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CRITICAL EXPERIMENTS FOR A PROPOSED TOWER SHIELDING REACTOR

Introduction

The redesign of the Tower Shielding Reactor includes stainless steel as a principle core structural material and the use of fuel elements similar to those being fabricated for the Army Package Power Reactor (APPR). The core is to contain only 25 elements instead of 45 as in the APPR. Some critical experiments, which have been done with the apparatus used in the recent APPR measurements, are reported here as bases for the design of the core.

I. Tower Shielding Reactor and Critical Experiment

In the fuel plates of the APPR-type elements uranium oxide is embedded in a stainless steel matrix 0.020 in. thick and 22 in. long which is clad with 0.005 in. of stainless steel. Then 18 fuel plates are brazed into side plates of stainless steel to form fuel elements whose nominal size is 2.900 x 2.952 in. The reactor core will consist of a 5 x 5 array of these fuel elements. Half of the fuel plates will be omitted from the middle of each of four fuel elements in order to form a void for four $B_{10}C$ control rods. It is proposed that changes in the central fuel element loading be used to compensate additional reactivity changes.

In the critical experiment for this reactor the APPR critical experiment materials were used. For the fuel elements, rectangular boxes were made with 18 slots into which stainless steel plates or uranium plates could be inserted to vary the uranium loading of the critical experiment reactor. The uranium plates consisted of a 0.002 in. uranium metal foil 2.50 in. wide and 22 in. long encased in a stainless steel sandwich. Some plates contained half-width uranium foil. The U-235 content of these plates were 31.13 g and 15.56 g, respectively.

The critical experiment used a 5 x 5 array of these fuel element boxes shown in Fig. 1. The middle ten slots of boxes 8, 12, 14 and 18 were left void for insertion of the $B_{10}C$ control rods. The $B_{10}C$ rod (furnished by C. E. Clifford) was mounted so that it could be calibrated in the void in box 12. A 1.25 in. O. D., aluminum cased, hollow cadmium rod was mounted so that it traversed the void in box 14. This round rod could be dropped as a safety rod. A control blade, a sheet of cadmium that extended over one entire side of the reactor, served as a fine control. It also could be dropped. A cadmium sheet, approximately 8 in. wide and encased in stainless steel, was used as a safety rod. It could be dropped between boxes 7, 12, and 17 and boxes 8, 13 and 18. This also is shown in Fig. 1.

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FIGURE 1. PROPOSED TOWER
SHIELDING REACTOR
CRITICAL EXPERIMENT

II. Critical Mass Measurements

Clean Critical. It was desired to measure the critical mass of the 5 x 5 element array without the voids. A previous measurement¹ on the 5 x 5 array with only uranium plates, i. e., some slots empty, showed the critical mass to be 4.65 kg U-235 for a metal volume fraction of 0.106. For a metal volume fraction of 0.197, i. e., all slots filled, the critical mass was found to be 7.36 kg U-235. These values are plotted in Fig. 2. Fuel worth in slot 9 box 9 was 0.58¢/g.

Mockup of Tower Shielding Reactor. The voids for the control rods were made by removing the plates from the middle ten slots of boxes 8, 12, 14, and 18. The center box was always loaded with half as many uranium plates as were in the remaining boxes but all slots were filled. Boxes 8, 12, 14 and 19 also had half the normal number of uranium plates.

Criticality was achieved with 28.7¢ excess reactivity when boxes 8, 12, 13, 14 and 18 contained six uranium plates, and the remaining boxes contained 12 uranium plates. The uranium loading was 8.405 kg U-235.

III. Fuel and Rod Evaluation

Fuel Worth in Boxes 9 and 17. Half uranium plates were substituted for full uranium plates in slot 9 of boxes 9 and 17, and the resulting reactivity change was 23.5¢ or 0.75¢/g of U-235.

Average Fuel Worth. One uranium plate was removed from the middle slot of each of boxes 1, 4, 7, 15 and 23 and from slot 2 of box 12. These six plates are representative of all the fuel element boxes except box 13. A total of 186.78 g U-235 was worth 68¢ or 0.364¢/g.

Fuel Worth in Box 13. The number of fuel plates in box 13 was increased from 6 to 12 in five steps, and the resulting reactivity changes measured. These experimental results are given in Table 1. The fuel worth is plotted vs the number of plates in Fig. 3.

