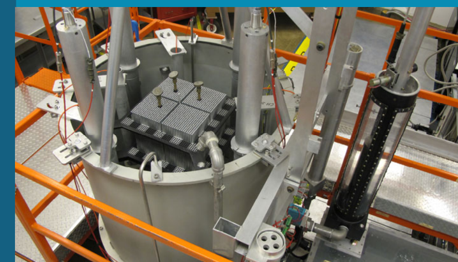
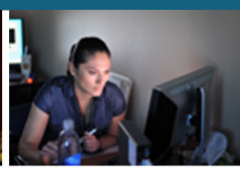
SAND2020-12667C

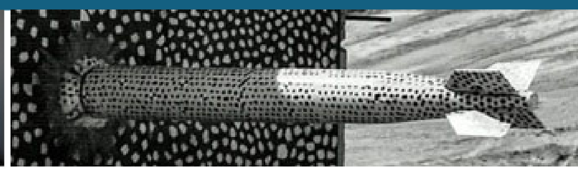
This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

Sandia National Laboratories

Experiments at Sandia to Measure the Effect of Temperature on Critical Systems







Gary A. Harms and David E. Ames

2020 ANS Virtual Winter Meeting
November 16-19, 2020

Temperature sensitivities in water-moderated critical experiments

Estimating the k_{eff} uncertainty in a water-moderated critical experiment contributed by uncertainty in the experiment temperature is done by

1. Estimating the sensitivity of k_{eff} to the temperature of the fuel
2. Estimating the sensitivity of k_{eff} to the temperature of the water
3. Combining the two sensitivities and multiplying by the uncertainty in the temperature

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

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

The two sensitivities are combined to obtain the overall sensitivity of the experiment

Experiments to measure temperature effects

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

The first series 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 will be done
- This series is currently lead by Justin Clarity at Oak Ridge National Laboratory

The second series will measure the inversion temperature of the isothermal reactivity coefficient

- 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 lead by Sandia

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

LEU-COMP-THERM-096 Case 10

In 2014-2015 Sandia performed water-moderated partially-reflected critical experiments using 6.9 % enriched UO2 fuel

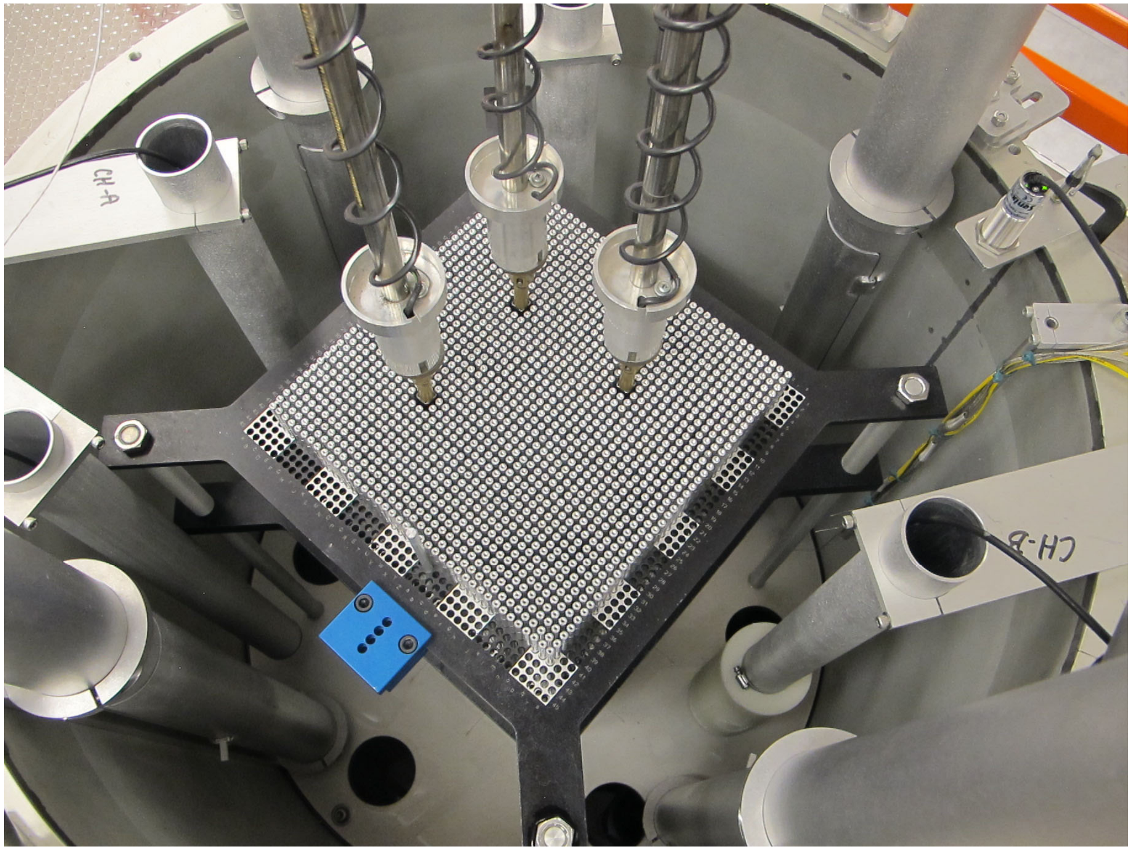
The experiments are documented as LEU-COMP-THERM-096

Case 10 was a 36x36 array of fuel rods.

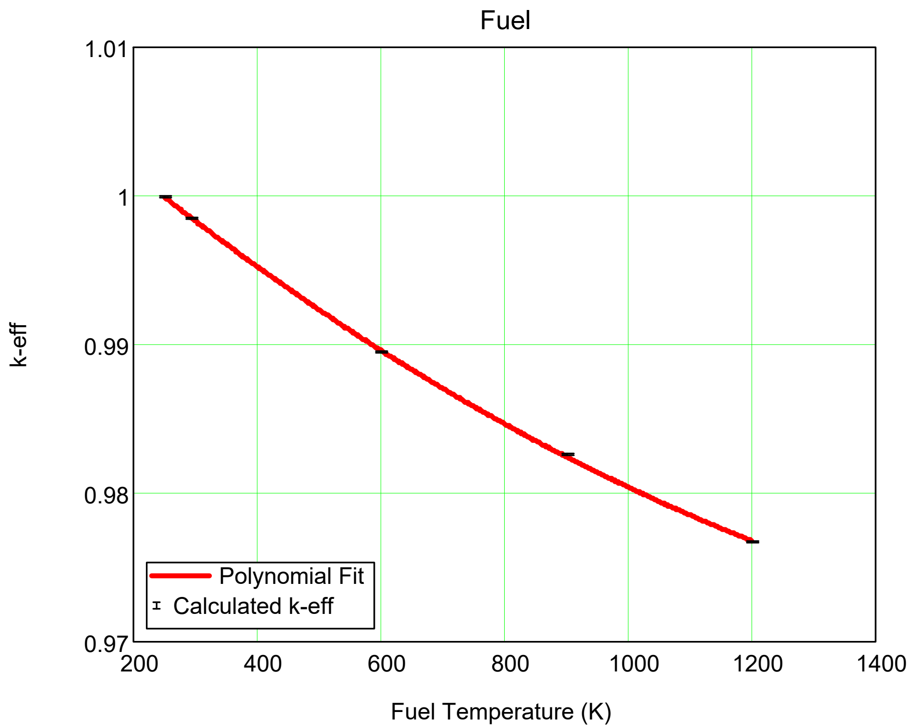
The critical water level was measured in an approach-to-critical experiment on the depth of the water in the core tank

