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

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INTRODUCTION

Estimation of the uncertainty in a critical experiment attributable to uncertainties in the measured experiment temperature is done by calculating the variation of the eigenvalue of a benchmark configuration as a function of temperature. In the low-enriched water-moderated critical experiments performed at Sandia, this is done by 1) estimating the effects of changing the water temperature while holding the UO_2 fuel temperature constant, 2) estimating the effects of changing the UO_2 temperature while holding the water temperature constant, and 3) combining the two results. This assumes that the two effects are separable. The results of such an analysis are nonintuitive and need experimental verification.

Critical experiments are being planned at Sandia National Laboratories (Sandia) to measure the effect of temperature on critical systems and will serve to test the methods used in estimating the temperature effects in critical experiments.

CRITICAL EXPERIMENT SENSITIVITY TO TEMPERATURE

Currently at Sandia, estimating the sensitivity of water-moderated low-enriched fuel rod lattice experiments to changes in temperature is performed with MCNP [1] using ENDF/B-VII.1 cross sections. The estimation of the effects of fuel temperature is done by calculating the eigenvalue of the configuration using uranium in the UO_2 fuel at five of the temperatures (250 K, 294 K, 600 K, 900 K, and 1200 K) provided in the default ENDF/B-VII.1 cross section set supplied with the code. Thermal expansion of the UO_2 fuel dimensions is included in the analysis. The results of these calculations are converted to reactivity space and normalized at a temperature described below.

The estimation of the effect of water temperature is done by calculating the eigenvalue of the system for different water temperatures. In this analysis, changes in the water density as well as changes in the thermal scattering are included. In 2014, Los Alamos National Laboratory supplied a set of S(a,b) files for MCNP at water temperatures of 5 K to 95 K in 5 K increments [2] that enabled this analysis. The results of these calculations are converted to reactivity space and normalized at a temperature described below.

The results of such an analysis are shown in Fig. 1. The left side of the figure shows the fuel configuration used in the analysis – a critical array of fully-reflected Seven Percent Critical Experiment (7uPCX) fuel on a 0.855 cm pitch that is very similar to Case 1 in benchmark evaluation LEU-COMP-THERM-078 [3]. This configuration is undermoderated – increasing the amount of water in the array, for example by increasing the water density or by increasing the pitch of the fuel rods, increases the reactivity of the system. The right side of the figure shows the calculated reactivity as a function of temperature contributed by the water (cyan curve), the calculated reactivity as a function of temperature contributed by the fuel (red curve), and the sum of the two (black curve). For the calculation of the reactivity as a function of water temperature the fuel was at a temperature of 293.6 K (20.45 ºC). This calculation had the moderator (water interspersed with the fuel) and the reflector (water outside the fuel array) at the same temperature. For the calculation of the reactivity as a function of fuel temperature the water was at a temperature of 25 ºC. As a function of temperature, the total reactivity increases with temperature at low temperatures, reaches a maximum, and then decreases with temperature.

The isothermal reactivity coefficient for the system is the derivative of the total reactivity curve. It is shown as the black dashed curve in the figure. A temperature labeled T_i is shown in Fig. 1 at which the slope of the total reactivity curve changes from positive to negative or where total reactivity of the system is at its maximum. This is the calculated inversion point of the isothermal reactivity coefficient described in [4,5], 21 ºC for this configuration. The reactivity curves are normalized to give zero at this temperature. The general behavior of the curves shown in the figure is typical for uniformly loaded experiment configurations explored at Sandia though the details differ from configuration to configuration.

Fig. 2 shows a configuration of the fully-reflected 7uPCX fuel on a 1.710 cm pitch. The number of 7uPCX fuel rods required to produce a critical system at room temperature is at the minimum possible near a pitch of 1.6 cm so the assembly in the figure is slightly overmoderated. A plot of the calculated water, fuel, and total reactivity as well as the reactivity coefficient is also shown in the figure. The estimated inversion point of the isothermal reactivity coefficient is 36 ºC, somewhat higher than for the undermoderated configuration addressed in Fig. 1.

