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SUMMARY LISTING OF SUBCRITICAL MEASUREMENTS OF HETEROGENEOUS WATER-URANIUM LATTICES MADE AT HANFORD

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CRITICAL MASS PHYSICS
PHYSICS AND INSTRUMENT RESEARCH
AND DEVELOPMENT OPERATION

6-8-60

HANFORD ATOMIC PRODUCTS OPERATION
RICHLAND, WASHINGTON

PRELIMINARY REPORT

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INTRODUCTION

Exponential and critical approach type measurements have been made to determine the critical mass, material buckling, and in a few cases, the extrapolation length for the lattices. This report attempts to list all measurements on water-uranium heterogeneous lattices made to date at Hanford. All lattices were water moderated hexagonal arrays loaded with uranium of enrichments up to 3.1%.

Ratios given are volume ratios. The radii of loadings are calculated assuming cylindrical geometry by the following formula

$$R = \sqrt{\frac{nl^2\sqrt{3}}{2\pi}}$$

where n is the number of tubes and l is the lattice spacing (distance between fuel rod centers).

Plots of buckling and critical mass in spherical geometry vs H_2O/U volume ratios are included. The critical masses in spherical geometry are calculated from the measured bucklings assuming the same value of extrapolation length as used in calculating the bucklings.

The value of extrapolation length, λ, was taken from Brookhaven experiments except where noted. The curve of BNL data used was from BNL-C-7592. Values of λ for some of the 3.063 percent enriched uranium measurements were calculated by setting the bucklings for exponential and critical approach measurements equal. R_s, Vol_s and CM_s are estimated critical values for spherical geometry as calculated from measured values of buckling or cylindrical critical masses.

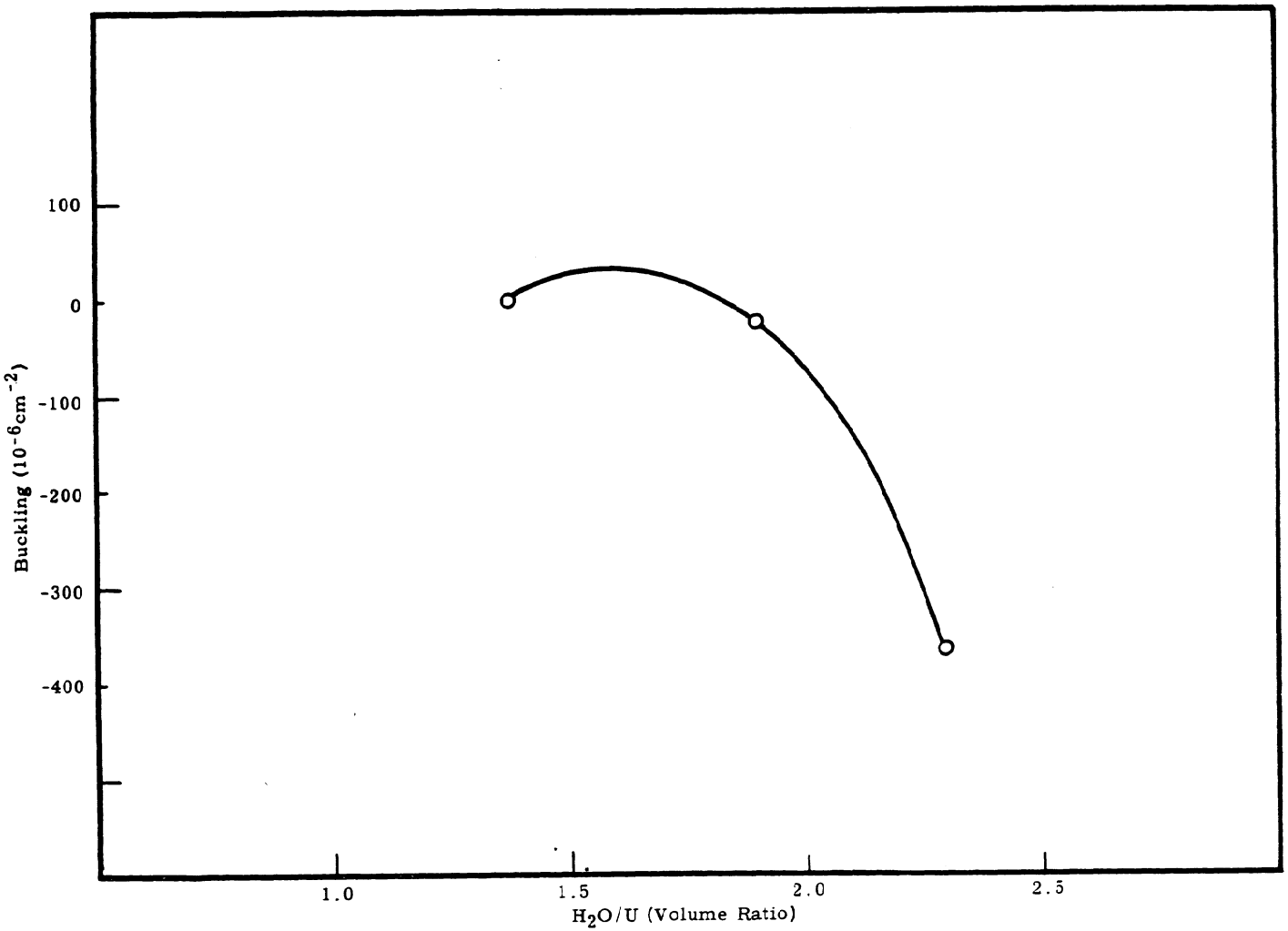
Standard error of the buckling is that calculated from the least square fit and does not include errors due to uncertainty in the value of extrapolation length.