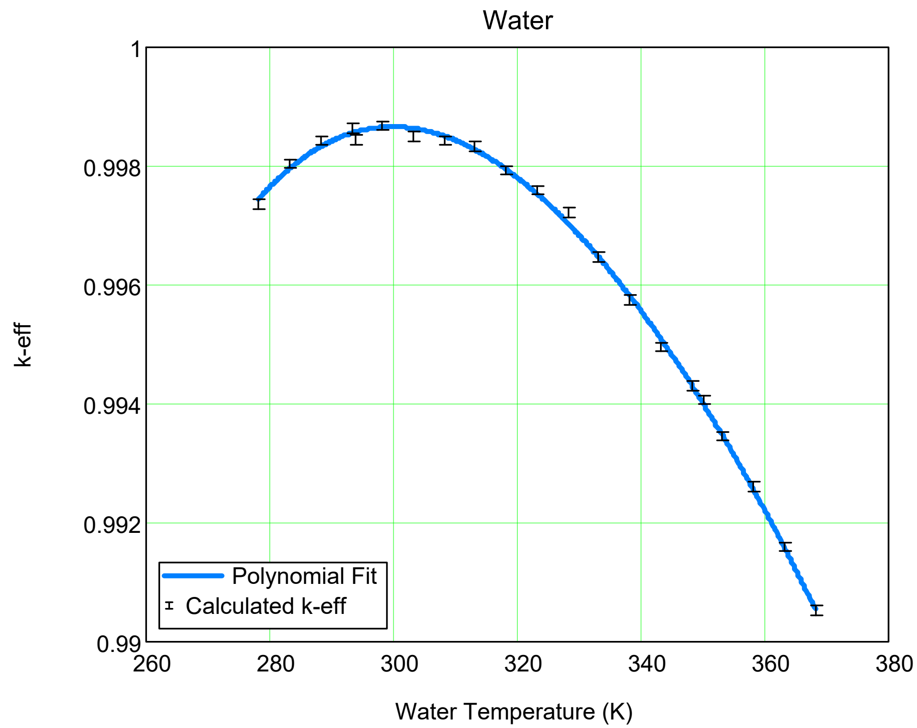
This configuration was the start of a series of experiments in which the fuel was equally split into two or four lobes with variable-width water channels between the lobes

The methods used to calculate the temperature sensitivity of this configuration are described in the slides that follow



LEU-COMP-THERM-096 Case 10

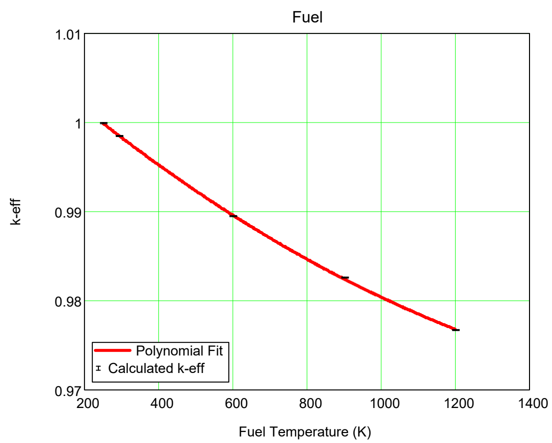


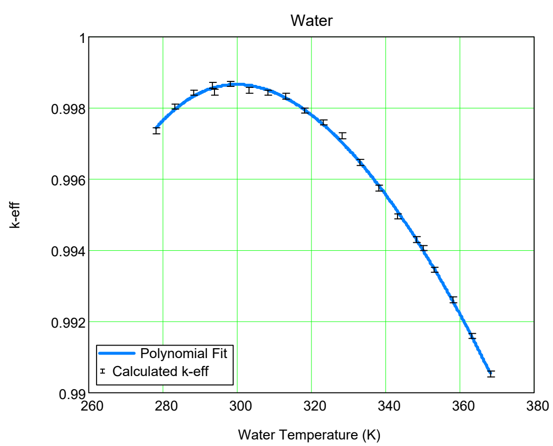


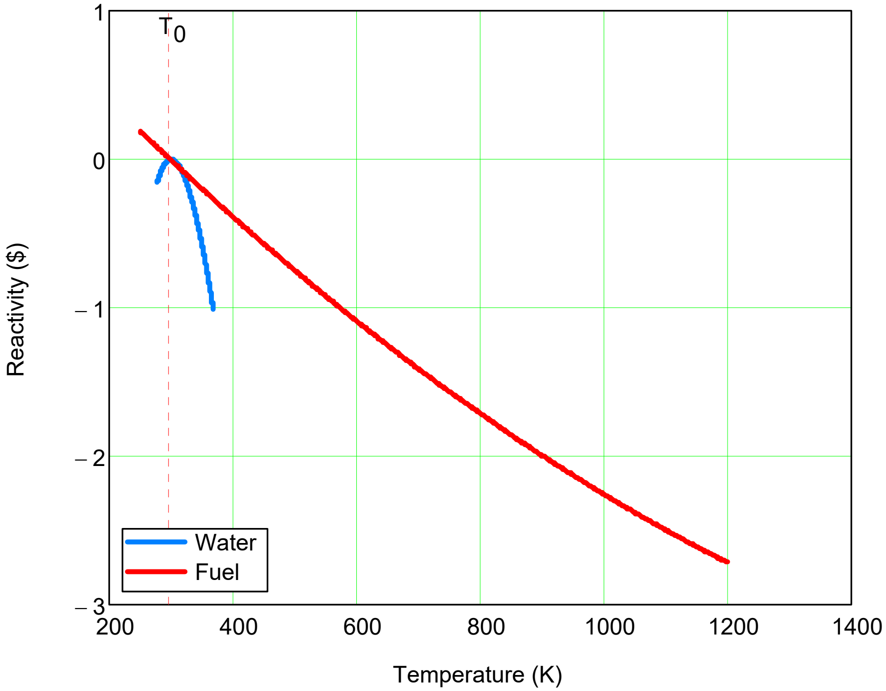
- **Hold water temperature at 298.15 K (25 ºC)**
- **Vary fuel temperature from 250 K to 1200 K**
  - **Use fuel cross sections appropriate for the temperature**
  - **Match fuel dimensions to temperature**
- **The curve is a second-order fit**

