appropriate for the temperature**
- **The curve is a fourth-order fit**

Combine the calculations



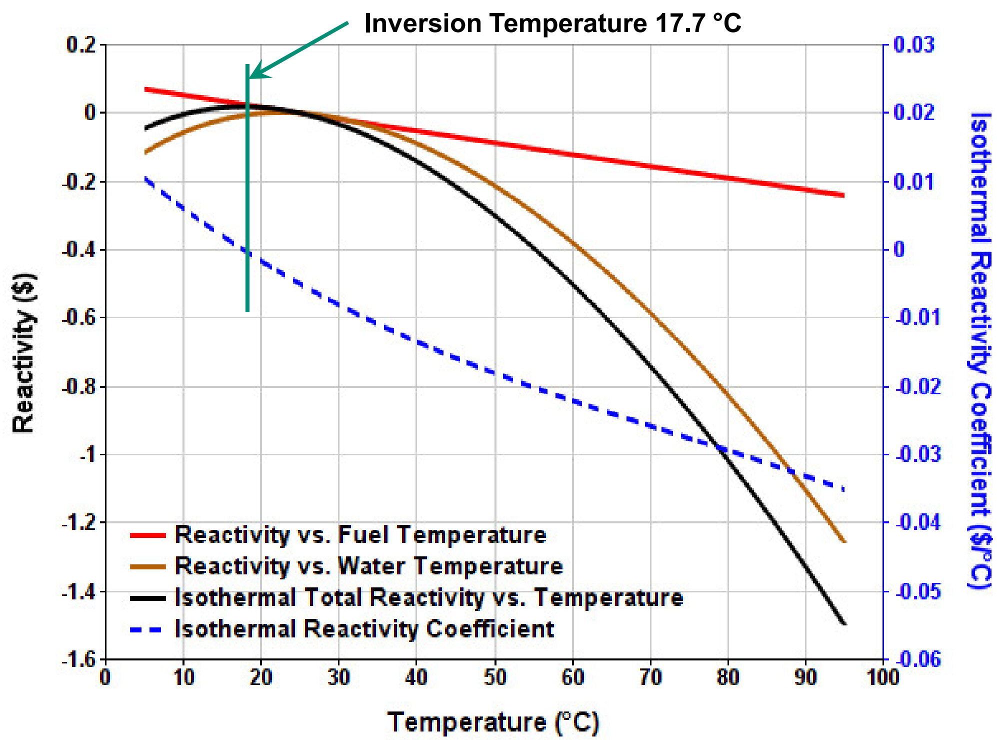


- **Put the two reactivity plots on the same temperature scale**
- **Change the reactivities to dollars (β_{eff}=0.00800)**

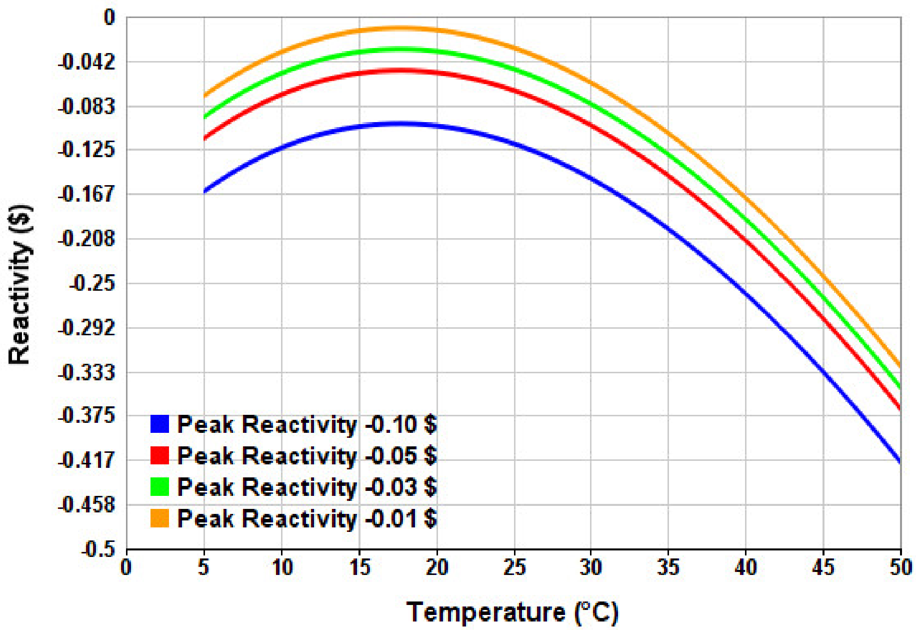
- **The reactivity as a function of fuel temperature is red**
- **The reactivity as a function of water temperature is brown**
- **Sum the two reactivities to get the total reactivity (black)**

