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Titanium and Aluminum Rod-Replacement Experiments in Fully-Reflected 6.90% Enriched UO_2 Fuel Rod Lattices

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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 Project 01-124 titled "Reactor Physics and Criticality Benchmark Evaluations for Advanced Nuclear Fuel" [1].

Three sets of benchmark experiments have been completed using the 7uPCX and documented as LEU-COMP-THERM-080, LEU-COMP-THERM-078, and LEU-COMP-THERM-096 [2]. The experiments for LEU-COMP-THERM-080 and LEU-COMP-THERM-078 were done in fully-reflected arrays with the number of fuel rods in the array as the approach parameter. The experiments for LEU-COMP-THERM-096 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. The experiments described here are similar to the fully-reflected experiments in LEU-COMP-THERM-080 with some of the central fuel rods in the array replaced by titanium rods, aluminum rods, and/or water. The experiments are designed to provide criticality safety benchmarks with significant reactivity from titanium and equivalent configurations with aluminum experiment rods. These experiments are documented as LEU-COMP-THERM-097 [2].

DESIGN OF THE CRITICAL ASSEMBLY

Details of the design of the experiment hardware are given in the LEU-COMP-THERM-097 benchmark evaluation [2]. The 7uPCX critical assembly has two tanks; the elevated assembly tank and the dump tank at a lower level. 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. 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.

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 safety elements and one control element, all of identical design, all fuel-followed. 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. The fuel followers are 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 above the level of the moderator.

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. 1. The inset on the lower left of the figure shows the tank with the assembly tank full of water. In this configuration, the fuel array has a water reflector at least 15 cm thick laterally, above, and below. The experiments described here were done in this fully-reflected configuration. Details of the design of the critical assembly are available in the evaluation.

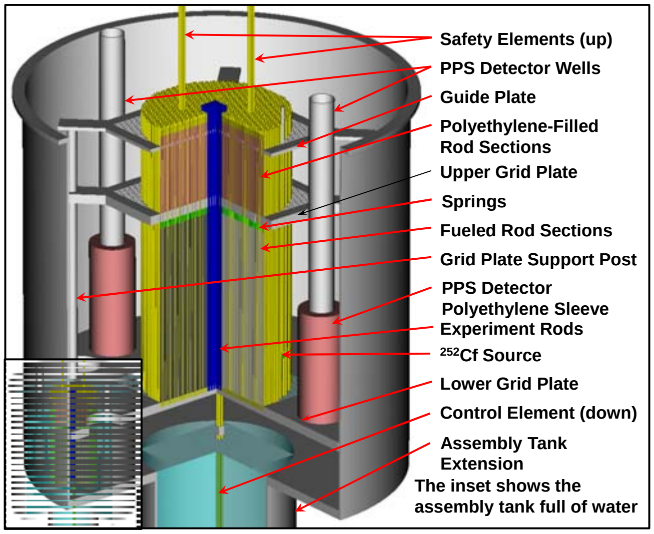

Fig. 1. Schematic cut-away view of the critical assembly.

EXPERIMENT RODS

Experiment rods, each designed to replace a fuel rod in the array, were fabricated from either Grade 2 titanium [3] or 6061 aluminum [4] and were placed near the center of the fuel array in several of the measured configurations. These rods were fabricated from round stock with a nominal diameter of 0.635 cm. The experiment rods were nominally 79.4512 cm in length, slightly longer than the fuel rods. The top and bottom of each rod were chamfered. After fabrication, each of the experiment rods was laser-scribed with a unique serial number.

The mass, outside diameter, and length of each experiment rod were measured. The density of each experiment rod was calculated from these data and knowledge of the design of the experiment rods.

EXPERIMENTAL METHOD

For each configuration, an approach-to-critical experiment was run with the number of fuel rods in the array as the approach parameter. For each measured array in the approach, the assembly fuel was "fully reflected" having a lower reflector of 16.51 cm below the lower grid plate and a radial reflector with a thickness of greater than 15.24 cm beyond the outermost fuel rod. During operation, water was continuously fed into the assembly tank at a low rate. The level of the water in the tank was set by the height of an overflow standpipe attached to the assembly tank. The standpipe was adjusted to give a water level 15.24 cm above the top of the upper grid plate.

The focus of these critical experiments was to measure the effects of titanium and aluminum rod replacements in the fuel array on the critical array size. Every experiment with titanium experiment rods has a corresponding experiment with aluminum experiment rods in the same configuration though the numbers of fuel rods in the array differ because of the differing effects of titanium and aluminum.

The critical array size for each configuration was determined in an approach-to-critical experiment with the number of fuel rods in the array as a free parameter. The inverse count rate at successive fuel configurations for two detectors as a function of the number of fuel rods was extrapolated to zero to obtain an estimate of the critical array size. During all measurements the control and safety elements were in their fully withdrawn or most reactive positions.

The square-pitched arrays were loaded from the center toward the outside while maintaining a roughly cylindrical cross section of the array. The loading order was identical for each experiment. Each fuel rod was in the same array location in every configuration that included that fuel rod.