- **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**

LEU-COMP-THERM-096 Case 10

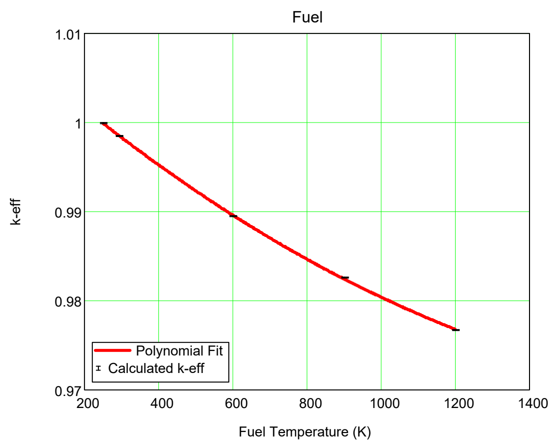


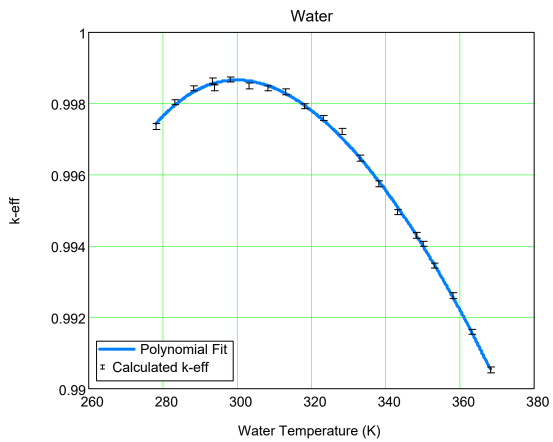


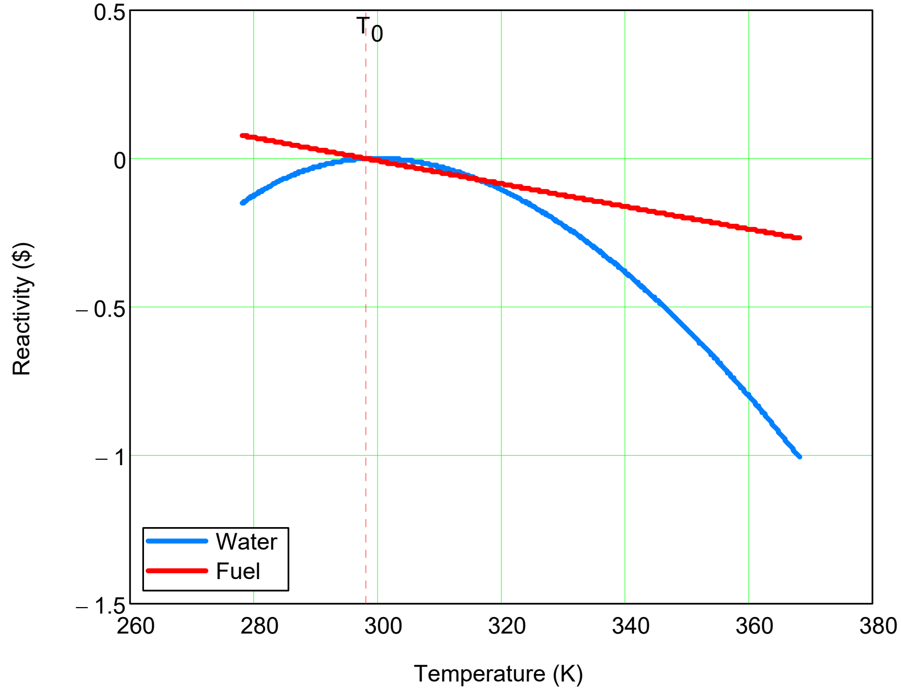


- **Convert k_{eff} data to reactivity normalized at 25 ºC (T_0)**

LEU-COMP-THERM-096 Case 10

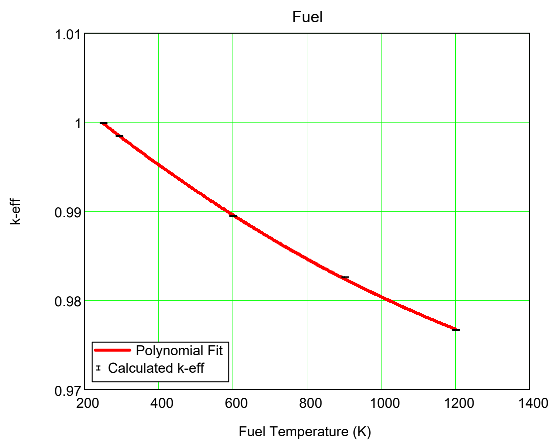


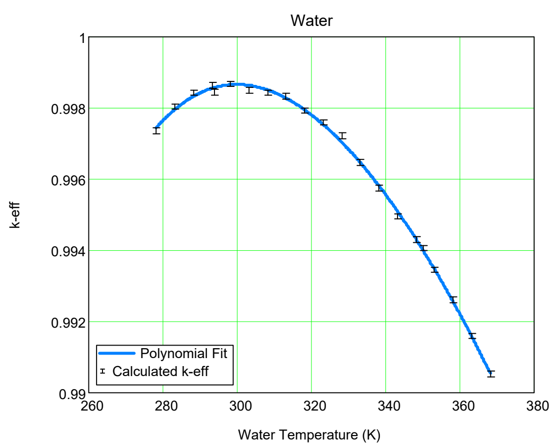


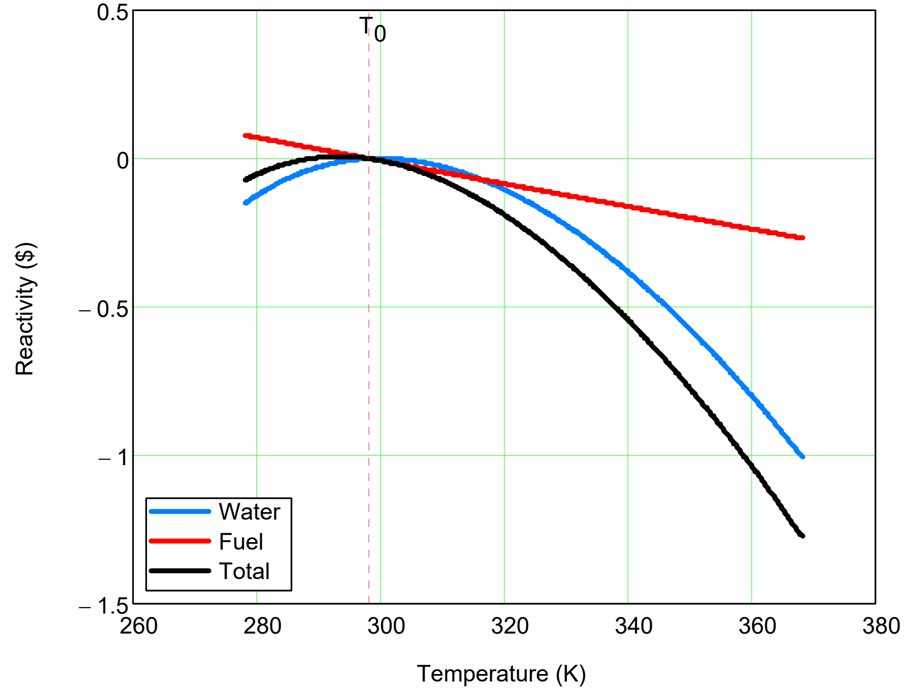


- **Convert k_{eff} data to reactivity normalized at 25 ºC (T_0)**
- **Expand the temperature scale to cover liquid water temperatures**

LEU-COMP-THERM-096 Case 10

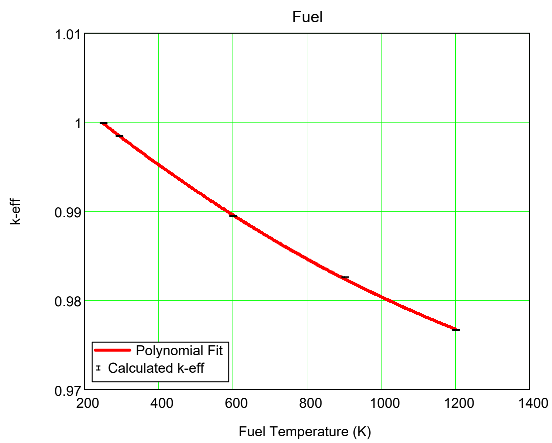


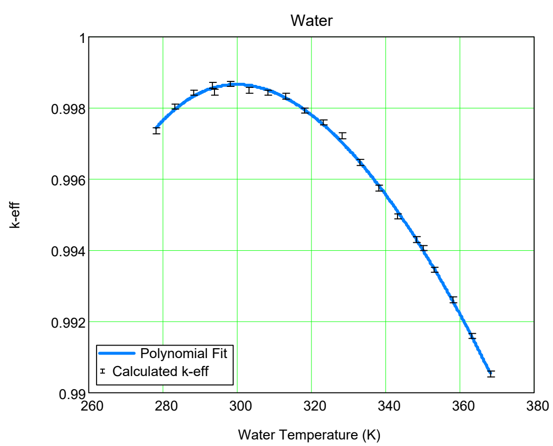


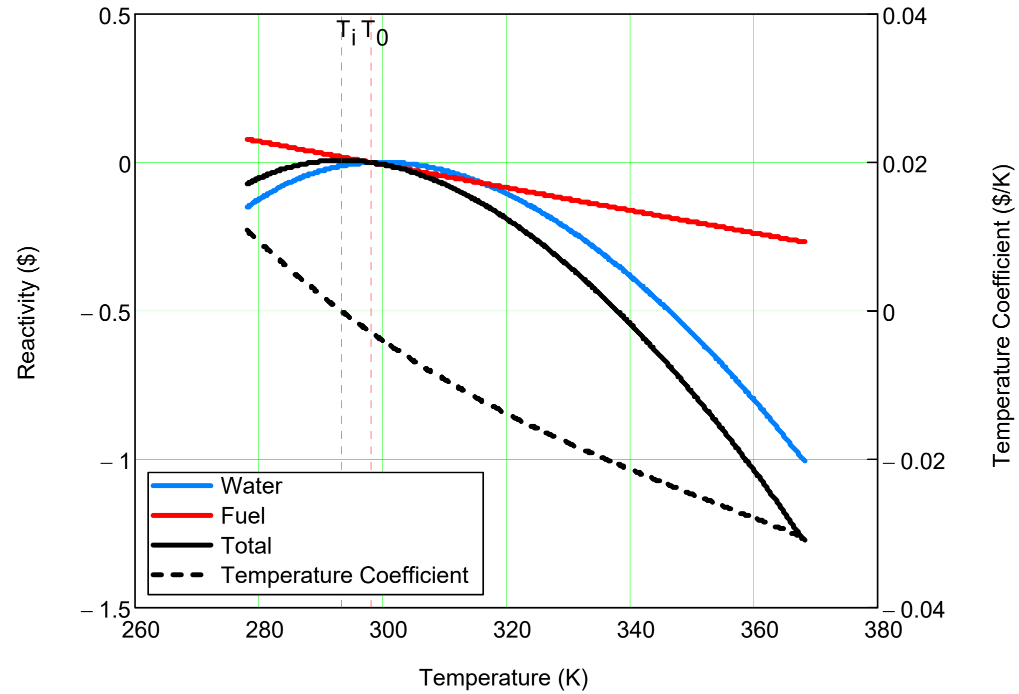


- **Convert k_{eff} data to reactivity normalized at 25 ºC (T_0)**
- **Expand the temperature scale to cover liquid water temperatures**
- **Sum the two curves to get the total reactivity curve**