Fig. 3 shows similar calculated data for a fully-reflected near-critical configuration with 0.855 cm pitch with the core split equally around a 4-row wide water channel. This configuration has two undermoderated fuel halves

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interacting across an unfueled water-filled region. A plot of the calculated water, fuel, and total reactivity as well as the isothermal reactivity coefficient is also shown in the figure. The calculated inversion temperature for this system is 43 ºC.

Fig. 4 is for an assembly similar to the one addressed in Fig. 3 with the width of the water channel at 6 rows. The calculated inversion temperature for this case moves up to 74 ºC.

CRITICAL EXPERIMENTS TO MEASURE SENSITIVITY TO TEMPERATURE

Sandia has operated research reactors at its Technical Area V near Albuquerque, New Mexico for many years. A series of critical experiments was initiated in 1999 [6] under DOE Nuclear Energy Research Initiative sponsorship that provided the base for the current Sandia Critical Experiments. The critical experiments program, now under the sponsorship of the DOE Nuclear Criticality Safety Program (NCSP), continues with an active series of critical experiments. The program has produced several benchmark critical experiment evaluations that are published in [3]. Examples are LEU-COMP-THERM-078, LEU-COMP-THERM-079, LEU-COMP-THERM-080, and others, all of which report benchmark experiments with arrays water-moderated and -reflected, UO_2 fuel pins. To date, all critical experiments in the current program have been operated near room temperature.

Sandia and partner Oak Ridge National Laboratory are currently designing critical experiments whose purpose is to provide benchmark data at several temperatures that can be used to test current nuclear analysis methods. Contributions to the design are also being made by the Naval Nuclear Laboratory and Lawrence Livermore National Laboratory.

Oak Ridge is leading the design of a series of critical experiments that will be operated above (or possibly below) room temperature [7]. As currently envisioned, the experiments will be inverse-multiplication approaches to critical at constant temperature with the temperature varying from experiment to experiment.

Sandia is leading the design of a separate but related set of experiments intended to directly measure the inversion point of the isothermal reactivity coefficient. A series of experiments at the Instituto de Pesquisas Energéticas e Nucleares (IPEN) in Brazil measuring the inversion point of the isothermal reactivity coefficient in the IPEN MB-01 reactor was documented in [8]. In these experiments, an automatic controller was used to keep the reactor power constant by adjusting a control rod while the temperature of the reactor was varied. The critical rod height was recorded as a function of reactor temperature. The reactor was at its most reactive state when the temperature was at the inversion point of the isothermal reactivity coefficient. This coincided with the lowest point (most inserted) of the automatically controlled rod.

In the Sandia inversion point experiments, the multiplication of a nearly-critical configuration of the assembly will be monitored by measuring the count rate in neutron detectors near the source-driven assembly as the assembly temperature is varied. The maximum count rate will occur at the temperature that gives the maximum reactivity in the system, the inversion point of the isothermal reactivity coefficient.

CONCLUSION

According to the analysis described above, the behavior of the reactivity as a function of temperature of a critical experiment can vary widely depending on the system configuration. Two sets of critical experiments are briefly described that are intended to measure these effects and provide benchmark results for comparison with the results of the analysis

