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**EXPONENTIAL EXPERIMENTS
AND NEUTRON MULTIPLICATION MEASUREMENTS
WITH 1.25 wt% ENRICHED N-REACTOR FUEL ELEMENTS
IN LIGHT WATER**

MARCH, 1965

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EXPONENTIAL EXPERIMENTS
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WITH 1.25 wt% ENRICHED N-REACTOR FUEL ELEMENTS
IN LIGHT WATER

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By

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March, 1965

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RICHLAND, WASHINGTON

EXPONENTIAL EXPERIMENTS
AND NEUTRON MULTIPLICATION MEASUREMENTS
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INTRODUCTION

A series of exponential and neutron multiplication experiments have been performed on spike enriched N-Reactor fuel elements. The spike enriched fuel element is a tube-in-tube assembly consisting of a 1.25 wt% enriched outer tube and an 0.95 wt% enriched inner tube. The purpose of the experiments was to provide needed data for nuclear safety guidance in processing and storing the spike enriched fuel in N-Reactor Department. (1, 2, 3)

SUMMARY

Subcritical experiments have been performed with N-Reactor spike enriched fuel elements in light water to provide data for nuclear safety guidance. Exponential and neutron multiplication measurements were performed on 1.25 wt% enriched outer tubes (2.41 in. OD, 1.76 in. ID) and on tube-in-tube assemblies comprised of the outer tube and an 0.95 wt% enriched inner tube (1.25 in. OD, 0.44 in. ID) in each of four lattice pitches. Maximum bucklings were found to be 4680 microbucks* for the outer tubes and 3900 microbucks for the tube-in-tube assemblies. Figures showing material buckling, critical mass, volume, slab thickness, and cylinder diameter as a function of water to fuel volume ratio are presented. Safe values for nuclear safety guidance are also presented. Pulsed neutron source measurements on two of the 1.25 wt% enriched outer tube lattices indicate the difference between delayed criticality and prompt criticality to be about five fuel columns for these lattices.

*Microbucks = 10^{-6} cm^{-2} .

(1) Letter, C. L. Brown to R. E. Trumble. May 27, 1964.

(2) Letter, L. M. Loeb to R. E. Trumble. June 2, 1964.

(3) Letter, E. D. Clayton to R. E. Trumble. August 11, 1964.

DISCUSSION

Fuel Description

The N-Reactor fuel element evaluated in this study is a tube-in-tube assembly comprised of a 1.25 wt% enriched outer tube and a 0.95 wt% enriched inner tube. The tubes were clad with Zircaloy-2 and were 26 in. long. Dimensions and other characteristics of the fuel are presented in Table I, and a photograph of the fuel is shown in Figure 1.

TABLE I
DESCRIPTION OF N-REACTOR SPIKE ENRICHED FUEL ELEMENTS

	0.95 wt% U ²³⁵ Enriched Inner Tubes	1.25 wt% U ²³⁵ Enriched Outer Tubes
Outside Diameter (Clad), in.	1.249	2.406
Inside Diameter (Clad), in.	0.438	1.764
Length (Clad), in.	26.2	26.2
Cladding Thickness, in.	0.035 in. Zircaloy-2 Outer Surface; 0.019 Zircaloy-2 Inner Surface	0.019 in. Zircaloy-2 Both Surfaces
Weight (Unclad)	15.33	30.69

Experimental Equipment

The experimental measurements were conducted in a square steel tank 5 x 5 x 6 ft, located in 326 Building. The fuel was held in position by templates drilled in a hexagonal lattice pattern. Three templates were used (one at the top and bottom and one in the center). The center template was Lucite and the others were aluminum.

Three BF₃ neutron counting tubes were used to monitor fuel additions during the multiplication measurements. Two large BF₃ tubes (1/2 x 4 in.) were positioned at the edge of the uranium lattice about half-way down in the tank, and the third BF₃ tube (5/16 in. dia. x 1-3/4 in. long) was positioned near the center of the lattice. This third BF₃ tube was also used to measure the axial neutron flux distribution in the exponential experiments.

FIGURE 1

N-Reactor Spike Enriched Fuel

A B^{10} loaded organic liquid scintillator for thermal neutron detection and an RCA-6810 photomultiplier tube were used in making the pulsed neutron measurements. The scintillator was located adjacent to the lattice, in the reflector, and 180° from the neutron generator. The generator, a Kaman 810A, was also positioned in the reflector and adjacent to the lattice.

