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Benchmark Evaluation of Fuel Effect and Material Worth Measurements for a Beryllium-Reflected Space Reactor Mockup

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Abstract. The critical configuration of the small, compact critical assembly (SCCA) experiments performed at the Oak Ridge Critical Experiments Facility (ORCEF) in 1962-1965 have been evaluated as acceptable benchmark experiments for inclusion in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [1]. The initial intent of these experiments was to support the design of the Medium Power Reactor Experiment (MPRE) program, whose purpose was to study "power plants for the production of electrical power in space vehicles." The third configuration in this series of experiments was a beryllium-reflected assembly of stainless-steel-clad, highly enriched uranium (HEU)-O_2 fuel mockup of a potassium-cooled space power reactor. Reactivity measurements cadmium ratio spectral measurements and fission rate measurements were measured through the core and top reflector. Fuel effect worth measurements and neutron moderating and absorbing material worths were also measured in the assembly fuel region. The cadmium ratios, fission rate, and worth measurements were evaluated for inclusion in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [2]. The fuel tube effect and neutron moderating and absorbing material worth measurements are the focus of this paper. Additionally, a measurement of the worth of potassium filling the core region was performed but has not yet been evaluated

Pellets of 93.15 wt.% enriched uranium dioxide (UO_2) were stacked in 30.48 cm tall stainless steel fuel tubes (0.3 cm tall end caps). Each fuel tube had 26 pellets with a total mass of 295.8 g UO_2 per tube. 253 tubes were arranged in 1.506-cm triangular lattice. An additional 7-tube cluster critical configuration was also measured but not used for any physics measurements. The core was surrounded on all side by a beryllium reflector.

The fuel effect worths were measured by removing fuel tubes at various radius. An accident scenario was also simulated by moving outward twenty fuel rods from the periphery of the core so they were touching the core tank. The change in the system reactivity when the fuel tube(s) were removed/moved compared with the base configuration was the worth of the fuel tubes or accident scenario.

The worth of neutron absorbing and moderating materials was measured by inserting material rods into the core at regular intervals or placing lids at the top of the core tank. Stainless steel 347, tungsten, niobium, polyethylene, graphite, boron carbide, aluminum and cadmium rods and/or lid worths were all measured. The change in the system reactivity when a material was inserted into the core is the worth of the material.

Keywords: Critical experiment, Uranium dioxide, Beryllium reflected, Reactivity measurement.

INTRODUCTION

A series of small, compact critical assembly (SCCA) experiments were completed from 1962–1965 at Oak Ridge National Laboratory's (ORNL's) Critical Experiments Facility (CEF) in support of the Medium-Power Reactor Experiments (MPRE) program. In the late 1950s, efforts were made to study "power plants for the production of electrical power in space vehicles."[3] The MPRE program was a part of those efforts and studied the feasibility of a stainless-steel system, boiling potassium 1 MW(t), or about 140 kW(e), reactor. The program was carried out in [fiscal years] 1964, 1965, and 1966. A summary of the program's effort was compiled in 1967 [3]. The delayed critical experiments were a mockup of a small, potassium-cooled space power reactor for validation of reactor calculations and reactor physics methods.

Initial experiments, performed in November and December of 1962, consisted of a core of un-moderated stainless-steel tubes, each containing 26 UO_2 fuel pellets, surrounded by a graphite reflector. Measurements were performed to determine critical reflector arrangements, fission-rate distributions, and cadmium ratio distributions. Subsequent experiments used beryllium reflectors and also measured the reactivity for various materials placed in the core. "The [assemblies were built] on [a] vertical assembly machine so that the movable part was the core and bottom reflector" [4]. The experiment studied in this evaluation was the third of the series and had the fuel in a 1.506-cm-triangular and 7-tube clusters leading to two critical configurations [5,6]. Once the critical configurations had been achieved, various measurements of reactivity, relative axial and radial activation rates of ^{235}U, and cadmium ratios were performed. These measurements were performed using the 1.506-cm-triangular pitch critical configuration. The reactivity measurements for fuel effect and material worth are the focus of this paper. The critical assembly configuration is briefly outlines for reference of the reader. The benchmark evaluations should be referenced a full description, evaluation, and discussion of the measurements [1,2].

