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PRELIMINARY CRITICAL ASSEMBLY FOR
PRATT AND WHITNEY REACTOR - Part II

I. Introduction

A description of the Super Critical Water Reactor critical experiment has been previously reported as Part I, CF 53-9-139, of a series of memos on work conducted at Building 9213. This report covers the initial start-up procedures, fuel loading specifications, and experimental results obtained to date. Constant reference is made to Part I to avoid unnecessary duplication.

II. Calibrations

Initial determinations of feed and dump rates of Furfural to and from the reactor tank were made in the presence of only those fuel tubes which might obstruct the normal flow, i.e., the tubes above the grating covering the line in the tank floor. From the discharge rate recorded in Table I the maximum time for the Furfural to drain from a given height can be determined. As fuel tubes are added the dump time decreases due to displacement of Furfural.

TABLE I

TIME REQUIRED FOR FURFURAL DISCHARGE

Furfural Height in.	Time After Opening Valve min.
30.500	0.00
23.125	0.50
15.625	1.00
8.750	1.50
2.625	2.00

The observed dumping rate from the maximum Furfural height is about 0.25 in./sec which was later found to correspond to a reactivity change in a critical reactor of 9 cents/sec. The maximum feed rate was determined empirically at 3 gal/min, a factor of five below the maximum delivery rate expected from the pump capacity.

The reactor height, i.e. the height of fuel solution below* the Furfural surface was determined from the Furfural level indicator, described in Part I, by the application of several corrections.

* The contribution to the reactivity of fuel in the tubes above the Furfural is neglected.

Figure I is a plot of the empirically determined additive correction that must be applied to the indicator reading to compensate for factors inherent in the mounting. An additional factor of 0.188 in. was subtracted from the Furfural height to compensate for the end plugs in the bottom of the fuel tubes. It was observed that individual Furfural heights were reproducible to within ± 0.015 in. over a 95% tolerance interval but the absolute height could be determined only to within ± 0.032 in. due to tank floor irregularities.

The English and Metric unit systems were used wherever they were consistent with the design or the experiment.

III. Design Fuel Loading

The designed incremental radial fuel loading, superimposed on a Goertzel distribution in Figure II, was predicted** by four group diffusion theory for a 76.2 cm equilateral cylinder. The critical mass was determined in these calculations to be 15.34 kg U-235 for a reactor containing 261 kg of stainless steel and with a 6.5 cm thick side reflector. The reflector and moderator were assumed to be water of density 0.5 gm/cc.

The experimental reactor core was composed of a number of stainless steel tubes described in Table II and Figure III, arranged in the prescribed array shown in Figure IV. The tubes were spaced in plates with holes drilled to accommodate 193 tubes 1 in. in diameter. Figure V is a photograph of the partially filled array and Table III lists the parameters for locating the individual tubes. The radial position of each tube is designated by a letter and the angle coordinate by a number, the latter increasing in the counter-clockwise direction from the positive X-axis. Various fuel loadings will be indicated by area numbers, i.e., I, II, etc. The stainless steel fuel tubes and tublar inserts, by which the loading of stainless steel in the core was altered, are also described in Table II. The plugs in the end of the fuel tubes are not included in the specified loadings since, in their position at the unreflected extremity of the reactor, their effect on reactivity is indeterminate but small.

The uranium, enriched to 93.15% in U-235, was used as an aqueous solution of UO_2F_2 having initially a concentration of 0.504 gm U-235/cc. Preparatory to the first loading 25 kg U-235 were distributed among all tubes. Although it was recognized that a complete loading of these fuel tubes would be considerably in excess of the predicted critical mass, uncertainties in calculations and

** George Chase, Fox Project, Pratt and Whitney Aircraft, private communication.

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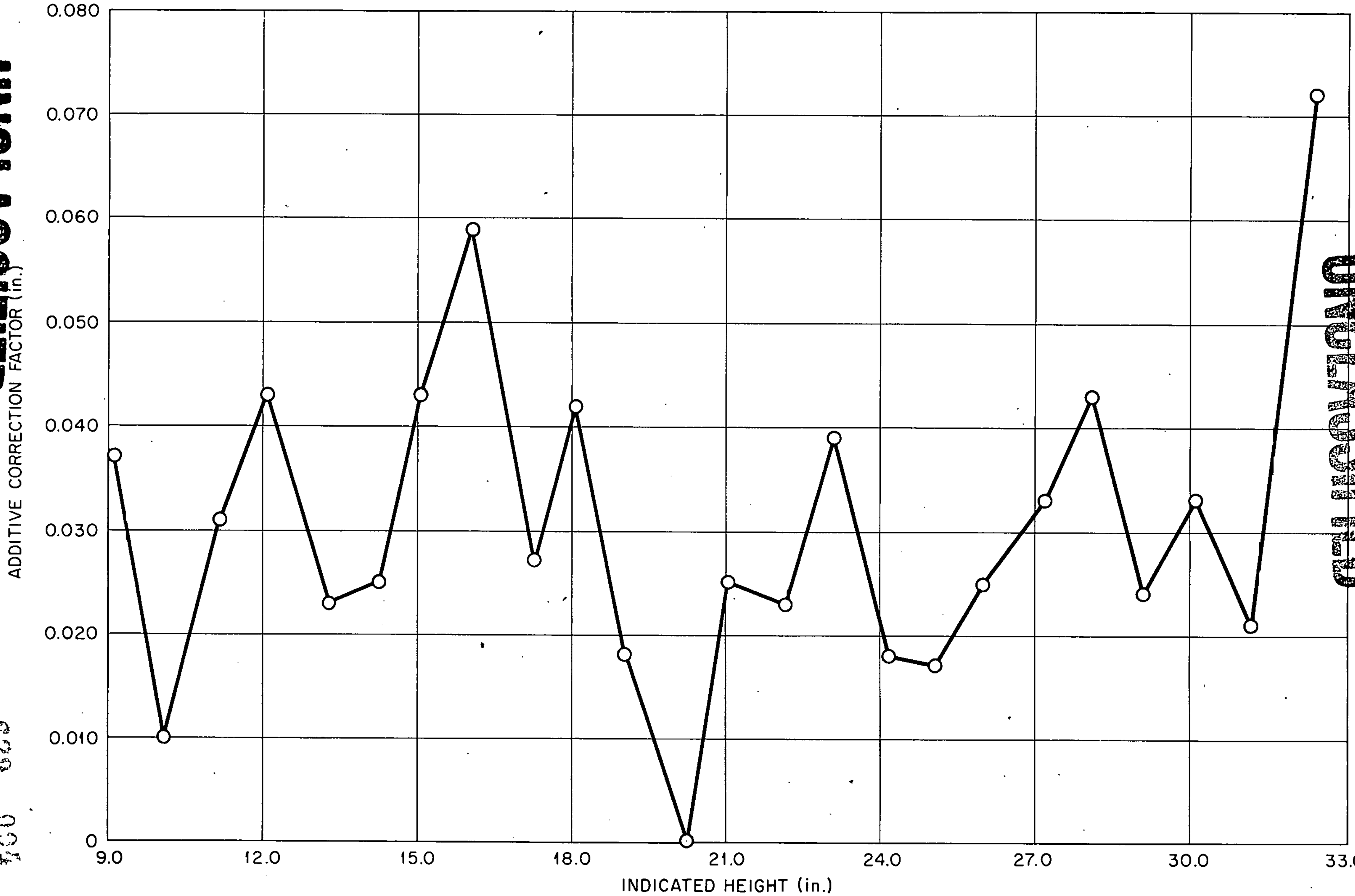

Fig. I. Correction Factor for Liquid Level Indicator.