For the multiplication measurements, a "pencil" size Ra-Be source was positioned in the center of the uranium lattice. This source contained 0.22 g radium and had a strength of about 10^6 n/sec. For the exponential measurements, the neutron flux was provided by four $\frac{1}{2}$ g Ra-Be neutron

sources, positioned at the bottom of the uranium lattice, from which the combined emission rate was about 2.5×10^7 n/sec.

Fuel Arrangement

Measurements were made on the 1.25 wt% enriched outer tube and on the tube-in-tube assembly with each of four lattice pitches (2.41 in., 2.8 in., 3.1 in., and 3.4 in.). These lattices bracketed the maximum material buckling and minimum critical mass for both fuel types.

The length of the clad fuel elements was 26.2 in. Being comprised of two elements, each fuel column in the experimental lattices was 52.4 in. long. A hexagonal loading pattern was used for the lattices, consequently, the lattice cell was an equilateral triangle with equal separation between adjacent rods.

Experimental Procedure

Special holders were fabricated for adding the inner and outer fuel tubes to the lattices. One of these holders and the fuel addition method used are shown in Figure 2.

The experimental procedure was the same for each lattice. First, neutron multiplication measurements were made until the maximum lattice loading was complete; second, the source was removed and a "back off" multiplication measurement was made; and finally, exponential measurements were made at two cylinder diameters. Pulsed neutron source measurements were performed concurrently with the multiplication measurements.

Results of Measurements

The extrapolation length was determined from a measurement of the relaxation length (b) in two assemblies of different diameter. Since the critical buckling is expected to hold reasonably constant, the value of λ can be determined from the measured relaxation lengths (b_1, b_2) and knowledge of the respective cylindrical radii (R_1, R_2):

$$\left(\frac{2.4048}{R_1 + \lambda} \right)^2 - \left(\frac{1}{b_1} \right)^2 = B^2 = \left(\frac{2.4048}{R_2 + \lambda} \right)^2 - \left(\frac{1}{b_2} \right)^2$$

FIGURE 2

Loading 0.95 wt% Enriched Inner Tubes
into 3/4 in. Lattice

Results of the measurements are presented in Tables II and III. Graphs showing the multiplication measurements on the 2.8 in. and 3.1 in. lattices with 1.25 wt% enriched outer tubes only are presented in Figures 3 and 4. Also shown on these graphs are the estimated number of tubes for prompt criticality from the pulsed neutron source measurements.

TABLE II
EXPERIMENTAL RESULTS FOR 1.25 wt% ENRICHED OUTER TUBES

Lattice Pitch, in.	V_w/V_u	No. Tubes	R_{eff} cm	b cm	Measured λ , cm ($B^2 = B^2$)	B^2 Micro-bucks	Minimum Critical Mass lb Uranium
2.4	1.660	37	19.52	17.95	8.20	4436	3799
2.8	2.530	19	16.28	13.66			
		37	22.71	18.50	7.82	4624	2681
3.1	3.355	19	18.02	14.05			
		37	25.15	24.95	7.58	3789	3177
3.4	4.266	19	19.764	13.24			
		37	27.581	19.73	7.32	2180	6946
V_w/V_u	Computed Critical No. of 52 in. Tubes from Buckling	Estimated Critical No. of 52 in. Tubes from Neutron Multiplication Measurements	Prompt Critical No. of 52 in. Tubes from Pulsed Neutron Source Measurements	Computed Critical No. of Tubes for Cylindrical Height of 26 in.			
1.660	86.7	-----	-----	124.7			
2.530	62.0	63 $\pm$ 2	66.7 $\pm$ 1	88.2			
3.355	67.9	64.4	65.2	106.5			
4.266	124.8	-----	-----	360.1			

TABLE III
EXPERIMENTAL RESULTS FOR TUBE-IN-TUBE ASSEMBLIES
(1.25 wt% Outer Tube; 0.95 wt% Inner Tube)