Table 1. Fuel Worth in Box 13

Change in Loading Box 13 (fuel plates)	U-235 Mass Difference (g)	Reactivity Change (¢)	Fuel Worth (¢/g)
6 to 7-1/2	46.69	+ 63.7	1.36
7-1/2 to 9	46.69	+ 64.9	1.39
9 to 10	31.13	+ 37.9	1.22
10 to 12	62.26	+ 50.0	0.80
Total Reactivity Change		216.5	

1. D. V. P. Williams, et al, "Preliminary Results of APPR Critical Experiment, Part I, CF-55-11-122 (Nov. 25, 1955).

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CRITICAL MASS, kg U-235

URANIUM AND STAINLESS STEEL METAL VOLUME FRACTION

FIGURE 2. CRITICAL MASS VS METAL VOLUME FRACTION

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FIGURE 3. FUEL WORTH VS. NUMBER OF PLATES IN BOX 13

Rod Calibrations. With the excess reactivity provided by the above additions of uranium plates to box 13, rod 3 was calibrated in small increments using the inhour equation with both positive and negative periods. The B₄C rod in box 12, rod 2, was used to compensate for the changes in reactivity produced by the displacement of rod 3. In this manner rod 3 and part of rod 2 were calibrated. The remaining portion of rod 2 was compared to rod 3 in small increments. Rod 4, the round cadmium rod, was compared to rod 2. The rod calibration data are given in Table 2, the calibrations for rods 2, 3 and 4 are plotted in Figs. 4, 5 and 6, respectively.

Rods 3 and 4 were dropped, and the total reactivity values of the rods were calculated from the rod drop formula: ρ (cents) = $100 \frac{N_0 - N}{N}$ in which ρ is the reactivity change, N_0 is the original neutron level, and N is the neutron level just after the drop. These data are also given in Table 2.

Table 2. Rod Calibration Data

Rod No. 2 Position (in.)	Reactivity (¢)	Rod No. 3 Position (in.)	Reactivity (¢)	Rod No. 4 Position (in.)	Reactivity (¢)
24.68	0	29.51	0	22.54	0
17.98	10.0	21.04	5.2	19.40	4.7
16.62	18.0	17.19	19.1	17.15	15.9
16.00	22.5	15.60	28.7	14.90	33.9
13.80	41.9	14.92	32.5	11.75	72.6
11.95	60.0	13.11	43.7	9.01	108.6
11.01	71.2	11.05	55.4	7.13	133.6
10.21	80.6	7.76	73.2	5.70	152.6
9.35	91.7	5.38	82.1	4.82	161.1
8.49	102.4	0.03	86.6	4.35	165.6
7.71	111.7			4.26	166.6
7.00	120.9	Rod Drop	90.5	- 1.65	193.1
6.03	132.5				
5.01	142.9				
4.01	150.6				
3.01	156.7			Rod Drop	186
2.01	161.7				
1.01	164.8				
- 0.03	166.6				

IV. Heterogeneity Effects

In the actual reactor the uranium will be distributed in all of the 18 plates of each element. In the critical experiment, the uranium is

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NO. 340- M DIETZGEN GRAPH PA
MILLIMETER

10

FIGURE 5. ROD #3 CALIBRATION

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NO. 340. M DIETZGEN GRAPH PA. .
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contained in only a fraction of these, and there is associated with the fuel lumping some reactivity losses. One APPR type fuel element was available from the APPR experiments. This special element contained 209.9 g of U-235 evenly distributed in 18 plates and corresponded to 90% of a 7-1/2 critical experiment uranium plate loading. When the center element, box 13, contained 7-1/2 uranium plates it was replaced by the special APPR element. A reactivity increase of 15.0¢ was measured from which the fuel worth in the APPR type element was calculated to be 1.60¢/g, which is to be compared to 1.375¢/g for the 7-1/2 uranium plate loading in box 13. The fuel worth ratio is 0.859. This ratio was 0.865 for the APPR 7 x 7 element array.

A special APPR type element which was equivalent to the 12 uranium plate loading was not available, and hence the reactivity losses associated with the critical experiment configuration could not be measured directly. If one assumes that there is no fuel lumping effect in an 18 plate loading and if one assumes a linear variation for the fuel worth ratio with number of plates, an estimate of the fuel worth ratio corresponding to the 12 uranium plate loading is obtained. This plot is shown in Fig. 7. From it the fuel worth ratio of 0.84 for a six plate loading is obtained and a value of 0.92 for a twelve plate loading.

