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

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ABSTRACT

A new set of critical experiments exploring the temperature-dependence of the reactivity in a critical assembly is described. In the experiments, the temperature of the critical assembly will be varied to determine the temperature that produces the highest reactivity in the assembly. This temperature is the inversion point of the isothermal reactivity coefficient of the assembly. An analysis of relevant configurations is presented. Existing measurements are described and an analysis of these experiments presented. The overall experimental approach is described as are the modifications to the critical assembly needed to perform the experiments.

Key Words: critical experiment, temperature-dependence, inversion point of the isothermal reactivity coefficient

1 INTRODUCTION

The Sandia Critical Experiments (SCX) Program is executed in a specialized facility for performing water-moderated and -reflected critical experiments with UO_2 fuel rod arrays. A history of safe reactor operations and flexibility in critical assembly core configuration has resulted in the completion of several benchmark critical experiment evaluations that are published in the International Handbook of Evaluated Criticality Safety Benchmark Experiments [1]. In the benchmark evaluations, the effective multiplication factor (k_{eff}) of known configurations of fuel are presented along with an estimate of the uncertainty in the k_{eff}. One of the components of this uncertainty is the uncertainty contributed by the uncertainty in the system temperature.

A new set of critical experiments is being designed to explore the temperature-dependent behavior of water-moderated pin-fueled critical experiments at Sandia. In these experiments, the relationship between the reactivity and the subcritical multiplication of the assembly will be used to measure the inversion point of the isothermal reactivity coefficient. The subcritical multiplication of the assembly will be monitored while the temperature of the assembly is varied. The inversion point of the isothermal reactivity coefficient is the temperature that yields the highest subcritical multiplication in the assembly.

The experiments described here are in the preliminary design phase. Subsequent experiment phases will finalize the design, prepare any needed new equipment for the experiments, execute the experiments, and document the experiments.

2 TEMPERATURE SENSITIVITY OF CRITICAL EXPERIMENTS

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

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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, and
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 the thermal expansion of the fuel and for the doppler broadening of the fuel cross section resonances. 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 for the temperature dependence of the thermal scattering cross section in the water. The reactivity values calculated at discrete temperatures are fit to polynomials – second-order for the fuel analysis and fourth-order for the water analysis – to obtain continuous functions. The two sensitivities are combined to obtain the overall temperature sensitivity of the critical experiment.

Here, the temperature sensitivity analysis is done using the MCNP6.1.1 code [2] with the ENFD/B-VII.1 cross sections supplied with the code. The water analysis was enabled by a set of $S(\alpha,\beta)$ data for water temperatures from 5 to 95 °C in 5 °C increments based on ENDF/B-VII provided by Los Alamos National Laboratory [3]. The variation of the water density with temperature was taken into account. The fuel temperature analysis was done using fuel cross sections provided with MCNP at temperatures between 250 and 1200 K. Thermal expansion of the fuel material was taken into account in the analysis.

In general, for the water-moderated low-enriched pin-fueled critical experiments investigated at Sandia National Laboratories (SNL), the k_{eff} as a function of fuel temperature monotonically decreases with increasing fuel temperature. On the other hand, the behavior of k_{eff} as a function of water temperature is more complex. In many configurations, there is a water temperature at which the k_{eff} is highest with k_{eff} decreasing both above and below that temperature. In other configurations the k_{eff} increases monotonically with water temperature.

Fig. 1 shows diagrams of the fuel layout in a 45×45 fuel array for four fuel configurations that will be used as analysis examples here. The fuel configurations are from LEU-COMP-THERM-101 (LCT101) in [1] a set of partially-reflected benchmark critical experiments completed at SNL in 2019 that measured the critical water heights in 22 fuel configurations. Each of the configurations shown had 1296 fuel rods in the fuel array. The first configuration (case 10) is the base configuration from which the other three configurations (cases 19, 20, and 21) differed by the width of the cruciform water channels between the four 324-rod fuel lobes in the array.

Figure 1. LCT101 fuel configurations analyzed.

