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

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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
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 $T_{\text{inv}}$ between 14.99 and 22.36 °C.
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

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

Combine to get

\[ M = \frac{1}{1 - k_{\text{eff}}} = \frac{\rho - 1}{\rho} \]

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.
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 $k_{\text{eff}}$ as a function of temperature in water-moderated critical experiments

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

1. Estimating the sensitivity of $k_{\text{eff}}$ to the temperature of the fuel
2. Estimating the sensitivity of $k_{\text{eff}}$ 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 $k_{\text{eff}}$ 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 $k_{\text{eff}}$ 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.
Calculate $k_{\text{eff}}$ as a function of temperature

- Hold water temperature at 298.15 K (25 °C)
- 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 °C to 95 °C
  - Vary water density with temperature
  - Use water scattering data [$S(\alpha,\beta)$] appropriate for the temperature
- The curve is a fourth-order fit
Convert to reactivity

- Convert $k_{\text{eff}}$ data to reactivity normalized at 25 °C ($T_0$)
Convert to a liquid-water-based temperature scale

- Convert \( k_{\text{eff}} \) data to reactivity normalized at 25 °C \( (T_0) \)
- Expand the temperature scale to cover liquid water temperatures
Sum the water and fuel reactivities

- Convert $k_{\text{eff}}$ data to reactivity normalized at 25 °C ($T_0$)
- 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.

### Water Temperature vs. Temperature Coefficient

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Reactivity ($$/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>0.04</td>
</tr>
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<td>280</td>
<td>0.02</td>
</tr>
<tr>
<td>300</td>
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</tr>
<tr>
<td>320</td>
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### Fuel Temperature vs. Temperature Coefficient

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### Configuration Channel Width $T_i$

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<th>Channel Width</th>
<th>$T_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed Expt.</td>
<td>3 rows</td>
<td>321 K (48 °C)</td>
</tr>
</tbody>
</table>
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.
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/reflectors
  - Ability to make detailed temperature measurements across core
Experiments with linear and cruciform water channels

![Graphs showing calculated inversion temperature vs. channel width for different channel widths and reflections.]

- 0.800 cm Full Refl.
- 0.800 cm Partial Refl.
- 0.855 cm Full Refl.
- 0.855 cm Partial Refl.
Experiments with differing fuel-to-water ratios (LCT102)
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.
Critical Experiments at Sandia

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