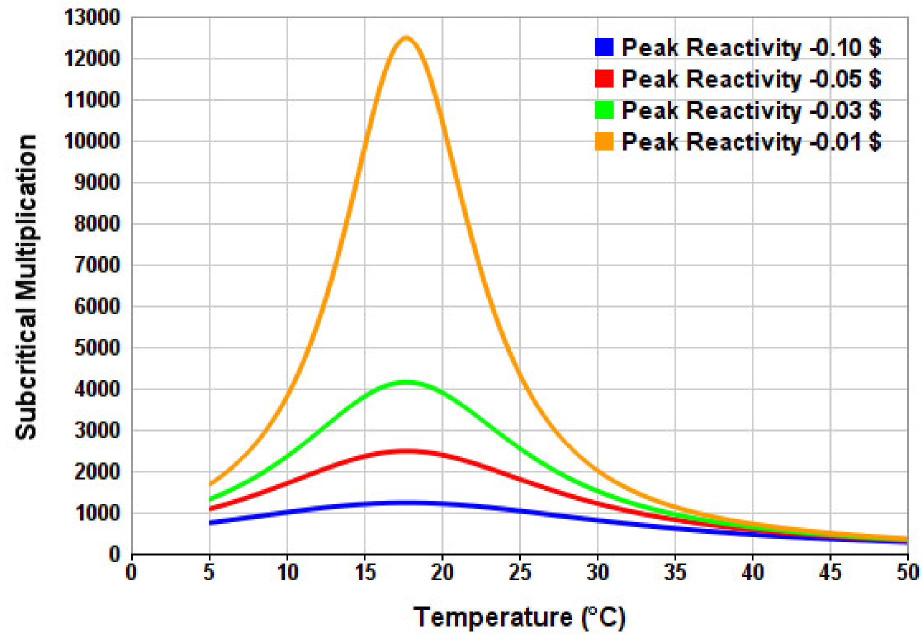
Differentiate the total reactivity to obtain the temperature coefficient

- **Take the plot from the last slide and add another curve (blue dashes)**
- **The isothermal reactivity coefficient is the derivative of the total reactivity**
- **The inversion temperature is the temperature at which the isothermal reactivity coefficient passes through zero**
- **Not surprisingly, it is also the temperature of the reactivity maximum**



A proposed inversion temperature experiment



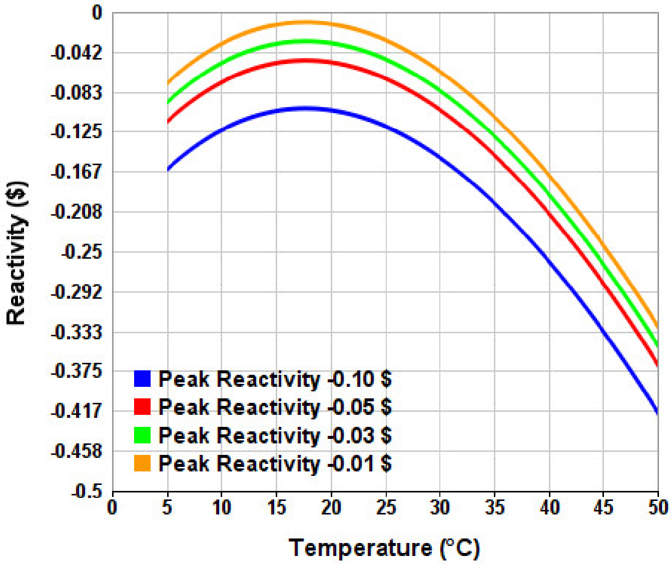


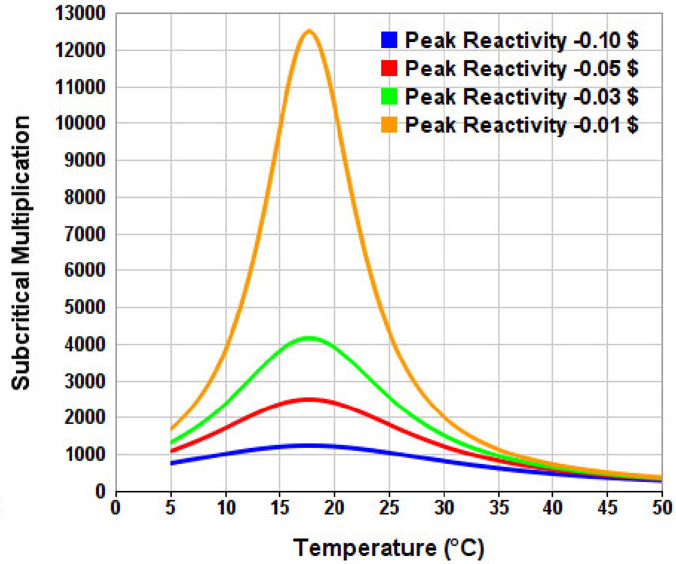
Using the relationship between the multiplication (count rate) and the reactivity