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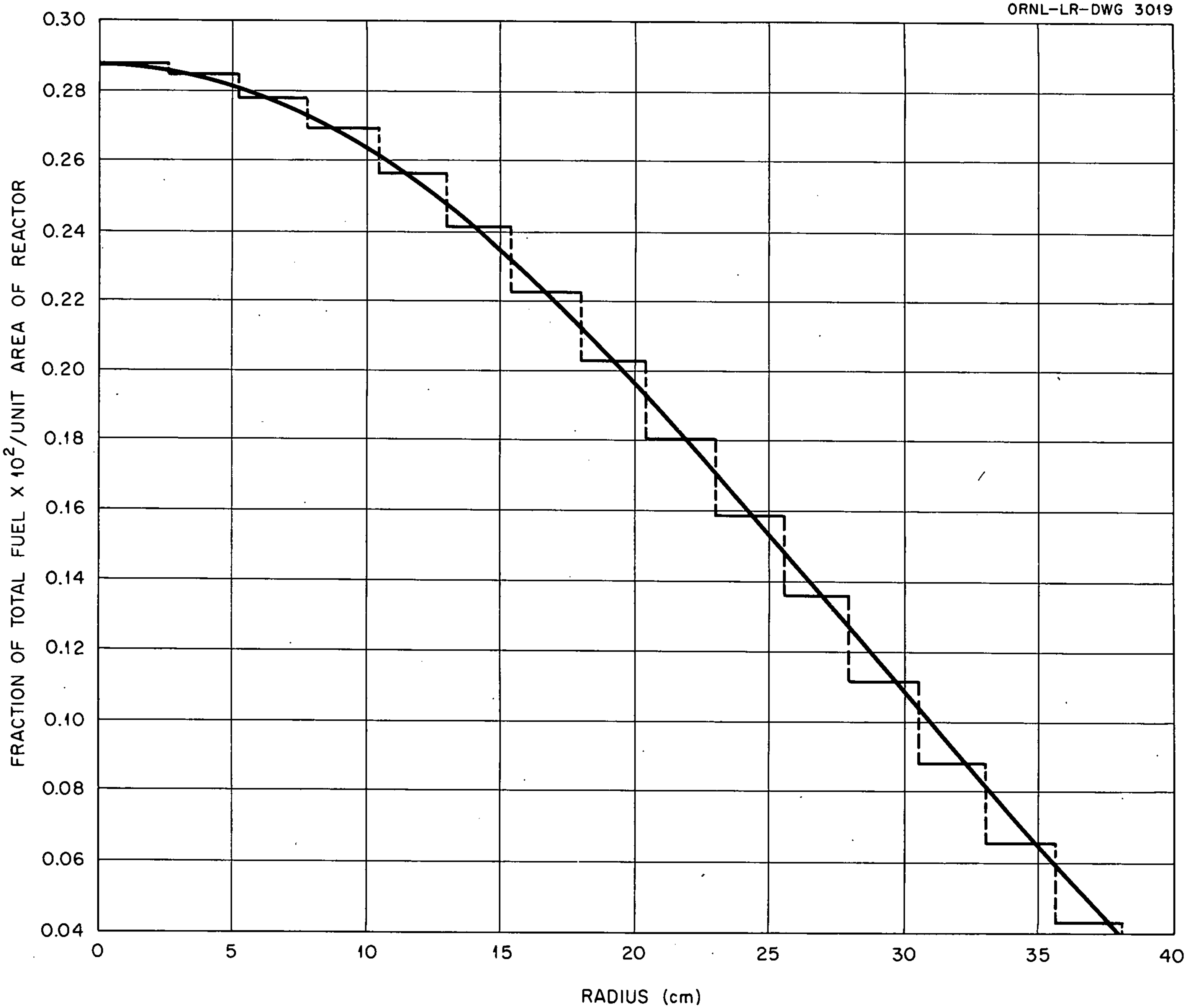

Fig. II. Radial Fuel Distribution (Designed Loading Superimposed on Goertzel Distribution).

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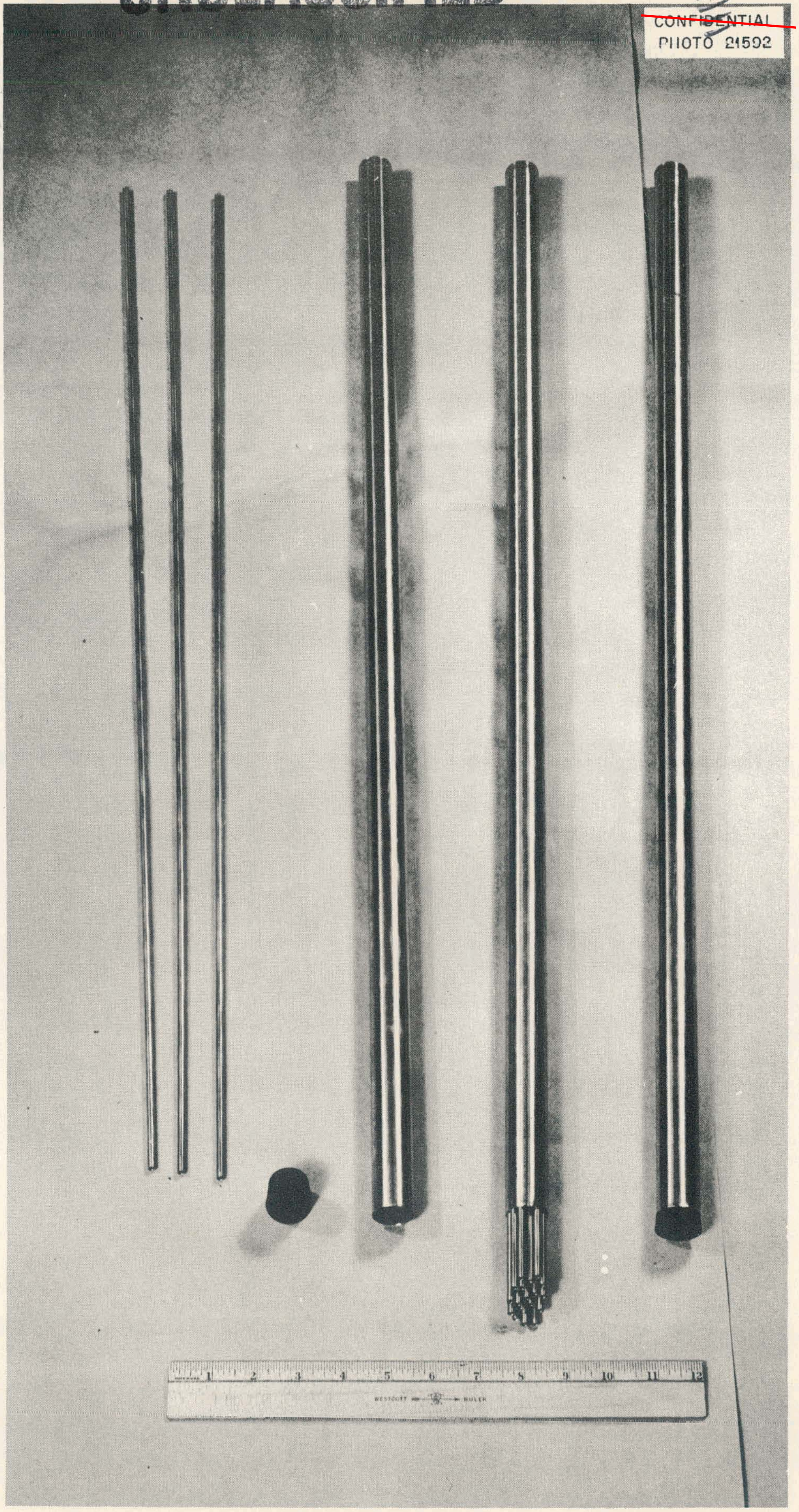

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Fig. III.

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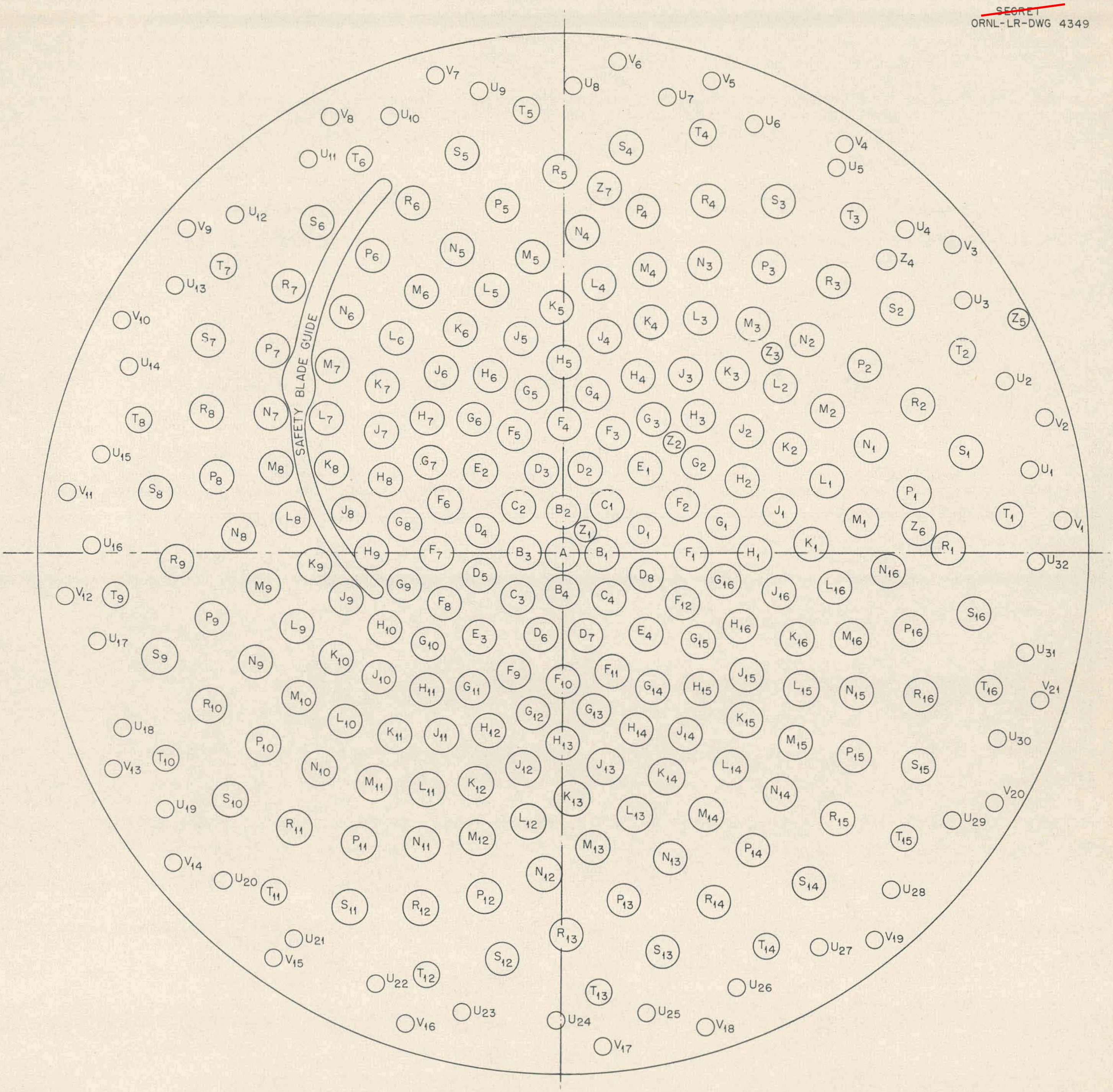

Fig. IV. Experimental Reactor Core Tube Array.