Fig. 2 shows the calculated normalized reactivity as a function of the isothermal temperature in the four arrays calculated as described above. The analysis was done using MCNP6.1.1 with ENDF/B-VII.1 cross sections. In the cases shown, the reactivity increases at low temperatures, passes through a maximum value, and decreases at high temperatures. The curves are normalized to have a reactivity of -0.05 $ at the temperature giving the maximum reactivity. In practice, the reactivity of each array is adjusted by changing the water level in the array to give the desired peak reactivity. The same effect in a fully-reflected critical assembly can be accomplished by changing the fuel loading of the assembly.

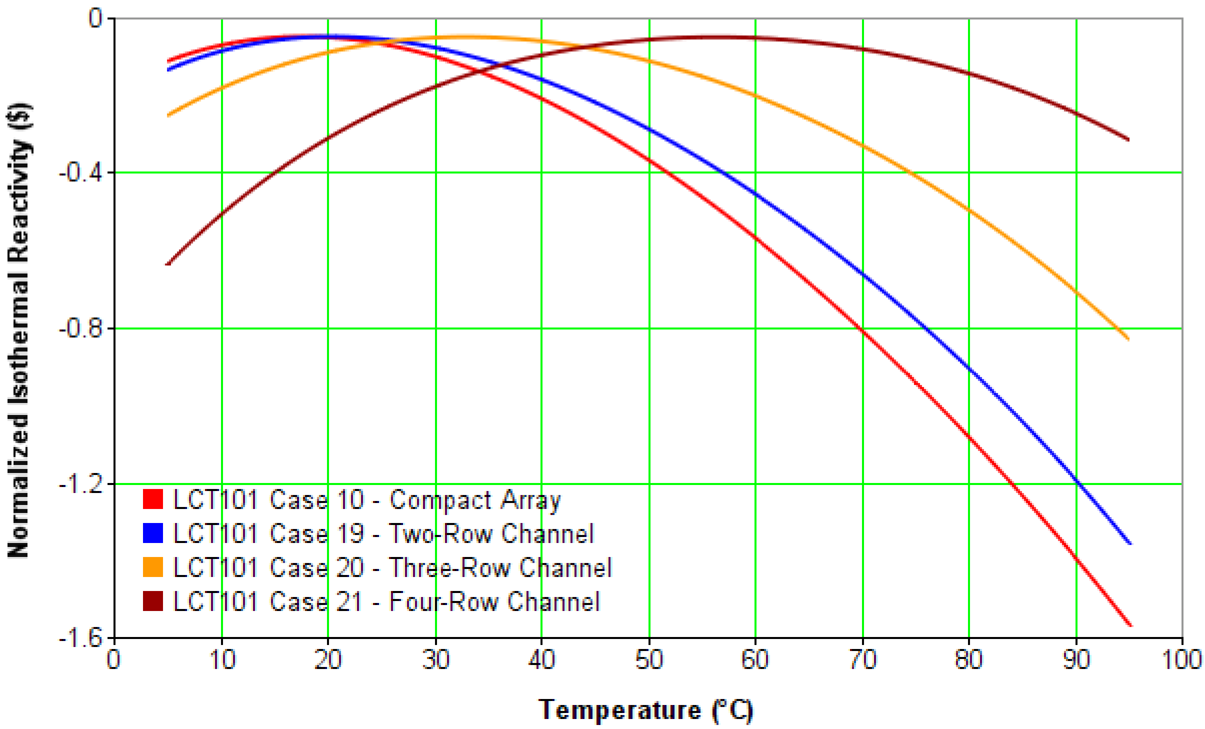

Figure 2. Reactivity as a function of temperature for the LCT101 configurations considered.

The isothermal reactivity coefficient of each array is the derivative of the isothermal reactivity as a function of temperature. Below the temperature of the reactivity maximum, the reactivity coefficient is positive. Above that temperature, the reactivity coefficient is negative. Fig. 3 shows the calculated isothermal reactivity coefficient of the four arrays. The inversion point of the isothermal reactivity coefficient is the temperature at which the isothermal reactivity coefficient plot passes through zero. This corresponds to the temperature of the reactivity maximum in the isothermal reactivity plots. The inversion point temperatures for the four fuel configurations are shown in Table I.