LEU-COMP-THERM-096 Case 10

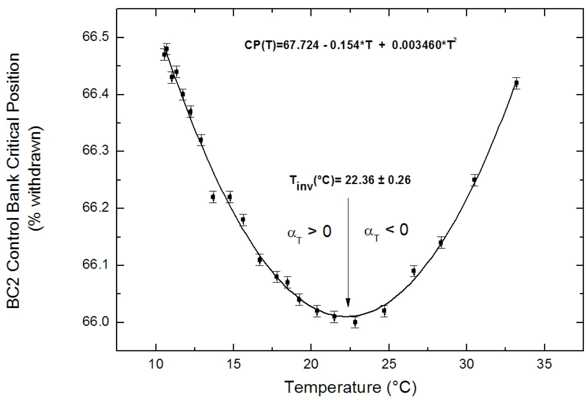


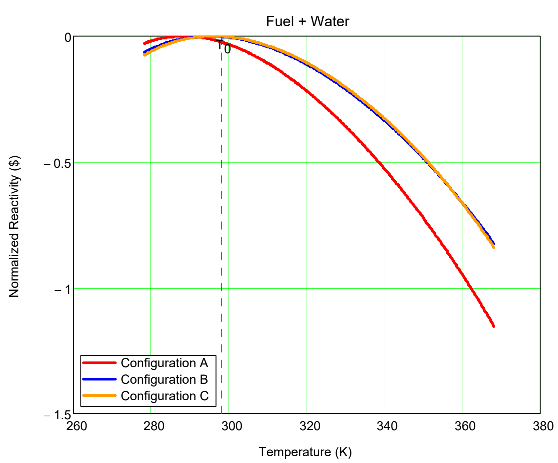




- **The slope of the total reactivity curve is the temperature coefficient (sensitivity)**
- **The point at which the temperature coefficient changes sign is the inversion temperature, T_i**

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





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.

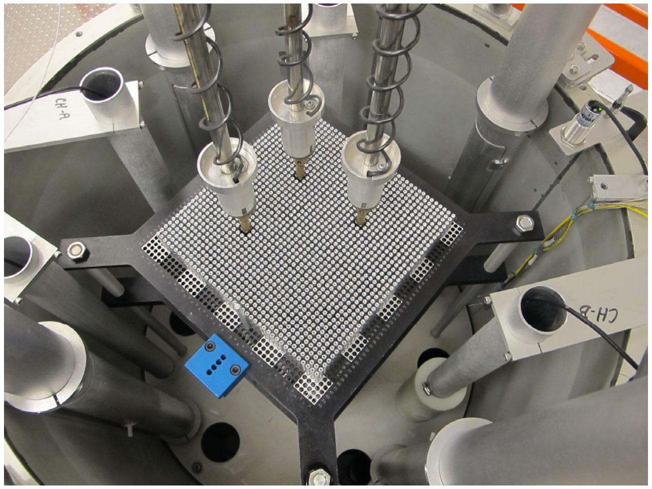
The experiment was done by measuring the critical control rod position as a function of reactor temperature

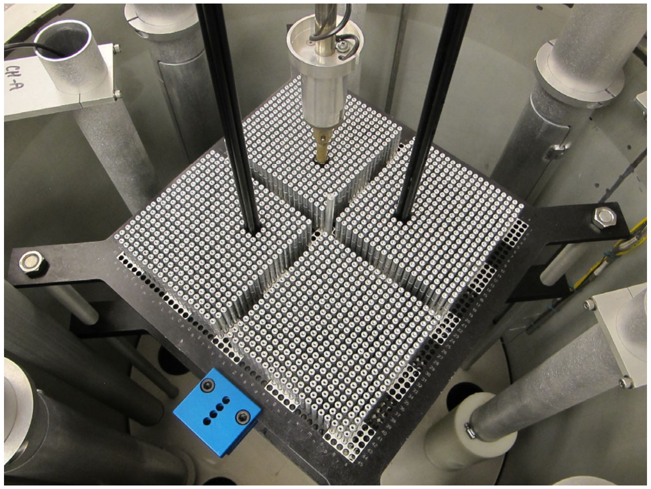
Adimir and his colleagues measured three systems with T_{inv} between 14.99 and 22.36 C

What IS NOT required:
Knowledge (measurement/calculation/guess) of the kinetics parameters of the system

LEU-COMP-THERM-096 Cases 10, 17, 18, and 19

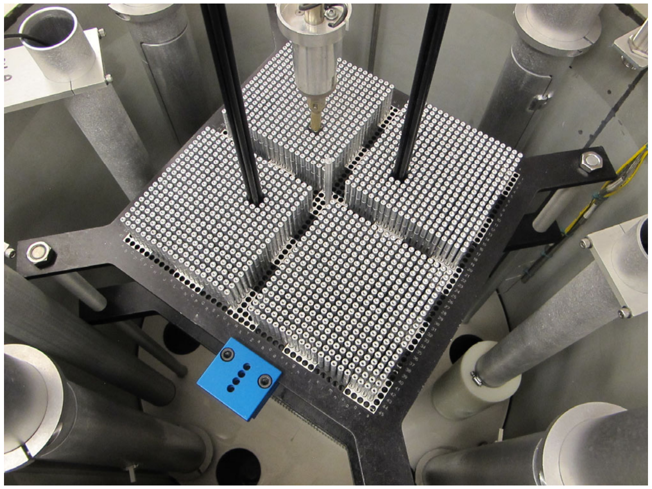
LCT096 Case 10
No channel
1600 fuel rods