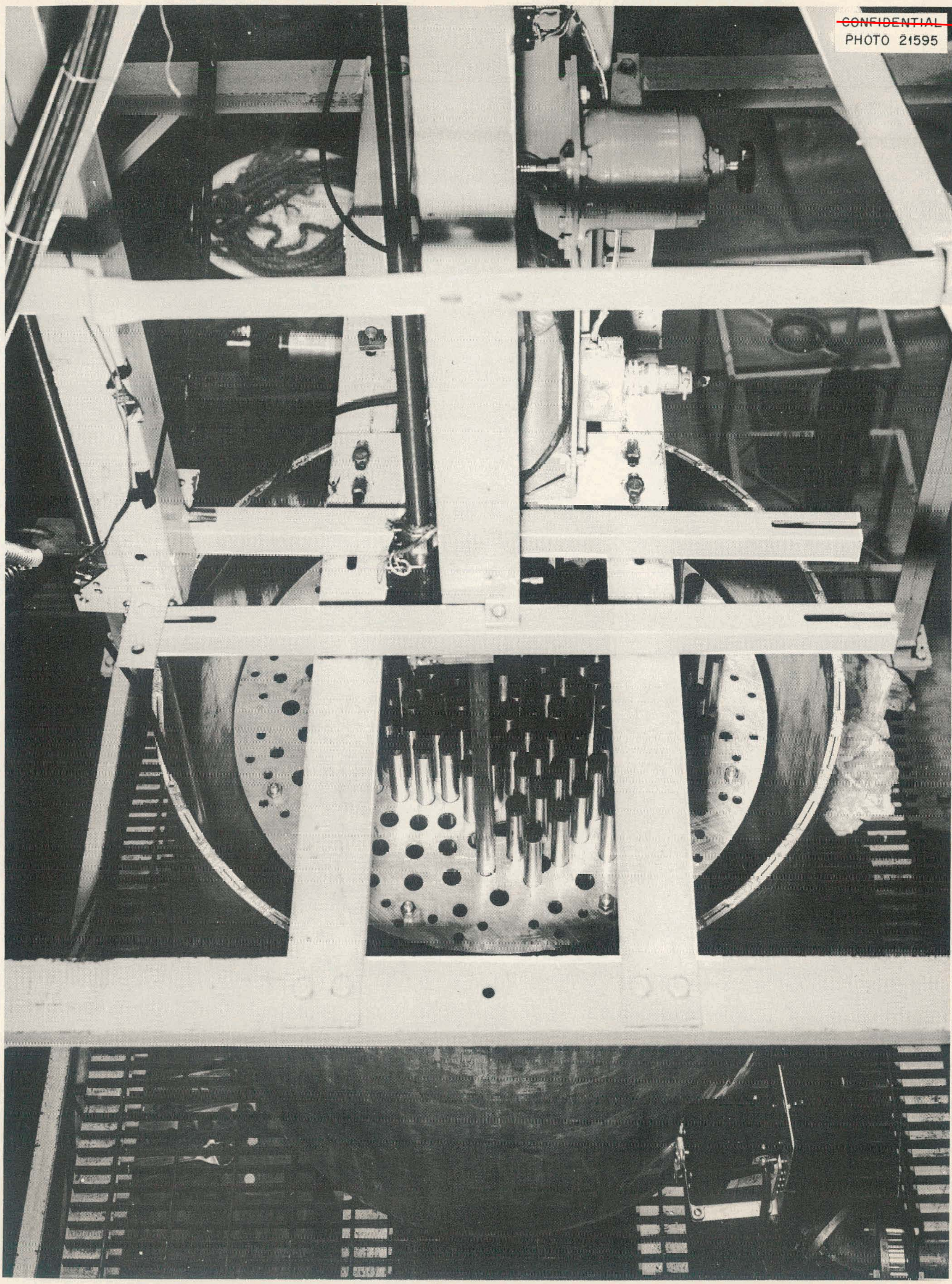

Fig. V.

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TABLE II

DESCRIPTION OF FUEL TUBES USED IN VARIOUS EXPERIMENTS

EXP. NO.	STEEL TUBE			STEEL INSERTS			LINEAR STEEL DENSITY	AREA OF STEEL	FUEL SOLUTION	
	Outside Diameter in.	Wall Thickness in.	Overall Area cm^2	Number	Outside Diameter in.	Wall Thickness in.	gm/cm	cm^2	Volume cm^3	Height cm
A-1	1.003	0.020	5.110	0	-	-	3.229	0.4101	230.2	49.0
A-2	1.003	0.020	5.110	2	3/16	0.025	4.611	0.5855	230.2	50.9
A-3	1.003	0.020	5.110	4	3/16	0.025	5.992	0.7610	230.2	52.9
A-4	1.003	0.020	5.110	8	3/16	0.025	8.755	1.112	230.2	57.6
A-5 B-1 C-1	1.003	0.020	5.110	8 4	3/16 3/16	0.025 0.028	11.778	1.495	230.2	63.7
C-2 D	1.003	0.020	5.110	8 8	3/16 3/16	0.025 0.028	14.801	1.877	230.2	71.2
-	0.754	0.020	2.880	0	-	-	2.320	0.2941	-	-
D	0.754	0.020	2.880	1 6	1/4 3/16	0.028 0.028	7.856	0.9966	129.7	71.2
-	0.504	0.020	1.285	0	-	-	1.537	0.1969	-	-
D	0.504	0.020	1.285	2 1	3/16 3/16	0.028 0.020	3.584	0.4572	57.88	71.2

* Includes steel in fuel tube wall.
** Fuel solution concentrations for each experiment are given in Table IV.

TABLE III

SPACER PLATE DESIGN PARAMETERS

Hole Designation	Hole Diameter in.	LOCATION Radius in.	Angle*
A	1.009 ± 0.002	0	0°
B_1	"	1.183	0°
B_2	"	"	90°
C_1	"	1.846	45°
D_1	"	2.500	15°
D_2	"	"	75°
E_1	"	3.440	45°
F_1	"	3.807	0°
F_2	"	"	22°30'
F_3	"	"	67°30'
F_4	"	"	90°
G_1	"	4.773	11°15'
G_2	"	"	33°45'
G_3	"	"	56°15'
G_4	"	"	78°45'
H_1	"	5.676	0°
H_2	"	"	22°30'
H_3	"	"	45°
H_4	"	"	67°30'
H_5	"	"	90°
J_1	"	6.500	11°15'
J_2	"	"	33°45'
J_3	"	"	56°15'
J_4	"	"	78°45'
K_1	"	7.343	2°
K_2	"	"	24°30'
K_3	"	"	47°
K_4	"	"	69°30'
L_1	"	8.098	15°15'
L_2	"	"	37°45'
L_3	"	"	60°15'
L_4	"	"	82°45'

* Measured counter-clockwise from the positive x-axis.

TABLE III - Continued

Hole Designation	Hole Diameter in.	Radius in.	Angle
M_1	1.009 ±0.002	8.868	6°
M_2	"	"	28°30'
M_3	"	"	51°
M_4	"	"	73°30'
N_1	"	9.627	19°15'
N_2	"	"	41°45'
N_3	"	"	64°15'
N_4	"	"	86°45'
P_1	"	10.500	10°
P_2	"	"	32°30'
P_3	"	"	55°
P_4	"	"	77°30'
R_1	"	11.318	0°45'
R_2	"	"	23°15'
R_3	"	"	45°45'
R_4	"	"	68°15'
S_1	"	12.245	14°
S_2	"	"	36°30'
S_3	"	"	59°
S_4	"	"	81°30'
T_1	0.759	13.176	4°45'
T_2	"	"	27°15'
T_3	"	"	49°45'
T_4	"	"	72°15'
U_1	0.509	13.964	10°22'
U_2	"	"	21°37'
U_3	"	"	32°52'
U_4	"	"	44°07'
U_5	"	"	55°22'
U_6	"	"	66°37'
U_7	"	"	77°52'
U_8	"	"	89°07'
V_1	"	14.750	4°
V_2	"	"	16°
V_3	"	"	39°
V_4	"	"	56°
V_5	"	"	73°
V_6	"	"	84°
V_7	"	"	105°

TABLE III - Continued

Hole Designation	Hole Diameter in.	Radius in.	Angle
V_8	0.509	14.750	118°
V_9	"	"	139°
V_{10}	"	"	152°
V_{11}	"	"	173°
V_{12}	"	"	185°
V_{13}	"	"	206°
V_{14}	"	"	219°
V_{15}	"	"	235°
V_{16}	"	"	252°
V_{17}	"	"	275°
V_{18}	"	"	287°
V_{19}	"	"	309°
V_{20}	"	"	330°
V_{21}	"	"	343°
Z_1**	0.634	.930	45°
Z_2	"	4.540	45°
Z_3	"	8.480	44°30'
Z_4	"	12.910	43°
Z_5	"	15.120	27°30'
Z_6	1.009	10.500	4°15'
Z_7	"	10.950	84°

** The holes designated "Z" are for experimental measurements.

the facility with which the solution could be diluted, compared to being concentrated, justified the high initial inventory.