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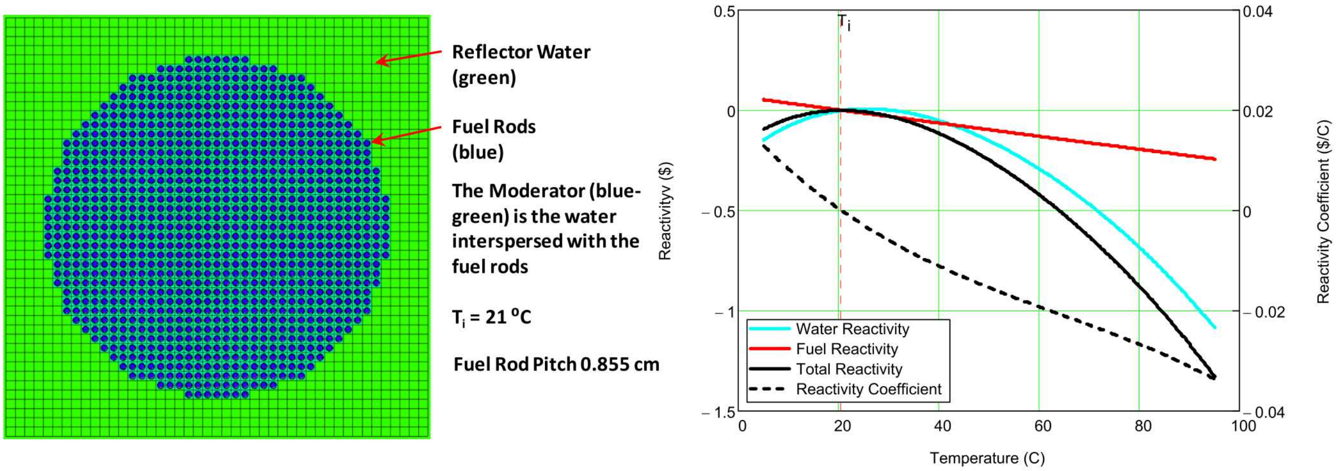

Fig. 1. Results of the reactivity analysis of an undermoderated fully-reflected critical experiment with the configuration shown.

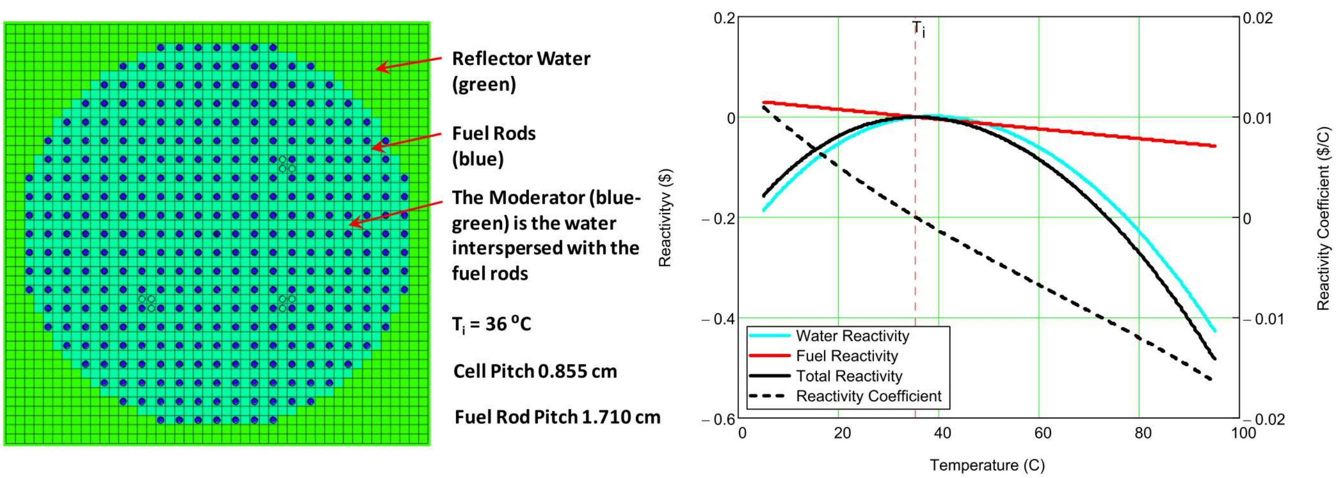

Fig. 2. Results of the reactivity analysis of an overmoderated fully-reflected critical experiment with the configuration shown.

