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Results of Partially-Reflected Critical Experiments in Square-Pitched Arrays of Water-Moderated 6.9 Percent Enriched Fuel Rods

Gary A. Harms, John T. Ford, and Rafe D. Campbell

Sandia National Laboratories, P. O. Box 5800, Albuquerque, NM 87185-1146
gaharms@sandia.gov, jtford@sandia.gov, and rcampbe@sandia.gov

INTRODUCTION

The Seven Percent Critical Experiment (7uPCX) was designed to provide benchmark criticality and reactor physics data for water-moderated pin-fueled nuclear reactor cores. The enrichment of the fuel was chosen to explore the enrichment range above the current 5% ceiling for US commercial pressurized water reactors. The experiment was part of the US Department of Energy (DOE) Nuclear Energy Research Initiative (NERI) Project 01-124 titled "Reactor Physics and Criticality Benchmark Evaluations for Advanced Nuclear Fuel" [1].

The NERI project was a collaboration between AREVA Federal Services, LLC; the University of Florida; Oak Ridge National Laboratory; and Sandia National Laboratories (SNL). The experiments at Sandia are currently supported by the DOE National Nuclear Security Administration Nuclear Criticality Safety Program.

Two sets of benchmark experiments have been completed and documented as LEU-COMP-THERM-080 and LEU-COMP-THERM-078 [2]. Those experiments were done with the number of fuel rods in the fully-reflected array as the approach parameter. The experiments reported here are similar to those in LEU-COMP-THERM-080 except that the arrays are partially-reflected – the arrays were larger than would be possible with full reflection and the approach-to-critical experiments were done with the depth of the water in the critical assembly as the approach parameter. These experiments are reported as LEU-COMP-THERM-096 [2].

DESIGN OF THE CRITICAL ASSEMBLY

Details of the design of the experiment hardware are given in the LEU-COMP-THERM-096 benchmark evaluation [2]. The 7uPCX critical assembly has two tanks; the elevated assembly tank and the dump tank at a lower level. The overall layout of the critical assembly is shown in Fig. 1. The two tanks are connected by two large-diameter dump lines. Each dump line includes a normally-open valve that allows the passage of the assembly moderator. When the assembly is shut down the moderator resides in the dump tank and the fuel array in the assembly tank is dry. In this condition, k_{eff} in the assembly is less than 0.2. To operate the assembly, the two dump valves are closed and the moderator is pumped from the dump tank to the assembly tank through a "fast fill" system. At the conclusion of an operation, the dump valves are opened to allow the moderator to drain from the assembly tank. A heater is present in the dump tank and is used to maintain the temperature of the assembly moderator.

Fig. 1. Cut-away view of the 7uPCX assembly tank.

The array of fuel rods in the critical assembly is supported by two 2.54-cm-thick 6061 aluminum grid plates and a guide plate that is used to align the fuel rods during insertion. The grid and guide plates each have a square-pitched 45x45 square array of holes that position the fuel rods in the array. The pitch of the holes in the array is 0.8001 cm. The upper grid and guide plates are supported from the lower grid plate by four aluminum support posts.

The assembly fuel rods are clad in 3003 aluminum tubes with welded upper and lower end plugs. From bottom to top, the material in the rods includes a 48.78 cm tall stack of 6.90 percent enriched UO_2 fuel pellets that are 0.5256 cm in diameter, a spring to maintain the vertical alignment of material in the fuel rod, an aluminum spacer, and a polyethylene spacer. The aluminum spacer is aligned vertically with the upper aluminum grid plate. The diameter of the polyethylene spacer was chosen so the hydrogen in the spacer replaces the hydrogen in the water that would be displaced by the part of the fuel rod above the upper grid plate.

The assembly has two fuel-followed safety elements and one control element, all of identical design. Each element is a four-rod cluster that replaces four fuel rods in the array. The upper absorber section of each element consists of four aluminum tubes filled with B_4C. The fuel follower of each element is four rods each filled with fuel pellets and a spring, each designed to be nearly identical to a fuel rod in the assembly. The absorber sections are separated from the fuel followers by a four-rod cluster of polyethylene-filled aluminum tubes. During measurements in the assembly, the control and safety elements are fully raised with the fuel followers are in the core, the polyethylene-filled sections are above the upper grid plate and the absorber sections are well away from the fuel in the array.

During approach-to-critical experiments, the assembly is driven by a small stainless-steel-clad ^{252}Cf source that can be placed either in the fuel grid or near it. The behavior of the neutron population in the assembly is monitored by several fission chambers located outside the fuel array either in dry wells or outside the assembly tank. Two of the detectors inside the tank are in dry wells surrounded by polyethylene and provide signals to the assembly plant protect system (PPS).