IV. Approach to Criticality at Design Dimensions

An initial loading of thirty-eight 1 in. tubes, containing no stainless steel inserts, located in an arbitrary manner near the center of the reactor, was made critical with a reactor height of 48.8 cm. Changes were made in the number of tubes in the array and the corresponding reactor heights required for criticality were measured, the data being given in Table IV and as curve A-1 in Figure VI. A stepwise approach was then made to a critical system of design configuration, that is, with all tubes containing the prescribed mass of stainless steel and volume of solution and with the Furfural and fuel solution at the same level. This approach was made by successive addition of steel inserts to the tubes, the addition of more tubes to the assembly, and the dilution of the UO_2F_2 solution. These data are recorded in Table IV and in Figure VI. The letter in the experiment designation represents a U-235 concentration and the numeric refers to the insert tube loading. Table II describes the fuel tubes under each set of conditions. The actual height of the fuel solution is indicated in each case by the horizontal line intersecting the appropriate curve. The positions of the tubes in the reactor in these experiments are shown in Figure VII. If one extrapolates each experimental curve of Figure VI to an abscissa value of 215, one obtains the critical height that would be expected if all tubes were in place, since their combined area is equal to that of 215 tubes 1 in. in diameter.

In Figure VIII these extrapolated values together with the experimentally determined critical heights have been plotted as a function of the mass ratio of U-235 and stainless steel, yielding a series of curves, each representing a particular tube array. These curves can be extrapolated to 71.2 cm, the height of fuel solution in the tubes with the maximum steel loading to be attempted in these experiments, thereby giving an estimate of the critical loading at near design dimensions. Since these extrapolations are inherently uncertain, particularly that of the "215 tube" curve, an additional plot was made in Figure IX, in an attempt to better predict the critical mass at a height of 71.2 cm with all tubes in place. This graph shows the number of tubes critical at a height of 71.2 cm, from the extrapolations of Figure VIII, as a function of the U-235-stainless steel mass ratio. Extrapolation, in turn, of this curve yields a value of the mass ratio corresponding to a critical mass of 11.3 kg of U-235. Because of an apparently unjustified lack of confidence in this extrapolation and to facilitate the fuel dilution a subsequent loading of 9.8 kg U-235 was selected. This is equivalent to a fuel solution density of 0.196 gm U-235/cc. As reloading with this

TABLE IV

FUEL LOADING FOR EXPERIMENTS SERIES A, B and C

Exp. Number	No. of 1 Inch Tubes	Solution Concentration gm U-235/cc	Location Areas*	Reactor Height cm	Critical Mass kg	Steel Mass kg
A-1	38	0.504	-	48.83	4.41	6.00
A-1	39	0.504	-	47.55	4.47	6.01
A-1	41	0.504	-	44.09	4.29	5.82
A-1	56	0.504	I	32.49	4.33	5.88
A-1	80	0.504	I + II	25.46	4.82	6.56
A-1	112	0.504	I + II + III	21.05	5.59	7.62
A-2	56	0.504	I	34.60	4.41	8.96
A-3	56	0.504	I	37.27	4.53	12.49
A-3	80	0.504	I + II	28.63	5.00	13.76
A-3	112	0.504	I + II + III	23.37	5.68	15.68
A-4	46	0.504	-	64.75	5.34	26.08
A-4	56	0.504	I	44.95	5.02	22.06
A-4	80	0.504	I + II	32.92	5.26	23.04
A-4	112	0.504	I + II + III	26.38	5.89	25.87
A-4	155	0.504	I + II + III + IV	23.13	7.15	31.47
A-4	175	0.504	I + II + III + IV + V	22.50	7.86	34.48
A-5	56	0.504	I	62.50	6.35	41.55
A-5	80	0.504	I + II	40.06	5.84	37.76
A-5	112	0.504	I + II + III	31.07	6.36	40.99
A-5	155	0.504	I + II + III + IV	26.50	7.53	48.36
A-5	175	0.504	I + II + III + IV + V	25.23	8.12	51.98
B-1	80	0.444	I + II	43.41	5.57	40.90
C-1	80	0.347	I + II	54.11	5.36	50.98
C-1	112	0.347	I + II + III	37.90	5.26	50.00
C-1	155	0.347	I + II + III + IV	31.45	6.04	57.42
C-1	175	0.347	I + II + III + IV + V	29.76	6.45	61.34
C-2	112	0.347	I + II + III	53.39	7.41	88.50
C-2	155	0.347	I + II + III + IV	40.70	7.82	93.37
C-2	175	0.347	I + II + III + IV + V	37.99	8.24	98.39

* Refer to Figure VII

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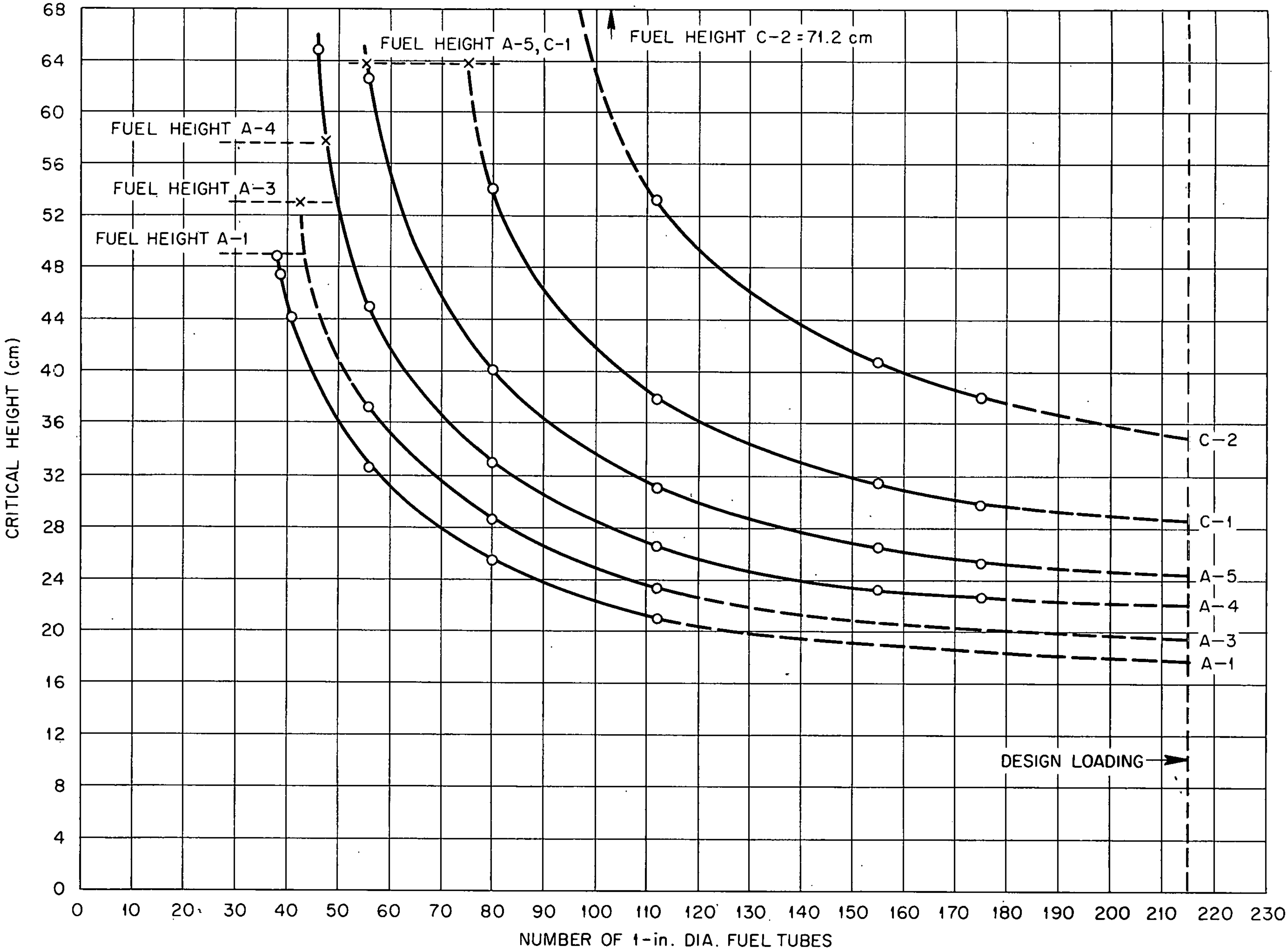

Fig. VI. Experimental Approach to Critical (Experiments A-1 Through C-2).