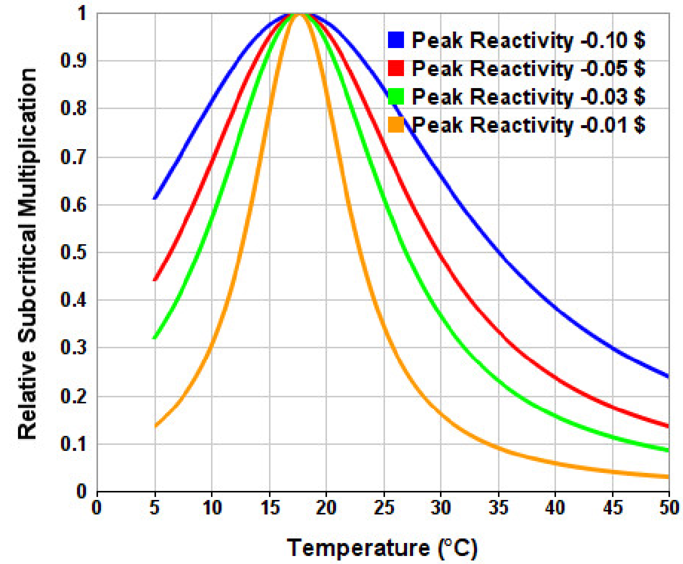
$$M = \frac{\rho - 1}{\rho}$$

The second plot shows the multiplication of the system as a function of temperature for several different values of the peak reactivity

A proposed inversion temperature experiment



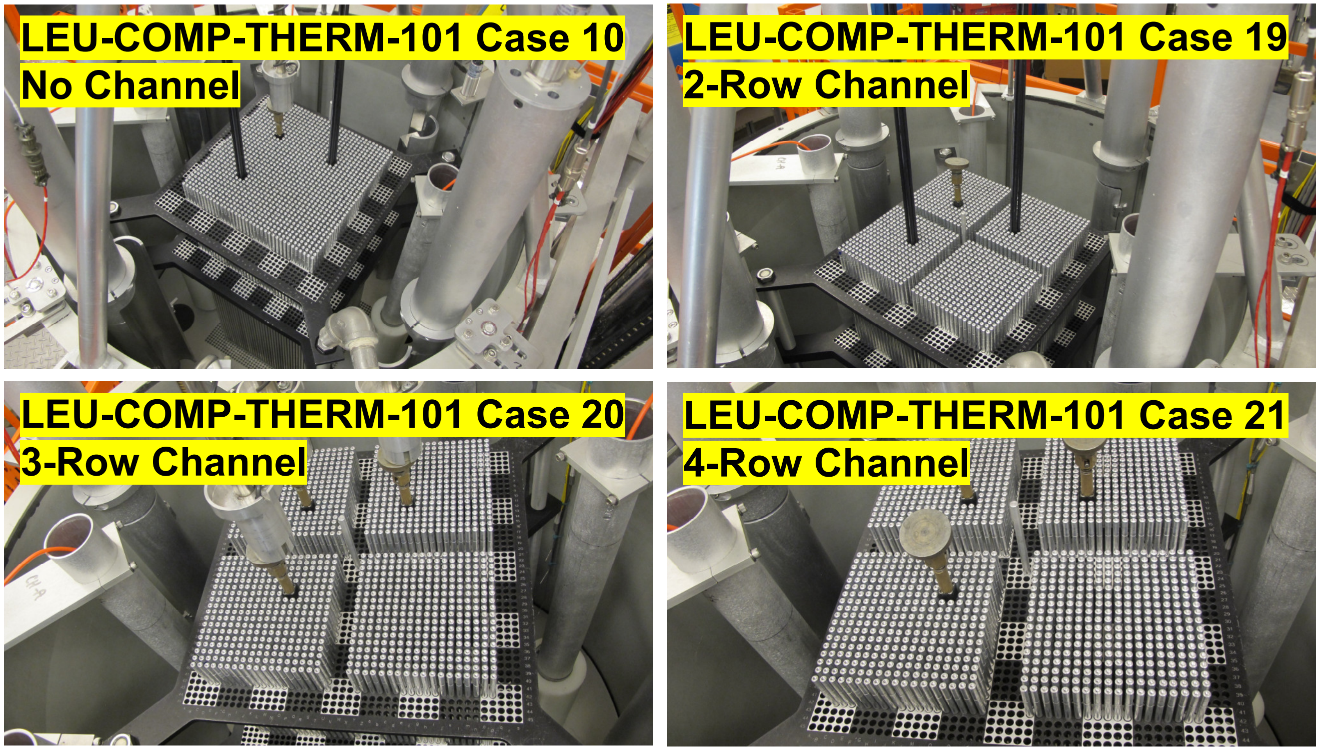




Our ability to pinpoint the inversion temperature depends on the width of the subcritical multiplication vs temperature curve and on the resolution of our count rate measurements