Table I. Calculated inversion points of the isothermal reactivity coefficient for the LCT101 configurations

LCT101 Case	Cruciform Channel Width (fuel rows)	Calculated Inversion Point (°C)
10	0	17.6
19	2	20.4
20	3	32.9
21	4	56.3

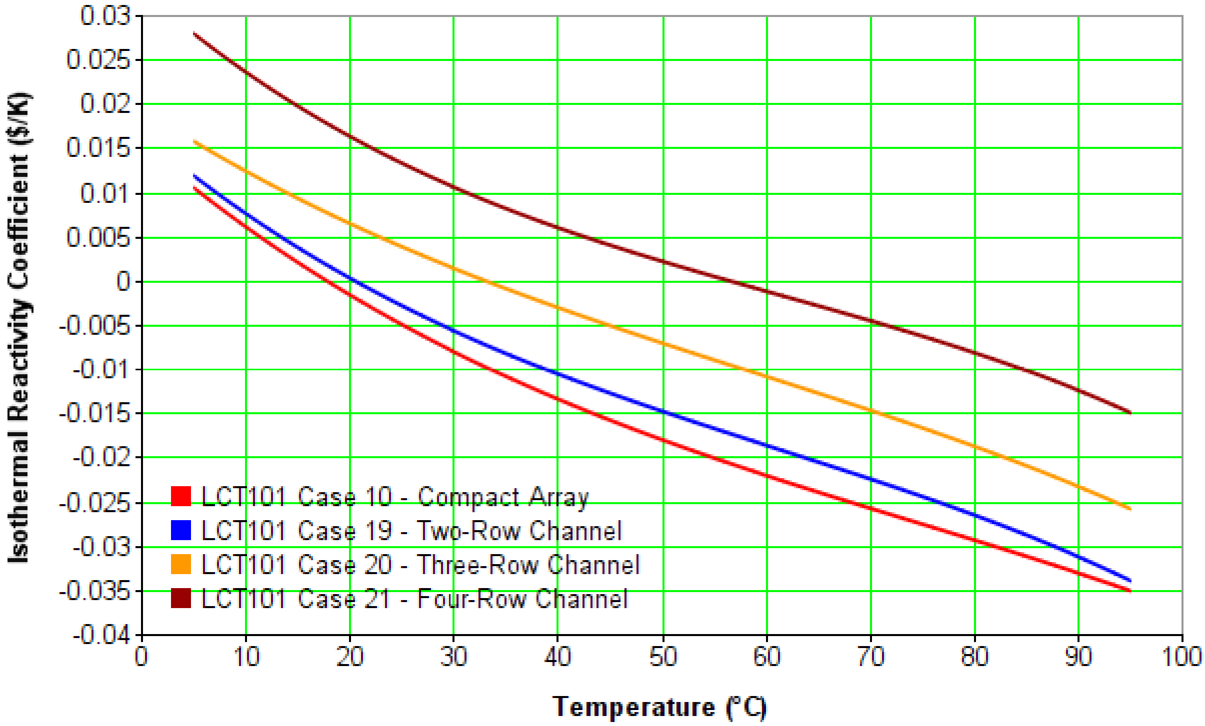

Figure 3. Isothermal reactivity coefficient as a function of temperature for the LCT101 configurations considered.

Similar inversion point analyses have been done for a wide range of fuel configurations in the SNL critical assemblies. The lowest inversion temperature found is about 11 °C for Case 2 of LCT101. Other configurations have been found that have no inversion temperature as the reactivity of the system increases continuously with temperature across the range of temperatures for which water is liquid.

3 EXISTING MEASUREMENTS OF THE INVERSION POINT OF THE ISOTHERMAL REACTIVITY COEFFICIENT

A set of experiments was conducted at the Instituto de Pesquisas Energéticas e Nucleares (IPEN) in Brazil to measure the inversion point of the isothermal reactivity coefficient in three configurations of the MB01 reactor at IPEN [4,5]. The experiments differed by the composition of a 12-rod central region of the 28×26 fuel array in the reactor. The experiments were documented as a reactor physics benchmark in [6].