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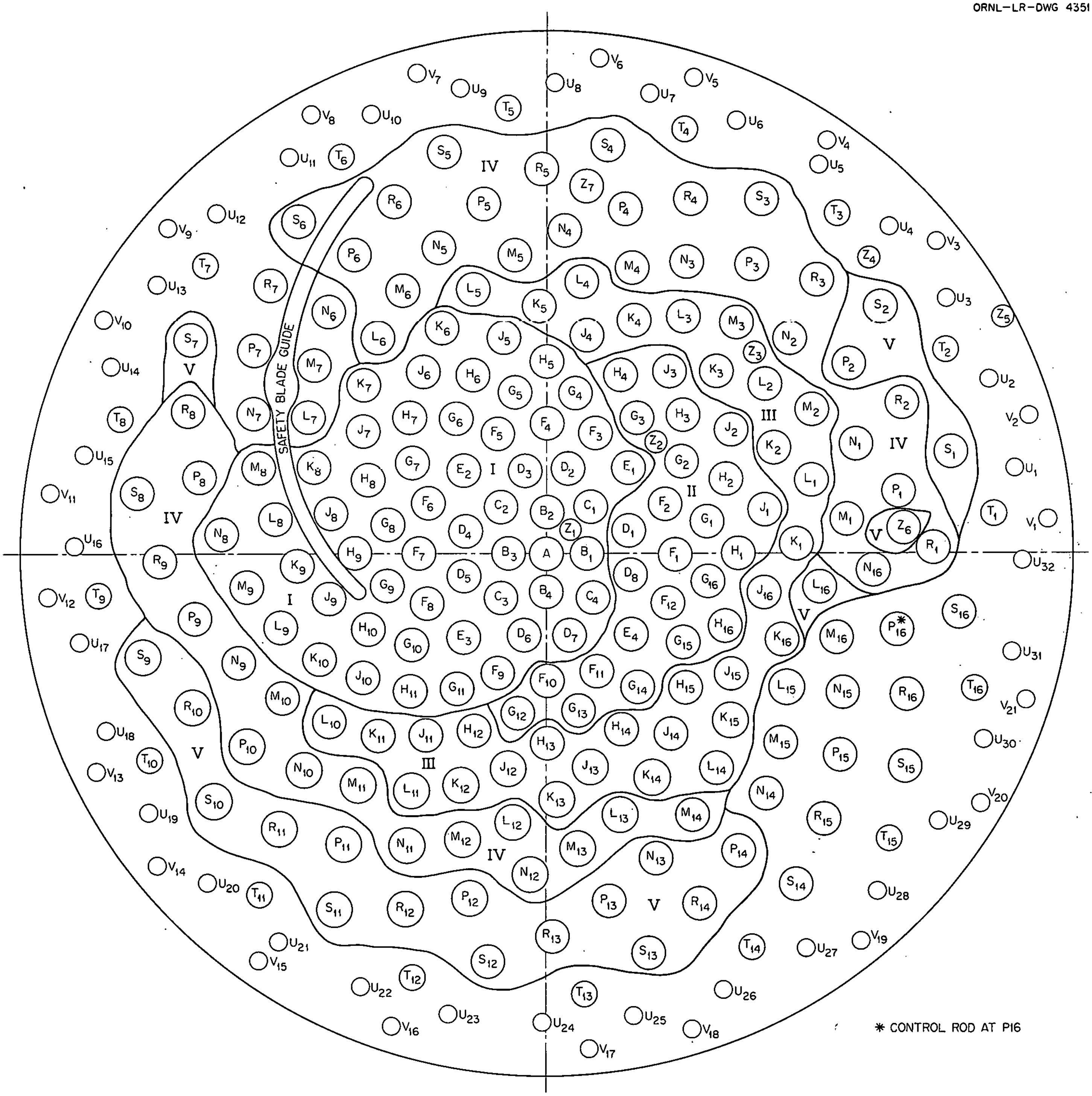

Fig. VII. Fuel Distribution: Experiments A to C Inclusive.

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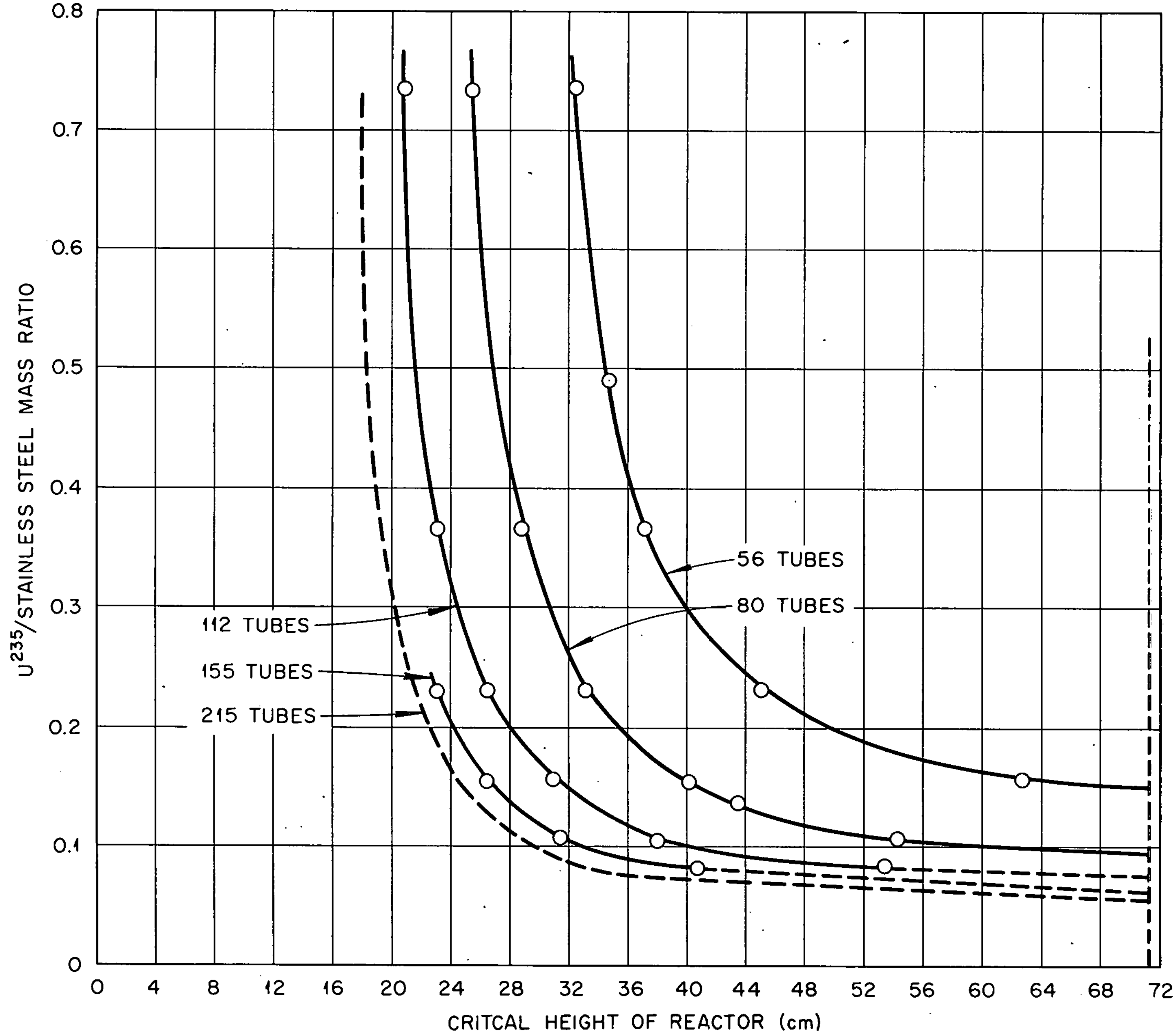

Fig. VIII. U^{235}/Stainless Mass Ratio vs. Critical Height. Ref. Table IV.