Lattice Pitch, in.	V_w/V_u	No. Tubes	R_{eff} cm	b, cm	Measured λ , cm ($B^2 = B^2$)	B^2 Micro-bucks	Critical Mass lb Uranium
2.4	0.690	37	19.62	13.00	8.40	1504	36,921
2.8	1.304	19	16.28	12.3			
		37	22.71	18.5	7.92	3244	7,512
3.1	1.857	19	18.02	13.74			
		37	25.147	24.5	7.13	3884	4,702
3.4	2.466	19	19.764	13.62			
			27.581	21.83	6.83	2785	7,058
V_w/V_u	Computed Critical No. of 52 in. Tubes from Buckling	Computed Critical No. of Assemblies for Cylindrical Height of 26 in.					
0.690	416.6	798.7					
1.304	101.2	173.7					
1.857	67.4	105.5					
2.466	90.3	185.1

FIGURE 3

Neutron Multiplication Measurements on 2.8 in. Lattice
1.25 wt% Enriched Outer Tubes (1.8 in. ID; 2.4 in. OD)

FIGURE 4

Neutron Multiplication Measurements on 3.1 in. Lattice
1.25 wt% Enriched Outer Tubes (1.8 in. ID; 2.4 in. OD)

Pulsed neutron source theory is based on the fact that if a burst of fast neutrons is injected into a finite system, a slowing down and thermalization occurs; and eventually, a characteristic neutron distribution in space and energy is established. The time behavior of this characteristic neutron distribution is initially controlled by the rate of decay of the system's prompt neutrons and eventually by the delayed neutrons alone. By analyzing the transient behavior of the system's neutron population, after injection of a burst of neutrons, physics parameters such as neutron lifetime and the fuel necessary for prompt criticality can be determined.

Pulsed neutron source measurements in the present study were made primarily for estimating the number of fuel columns for prompt criticality. Reasonable estimates were obtained on two lattices only (1.25 wt% enriched outer tubes in the 2.8 and 3.1 in. pitch lattices). The results are shown in Table II. The other lattices were too far subcritical to obtain valid data.

Nuclear Safety Parameters

Material bucklings derived from the measurements are plotted in Figure 5. Critical parameters were calculated from these values; the results are shown in Figures 6-9. Minimum critical values obtained from the curves are summarized in Table IV.

FIGURE 5

Material Buckling as a Function of Water to Uranium Volume Ratio

FIGURE 6

Minimum Critical Mass as a Function
of Water to Uranium Volume Ratio

FIGURE 7

Minimum Critical Volume as a Function
of Water to Fuel Volume Ratio

FIGURE 8

Minimum Critical Cylinder Diameter as a Function of Water to Uranium Volume Ratio

FIGURE 9

Minimum Critical Slab Thickness as a Function of Water to Uranium Volume Ratio

TABLE IV
SUMMARY OF CRITICAL PARAMETERS FOR N-REACTOR FUEL
DERIVED FROM EXPERIMENTAL MEASUREMENTS

	<u>1. 25 wt% U²³⁵</u> <u>Enriched</u> <u>Outer Tubes</u>	<u>Tube-in-Tube</u> <u>Assemblies</u> <u>(0. 95 wt% Inner Tube;</u> <u>1. 25 wt% Outer Tube)</u>
Maximum Buckling, Microbucks	4680 ± 234	3900 ± 195
Minimum Critical Mass, lb U	2675. 0	4700. 0
Minimum Critical Volume, ℓ	232. 0	339. 0
Minimum Critical Cylinder Diameter, in.	21. 3	24. 7
Minimum Critical Slab Thickness, in.	12. 0	14. 2
Minimum Critical Mass per Unit Area, lb/ft ²	303. 0	441. 0

From the critical values in Table IV, safe values were obtained for use in nuclear safety evaluations by applying a factor that covers uncertainties in measurements and gives a suitable margin of safety. The results are shown in Table V.

TABLE V
RECOMMENDED SAFE PARAMETERS FOR N-REACTOR
SPIKE ENRICHED FUEL

	<u>1. 25 wt% U²³⁵</u> <u>Enriched Outer</u> <u>Tubes</u>	<u>Tube-in-Tube</u> <u>Assemblies</u> <u>(0. 95 wt% Inner Tube;</u> <u>1. 25 wt% Outer Tube)</u>
Safe Mass, lb	1204. 0	2115. 0
Safe Volume ℓ	174. 0	254. 0
Safe Cylinder Diameter, in.	18. 1	21. 0
Safe Slab Thickness, in.	10. 2	12. 0
Safe Mass/Area, lb/ft ²	227. 0	331. 0

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