For all configurations, a final approach-to-critical experiment was performed in which count rate measurements were taken for specific symmetrical fuel arrays. In an orderly loading process, these arrays occur at intervals of four or eight fuel rods. Some of the experiments split an interval of eight rods into two four-rod intervals. The measured count rates were inverted. A linear fit to the inverse count rate as a function of number of fuel rods in the array was extrapolated to zero inverse count rate to estimate the critical configuration of the experiment. The extrapolated critical array sizes were developed from the inverse count rate data measured during these final experiments. The experimental k_{eff} for each configuration was obtained as described in LEU-COMP-THERM-097 [2].

EXPERIMENTAL CONFIGURATIONS

The experiments can be divided into six groups by the number, configuration, and arrangement of the experiment rods. The first group consists of a single experiment, Case 1, that has no experiment rods and no water holes. The second group consists of five experiments, Cases 2 through 6 having a close-packed square array of 4, 9, 16, 25, or 36 titanium experiment rods near the center of the fuel array respectively. Cases 7 through 9 (like Case 6) each have 36 titanium experiment rods in a square array with the pitch of the experiment rods increasing with case number. Case 6 has an experiment rod pitch P of 0.8001 cm, Case 7 has a pitch of 1.1315 cm ($\sqrt{2}\times P$), Case 8 has a pitch of 1.6002 cm ($2\times P$), and case 9 has a pitch of 2.4003 cm ($3\times P$). In Cases 7 through 9, the array locations between neighboring experiment rods contains a fuel rod. There were no empty array locations.

Cases 10 through 17 are identical to Cases 2 through 9 respectively except that the titanium experiment rods are replaced with aluminum experiment rods.

The fuel arrays with 0.8001 cm pitch were significantly undermoderated. For Cases 18 through 24, the fuel-to-water ratio in the central part of the assembly was decreased by removing a significant amount of fuel but leaving one-fourth of the fuel rods. The pitch of the fuel rods in this central zone was thus increased to 1.6002 cm. This configuration was used for Case 18 with no experiment rods. In Cases 19 through 24, a square array of 36 experiment rods with a center-to-center spacing of 1.6002 cm was interspersed between the remaining fuel rods in the central zone. In Case 19, all the experiment rods were aluminum. In cases 20 through 23, the aluminum rods in a square array of 4, 9, 16, and 25 experiment rods were replaced with titanium rods. In Case 24, all 36 experiment rods were titanium. Figure 2 is a photograph of the fuel array for Case 22. In the photograph, the ends of the 16 titanium experiment rods have been colored to distinguish them from the aluminum experiment rods and the fuel rods. Details of the rod configurations in each case are available in LEU-COMP-THERM-097 [2].

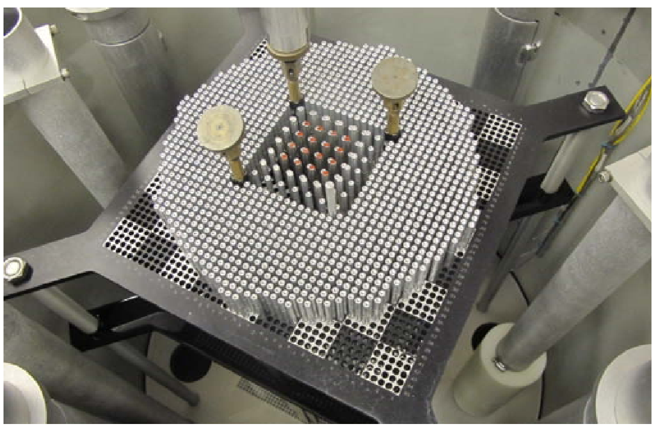

Fig. 2. Fuel and experiment rod array of Case 22.

EXPERIMENTAL RESULTS

Twenty-four fully-reflected configurations were addressed by the critical experiments described here. The fuel array in each configuration had a roughly circular cross section. Table I lists the twenty-four cases with the number of titanium and aluminum experiment rods in each. Also listed is the pitch of the experiment rods and the number of water holes inside the outer boundary of the array. In the benchmark evaluation, some of the geometrical and material details of the experiments were simplified to arrive at a benchmark configuration. The small biases associated with the simplifications were added to the experimental k_{eff} for each configuration to arrive at the benchmark model k_{eff}. The benchmark model k_{eff} with its uncertainty for each configuration is shown in Table I.

COMPARISON TO CALCULATION

Figure 3 shows the reactivity offset in MCNP6.1.1 [5] calculations of the benchmark models where the reactivity offset ρ is defined by

$$\rho = \frac{k_c - k_b}{k_c k_b}, \qquad (1)$$

k_c is the calculated k_{eff} for the benchmark model of a given configuration, and k_b is the evaluated benchmark model k_{eff} for the same configuration.

CONCLUSION

The critical experiment series reported here was designed to provide criticality safety benchmarks for systems that include significant amounts of titanium. Each configuration that has titanium in it has a corresponding configuration where the titanium experiment rods are replaced with aluminum experiment rods.