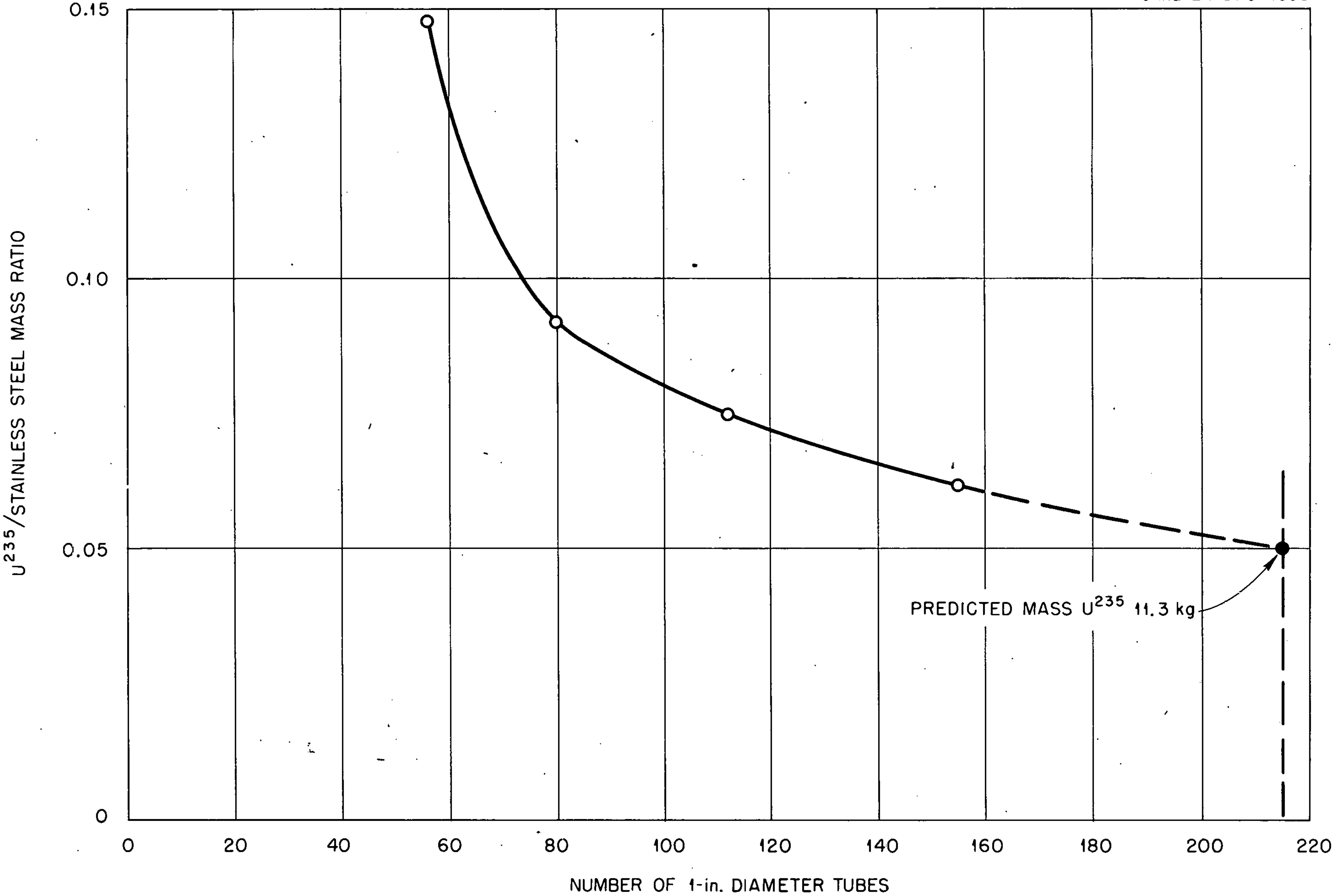

Fig. IX. U^{235}/Stainless Steel Mass Ratio vs. Tube Loading at Critical Reactor Height of 71.2 cm.

solution progressed it became apparent that the mass had been underestimated and it was necessary to supplement the loading with a few tubes containing solution at a higher concentration. These latter tubes were located on one side of the assembly to minimize the effect of the perturbation and most of the measurements reported here were made with this loading, D-1 described in Table V and Figure X.

TABLE V

FUEL LOADING IN EXPERIMENT D-1

Number of Tubes	Tube Dia. in.	Solution Concentration gm U-235/cc.	Location Areas	Reactor Height cm	Critical Mass U-235 kg	Mass of Stainless Steel
175	1	.196	XI	69.47	11.48	220.4
18	1	.505	X			
8	3/4	.505	X			
8	3/4	.196	XI			
25	1/2	.505	X			
28	1/2	.196	XI			

V. Neutron Flux Measurements

Bare and cadmium-covered indium foil traverses were measured radially and longitudinally in the reactor. The radial traverse was taken 37.6 cm from the bottom of the reactor (38.1 cm from the tank floor) in experimental holes Z_1 to Z_5. A single longitudinal traverse was made in hole Z_1. The foils were supported with their planes perpendicular to the traverse by aluminum strips.

All foils were exposed for 20 minutes at a sufficiently high power level to reduce statistical variations in the following counting procedure. The activity of both sides of each foil was measured by four GM counters and the results were averaged after being corrected for dead time, background, decay, counter variations, and power level. Relative power levels were determined from the activity of a large indium foil located at a given point in the reactor during each exposure.

The results of these traverses are given in Tables VI and VII and Figures XI and XII.

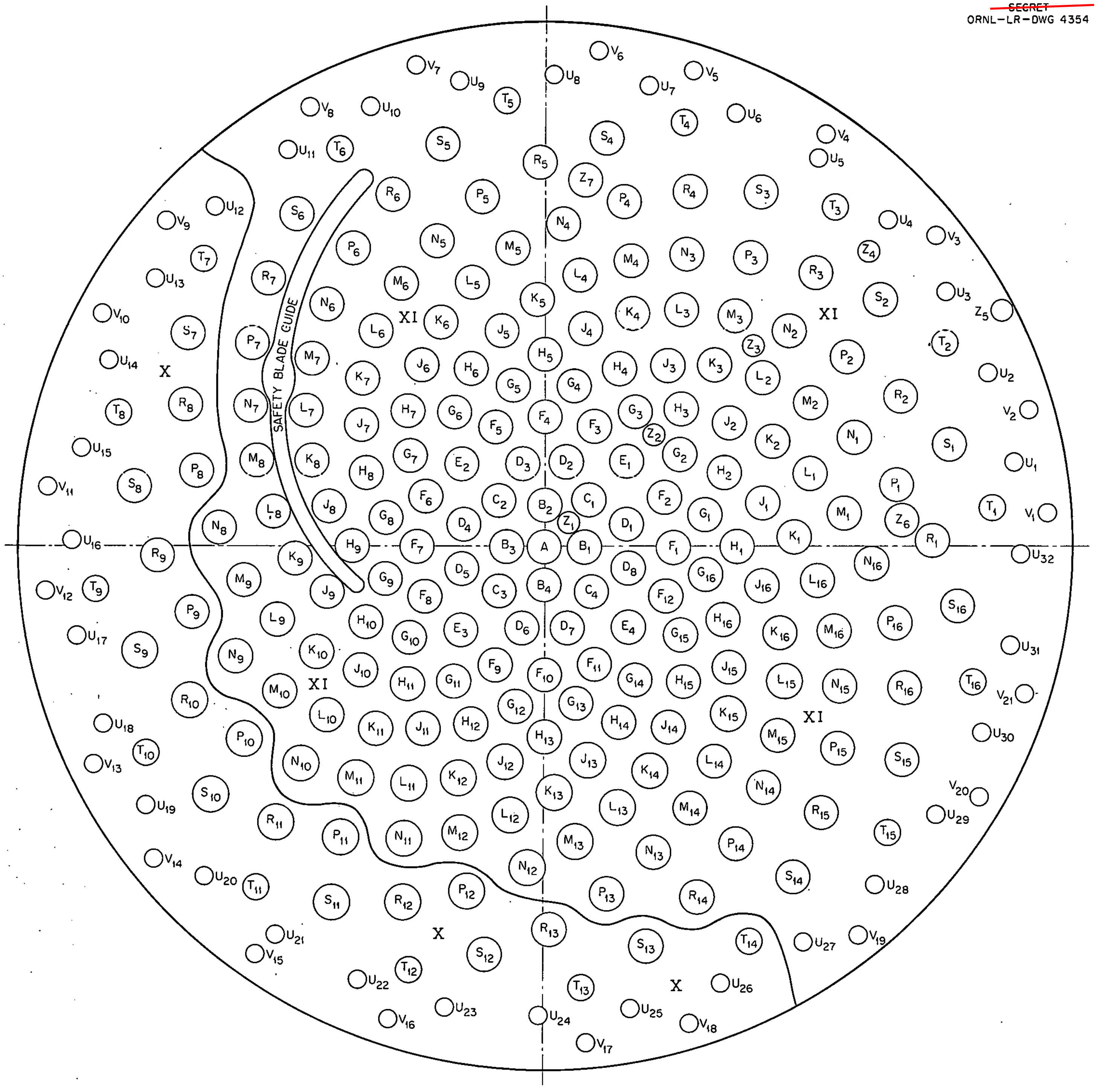

Fig. X. Fuel Distribution: Experiment D-1.