The benchmark configurations of the IPEN experiments were analyzed using the methods described above to obtain the calculated inversion point of the isothermal reactivity coefficient. Table II compares the results of the analysis with the inversion points measured in the experiments. The calculated values fall within 0.5 °C of the measured values.

Table II. Comparison of the Calculated and Measured Inversion Points of the Isothermal Reactivity Coefficient for the IPEN Experiments

IPEN Experiment Configuration	Calculated Inversion Point (°C)	Measured Inversion Point (°C)	C – M Difference (°C)
A	15.2	14.99 ± 0.24	0.2
B	21.9	21.54 ± 0.24	0.5
C	22.8	22.36 ± 0.26	0.4

4 EXPERIMENTS TO MEASURE THE INVERSION POINT OF THE ISOTHERMAL REACTIVITY COEFFICIENT

The inversion point of the isothermal reactivity coefficient was measured in the IPEN experiments by determining the temperature at which the control rod in the reactor was most inserted at delayed critical. An automatic reactivity control system was used to adjust the control rod position to maintain the reactor at delayed critical as the temperature of the reactor was changed. The critical assembly at Sandia does not have a similar automatic control system.

The experiments at Sandia will be performed by observing the subcritical multiplication in the critical assembly as a function of critical assembly temperature. The subcritical multiplication M of a system is given in terms of the system effective multiplication factor k_{eff} by

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

The reactivity of the system ρ is given by

$$\rho = \frac{k_{eff}-1}{k_{eff}} \tag{2}$$

Combining, the subcritical multiplication is given in terms of reactivity by

$$M = \frac{\rho-1}{\rho} \tag{3}$$

The subcritical multiplication only has meaning when the system has a negative reactivity (is actually subcritical). From the form of Equation (3), it is clear that a discontinuity occurs when the reactivity approaches zero from below.

The count-rate in a detector near a driven subcritical assembly follows the subcritical multiplication of the system. The temperature at which the highest subcritical multiplication occurs is the temperature at which the highest count rate occurs. This is the inversion point of the isothermal reactivity coefficient of the system. In the proposed experiments, the count rate in detectors near the driven subcritical system will be observed as a function of assembly temperature to determine the temperature that yields the highest count rate.

Fig. 4 shows the subcritical multiplication of the LCT101 arrays with the reactivity normalized to give a peak value of -0.05 $. The shape of these curves is affected by the peak value of the reactivity as a function of temperature. As the peak value of the reactivity approaches zero, the curves become narrower. Thus to localize the temperature at which the count rates are maximum, it is desired to set the peak value of the reactivity as close to zero as possible. However, there are practical considerations that will limit how close to zero the peak reactivity can be made.

