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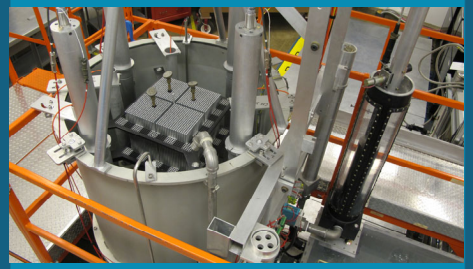
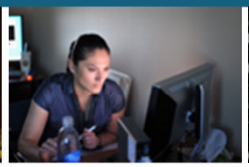
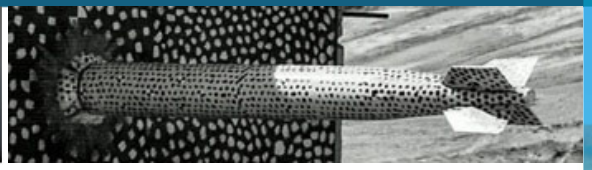
This work was supported by the DOE Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the Department of Energy.

Sandia National Laboratories

Measuring the Inversion Point of the Isothermal Reactivity Coefficient in a Water-Moderated Pin-Fueled Critical Assembly







Gary A. Harms and David E. Ames

2021 NCSP Technical Program Review
February 23-25, 2021

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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

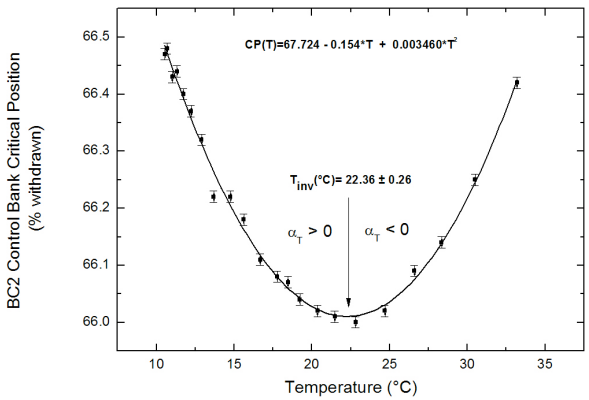
- The temperature of the critical assembly will be set and an approach-to-critical experiment on the number of fuel rods in the critical assembly or the water depth in the core tank will be done
- This series is currently lead by Justin Clarity at Oak Ridge National Laboratory

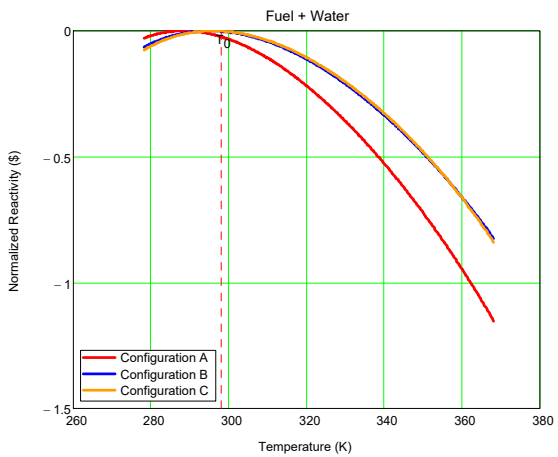
The second series (IER-452) will measure the inversion temperature of the isothermal reactivity coefficient

- 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

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

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 ºC

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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)

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

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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

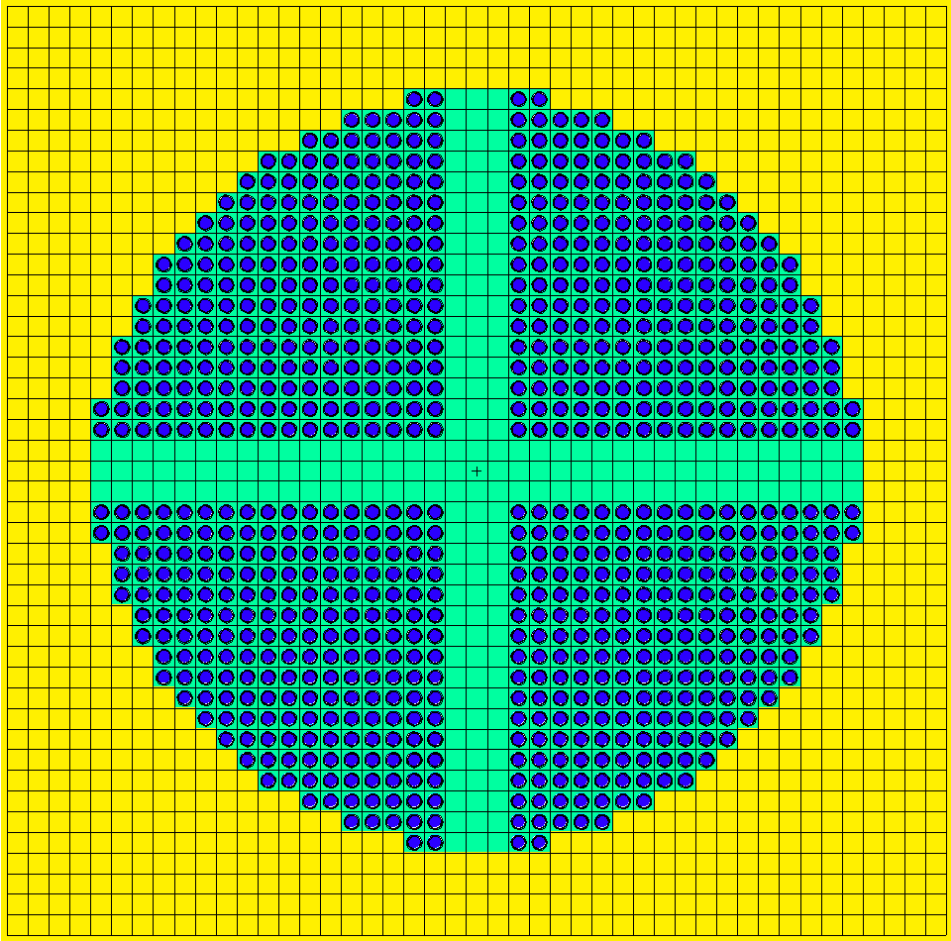
The experiment configuration is similar to LEU-COMP-THERM-101 Case 20 but fully reflected