CRITICAL CONFIGURATION

The critical configurations used for the fuel effect and material worth measurements was a core of 253 stainless steel rods each containing 26 UO_2 (93.2 wt.% U-235 enrichment) pellets. The dimensions of the fuel pellets, the fuel tubes, and the isotopic composition of the fuel is given in Table 1and 2. The tubes were arranged in a 1.506-cm-triangular-pitch arrangement and held in place using two grid plates. The fuel was contained within an aluminum core tank. The core tank was surrounded on all side by beryllium reflector. Dimensions of the reflectors are given in Table 3. The configuration was brought to critical using a vertical assembly machine; the core tank and bottom reflector were lifted into and under the side reflector and top reflector. Photographs of the vertical assembly machine and the critical configuration are given as Figure 1.

The critical configuration was evaluated and a detailed and simple benchmark model was derived. The detailed and simple benchmark models of the critical configuration were used in the evaluation of the fuel effect and material worth measurements. The detailed benchmark model of is shown in Figure 2. For more detail regarding the derivation of the critical configuration benchmark models refer to the full benchmark evaluation [1].

TABLE 1. Fuel Pellet and Tube Data

Number of Pellets per Tube	26		**Number of Fuel Tubes**	253	
UO_2 Density	9.71	g/cm^3	**Length**	30.48	cm
UO_2 Mass per Tube	295.8	g	**Outside Diameter**	1.27	cm
Pellet Diameter	1.141	cm	**Wall Thickness**	0.051	cm
Length of One Pellet	1.145	cm	**Weight with End Caps**	45.37	g
Length of 26 Pellets	29.88	cm[(a)]	**Weight of One End Cap**	0.64	g

(a) This length "includes 0.110 cm of void or ~0.0044 cm of void between each pellet".[2]

TABLE 2. Fuel Isotopic Composition

^{234}U	1.01	wt.%
^{235}U	93.15	wt.%
^{236}U	0.47	wt.%
^{238}U	5.37	wt.%

TABLE 3. Reflector Dimensions.

Top Reflector		**Bottom Reflector**	
Thickness (cm)	6.985	Thickness (cm)	7.62
Nominal Diameter (cm)[(a)]	41.2	Nominal Diameter (cm)[(a)]	41.2
Mass (kg)	17.13	Mass (kg)	18.7
Top Reflector Tank-Aluminum (Type 1100)		**Bottom Reflector Tank-Aluminum (Type 1100)**	
Side Wall Thickness (cm)	0.635	Side Wall Thickness (cm)	0.635
Height (cm)	12.95	Height (cm)	8.51
Bottom Thickness (cm)	0.22	Bottom Thickness (cm)	0.89
Mass (kg)	4.38	Mass (kg)	5.75
Side Reflector			
Height (cm)	30.63		
Thickness (cm)	11.37		
Inside Diameter (cm)	26.16		
Mass (kg)	75.7		

(a) This nominal diameter was given in the published report [4]. The top and bottom reflector were composed of 7.3- and 3.65-cm-square blocks, 2.54- or 0.635-cm-thick, and some triangular shaped pieces.