A cut-away view of the assembly tank with the moderator drained is shown in Fig. 2. The inset on the lower left of the figure shows the tank with the moderator at the critical level for the fuel configuration shown. In this configuration, the fuel array has a water reflector at least 15 cm thick laterally and below but has no top reflector. The experiments described here were done in this partially-reflected configuration. Several relevant physical characteristics of the critical assembly are shown in Table I.

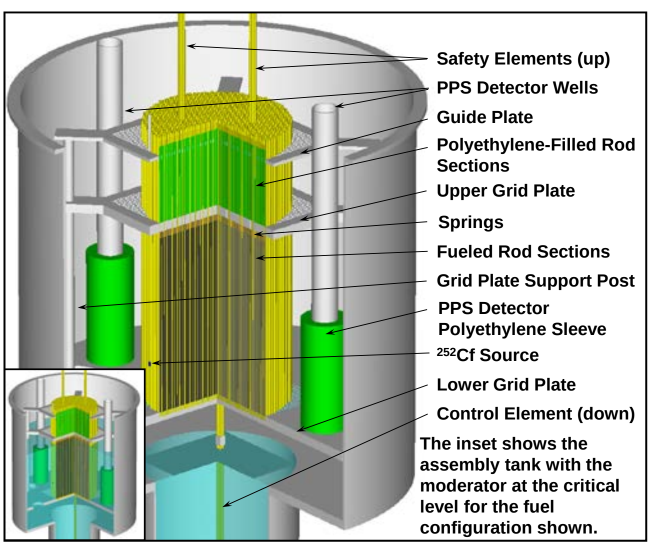

Fig. 2. Cut-Away View of the 7uPCX Assembly Tank

Table I. Characteristics of the Critical Assembly

Moderator	Light Water
Fuel Pellet Material	UO2
Uranium Enrichment	6.90%
Fuel Pellet OD	0.526 cm
Fuel Pellet Stack Length	48.78 cm
Fuel Column Mass	108.72 g
Cladding Material	3003 Aluminum
Cladding OD	0.635 cm
Cladding ID	0.569 cm
Array Pitch	0.8001 cm
Assembly Temperature	25°C

EXPERIMENTAL METHOD

During operation of the critical assembly, water is continuously pumped from the dump tank to the assembly tank through a “slow fill” system. The temperature of the water is held constant by an automatic heater in the dump tank. The level of the moderator in the assembly tank is maintained by overflow into a remotely-adjustable standpipe (RASP), shown in Fig. 1, that is operated from the control console of the critical assembly. The RASP limits the reactivity available in the assembly during an approach-to-critical experiment with the level of the moderator/reflector in the assembly tank as the approach variable.

The level of the moderator/reflector in the core tank is monitored by two systems, one an uncalibrated linear level-indicating system located in a standpipe outside the core tank, and one a calibrated system of four ultrasonic distance measurement devices in still tubes around the periphery of the core tank. A view of the critical assembly core showing the still tubes of the ultrasonic level measurement system is shown in Fig. 3.

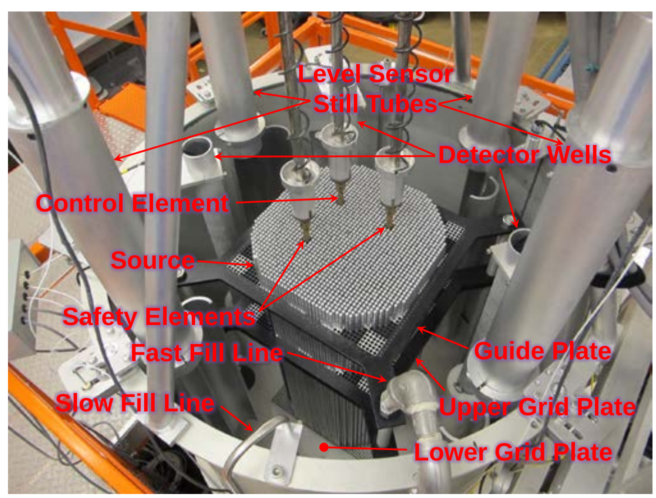

Fig. 3. View of the hardware in the assembly tank.

The ultrasonic sensors operate by emitting a pulse of ultrasound and measuring the time required to receive an echo from a surface. The still tubes restrict the field of view of the ultrasonic sensors to an area in which surface disturbances of the moderator are limited by the presence of the still tube. Each still tube has a hinged door on the side, shown open in Fig. 3, that allows placement of the length standards used to calibrate the system. The air temperature in each still tube is monitored by a high-precision platinum resistance temperature detector (RTD) to allow corrections to be made for the temperature-dependent velocity of sound in the tubes.