The system will be critical with about 836 fuel rods

The incremental fuel rod worth at delayed critical is about 0.02 $

In the diagram:

- Blue is fuel
- Green is the water moderator
- Yellow is the water reflector



Calculating k_{eff} as a function of temperature 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 **fuel** temperatures accounting for thermal expansion of the fuel and doppler broadening of the cross section resonances and taking the derivative

The water sensitivity is obtained 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 and taking the derivative

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

The overall sensitivity is also used in determining bias in experiments contributed by temperature offsets

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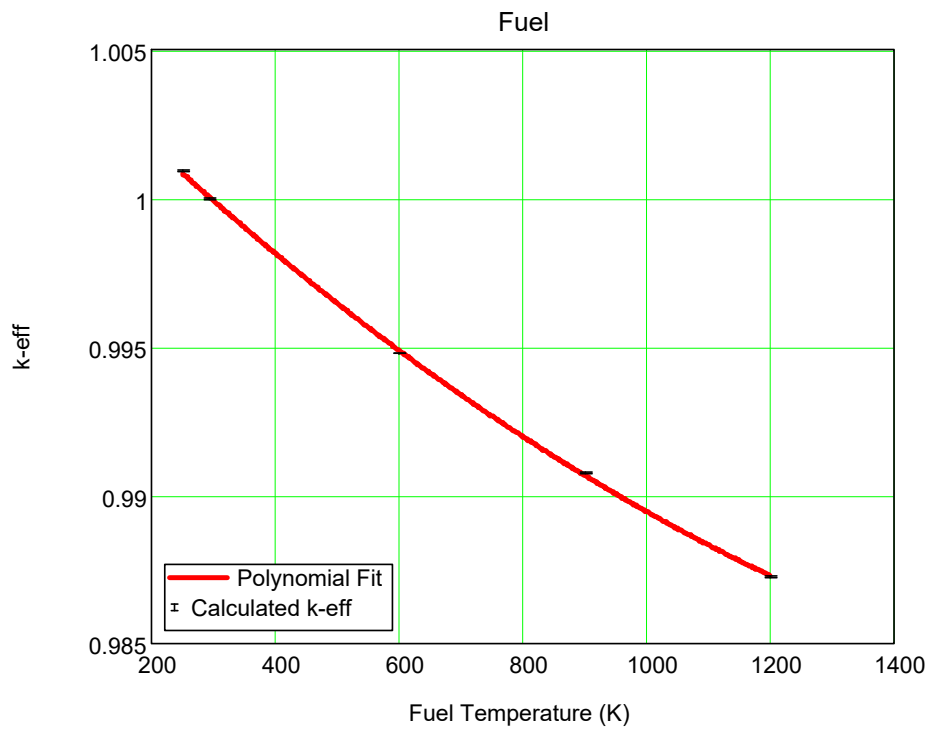
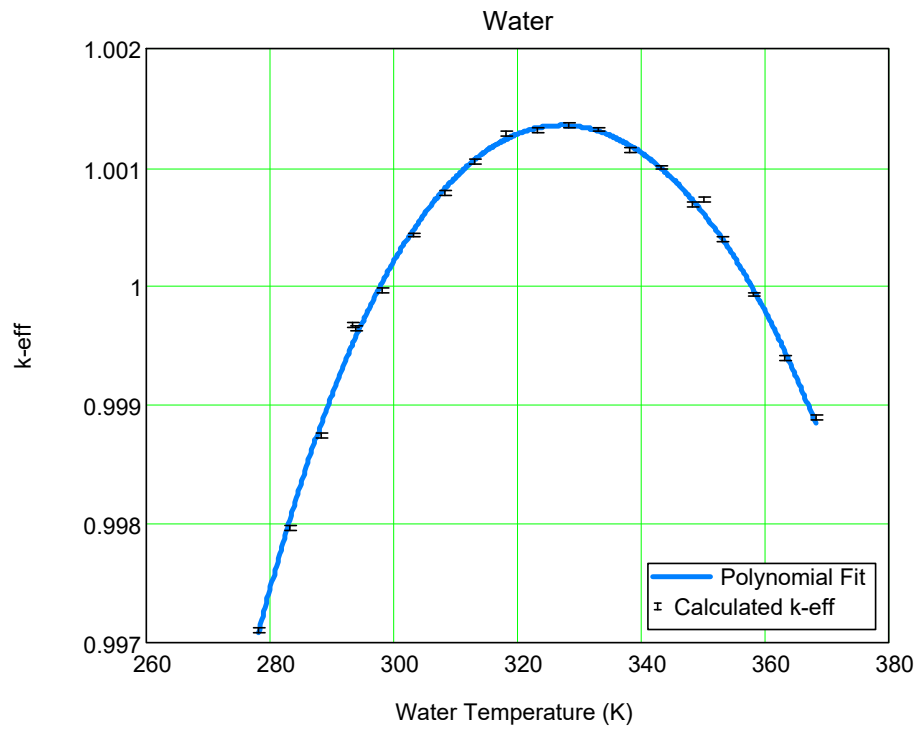
Calculate k_{eff} as a function of temperature