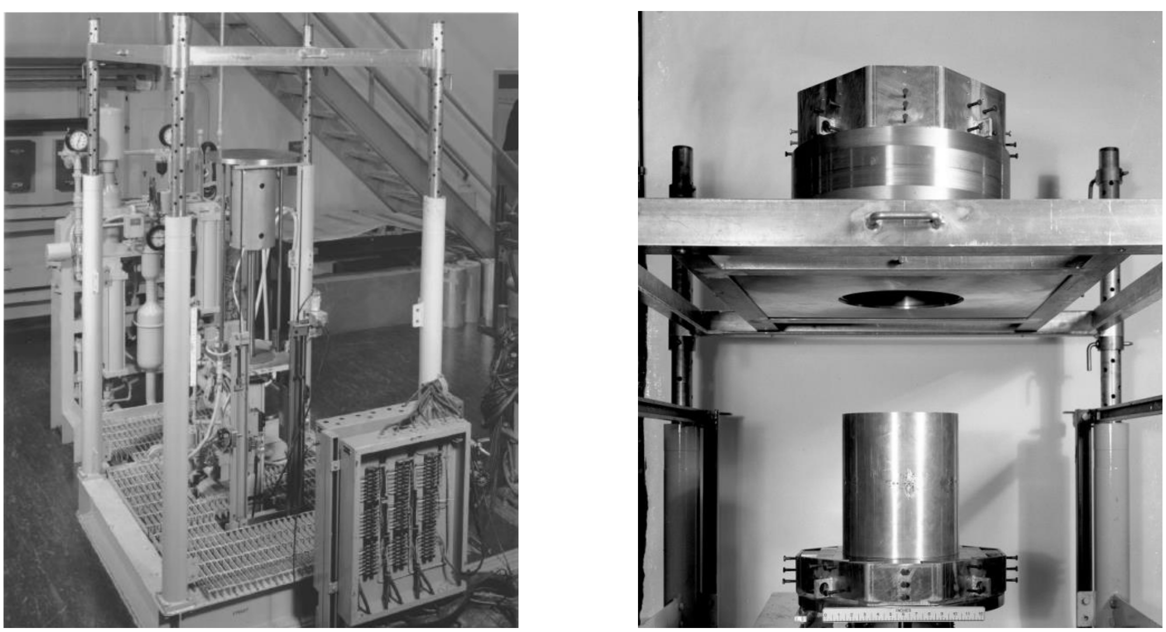

FIGURE 1. Vertical Assembly Machine and Disassembled Beryllium Reflected Core.