References are listed so that more detailed information of each measurement can be readily obtained if desired.

EXPONENTIAL MEASUREMENTS OF NATURAL URANIUM

(0.925" dia.)

Date	Exp. No.	Lattice Spacing (inches)	Height, h (cm)	No. Tubes	H_2O/U Vol. Ratio	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling $10^{-6}cm^{-2}$	Std. Error
5-60	108	1.400"	101.60	85	1.37	17.21	10.30	7.56	0	±55
3-60	102	1.500"	"	"	1.89	18.44	10.63	7.16	-24	±61
3-60	103	1.600"	"	"	2.29	19.67	10.83	6.96	-367	±40

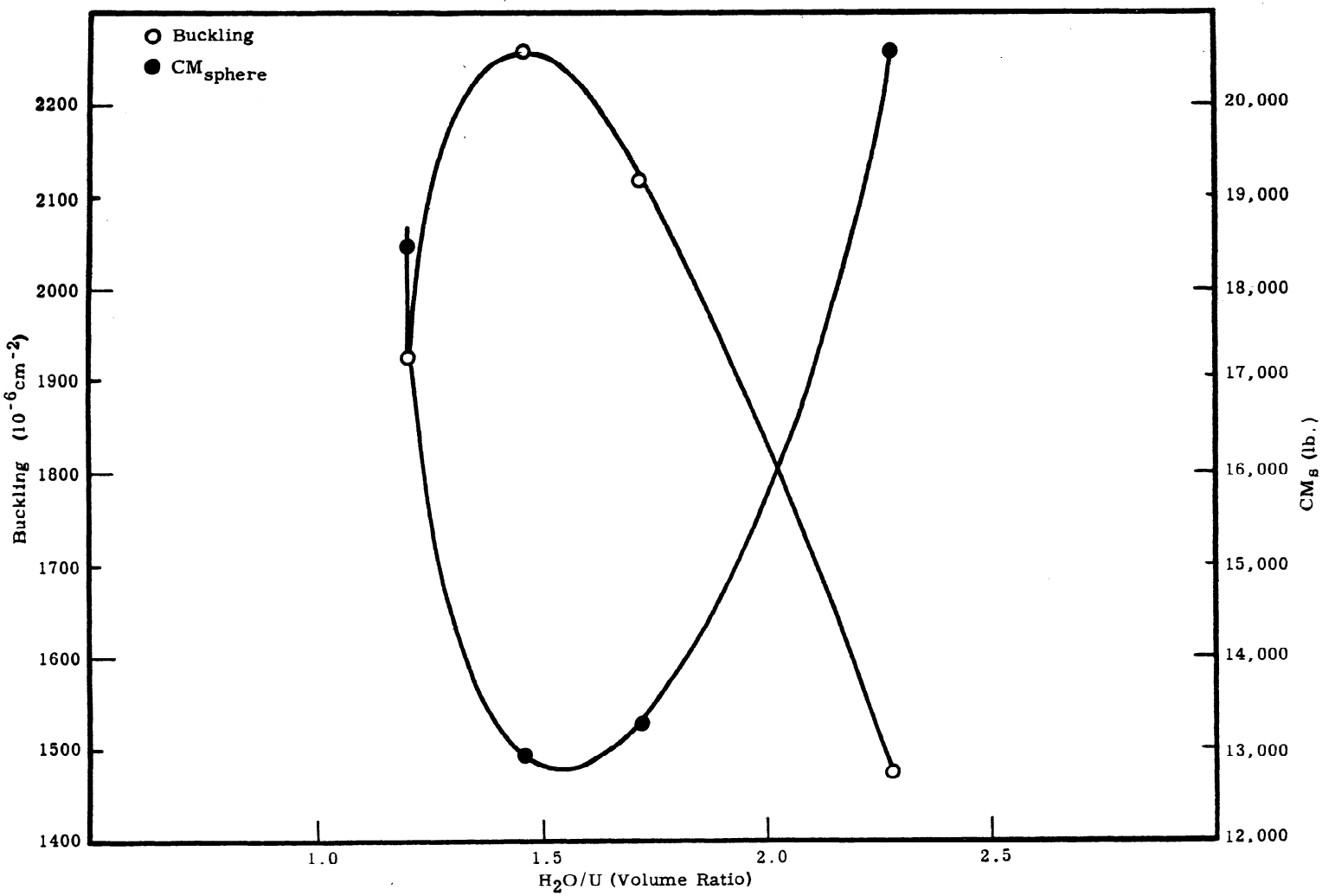


Buckling vs. H_2O/U Ratio
(Natural Uranium, 0.925" Dia.)

EXPONENTIAL MEASUREMENTS OF 0.95 PER CENT ENRICHED URANIUM[1,2]