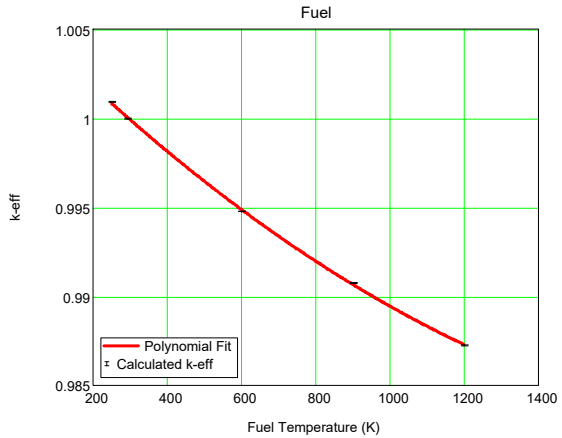


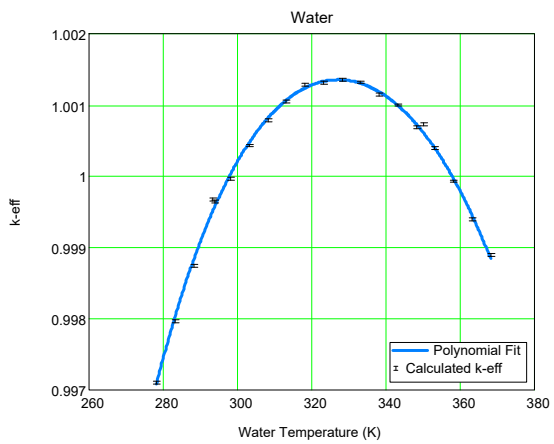


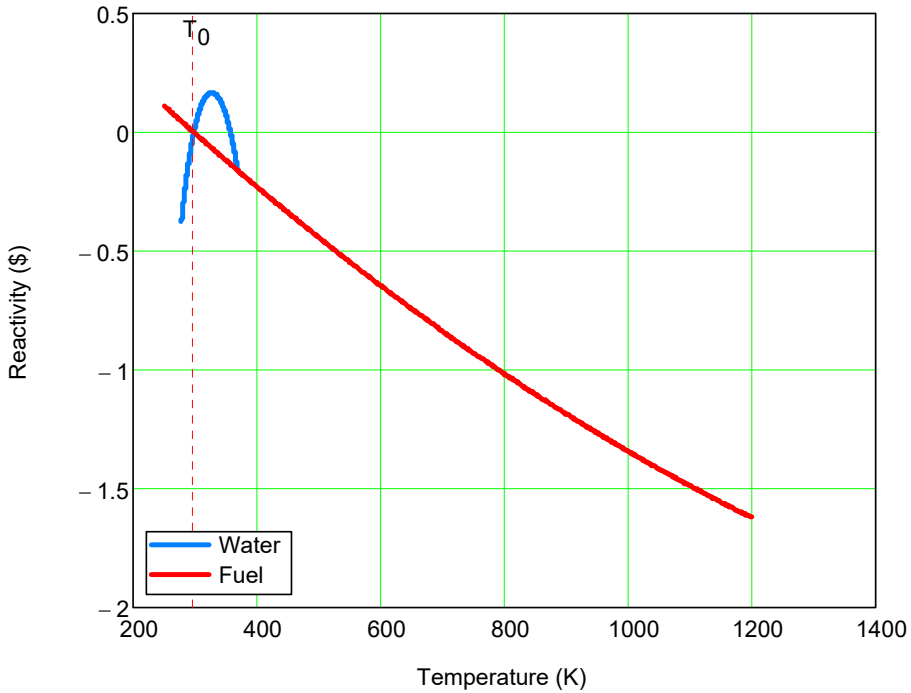
- **Hold water temperature at 298.15 K (25 ºC)**
- **Vary fuel temperature from 250 K to 1200 K**
  - **Use fuel cross sections appropriate for the temperature**
  - **Match fuel dimensions to temperature**
- **The curve is a second-order fit**