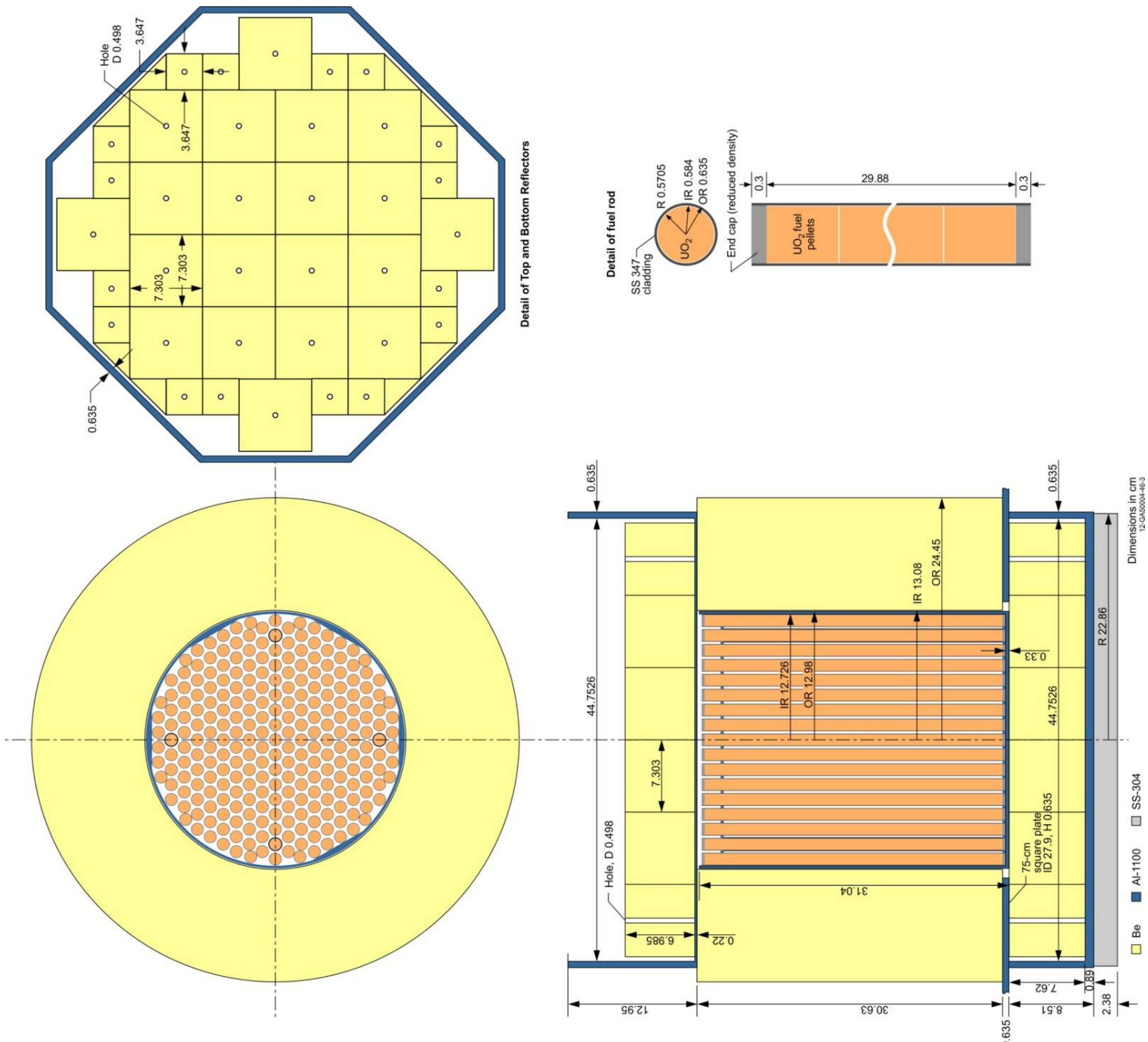

FIGURE 2. Detailed Benchmark Model of Critical Configuration.

REACTIVITY EFFECT MEASUREMENTS

Various reactivity measurements were performed. The reactivity of fuel tubes at various locations in the core and the effect of fuel tube movement at the periphery of the core were measured. The worth of various neutron absorbing and moderating materials inserted into the core and the worth of adding thickness to the top reflector were also measured. Finally the worth of adding potassium to the core was measured, which also led to some other worth measurements as the core was reconfigured to accommodate the potassium. The fuel effect and material reactivity measurements have been evaluated and are described in this paper. The potassium measurements have not yet been evaluated.

Experimental Results

Various reactivity measurements were performed. The reactivity of fuel tubes at various locations in the core and the effect of fuel tube movement at the periphery of the core were measured. The worth of various neutron absorbing and moderating materials inserted into the core were also measured. All worth measurements were performed by measuring the stable reactor period of the system before and after the system was perturbed. The stable reactor period was then converted to a system reactivity in units of dollars. The change in the system reactivity is the worth of the perturbation.

Fuel Effect Reactivity Measurements

The worth of fuel tubes at various radial locations in the core was measured by "observing the change in the stable reactor period when the fuel tube was removed"[5]. The worth of fuel tubes versus radial position is given in Table 4. The locations of the fuel tubes are shown in Figure 3.

A credible accident condition where twenty fuel tubes at the periphery of the core were moved from their normal location in the lattice out to the edge of the core was simulated. An example of this movement is shown for two fuel tubes in Figure 3. It is clear from the grid plate, Figure 4, which twenty rods were moved. The measured reactivity effect was -8.2 ¢ for displacement of twenty fuel tubes.

TABLE 4. Fuel Tube Reactivity Worth Versus Radial Position

Fuel Tube Position[(a)]	Distance From Core Center	Reactivity (¢)
1	0	32.0
2	2.59	32.0
3	5.23	30.8
4	7.75	27.2
5	10.48	25.5
6	10.56	25.6
7	11.78	22.6

(a) Positions given in Figure 3.

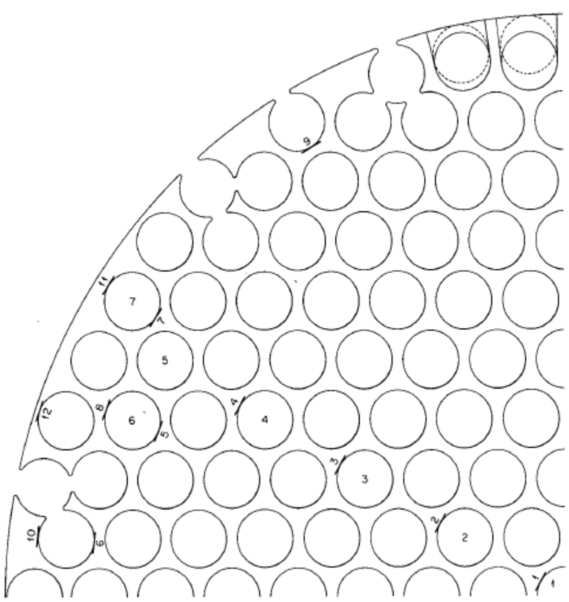

FIGURE 3. Fuel Tube Locations for Fuel Reactivity Measurements.