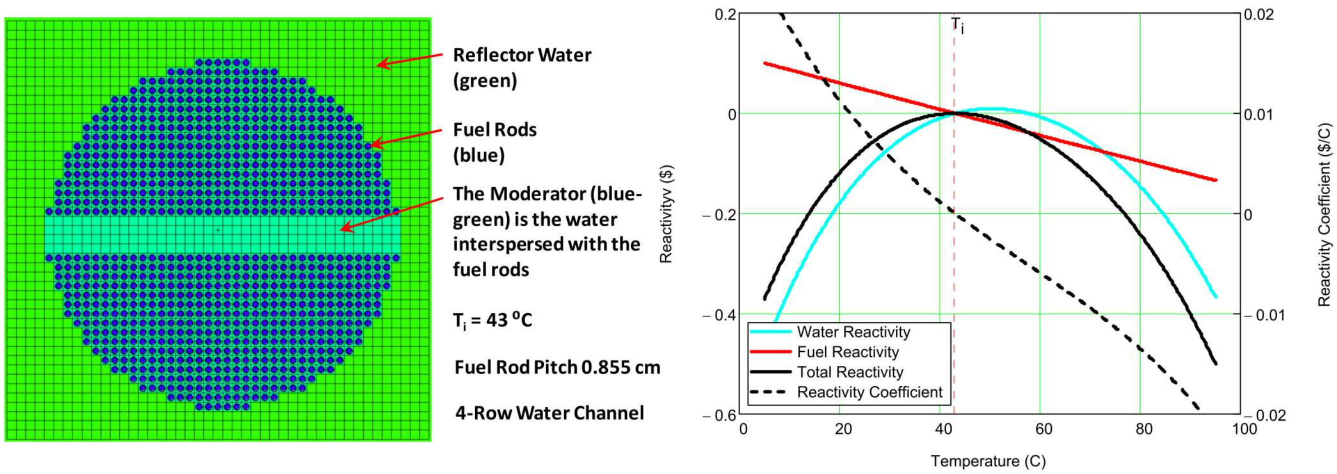

Fig. 3. Results of the reactivity analysis of a fully-reflected critical experiment having two undermoderated halves interacting across a water channel with the configuration shown.

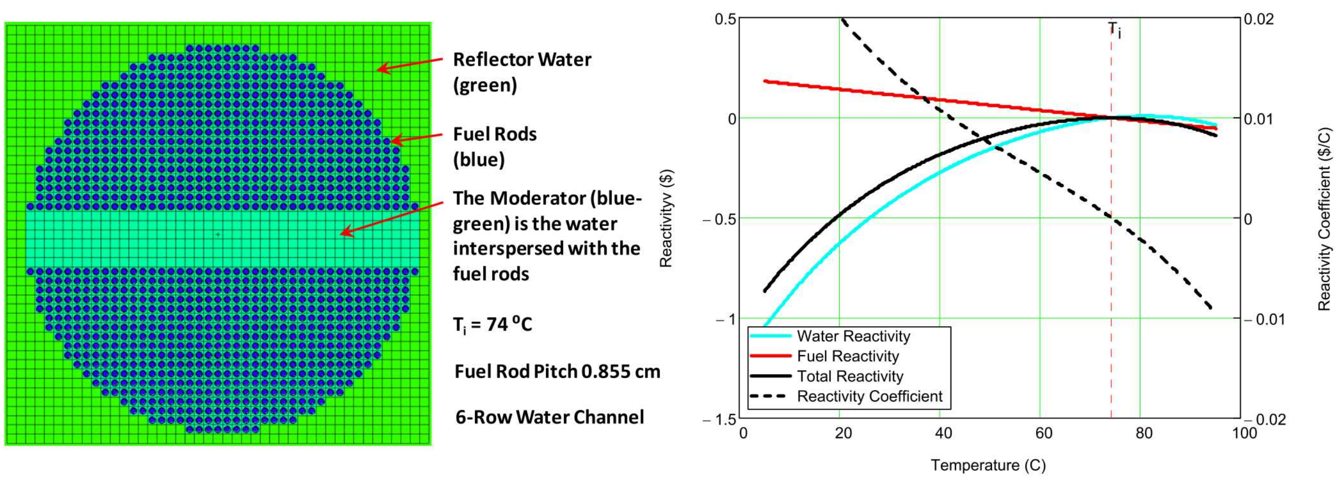

Fig. 4. Results of the reactivity analysis of a fully-reflected critical experiment having two undermoderated halves interacting across a water channel with the configuration shown.