- **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**

Convert to reactivity







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

Convert to a liquid-water-based temperature scale

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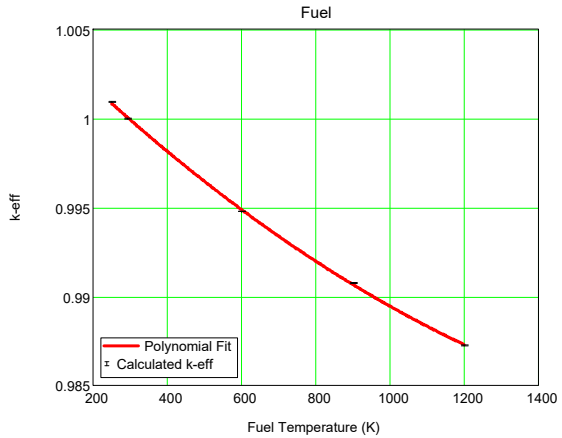
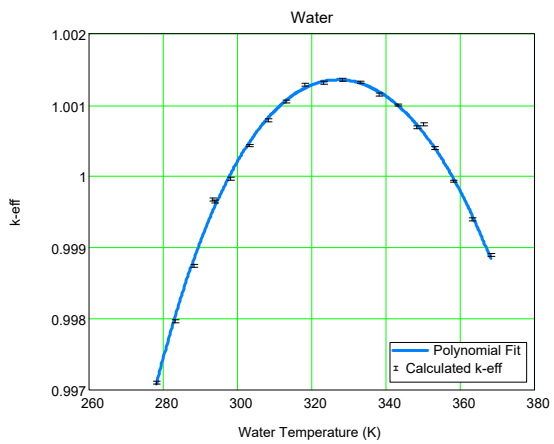
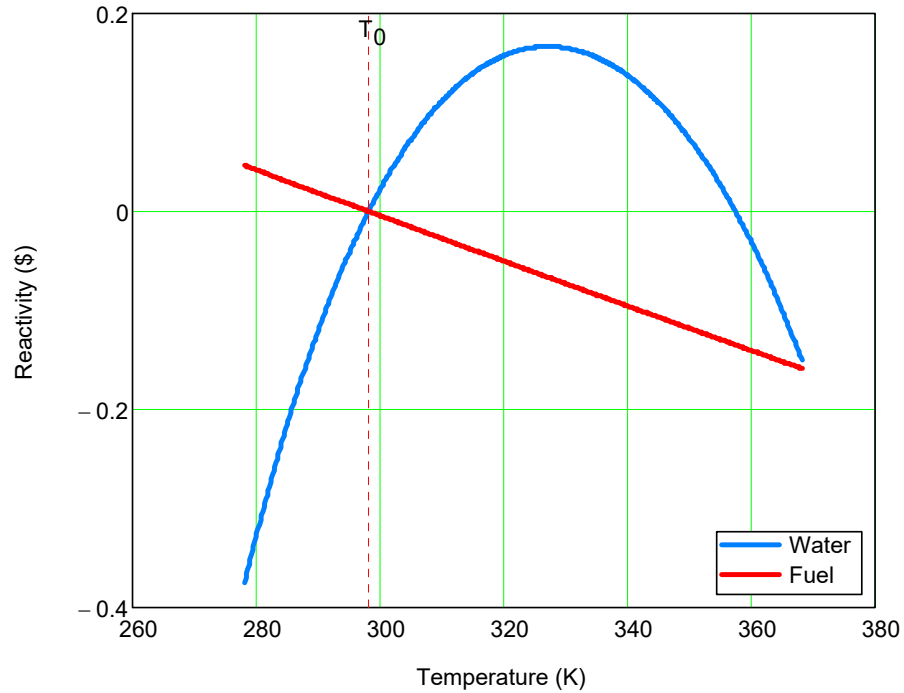
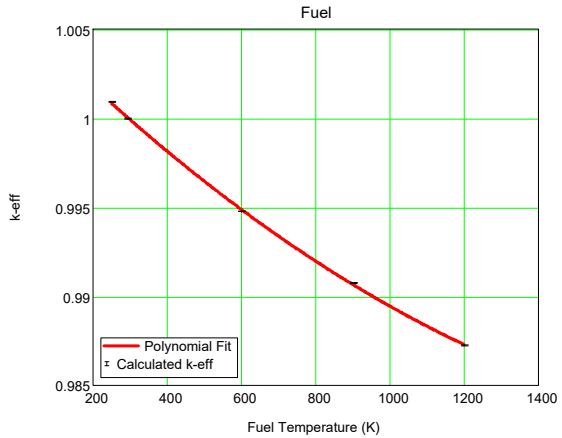


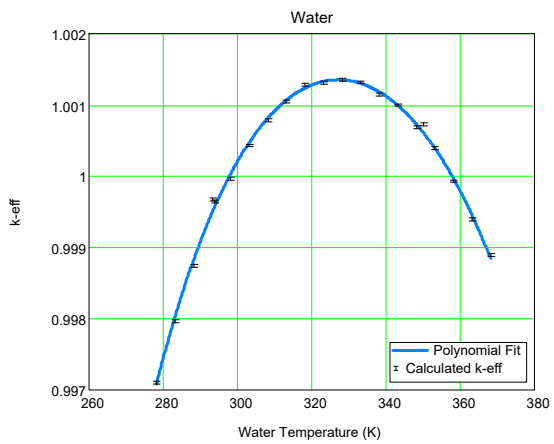


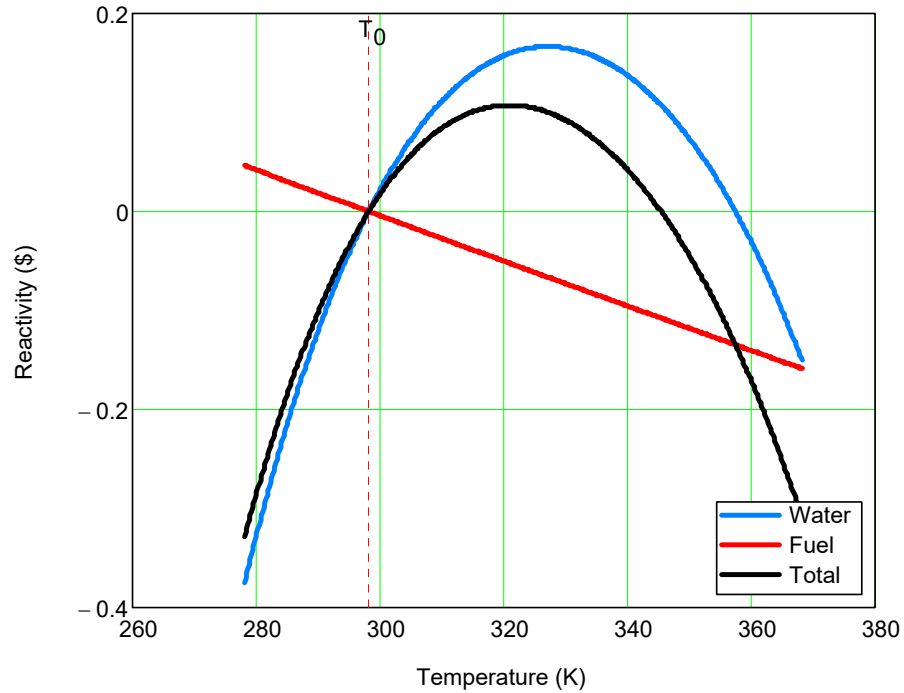


- **Convert k_{eff} data to reactivity normalized at 25 ºC (T_0)**
- **Expand the temperature scale to cover liquid water temperatures**