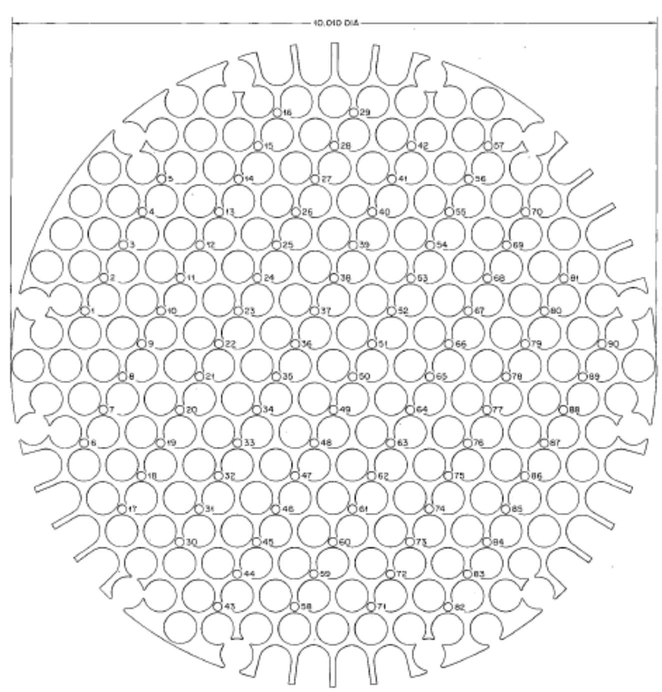

FIGURE 4. Drawing of Grid Plate with Sample Rod Locations.

Neutron Absorbing and Moderating Material Reactivity Measurements

The effect of adding various neutron absorbing and moderating materials was also measured. Materials were added to the core as rods, filled stainless steel tubes, and discs or lids that fit between the top of the fuel tubes and the top of the core tank. The results of the reactivity measurements are summarized in Table 5.

TABLE 5. Reactivity Effects of Absorbing and Moderating Material in the Core

Material	Form	Number	Location[(a)]	Total Weight (g)	Total Reactivity (cents)
Type 347 Stainless Steel	0.317 cm dia rods 30.5 cm long	90	All positions filled	1704	14.8
	0.317 cm dia rods 30.5 cm long	46	Every other position	871	7.92
W	0.317 cm dia rods 30.5 cm long	46	Every other position	2110	-4.27
Nb	3/32 inch dia rods 30.48 cm long[(c)]	90	All positions	1050	4.9
CH_2	0.317 cm dia rods 30.5 cm long	8	Odd number holes between 43-57	18.42	24.43
C	0.120 inch dia rods 30.5 cm long	23	Every 4th position	82	7.5
B_4C	Filled with B_4C[(g)]	1	Center fuel tube position	30.5	-6.65
Stainless Steel	Disc 0.317 cm thick for top of core tank	1	Top of core	1290	7.97
Al	Lid for top of core tank, 0.317 cm thick	1	Top of core	464	16.62
Al	Lid for top of core tank, 0.159 cm thick	1	Top of core	226	8.14
Cd	Lid for top of core, 0.066 cm thick	1	Top of core	286.5	-45.7

(a) Rod locations are labeled in Figure 4.

Evaluation of Experimental Results

The reactivity measurements were evaluated as benchmark experiments and found to be acceptable. The effect of the uncertainty in various experimental, geometrical, and material uncertainties was evaluated. The measurement uncertainty of the reactivity measurement was $10\%\sqrt{2}$.