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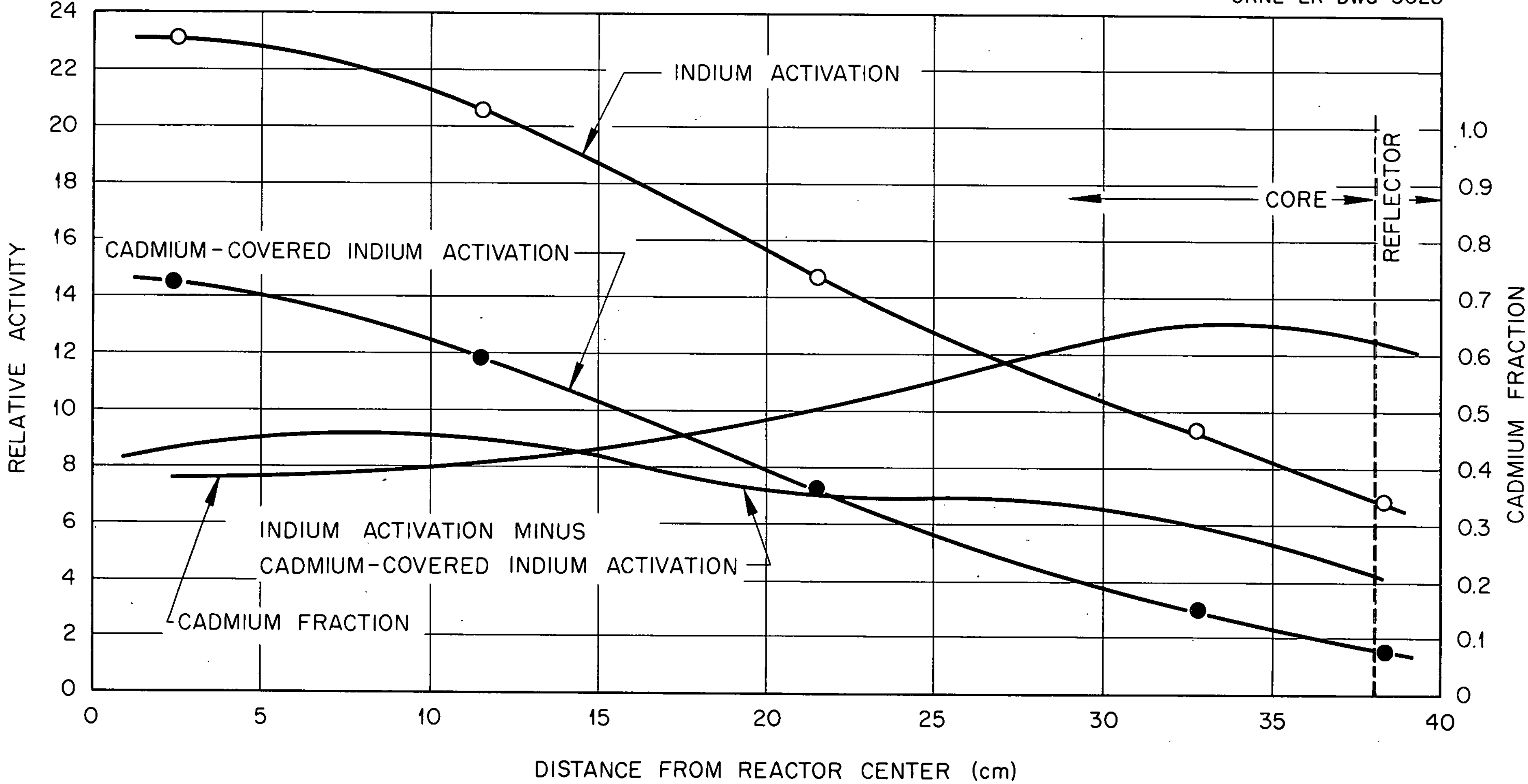

Fig. XI. Radial Flux 37.6 cm from the Bottom of the Reactor.

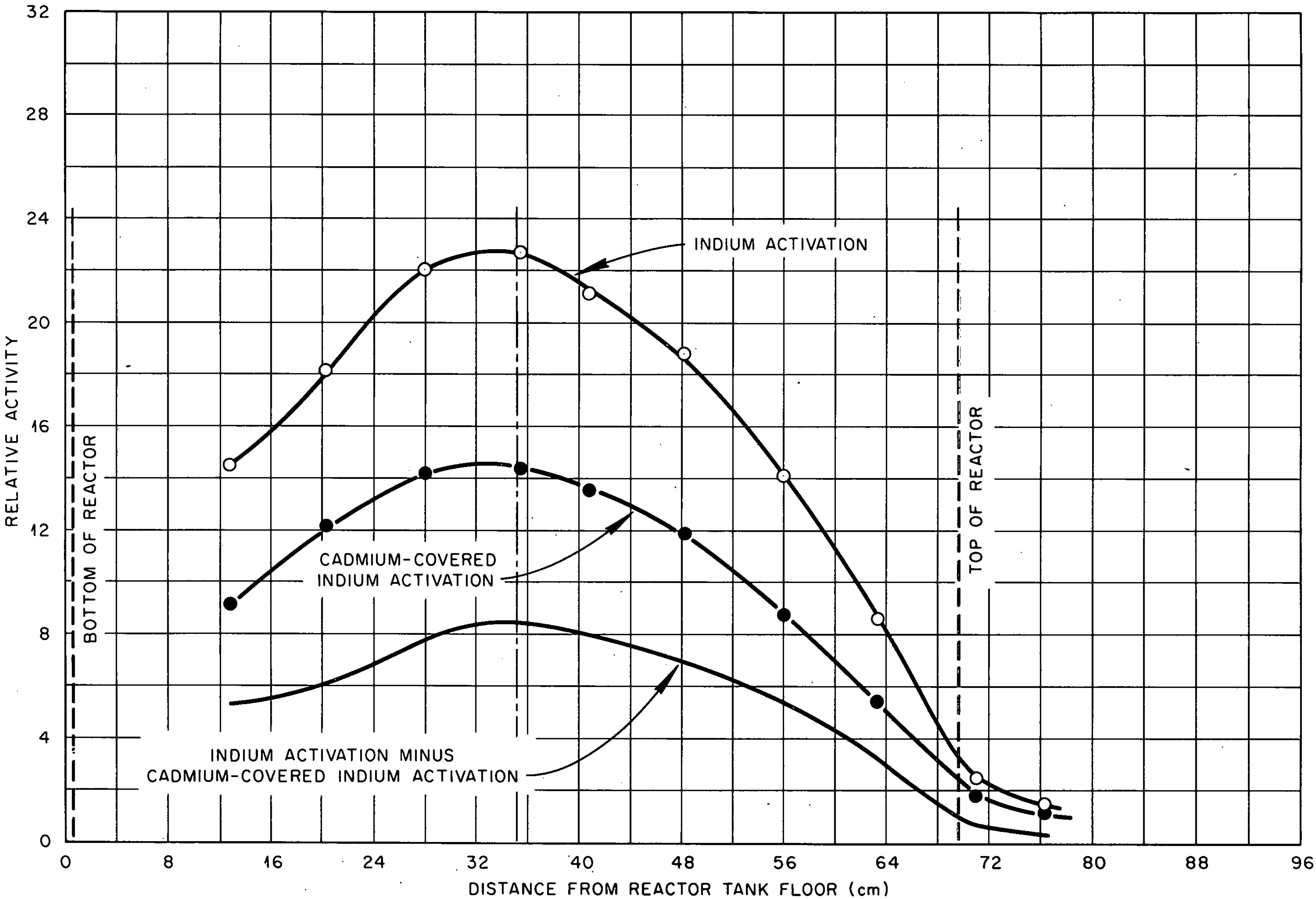

Fig. XII. Longitudinal Flux in Position Z.

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TABLE VI

RADIAL NEUTRON FLUX AT MID-PLANE

Location Radius	RELATIVE ACTIVITY Indium	Cd Covered In	In-(Cd In Cd)
Z_1	23189	14550	8639
Z_2	20740	11852	8888
Z_3	14836	7438	7398
Z_4	9490	3179	6311
Z_5	7051	1678	4373

TABLE VII

LONGITUDINAL NEUTRON FLUX AT POSITION Z_1

Distance From Floor - cm	RELATIVE ACTIVITY Indium	Cd Covered In	In-(Cd In Cd)
12.7	14459	9104	5355
20.3	18131	12117	6014
28.0	21987	14184	7803
35.6	22675	14327	8348
40.7	21146	13539	7607
48.3	18756	11825	6931
55.9	14037	8690	5347
63.5	8520	5373	3147
71.1	2494	1778	716
76.2	1481	1162	319

VI. Importance of Fuel

The increases in reactivity resulting from incremental additions of Furfural to an already critical system were determined from the concomitant reactor periods and the usual in-hour equation. The data, given in Table VIII and Figure XIII, serve in the evaluation of subsequent reactivity changes due to alterations in the fuel loading. The importance of the fuel as a function of position was determined from the reactivity changes incurred by successively exchanging one of the heavier loaded tubes, S-7, with one of those along a radius in the unperturbed region. In this manner 70.8 gms U-235 were added to the location under test without changing the total core loading. The data, given in Table IX, include the tube position, reactor height and the corresponding change in reactivity per unit of U-235 transferred. The latter is plotted in Figure XIV as a function of the radius of the test position.

TABLE VIII

EXCESS REACTIVITY RESULTING FROM INCREASED REACTOR HEIGHT

Measured at Critical Height = 27.557 inches.