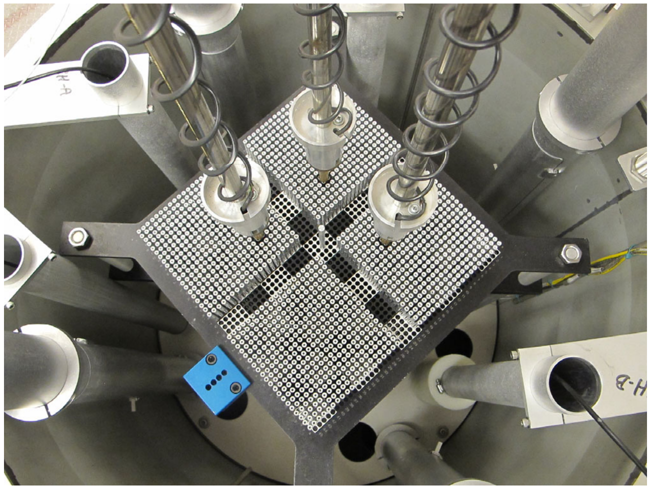




LCT096 Case 17
Two-row channel
1600 fuel rods

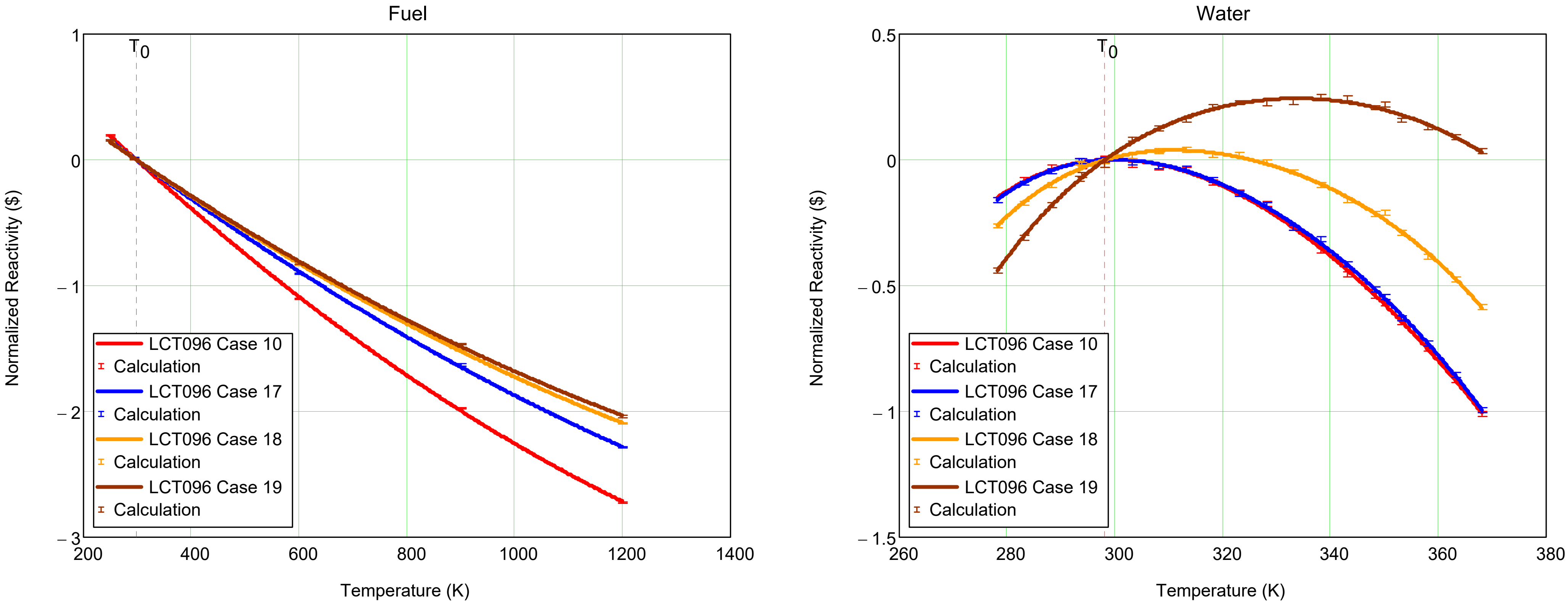
LCT096 Case 18
Three-row channel
1600 fuel rods



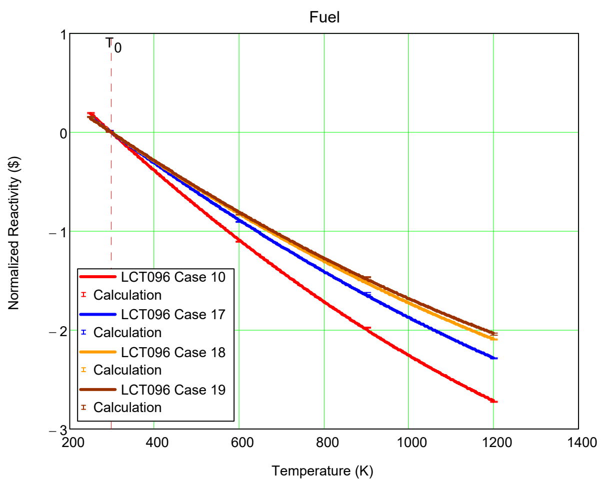


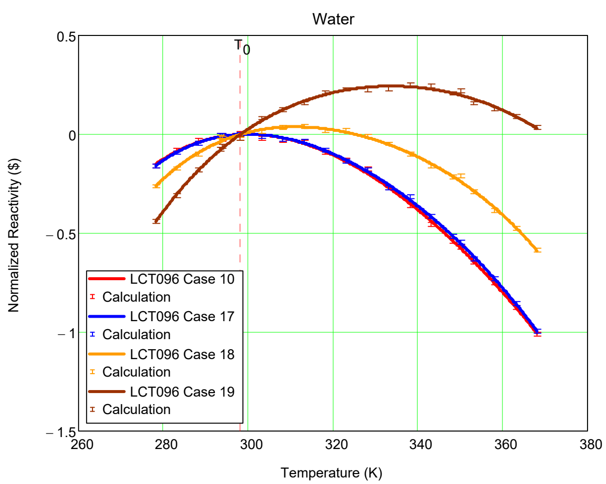
LCT096 Case 19
Four-row channel
1600 fuel rods

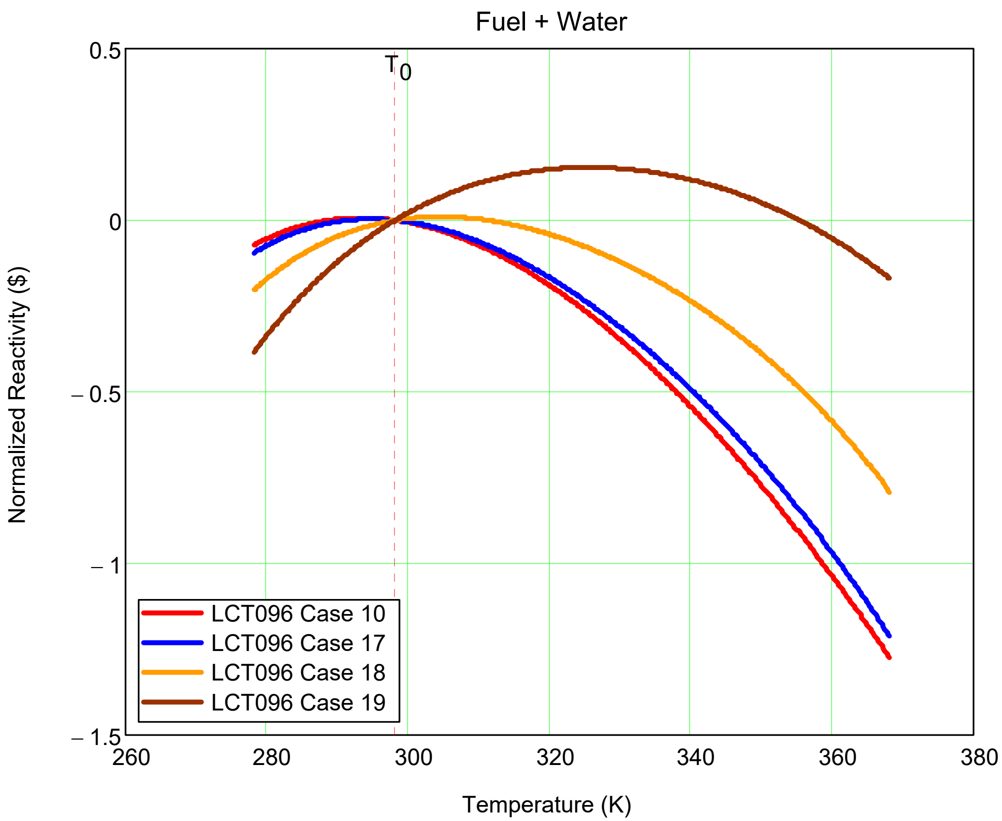
LEU-COMP-THERM-096 Cases 10, 17, 18, and 19



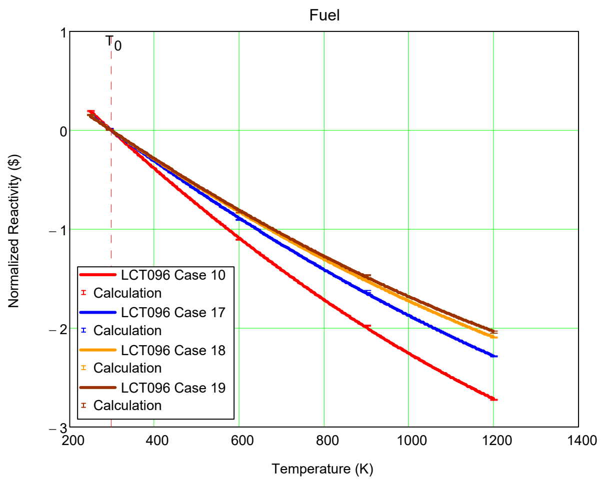
LEU-COMP-THERM-096 Cases 10, 17, 18, and 19