V. Calculation of Loading for Proposed Tower Shielding Reactor

The proposed Tower Shielding Reactor contains five half-loaded fuel elements, one of which has 18 plates which are half loaded with uranium, and the other four have missing plates to form voids for control rods.

An average fuel worth for the critical experiment is

$$\frac{22 \times 0.364 + 0.5 \times 1.36}{22.5} = 0.386¢/g$$

The critical-experiment critical mass corrected for 28.7 cents excess reactivity is

$$8,405 - 28.7/0.386 = 8,331 \text{ g or } 370.3 \text{ g per element}$$

For the proposed reactor, box 13 fuel worth is

$$1.36/0.84 = 1.619¢/g$$

and for the other boxes the fuel worth is

$$0.364/0.92 = 0.396¢/g$$

Therefore for the reactor the average fuel worth is

$$\frac{22 \times 0.396 + 0.5 \times 1.619}{22.5} = 0.423¢/g$$

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FIGURE 7. VARIATION OF FUEL WORTH RATIO

The fuel element loadings for a reactor can be obtained by multiplying the U-235 masses in the elements of the critical experiment by their respective fuel worth ratios. However, this reactor does not have the center element half-loaded. Adjusting the element loadings by using the reactor fuel worths for these elements, a reactor can be specified which has exactly half as much fuel in the center element. This fuel loading is 338.8 g/element which is obtained from the following equation.

$$(370.3 \times 0.92 - x) 22 \times 0.396 = (x - 370.3 \times 0.84) \frac{1.619}{2}$$

The reactor critical loading is 7.62 g of U-235.

The U-235 mass loadings for several values of excess reactivity using the average worth of 0.423¢/g are given in Table 3.

Table 3. Proposed Tower Shielding Reactor Loadings

Excess Reactivity	Mass Equiv. (g)	Total Reactor Loading (kg U-235)	Mass U-235 (g/element)	Mass U-235 (g/plate)
0	0	7.62	339	18.8
1% (137¢)*	324	7.95	353	19.6
2% (274¢)	648	8.27	368	20.4
3% (411¢)	972	8.60	382	21.2

* An effective delayed neutron fraction of 0.0073 was assumed.

An uncertainty of ± 0.02 in the fuel worth ratio, 0.92, results in an uncertainty of ± 150 g in the reactor critical loading.

VI. Estimation of Heterogeneity Effects in Clean Critical 5 x 5 Element Array.

The average fuel worth was not measured in this reactor. A half plate was evaluated in slot 9 of box 9 resulting in a fuel worth of 0.58¢/g, but it is believed that the average fuel worth would be less since about two-thirds of the fuel is outside this position in the core. This fuel worth becomes 0.65¢/g when corrected for heterogeneity effects. A very rough approximation can be derived from the fuel worth obtained in the proposed tower shielding reactor by multiplying that fuel worth by the ratio of the critical masses:

$$\text{clean critical fuel worth} = 0.423 \times \frac{7.62}{6.52} = 0.50$$

The fuel worth ratio for a 9-1/2 uranium plate loading, the critical experiment 5 x 5 loadings, was taken from Fig. 7 to be 0.886. Values of the critical mass for various excess reactivities from both the estimated and measured fuel worths, 0.50¢/g and 0.65¢/g, respectively, are presented in Table 4.

Table 4. Uniform 5 x 5 Element Array Mass Loadings

Excess Reactivity	Mass (kg U-235)	
	@ 0.65¢/g	@ 0.50¢/g
0	6.52	6.52
1% (137¢)	6.73	6.79
2% (274¢)	6.94	7.06
3% (411¢)	7.15	7.33

By removing one plate in a fuel element a void is formed that is large enough for a flat plate control rod. The reactivity loss associated with removing four plates from the uniformly loaded core, one from each of four boxes, the middle of 7, 9, 17 and 19 corresponding to the experimental determination of fuel worth in slot 9 box 9, is

$$14.5g \times 4 \times \frac{0.58¢/g}{0.886} = 38¢ \text{ or } 0.28\%$$

An error in the fuel worth ratio of ± 0.02 results in an error of $\pm 130g$ in the critical masses.

VII. Acknowledgement

The writer gratefully acknowledges the assistance of D. F. Cronin and J. L. Hull throughout this experiment.