Iron and Aluminum Encased 1.336" Diameter, 42" Length

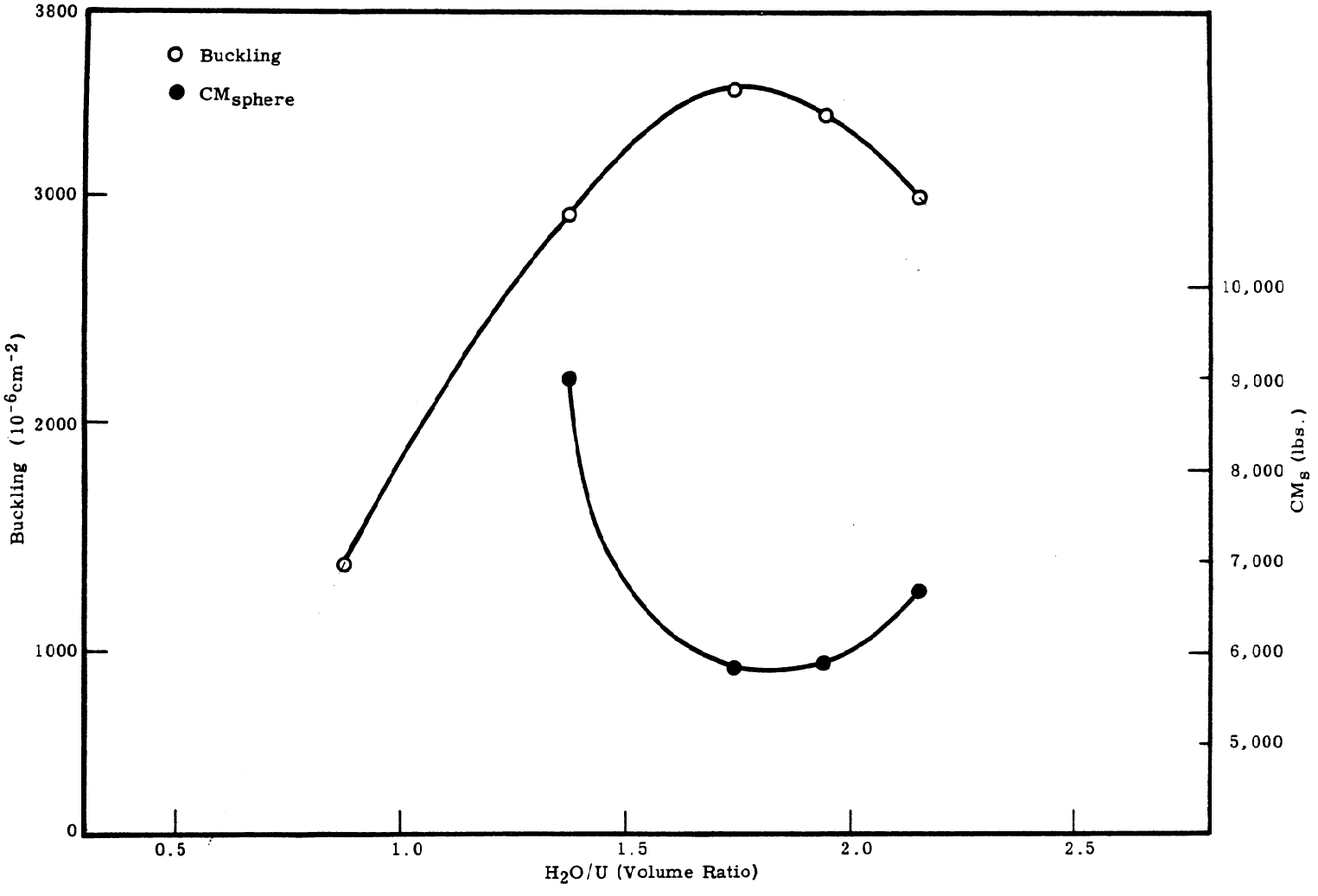
Date	Exp. No.	Lattice Spacing (inches)	No. Tubes	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (liters)	CM_s (lbs)
8-58	70	2.00	55	0.159	1.20	19.78	13.21	7.70	1924	± 40	63.92	1,094	18,450
4-58	63	2.10	55	0.159	1.46	20.77	14.14	7.46	2257	± 32	58.68	846	12,943
4-58	62	2.20	55	0.159	1.72	21.76	14.51	7.27	2115	± 22	61.05	953	13,279
4-58	64	2.40	55	0.159	2.28	23.74	14.65	6.97	1474	± 34	74.86	1,758	20,582
				Fe/U									
8-58	71	2.00	55	0.160	1.19	19.78	11.22	7.72	- 303	± 52	-	-	-
5-58	65	2.10	55	"	1.44	20.77	11.89	7.48	169	± 75	-	-	-
5-58	66	2.20	55	"	1.70	21.76	12.03	7.28	- 52	± 69	-	-	-
5-58	67	2.40	55	"	2.27	23.74	12.01	6.98	- 800	± 71	-	-	-



Buckling and Critical Mass vs. H_2O/U Ratio
(.95% U-235 - 1.336" Diameter)

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM[3,4,5,6]
.925" DIAMETER, 44" LENGTH