ACKNOWLEDGEMENTS

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Table I. Characteristics of the critical experiments.

	Experiment Rods			Internal	Fuel	Benchmark Model k_{eff}		Experiment Rod Reactivity Worth (%)	
Case	Titanium	Aluminum	Pitch (cm)	Water Holes	Rods	Value	σ	Value	σ
1	0	0	0.8001	0	1457	0.99940	0.00109	0	–
2	4	0	0.8001	0	1473	0.99942	0.00099	-0.22	0.01
3	9	0	0.8001	0	1492	0.99934	0.00098	-0.50	0.01
4	16	0	0.8001	0	1521	0.99955	0.00098	-0.92	0.01
5	25	0	0.8001	0	1560	0.99947	0.00098	-1.42	0.01
6	36	0	0.8001	0	1609	0.99969	0.00098	-2.01	0.01
7	36	0	1.1315	0	1585	0.99953	0.00098	-1.84	0.01
8	36	0	1.6002	0	1573	0.99961	0.00099	-1.69	0.01
9	36	0	2.4003	0	1557	0.99946	0.00098	-1.52	0.01
10	0	4	0.8001	0	1453	0.99913	0.00107	0.02	0.01
11	0	9	0.8001	0	1448	0.99909	0.00107	0.01	0.01
12	0	16	0.8001	0	1445	0.99930	0.00107	-0.02	0.01
13	0	25	0.8001	0	1444	0.99955	0.00107	-0.03	0.01
14	0	36	0.8001	0	1441	0.99943	0.00107	-0.04	0.01
15	0	36	1.1315	0	1429	0.99972	0.00107	0.03	0.01
16	0	36	1.6002	0	1429	0.99978	0.00107	0.07	0.01
17	0	36	2.4003	0	1425	0.99946	0.00107	0.06	0.01
18	0	0	1.6002	172	1037	0.99965	0.00078	0	–
19	0	36	1.6002	136	1097	0.99950	0.00078	-0.16	0.01
20	4	32	1.6002	136	1153	0.99965	0.00078	-0.91	0.01
21	9	27	1.6002	136	1213	0.99976	0.00078	-1.66	0.01
22	16	20	1.6002	136	1285	0.99945	0.00068	-2.60	0.01
23	25	11	1.6002	136	1377	0.99952	0.00068	-3.56	0.01
24	36	0	1.6002	136	1485	0.99966	0.00068	-4.58	0.01

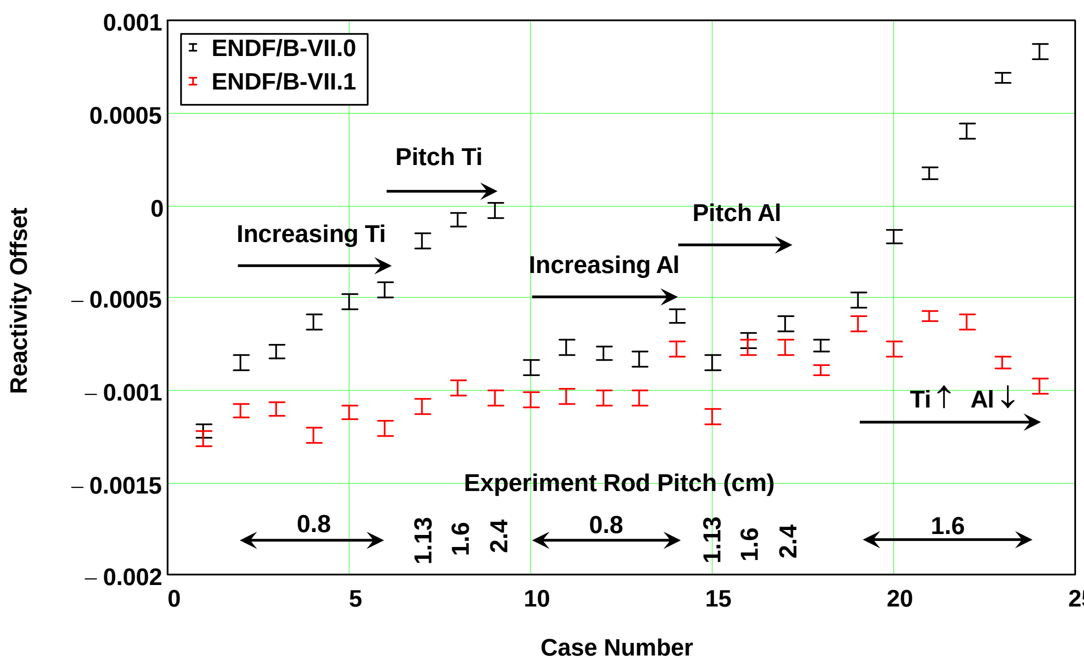

Fig. 3. Reactivity offset for MCNP6.1.1 calculations of the benchmark configurations for ENDF/B-VII.0 and ENDF/B-VII.1 cross sections. The calculations were otherwise the same. The error bars show only the stochastic uncertainty in the Monte Carlo calculations.