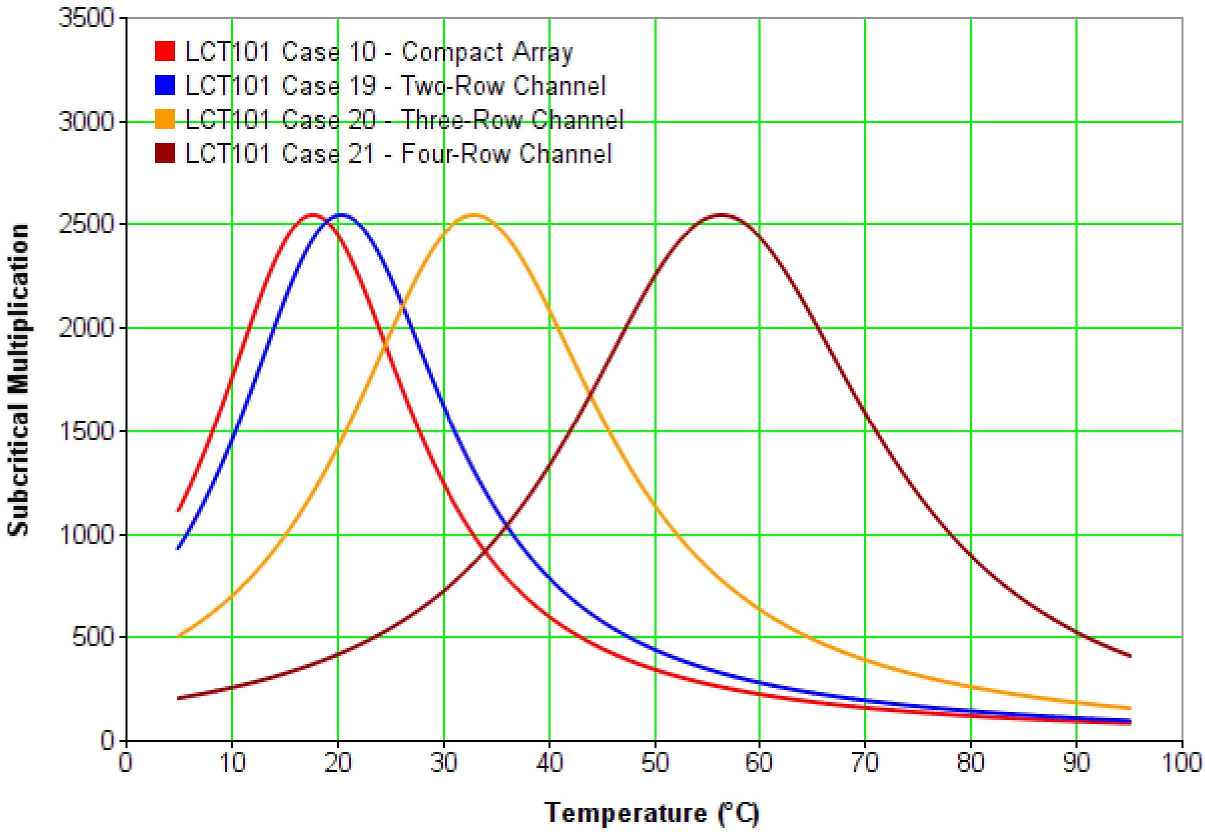

Figure 4. Subcritical multiplication of the LCT101 configurations considered.

5 NEW COMPONENTS NEEDED FOR TEMPERATURE-DEPENDENT EXPERIMENTS

The critical assembly at Sandia currently operates at a temperature near 25 °C. The temperature of the uninsulated assembly is controlled by controlling the temperature of the room in which the assembly resides. Modifications to the assembly will be required to operate at temperatures significantly different from room temperature. Sandia is working with Oak Ridge National Laboratory (ORNL) on a set of ORNL-proposed critical experiments in which the critical assembly will be operated at a temperature significantly different from room temperature [7]. As part of that experiment, the systems needed to accomplish those experiments are being designed and implemented. The systems are:

- Insulation of the water tanks including covers
- A heating system to maintain elevated temperatures
- A cooling system to maintain temperatures below room temperature
- A larger water storage (dump) tank
- Improved temperature instrumentation
- A dehumidification system

The specifications and approximate costs of these systems have been determined by ORNL. The systems are currently being implemented at the experiment facility by Sandia.

6 CONCLUSIONS

A new set of experiments to measure the inversion point of the isothermal reactivity coefficient is described. First, the methods used to analyze the temperature-dependent behavior of critical assembly configurations are described. The analysis results for four configurations are given. The same analysis methods are applied to a system in which the inversion point of the isothermal reactivity coefficient had been measured and the results of analysis compared to measured values. The results of the analysis differed by less than 0.5 °C from the measured values.

The experiments will be done in a critical assembly by measuring the subcritical multiplication of an array of fuel while varying the temperature of the assembly. The temperature that yields the highest subcritical multiplication as indicated by neutron detectors near the assembly is the inversion point of the isothermal reactivity coefficient. Finally, modifications to the existing critical assembly at Sandia are described.

The experiments described here are in the preliminary design phase. Subsequent experiment phases will finalize the experiment design, prepare any needed new equipment for the experiments, execute the experiments, and document the experiments.

7 ACKNOWLEDGMENTS

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