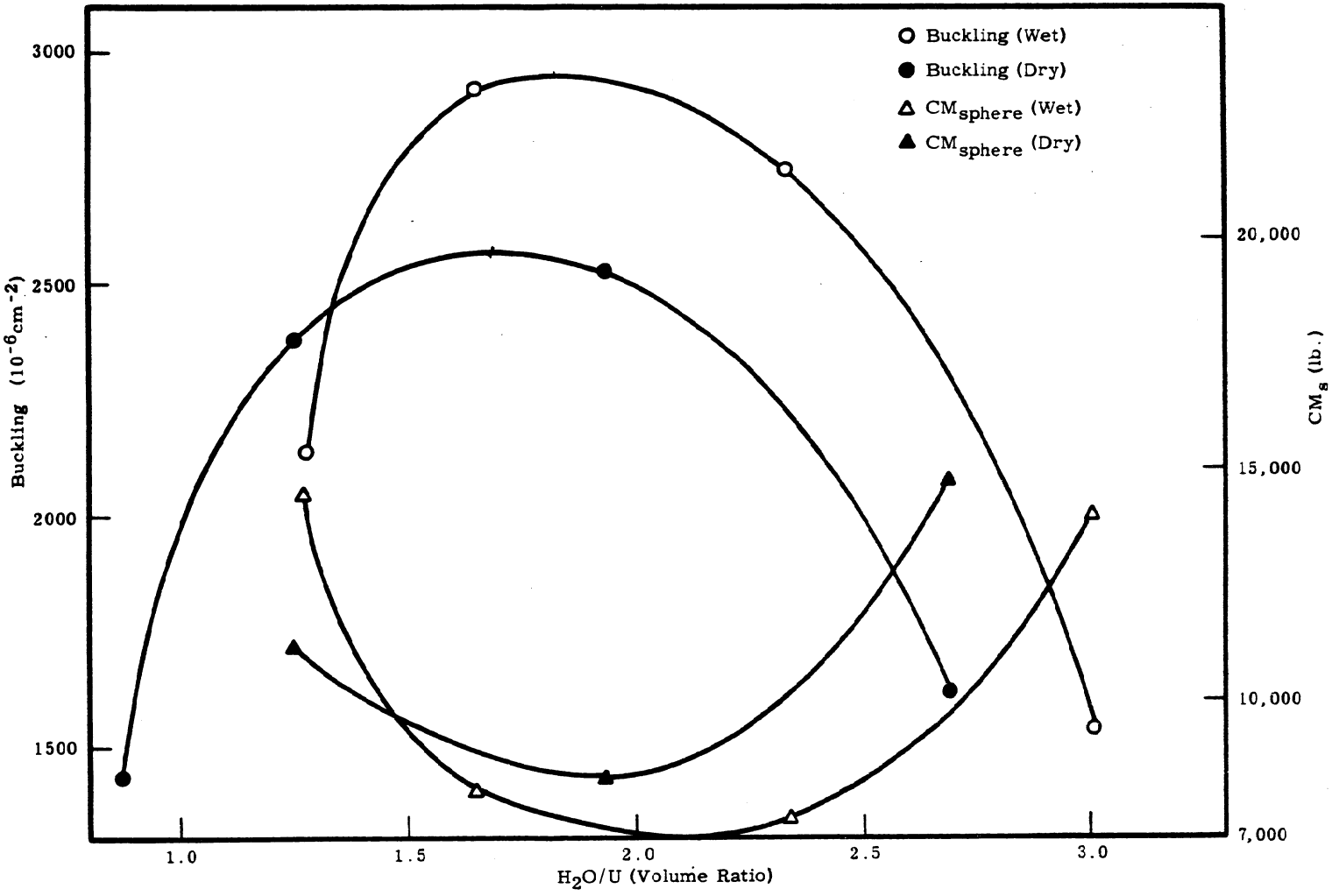
Date	Exp. No.	Lattice Spacing (inches)	No. Tubes	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vols. (liters)	CM_s (lbs)
11-57	37	1.26	85	0.157	.87	15.49	10.58	8.20	1377	±42	76.47	1,873	38,146
10-55	Project Bath Tub	1.40	89	"	1.37	17.61	12.68	7.56	2903	±16	50.75	548	9,018
10-55	"	1.50	89	"	1.74	18.87	14.14	7.25	3470	±19	46.08	410	5,889
10-55	"	1.55	91	"	1.94	19.72	14.65	7.14	3357	±25	47.08	437	5,876
10-55	"	1.60	89	"	2.15	20.13	14.38	7.02	3012	±21	50.22	531	6,698



Buckling and Critical Mass vs. H_2O/U Ratio
(1.007 % U-235 - 0.925" Diam.)

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM[7]
1.66" O.D.; 0.94" I.D., 44" LENGTH