Sum the water and fuel reactivities

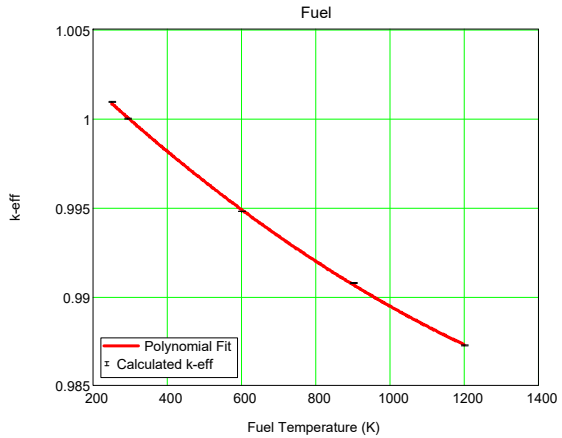


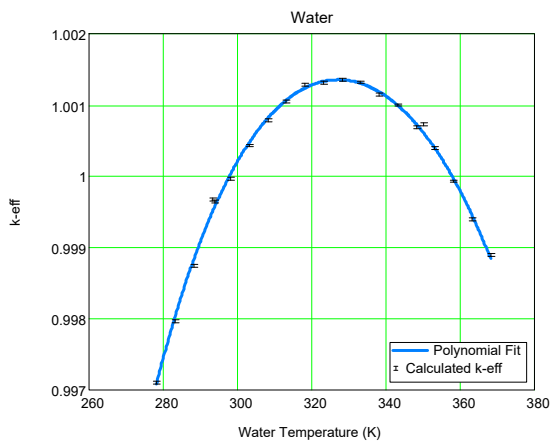


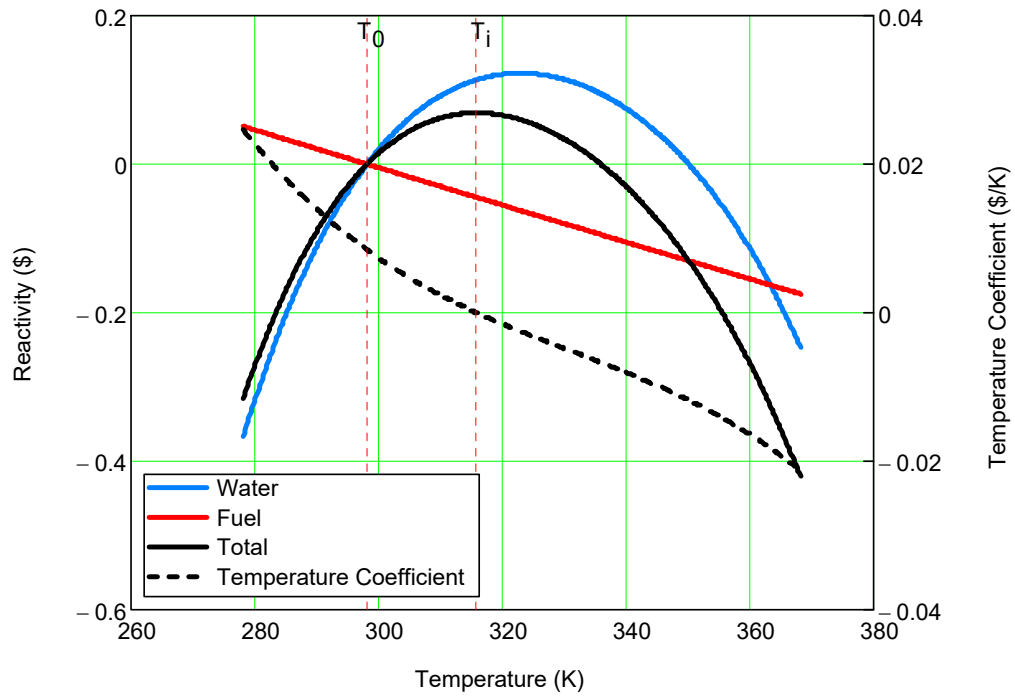


- **Convert k_{eff} data to reactivity normalized at 25 ºC (T_0)**
- **Expand the temperature scale to cover liquid water temperatures**
- **Sum the two curves to get the total reactivity curve**