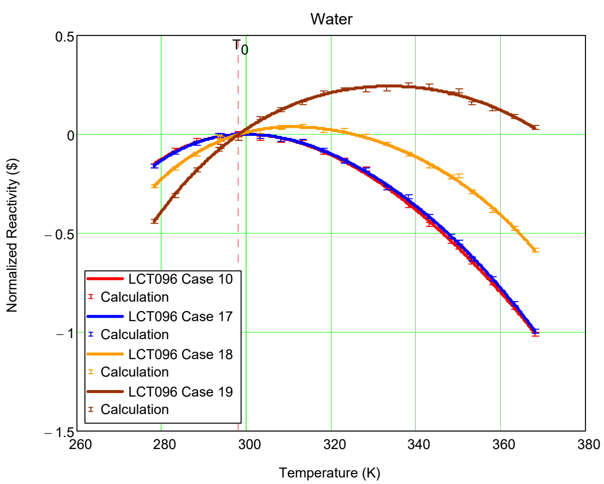


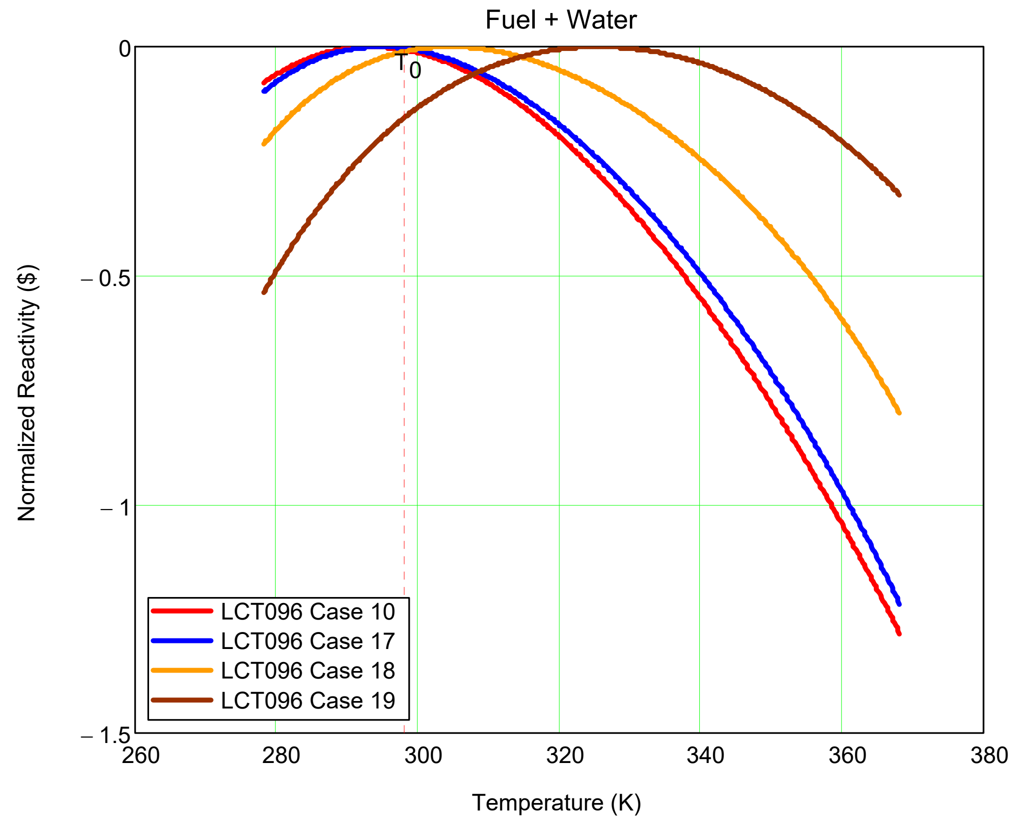




Configuration	Channel Width	T_i
LCT096 Case 10	0 rows	20 °C
LCT096 Case 17	2 rows	22 °C
LCT096 Case 18	3 rows	31 °C
LCT096 Case 19	4 rows	52 °C







Configuration	Channel Width	T_i
LCT096 Case 10	0 rows	20 °C
LCT096 Case 17	2 rows	22 °C
LCT096 Case 18	3 rows	31 °C
LCT096 Case 19	4 rows	52 °C

LEU-COMP-THERM-102 Cases 1, 16, 20, and 21

In 2020 Sandia performed water-moderated fully-reflected critical experiments using 6.9 % enriched UO_2 fuel with several different fuel-rod spacings

These experiments are being documented as LEU-COMP-THERM-102

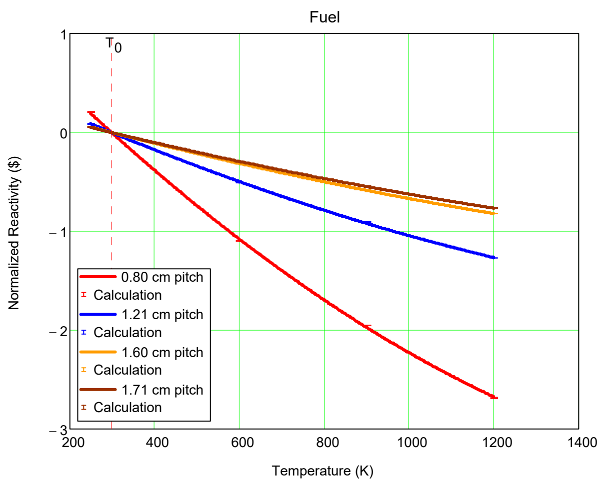
LCT102 Case 1
0.80 cm pitch
1461 fuel rods
Undermoderated

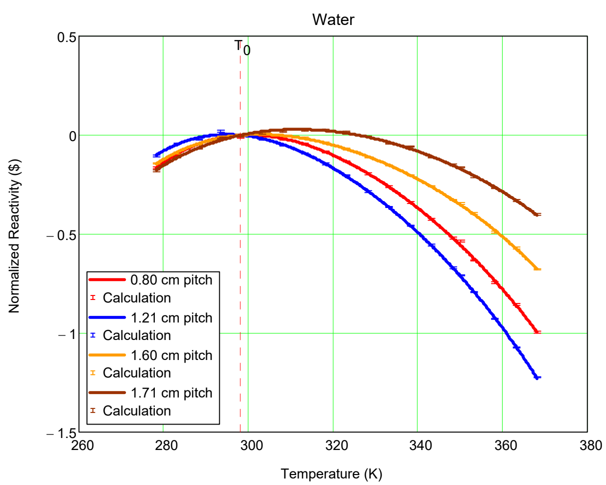
LCT102 Case 16
1.21 cm pitch
413 fuel rods
Undermoderated