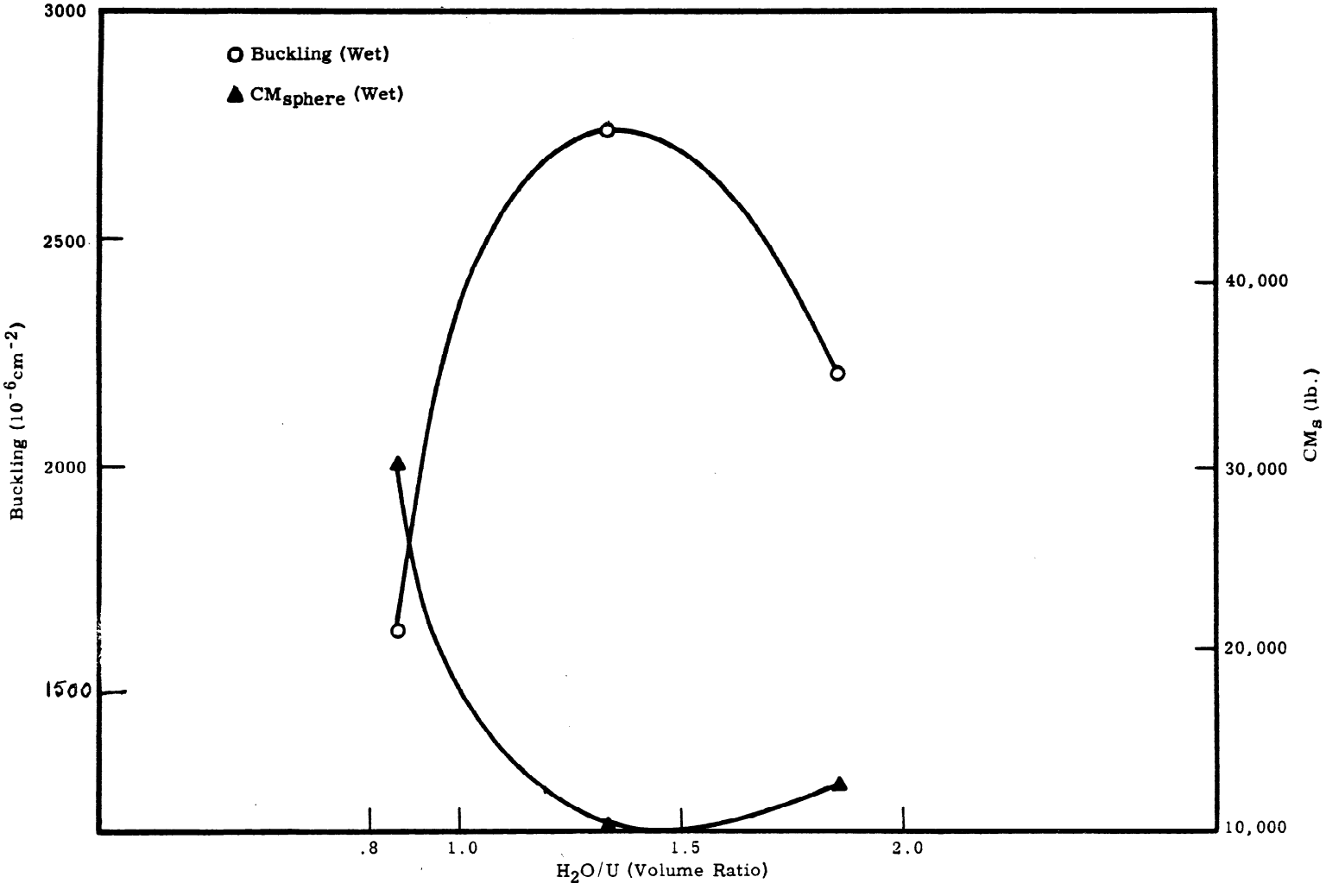
Date	Exp. No.	Lattice Spacing (inches)	No. Tubes	Fuel Core Cond.	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6} cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (liters)	CM_s (lbs.)
8-56	31-5	2.05	85	Dry	0.163	.873	25.20	16.36	8.25	1434	±42	74.711	1,747	29,348
8-56	31-4	2.05	"	Wet	"	1.272	25.20	17.61	7.66	2133	±9	60.365	921	15,480
7-56	31-3	2.20	"	Dry	"	1.248	27.05	20.33	7.67	2378	±6	56.760	766	11,195
7-56	31-2	2.20	"	Wet	"	1.648	27.05	22.53	7.34	2920	±15	50.795	549	8,023
9-56	31-9	2.45	"	Dry	"	1.933	30.12	24.72	7.14	2529	±13	55.331	710	8,361
9-56	31-8	2.45	"	Wet	"	2.333	30.12	26.12	6.94	2745	±14	53.027	625	7,360
8-56	31-6	2.70	"	Dry	"	2.692	33.20	22.38	6.80	1619	±20	71.275	1,517	14,717
8-56	31-7	2.70	"	Wet	"	3.091	33.20	21.79	6.68	1531	±5	73.602	1,670	14,036



Buckling and Critical Mass vs. H_2O/U Ratio
(1.007% U-235 - 1.66" O.D. - 0.94" I.D.)