Differentiate the total reactivity to obtain the temperature coefficient







Configuration	Channel Width	T_i
Proposed Expt.	**3 rows**	**321 K (48 ºC)**

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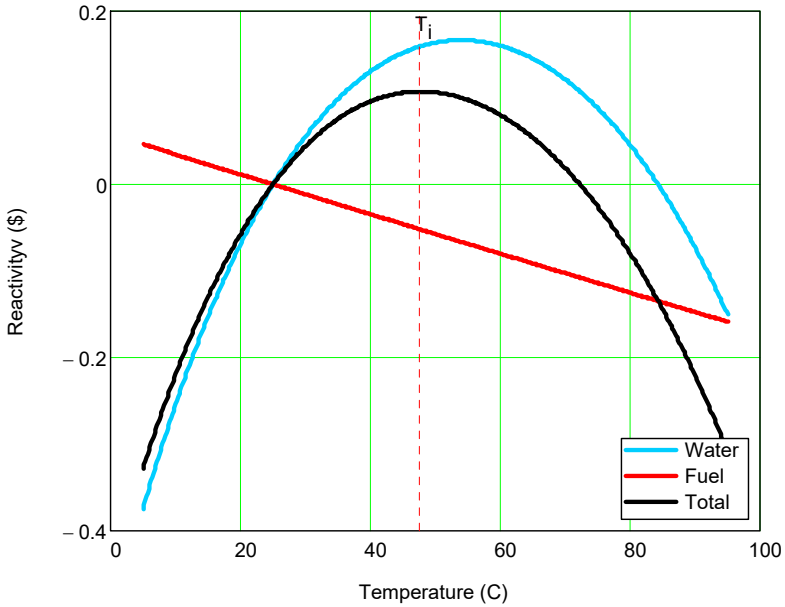
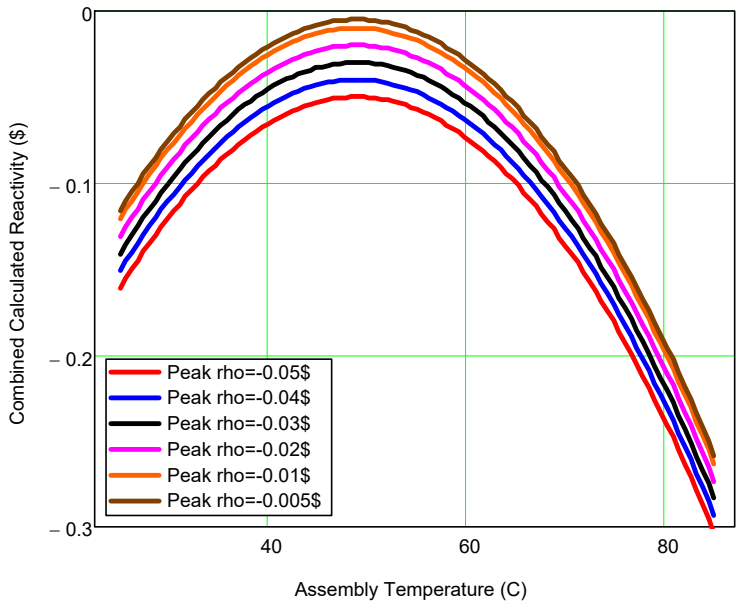
A proposed inversion temperature experiment



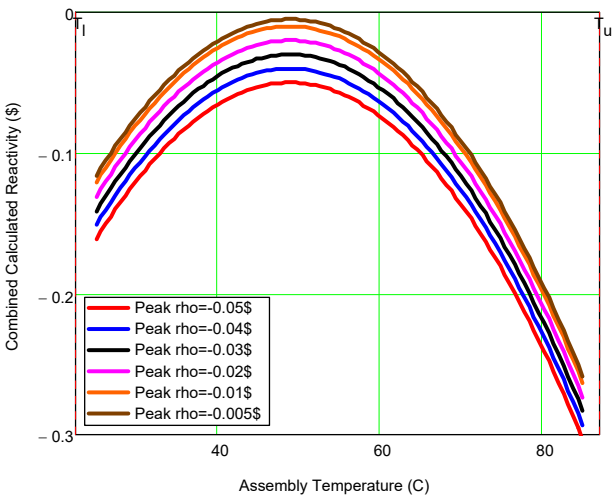


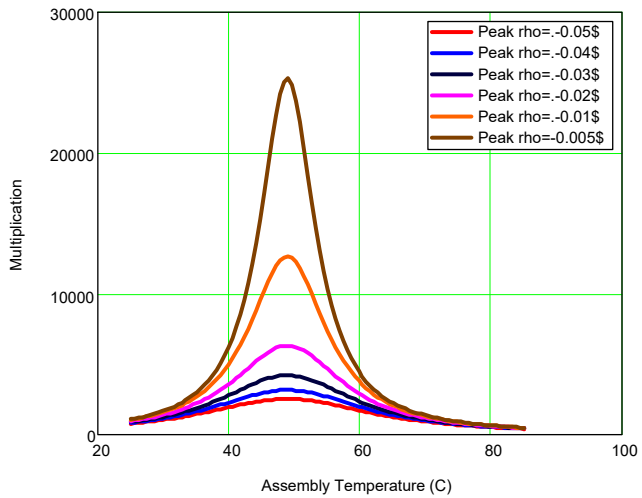
The peak reactivity of the system can be arbitrarily adjusted within the limitations of the incremental fuel rod worth

- In this case we pull a few rods to decrease the peak reactivity

The plot on the left shows the reactivities of the system with the 3-row water channel. The plot on the right shows the reactivity of the system for several different values of the peak reactivity