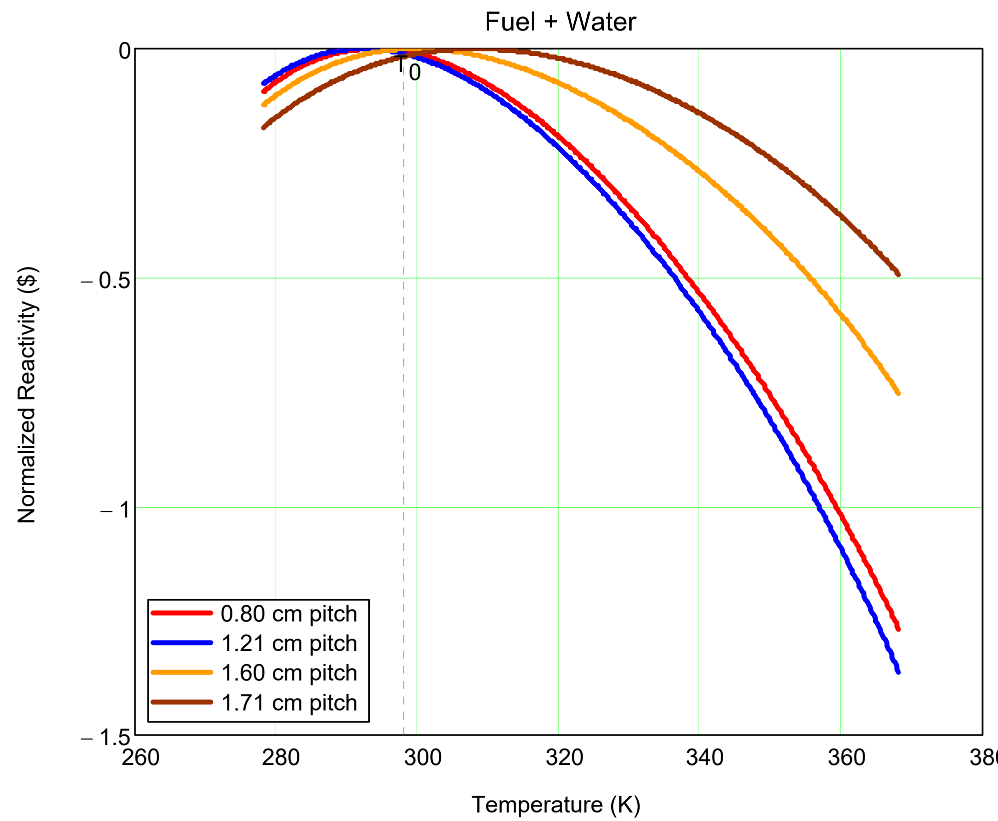
LCT102 Case 20
1.60 cm pitch
338 fuel rods
Slightly Overmoderated

LCT102 Case 16
1.71 cm pitch
346 fuel rods
Overmoderated

LEU-COMP-THERM-102 Cases 1, 16, 20, and 21







Configuration	Fuel Rod Pitch	T_i
LCT102 Case 1	0.80 cm	21 ºC
LCT102 Case 16	1.21 cm	19 ºC
LCT102 Case 20	1.60 cm	27 ºC
LCT102 Case 24	1.71 cm	35 ºC

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

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

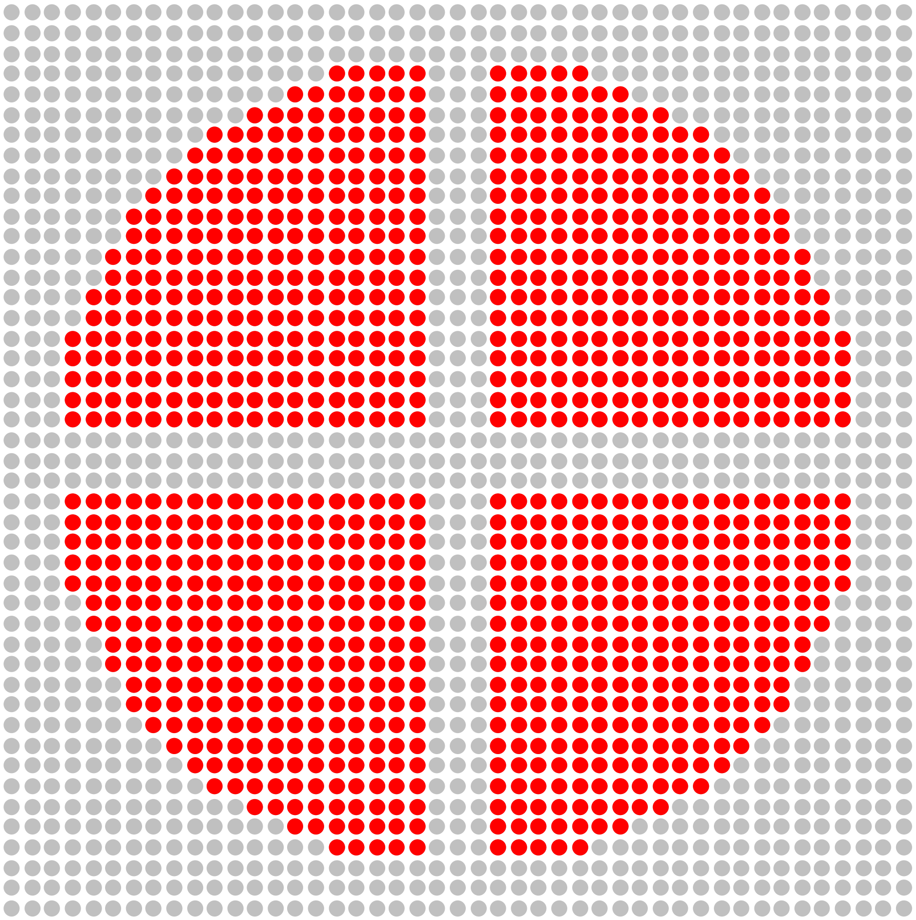
$$M = \frac{1}{1-k_{eff}} = \frac{1-\rho}{\rho}$$

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

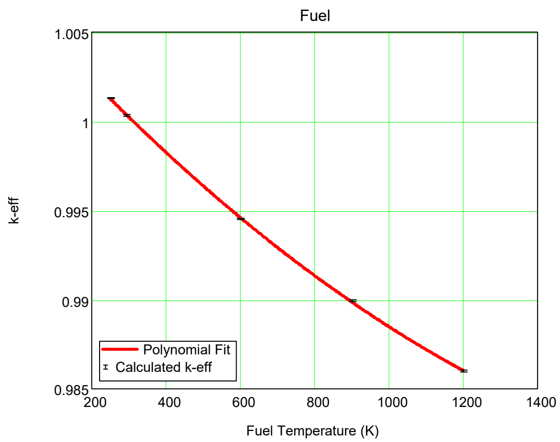
If the count rates are measured as a function of temperature, the inversion temperature will be the temperature with the highest count rate

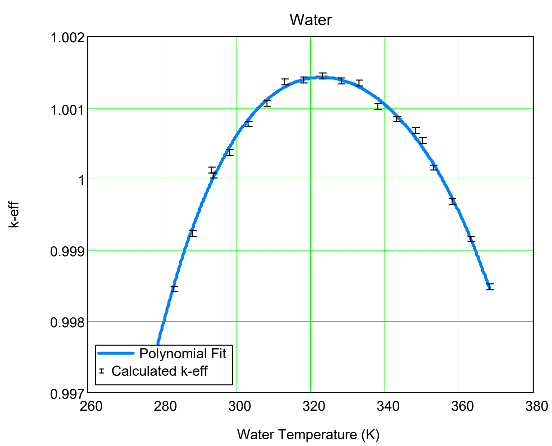
A proposed inversion temperature experiment

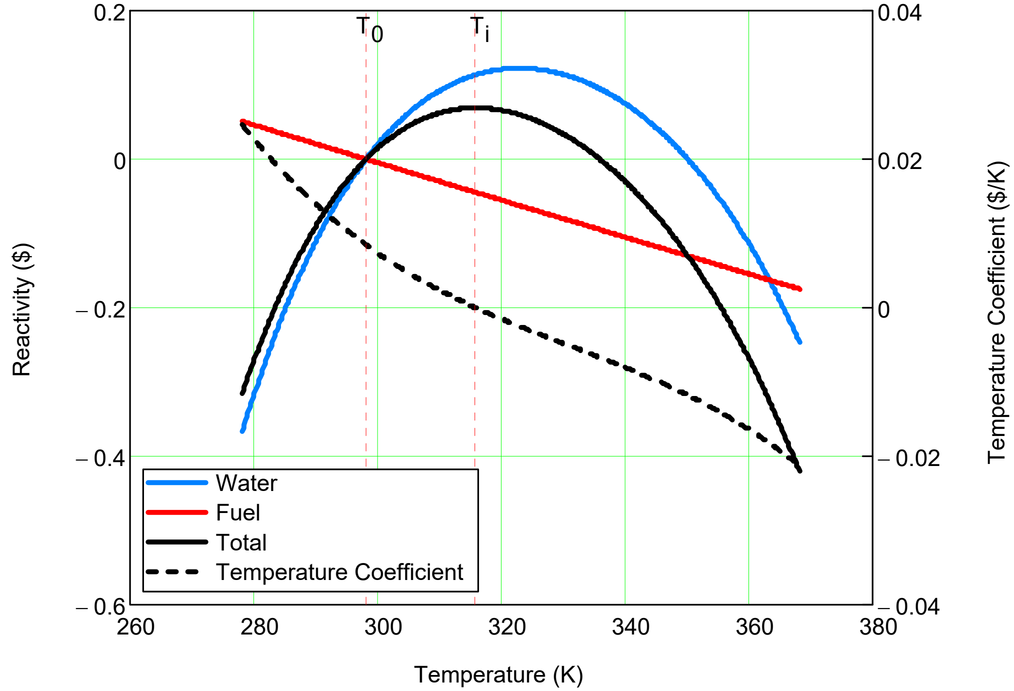
- The diagram shows a schematic view of the fuel rod layout in a proposed experiment to measure the inversion temperature of the isothermal reactivity coefficient
- The experiment configuration is similar to LEU-COMP-THERM-096 Case 18 but fully reflected
- The system will be critical with about 1032 fuel rods
- The incremental fuel rod worth at delayed critical is about 0.02 $