Fuel Effect Reactivity Measurements

The uncertainty in the fuel and fuel tube dimensions and composition were evaluated as part of the evaluation of the critical configuration [1]. It was found that all parameters had a negligible effect on the critical system reactivity except for the fuel tube composition and the fuel mass. The fuel tube composition uncertainty was judged to be systematic across all fuel tubes. The effect of perturbing all fuel tubes simultaneously was $\pm$ 0.00025 Δk_{eff}. Because this uncertainty is rather small when perturbing all 253 fuel rods in the critical configuration and because the uncertainty is systematic across all fuel tubes, the effect of the fuel tube composition on the worth measurement of a single fuel tube would be negligible.

The uncertainty effect of the mass of fuel per fuel tube was 0.00010 Δk_{eff} or ±1.37 ¢. For the fuel tube worth measurements, this was added in quadrature to the 10%√2 measurement uncertainty.

For the accident configuration, the fuel tube composition and the fuel mass uncertainties would have a negligible effect because no fuel was removed but only moved. The fuel position uncertainty was evaluated for the critical configurations and was found to have a negligible effect. Thus, only the 10%√2 measurement uncertainty applied to the accident configuration worth measurement.

The experimental uncertainty for the fuel effect reactivity measurements is summarized in Table 6.

Neutron Absorbing and Moderating Material Reactivity Measurements

The uncertainty in dimensions, position/placement, and material composition was evaluated for all neutron absorbing and moderating materials inserted into the core. Each parameter was perturbed individually for each worth measurement. The total uncertainty for each reactivity measurement is given in Table 7. A summary of the uncertainty effect of each parameter can be found in [2].

TABLE 6. Fuel Effect Reactivity Measurements and Uncertainties

Distance from Core Center (Fuel Tube Position)	Experimental Worth with Experimental Uncertainty (¢)		
0 cm (1)	-32.0	±	4.73
2.59 cm (2)	-32.0	±	4.73
5.23 cm (3)	-30.8	±	4.57
7.75 cm (4)	-27.2	±	4.08
10.48 cm (5)	-25.5	±	3.86
10.56 cm (6)	-25.6	±	3.87
11.78 cm (7)	-22.6	±	3.48
Accident Configuration Worth	-8.2	±	1.79

TABLE 7. Material Reactivity Measurements and Uncertainties

Absorbing or Moderating Material	Experimental Worth with Experimental Uncertainty (¢)		
90 Stainless Steel 347 Rods	14.8	±	2.15
46 Stainless Steel 347 Rods	7.92	±	1.89
46 Tungsten Rods	-4.27	±	0.91
90 Niobium Rods	4.9	±	1.27
8 Polyethylene Rods	24.43	±	3.49
23 Graphite Rods	7.5	±	1.20
B_4C Filled Tube	-6.65	±	0.94
Stainless Steel Lid	7.97	±	1.38
0.3175 cm Thick Al Lid	16.62	±	2.59
0. 15875 cm Thick Al Lid	8.14	±	1.58
Cadmium Lid	-45.7	±	6.63

Evaluation of Experimental Results

Detailed and simple benchmark models were derived for the reactivity effect measurements. The simplifications made were simplifications to the critical configuration. Additionally, impurities were removed from the fuel, the tungsten rods, the niobium rods, the graphite rods, and the cadmium lid. The effect of all simplifications on the worth measurements were negligible; however, an additional bias uncertainty was required due to modeling limitations. The detailed benchmark model benchmark values for the reactivity measurements are given in Table 8 for the fuel effect reactivity measurements and Table 9 for the neutron absorbing and moderating material worth measurements.

TABLE 8. Fuel Effect Reactivity Measurements and Uncertainties

Distance from Core Center (Fuel Tube Position)	Detailed Benchmark Model Value (¢)		
0 cm (1)	-32.00	±	5.014
2.59 cm (2)	-32.00	±	5.014
5.23 cm (3)	-30.80	±	4.861
7.75 cm (4)	-27.20	±	4.411
10.48 cm (5)	-25.50	±	4.203
10.56 cm (6)	-25.60	±	4.215
11.78 cm (7)	-22.60	±	3.828
Accident Configuration Worth	-8.20	±	2.448