A proposed inversion temperature experiment



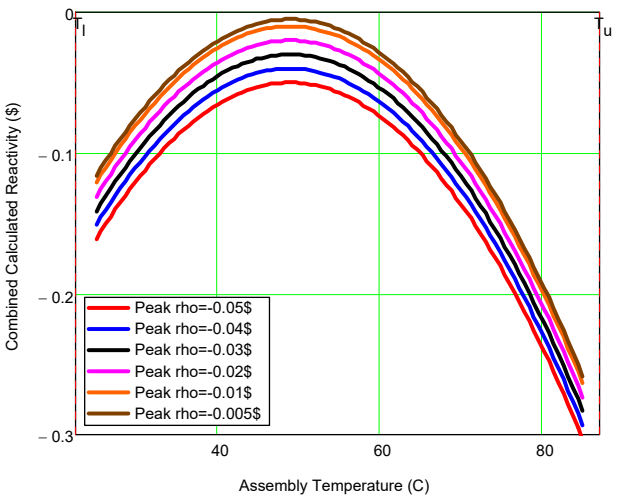


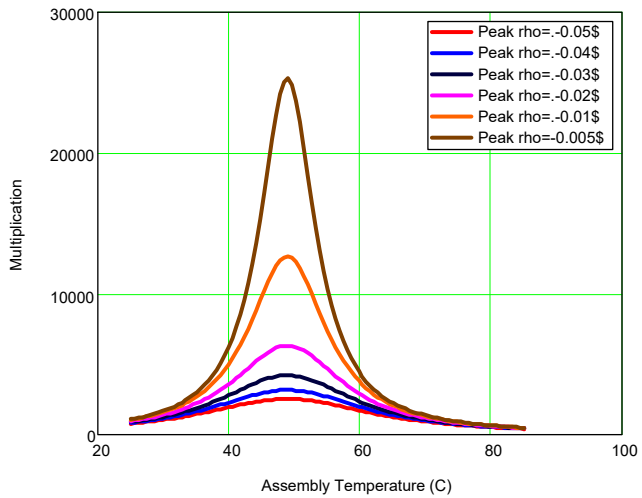
Using the relationship between the multiplication (count rate) and the reactivity

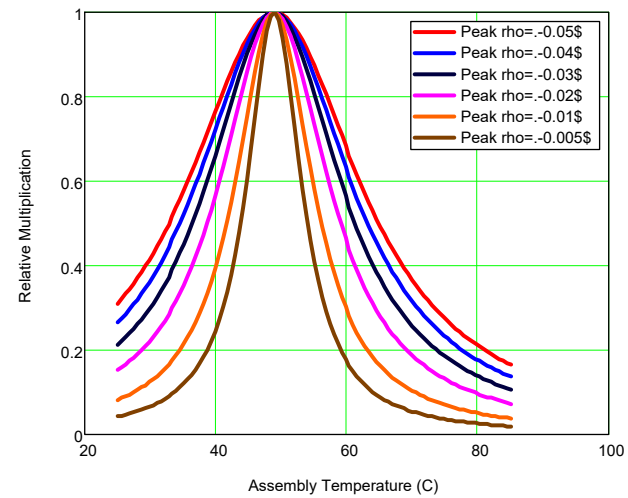
$$M = \frac{\rho - 1}{\rho}$$

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

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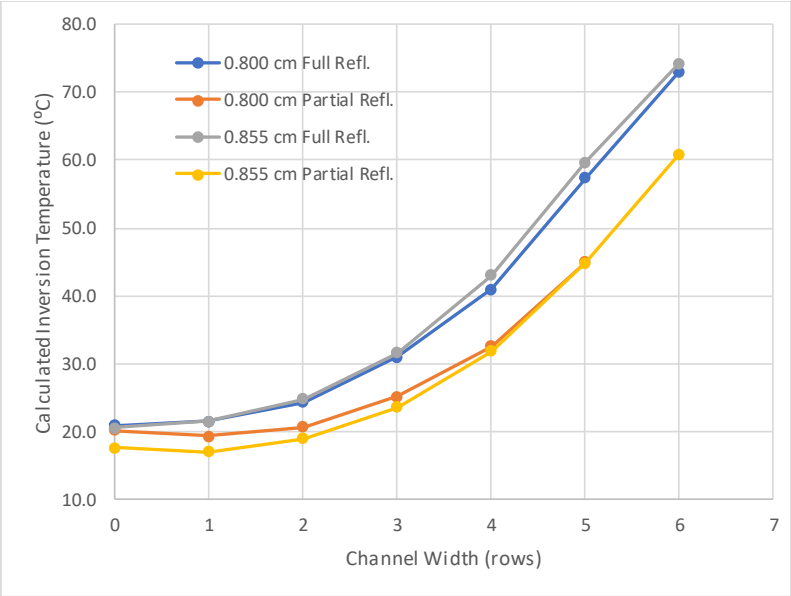
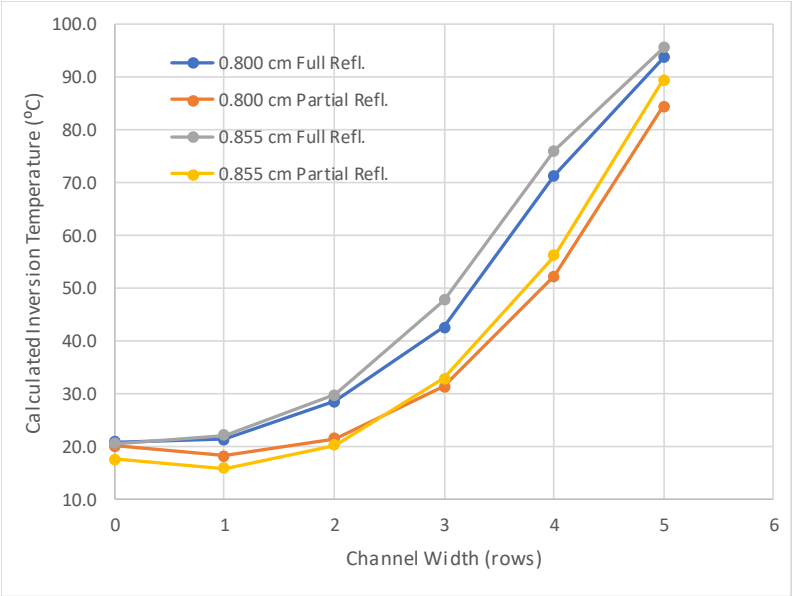
New critical assembly features needed for inversion temperature experiments