ΔH - Inches	ΔK - Cents
0.051	2.75
0.128	5.55
0.200	8.75
0.306	13.20
0.338	14.30

TABLE IX

U-235 IMPORTANCE

Location	Radial Distance in.	Reactor Height in.	Reactivity Coefficient cents/gm
A	0.00	26.997	0.345
E_1	3.44	27.081	0.292
K_3	7.34	27.392	0.101
R_3	11.32	27.634	0.0473
Unperturbed Reactor		27.557	

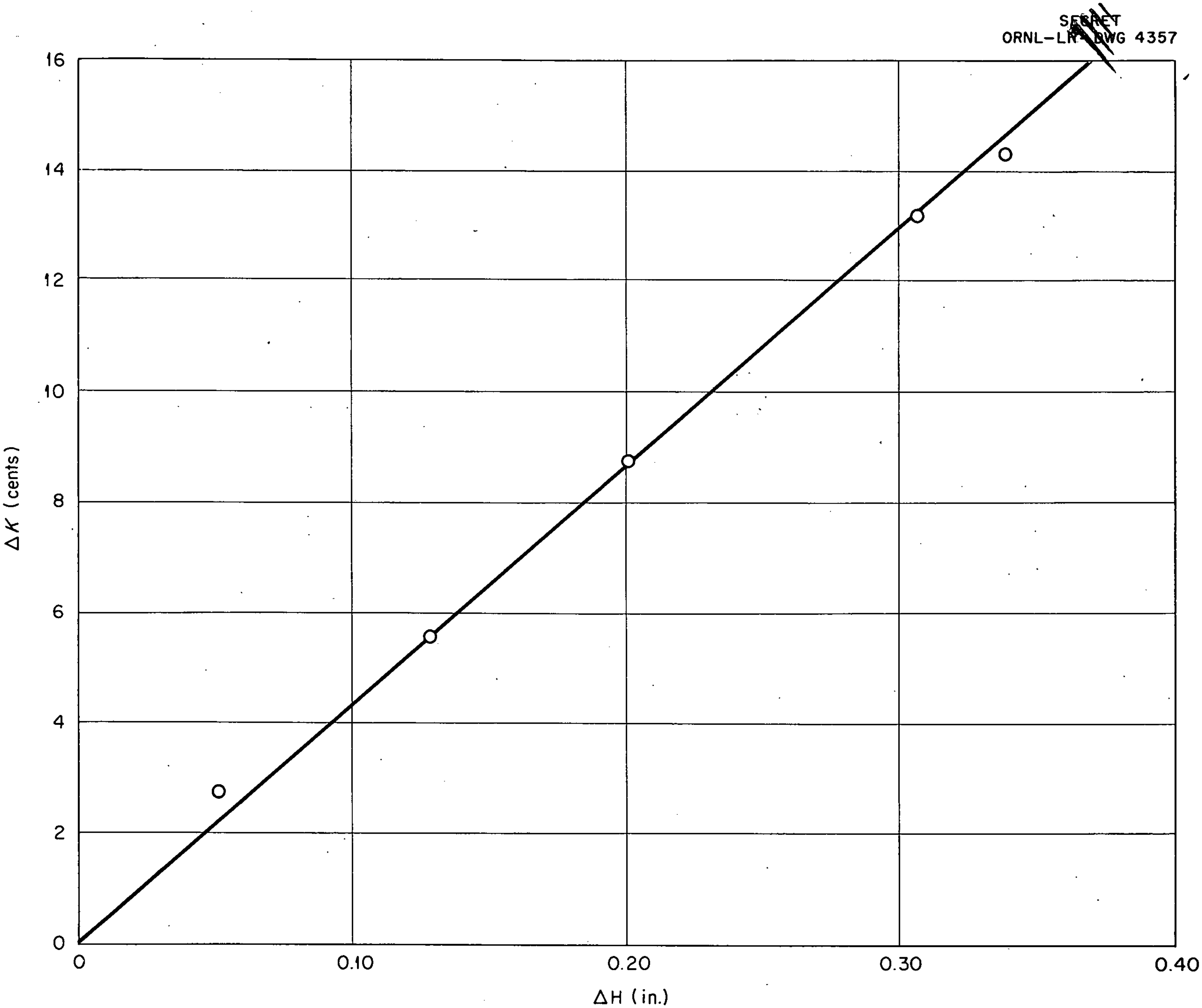

Fig. XIII. Excess Reactivity vs. Furfural Height.

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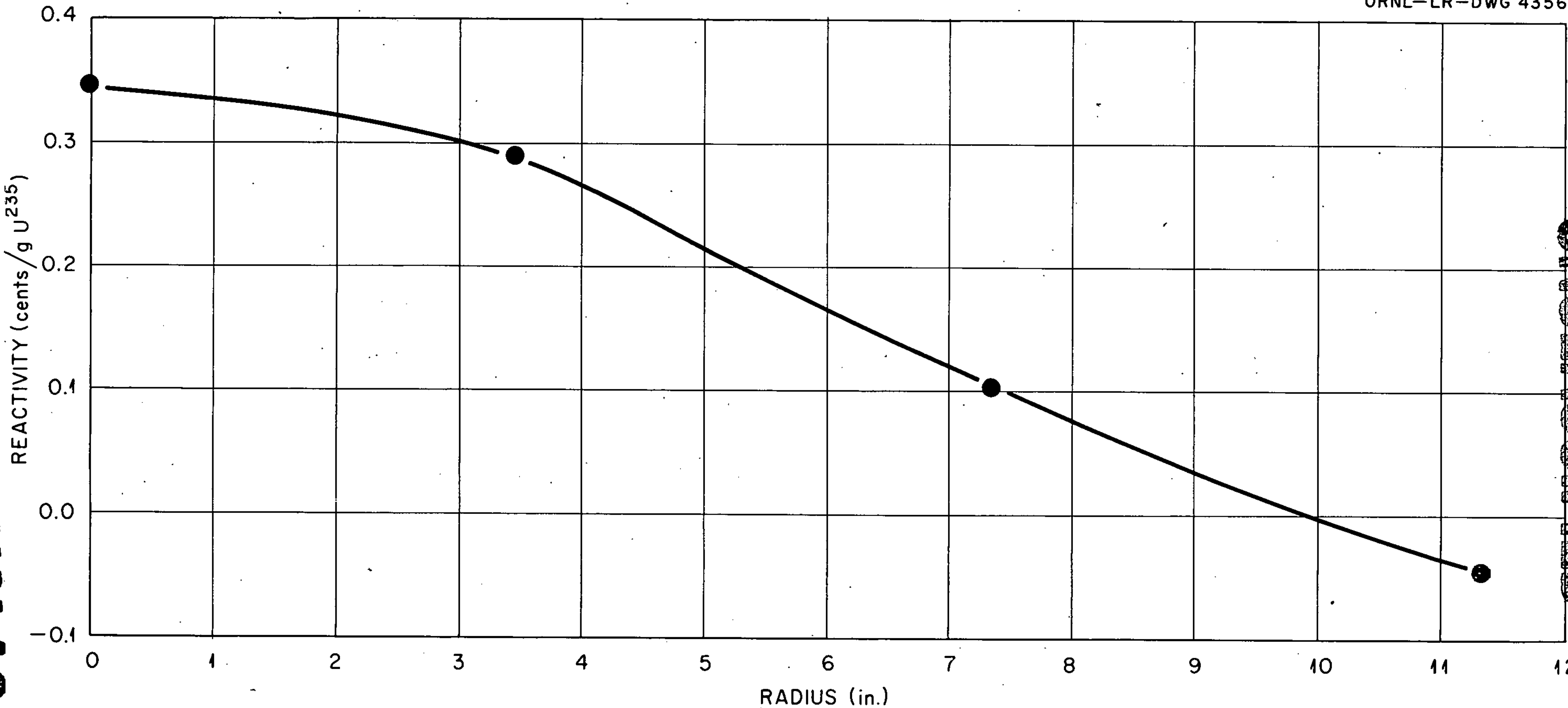

Fig. XIV. Radial Fuel Importance.

VII. Importance of Reflector

In the C-2 loading of 175 tubes, aluminum sheets, described in Part I, were inserted in the tank, adjacent to the walls, displacing an annulus of Furfural 2.5 in. thick and correspondingly reducing the thickness of the liquid reflector. The effect of this change in reflector was a slight increase in reactivity as evidenced by the requirement of a critical reactor height 0.100 in. lower than previously measured. The implication of the near equivalence of Furfural and aluminum as reflectors, at least when removed somewhat from the core, precluded the use of the latter in reducing the liquid reflector thickness to the 6.5 cm design value.

VIII. Summary

This report records the progress made in the critical experiments for the Super-Critical Water Reactor up to mid 1954 when the program was severly curtailed by the shift in emphasis to the Reflector Moderated Reactor. In this sense it is an interim report on largely unfinished work and cannot present firm conclusions and comparisons with theory or calculations. The measurements which have been made were probably influenced by the non-uniform loading of the assembly, an expedient to achieve criticality at near design conditions, and are not, therefore, entirely amenable to interpretation. The value of the critical mass in a uniformly loaded core is 10.8 ± 0.5 kg U-235. The longitudinal neutron flux, measured with indium foils, is typical. The radial thermal flux, i.e. neutrons of energy below the cadmium cut-off, decreases somewhat with increasing radius but not as severely as in a homogeneously loaded core, the decrease, from center to edge, being only about 50%. A somewhat greater change was noted in the importance of a quantity of fuel over the same traverse.

The next step in a continuation of the program would be the adjustment of the uranium distribution to the same concentration in all fuel tubes and a measurement of the fission rate within the tubes along a radius. These data would allow any necessary redesign of the fuel tube distribution to achieve uniform specific power - one of the characteristics of the reactor.

APPENDIX

Material Analyses

Furfural with 0.1% by volume Tri-n-propylamine as an autoxidation inhibitor:

Carbon	62.2%	Relative Standard Error 2%
Hydrogen	4.3%	

Stainless Steel (347) fuel tubes and inserts:

Chromium	17.7%	
Nickel	12.0%	Relative Standard Error 10%
Iron	69.0%	
Columbium	0.6%	

Aluminum: Reported in Part I, CF 53-9-139