The ultrasonic sensors are operated in sets of two with the still tubes for the two sensors in a set positioned in diametrically-opposed locations across the critical assembly core from one another. The moderator/reflector level in the center of the assembly core is obtained by averaging the measured levels of the two sensors in a set. Two measurements of the level of the moderator/reflector at the center of the core are thus provided by the two sets of two ultrasonic level sensors.

For an experiment with an unknown core, the approach to critical begins by making count-rate measurements at two moderator levels that have been shown by analysis to be subcritical. These first moderator levels had calculated values of the effective multiplication factor (k_{eff}) of approximately 0.90 and 0.95. Succeeding moderator levels are guided by the count-rate results of the two most recent measurements. For pairs of moderator levels, a linear fit of the relative inverse count rate to the moderator level in the assembly is used to determine the moderator level that would give an inverse count rate of zero. This is the equivalent of an infinite count rate which indicates the delayed critical condition. The moderator level is then increased to a level about half way between the last measured level and the estimated critical level and count rates measured. This process is repeated until a final count rate measurement is made at a level within a few millimeters of the critical level.

EXPERIMENTAL CONFIGURATIONS

The fuel rod configurations addressed by the experiments fall notionally into four series. The first series of three configurations is made up of arrays with fuel rods distributed throughout the 45x45 grid of fuel positions in the grid plates with or without internal water holes in the array. In the second series, a roughly cylindrical outer boundary of decreasing diameter is superimposed on the square array to yield six different fuel rod configurations, each with no internal water holes. The third series begins with a 40x40 square array of fuel rods and proceeds with the inclusion of a one- to five-row wide central linear array of water holes. The fourth series is similar to the third except that the central slot in the core is formed by a one- to four-row cruciform array of water holes. Table II lists some of the characteristics of the nineteen configurations addressed.

EXPERIMENTAL RESULTS

The measured critical water heights in the critical assembly are given for each experiment in Table II. The water heights are given relative to the bottom of the fuel pellet stack in the assembly fuel rods. Because these heights were determined for the delayed-critical state of the assembly, the experimental k_{eff} for these heights is 1.0000.

During the evaluation process described in LEU-COMP-THERM-096, the experimental configurations were simplified to arrive at benchmark models of the experiments. Figure 4 shows the resulting fuel rod arrays for some of the benchmark models of the critical experiments.

The biases introduced in the simplification process were determined by calculating the k_{eff} of the experimental configuration and comparing it to the k_{eff} of the simplified benchmark configuration. The bias was then added to the experimental k_{eff} (1.0000) to obtain the benchmark model k_{eff}. The k_{eff} uncertainties in the experiments from many physical uncertainty sources were determined and combined with the uncertainties introduced by the simplification process to arrive at the benchmark model k_{eff} uncertainties. The benchmark model k_{eff} and its uncertainty are listed in the final two columns of Table II.

CONCLUSION

A set of approach-to-critical experiments was done to measure the critical water level in nineteen fuel rod configurations. The results of those experiments are presented here. Detailed documentation of the experiments is included in LEU-COMP-THERM-096 in Reference 1.

ACKNOWLEDGEMENT

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REFERENCES

1. “Reactor Physics and Criticality Benchmark Evaluations for Advanced Nuclear Fuel, Final Technical Report.” TDR-30000849-000, Areva Federal Services, LLC (2008).

2. International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, Organisation for Economic Co-operation and Development-Nuclear Energy Agency, (2015).

Table II. Characteristics of the Critical Experiments with the Measured Critical Water Levels and Benchmark k_{eff} Data

Case	Fuel Rods	External Array Configuration	Internal Array Configuration	Critical Water Level (cm)	Benchmark Model k_{eff} Value	σ
1	2025	45x45 Square	No Water Holes	36.54	0.9999	0.0010
2	2024	45x45 Square	One Central Water Hole	36.52	0.9999	0.0010
3	1836	45x45 Square	189 Distributed Water Holes	31.53	0.9999	0.0009
4	1977	Rough Cylinder	No Water Holes	37.12	0.9999	0.0010
5	1873	Rough Cylinder	No Water Holes	38.65	0.9998	0.0010
6	1781	Rough Cylinder	No Water Holes	40.39	0.9998	0.0009
7	1673	Rough Cylinder	No Water Holes	43.10	0.9999	0.0009
8	1573	Rough Cylinder	No Water Holes	46.57	0.9999	0.0009
9	1525	Rough Cylinder	No Water Holes	48.70	1.0000	0.0009
10	1600	40x40 Square	No Water Holes	46.78	0.9999	0.0009
11	1600	41x40 Rectangle	1-Row Linear Slot	42.18	1.0000	0.0010
12	1600	42x40 Rectangle	2-Row Linear Slot	39.61	1.0000	0.0010
13	1600	43x40 Rectangle	3-Row Linear Slot	39.03	0.9999	0.0010
14	1600	44x40 Rectangle	4-Row Linear Slot	39.98	0.9999	0.0010
15	1600	45x40 Rectangle	5-Row Linear Slot	42.58	0.9999	0.0010
16	1600	41x41 Square	1-Row Cruciform Slot	38.70	0.9999	0.0010
17	1600	42x42 Square	2-Row Cruciform Slot	35.31	0.9999	0.0010
18	1600	43x43 Square	3-Row Cruciform Slot	35.10	1.0000	0.0010
19	1600	44x44 Square	4-Row Cruciform Slot	37.49	0.9999	0.0010