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

Experiments with linear and cruciform water channels





Experiments with differing fuel-to-water ratios (LCT102)

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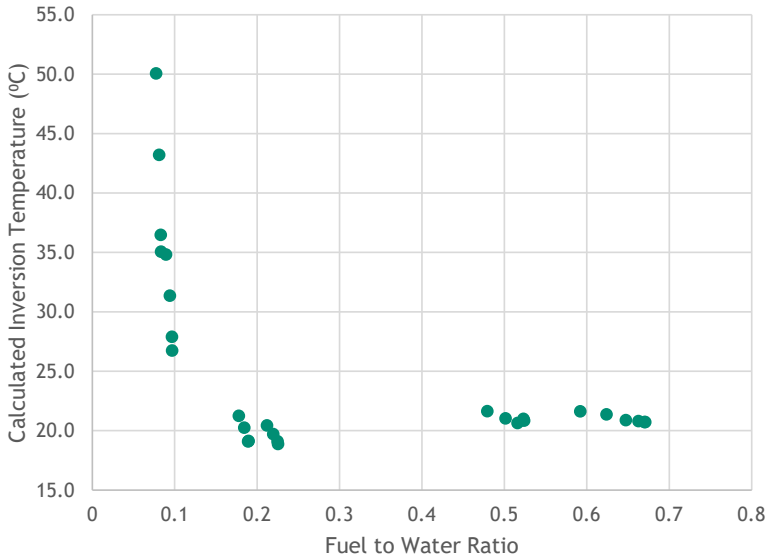
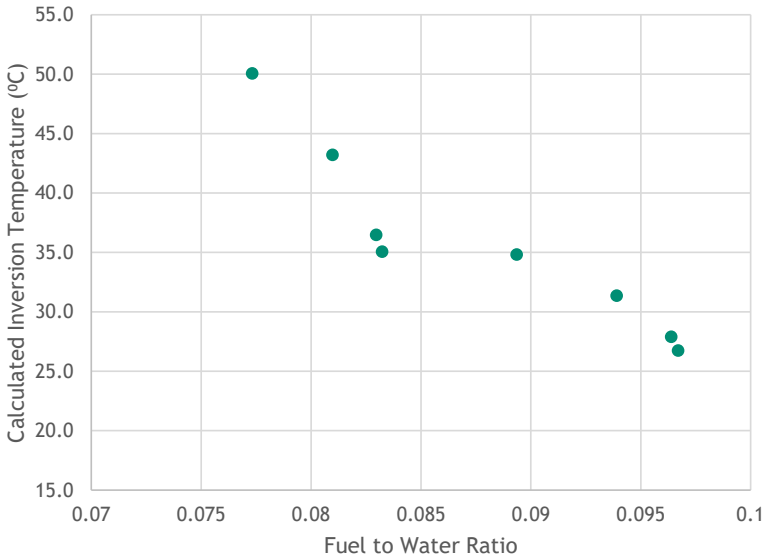
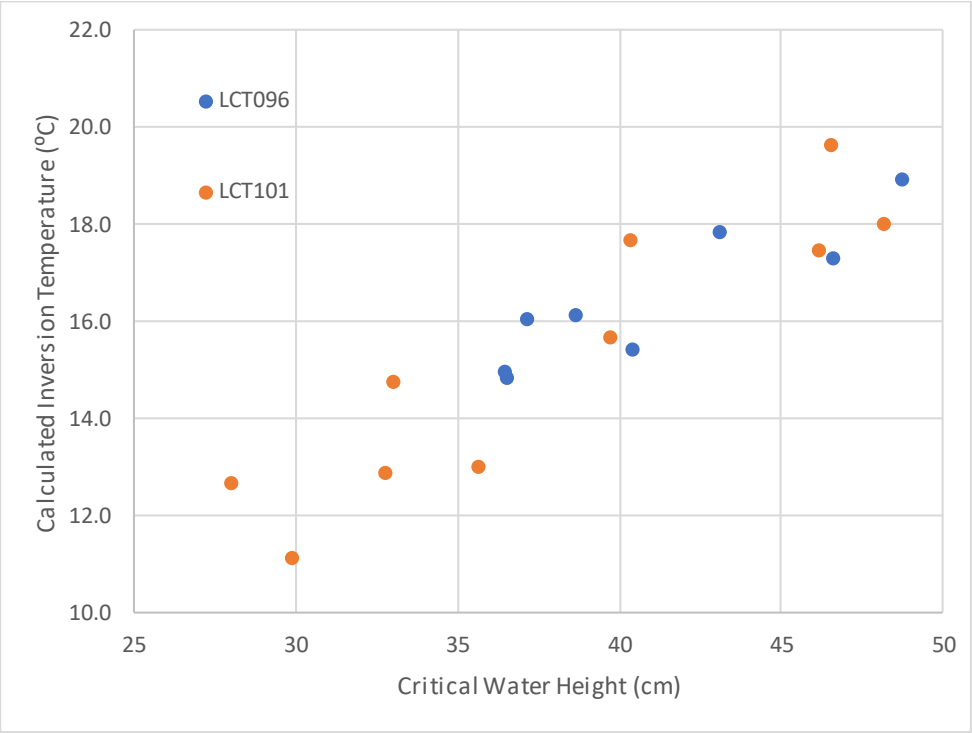




LCT096 and LCT101 partially-reflected configurations without channels



Conclusion

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

The first (IER-304) 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 (IER-452) 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

The results of the experiments can be used to test the ability of current methods and data to estimate thermal effects in water-moderated systems

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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.