A proposed inversion temperature experiment

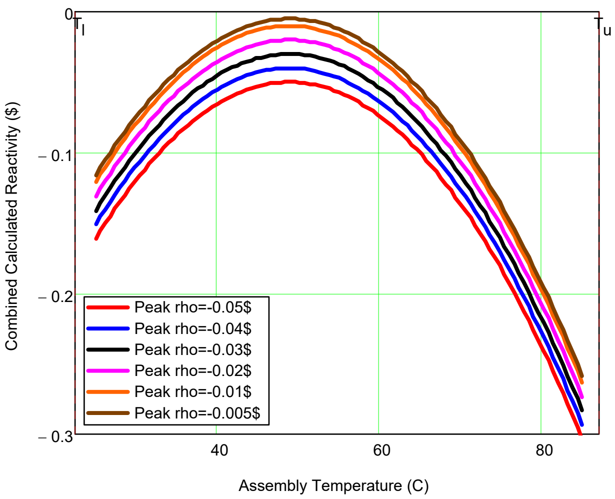






Configuration	Channel Width	T_i
Proposed Expt.	3 rows	43 ºC

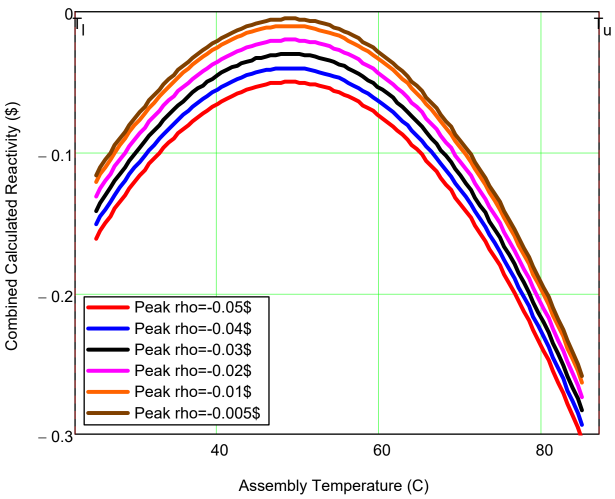
A proposed inversion temperature experiment

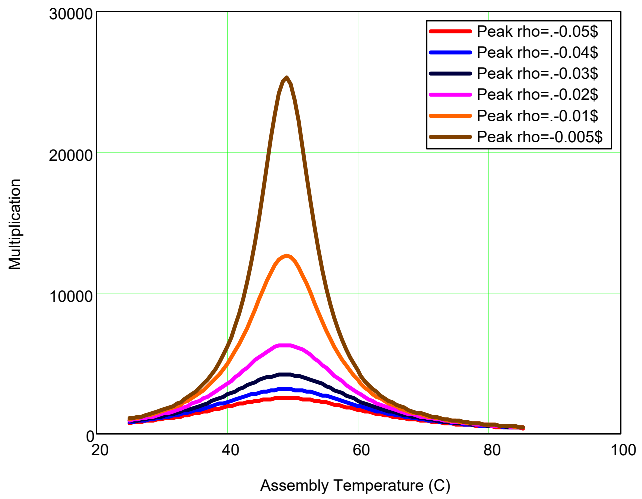


The peak reactivity of the system can be arbitrarily adjusted within the limitations of the incremental fuel rod worth

The first plot shows the reactivity of the system for several different values of the peak reactivity

A proposed inversion temperature experiment



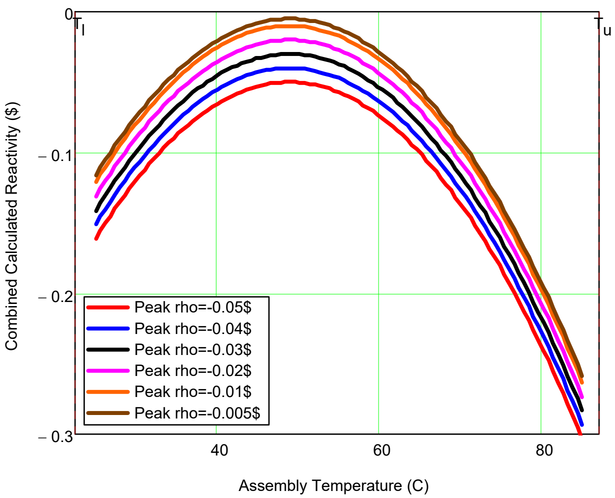


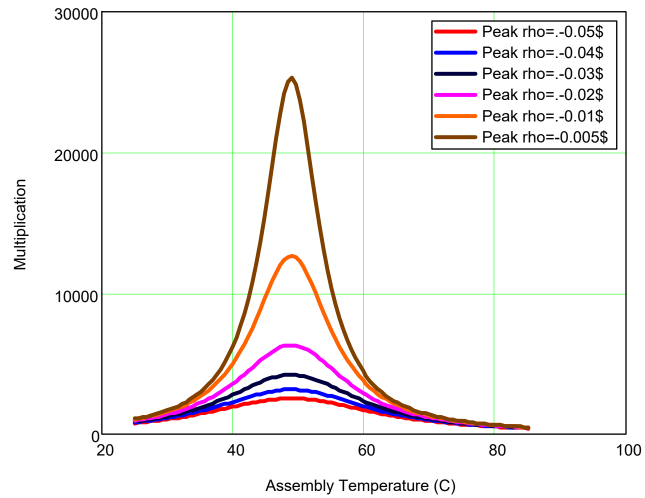
Using the relationship between the inverse multiplication (count rate) and the reactivity

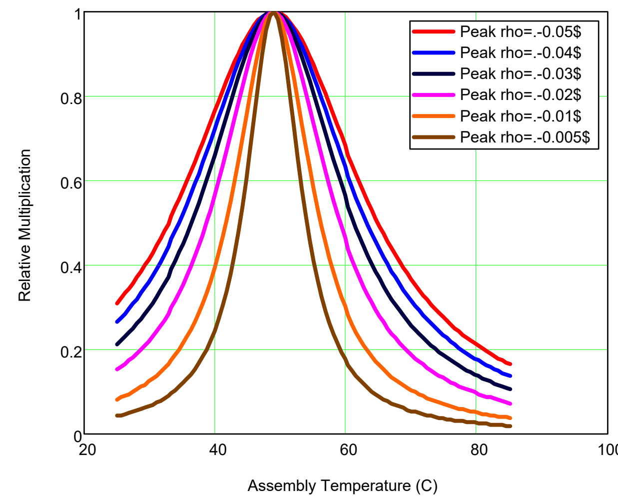
$$M = \frac{1-\rho}{\rho}$$

The second plot shows the inverse multiplication of the system 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

New critical assembly features needed for inversion temperature experiments

Temperature control of the assembly

- Heater/chiller with significant capacity
- Larger water volume outside the core tank
- Insulation of tanks to limit heat losses
- Homogenization of core moderator/reflector
- Ability to make detailed temperature measurements across core

Conclusion

Two related series of temperature-dependent experiments are being planned at Sandia

The first will measure the number of fuel rods at delayed critical as a function of temperature

- This series is in final design
- Current plans call for execution in 2022

The second will measure the temperature that yields the peak reactivity in a given collection of fuel rods

- This series is in preliminary design
- Current plans also call for execution in 2022

Critical Experiments at Sandia