TABLE 9. Material Reactivity Measurements and Uncertainties

Absorbing or Moderating Material	Detailed Benchmark model Value (¢)		
90 Stainless Steel 347 Rods	14.80	±	2.716
46 Stainless Steel 347 Rods	7.92	±	2.514
46 Tungsten Rods	-4.27	±	1.840
90 Niobium Rods	4.90	±	2.094
8 Polyethylene Rods	24.43	±	3.864
23 Graphite Rods	7.50	±	2.053
B_4C Filled Tube	-6.65	±	1.919
Stainless Steel Lid	7.97	±	2.163
0.3175 cm Thick Al Lid	16.62	±	3.076
0. 15875 cm Thick Al Lid	8.14	±	2.295
Cadmium Lid	-45.70	±	6.823

Evaluation of Experimental Results

The worths were calculated using MCNP5-1.60 and ENDF/B-VII.0 neutron cross section libraries. For each run, a total of 2,150 cycles were run, skipping the first 150 cycles, with 100,000 histories per cycle. For each reactivity effect measurement the base and perturbed benchmark model eigenvalues were calculated. The change in eigenvalues was then converted to a reactivity in units of cents using β_{eff}, 0.0073± 5% [1]. The fuel effect reactivity sample calculations for the detailed benchmark model are presented in Table 10. They calculations agree well with the benchmark results. The material worth sample calculations for the detailed benchmark model are presented in 11. Some calculated results have a large deviation from the benchmark. This cause for this deviation is not known; however, all results are within 3σ of the benchmark value.

CONCLUSION

The reactivity effect measurements for the beryllium-reflected, UO_2, small, compact critical assembly have been evaluated. The fuel effect measurements, including an accident scenario configuration, and neutrol absorbing and moderation material worth measurements were measured. All measurements are acceptable as benchmark experiments. Sample calculation results, using MCNP, show that a large deviation from the benchmark model, however, all results are within 3σ.

Future work includes the evaluation of potassium worth measurements.

TABLE 10. Calculation Results for Fuel Effect Reactivity

Distance from Core Center (Fuel Tube Position)	Calculated Reactivity (¢)			(C-E)/E [(a)]			C/E Ratio[(a)]
0 cm (1)	-31.67	±	1.18	-8.7%	±	15.9%	0.91
2.59 cm (2)	-30.14	±	1.18	-5.8%	±	15.2%	0.94
5.23 cm (3)	-28.47	±	1.18	-7.6%	±	15.1%	0.92
7.75 cm (4)	-27.21	±	1.18	0.0%	±	16.8%	1.00
10.48 cm (5)	-24.57	±	1.18	-3.6%	±	16.5%	0.96
10.56 cm (6)	-23.18	±	1.18	-9.5%	±	15.6%	0.91
11.78 cm (7)	-20.40	±	1.08	-9.7%	±	16.0%	0.90
Accident Configuration Worth	-8.04	±	1.18	-1.9%	±	32.6%	0.98

(a) "E" is the experimental benchmark value. "C" is the calculated value..

TABLE 11. Calculation Results for Material Reactivity

Absorbing or Moderating Material	Calculated Reactivity (¢)			(C-E)/E [(a)]			C/E Ratio[(a)]
90 Stainless Steel 347 Rods	21.44	±	1.18	21.1%	±	27.7%	1.21
46 Stainless Steel 347 Rods	8.45	±	1.18	47.8%	±	37.0%	1.48
46 Tungsten Rods	-1.11	±	1.08	-74.0%	±	27.7%	0.26
90 Niobium Rods	8.45	±	1.18	72.4%	±	77.5%	1.72
8 Polyethylene Rods	22.83	±	1.18	2.6%	±	15.5%	1.03
23 Graphite Rods	7.76	±	1.18	3.4%	±	32.4%	1.03
B_4C Filled Tube	-8.22	±	1.18	23.6%	±	39.8%	1.24
Stainless Steel Lid	9.83	±	1.18	23.4%	±	36.6%	1.23
0.3175 cm Thick Al Lid	19.65	±	1.18	18.2%	±	23.0%	1.18
0.315875 cm Thick Al Lid	8.86	±	1.18	8.9%	±	33.9%	1.09
Cadmium Lid	-31.94	±	1.18	-30.1%	±	10.8%	0.70

(a) "E" is the experimental benchmark value. "C" is the calculated value.

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