The third plot shows the inverse multiplication of the system for several different values of the peak reactivity normalized to the same peak inverse multiplication

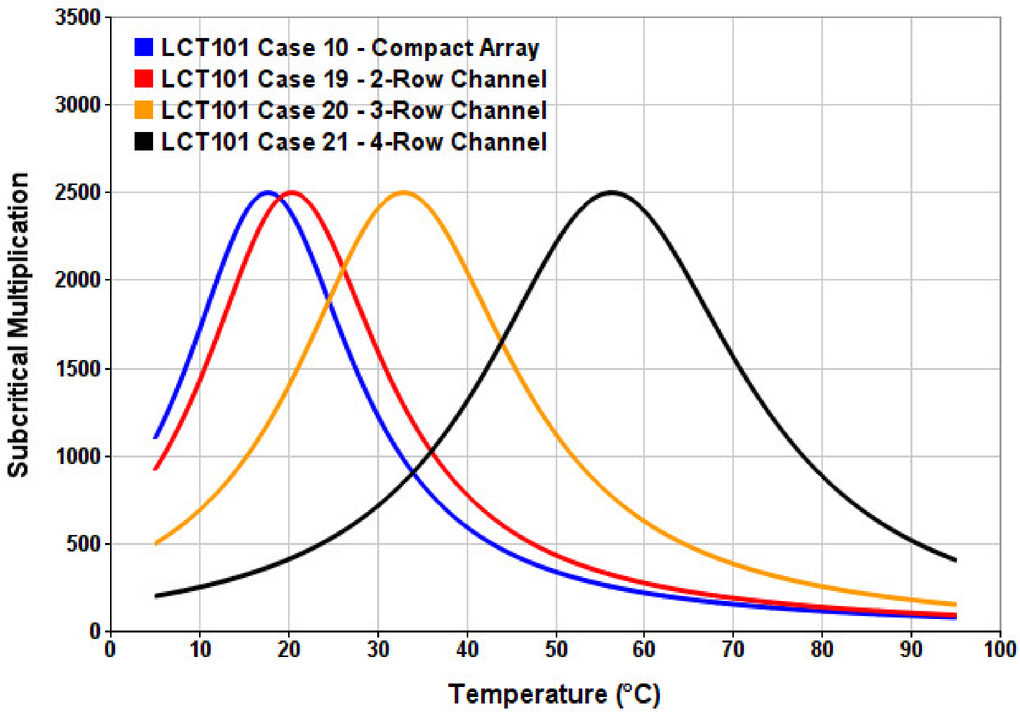
Now look at a potential experiment series



The upper left photo is the 36x36 array of 1296 fuel rods discussed earlier.

The remaining configurations split the 36x36 array into four 18x18 arrays with varying inter-array water channel widths

Calculated inversion temperature results for the experiment series



Channel Width (rows)	Linear Water Channels			Cruciform Water Channels		
	LCT101 Case	Critical Water Height (cm)	Inversion Temp-erature (°C)	LCT101 Case	Critical Water Height (cm)	Inversion Temp-erature (°C)
0	10	40.34	17.7	10	40.34	17.7
1	12	37.32	17.1	18	35.02	15.9
2	13	36.00	19.1	19	33.29	20.4
3	14	36.31	23.6	20	34.28	32.9
4	15	37.87	31.9	21	37.91	56.3
5	16	40.90	44.9	22	45.21	89.5
6	17	45.61	60.8	—	—	—

The plot shows the calculated subcritical multiplication of the four configurations of 1296 fuel rods as a function of temperature for a peak reactivity of -0.05 $

LEU-COMP-THERM-101 reported on eleven configurations with 1296 fuel rods shown in the table.

Some had linear water channels between halves of the original fuel array while the others had cruciform water channels between quarters of the original fuel array – all would make good experiments here

To wrap it up …

Here is what I've discussed:

1. A brief description of two temperature experiments in the works at Sandia
2. Adimir Dos Santos' experiments that provided the concept for our inversion temperature experiments
3. Our proposed method of measuring the inversion temperature
4. The methods we use to calculate the temperature effects in our experiments
5. An analysis of a specific experiment configuration (LEU-COMP-THERM-101 Case 10)
6. A proposed experiment series and calculated results for four related configurations giving significantly different calculated inversion temperature results

Thank you for your attention.

Critical Experiments at Sandia

This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.