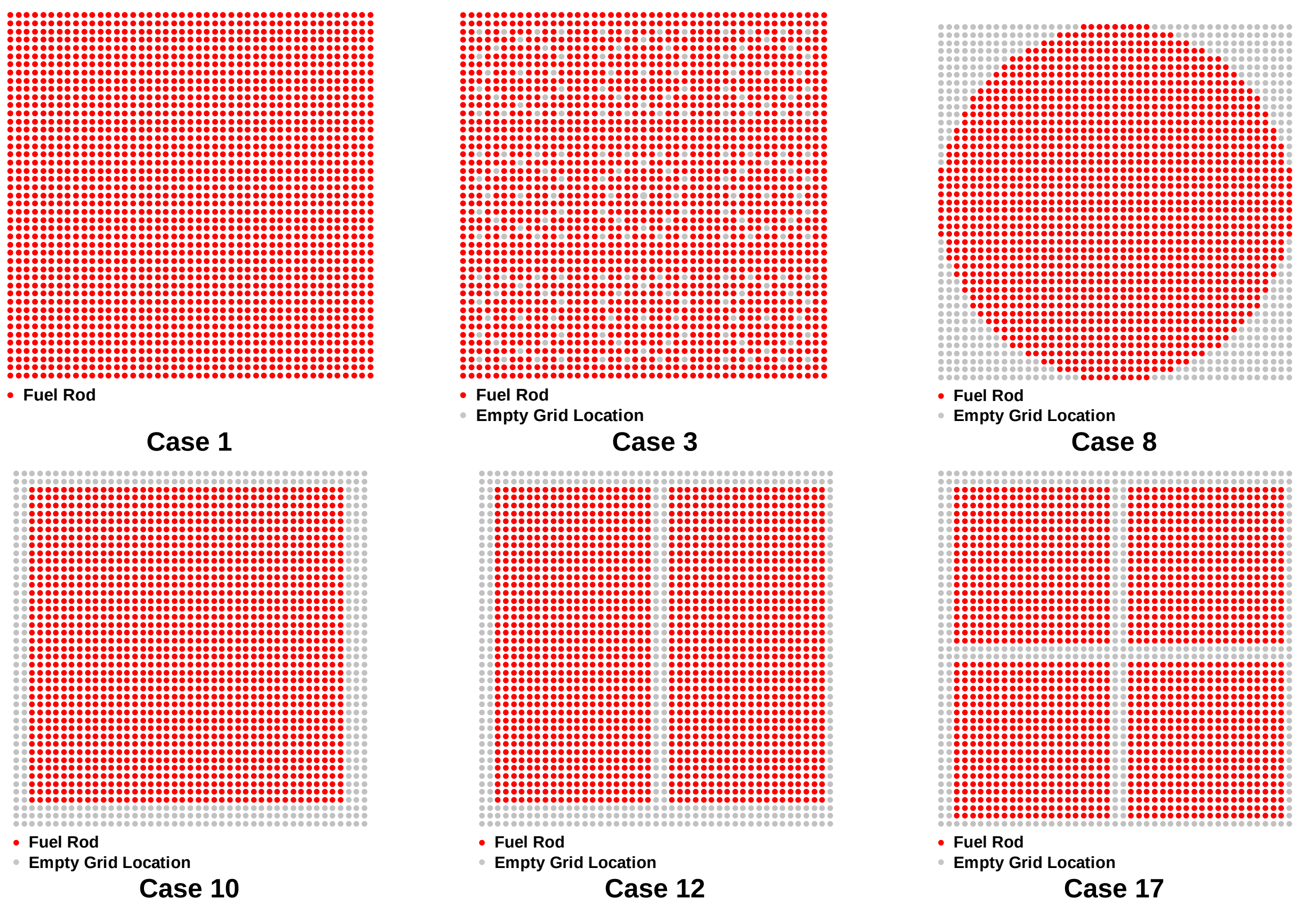

Fig. 4. Some of the fuel rod configurations addressed in the experiments.