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM[3,4]
1.66" DIAMETER, 44" LENGTH

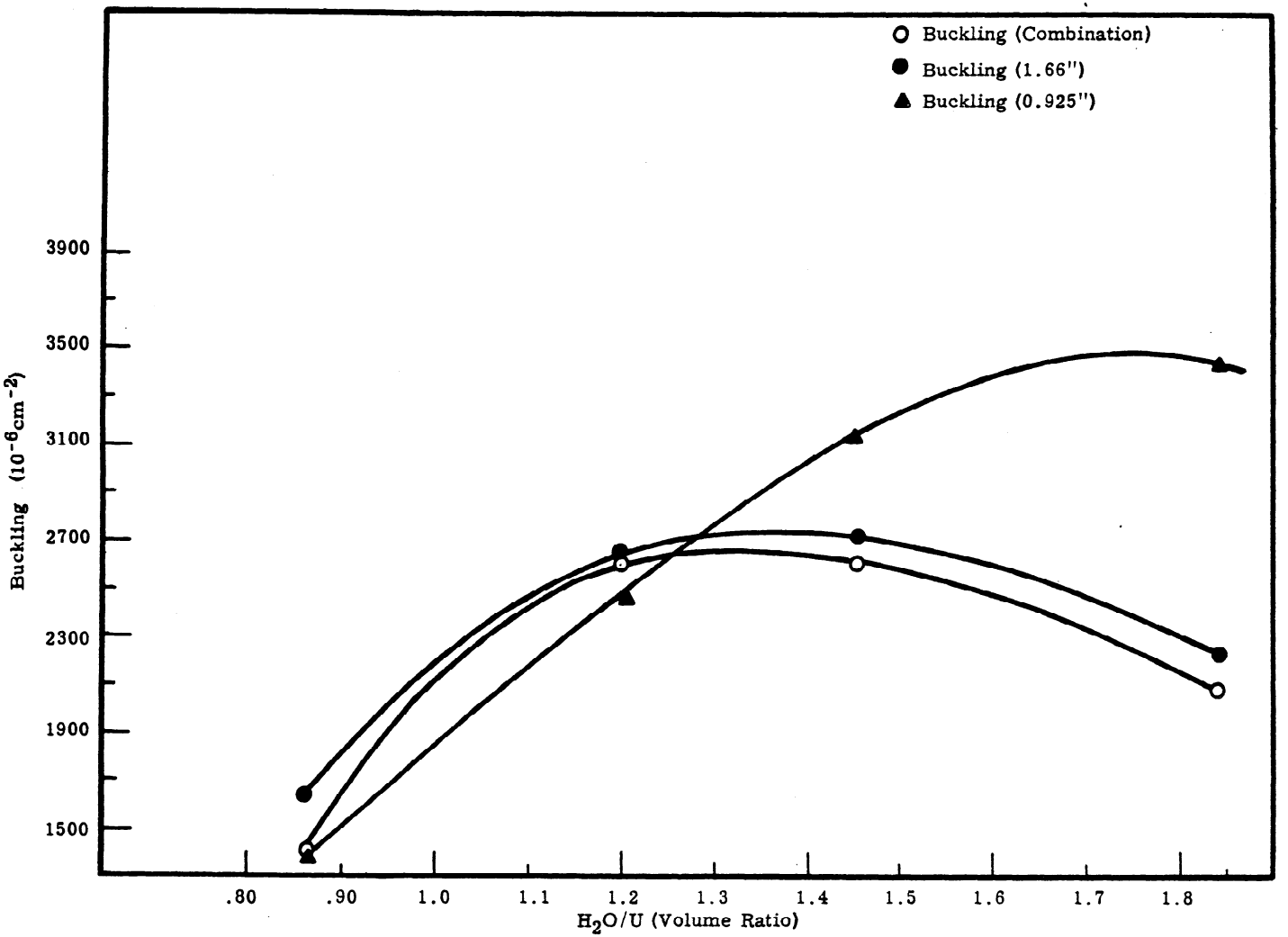
Date	Exp. No.	Lattice Spacing (inches)	No. Tubes	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol. (liters)	CM_s (lbs)
10-55	Project Bath Tub	2.20	87	.069	0.86	27.37	18.48	8.22	1639	±36	69.39	1,399	30,104
10-55	"	2.45	"	"	1.33	30.48	28.34	7.59	2747	±7	52.36	601	10,428
10-55	"	2.70	"	"	1.85	33.59	28.00	7.18	2205	±11	59.73	893	12,749



Buckling and Critical Mass vs. H_2O/U Ratio
(1.007% U-235 - 1.66" Diameter)

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM[8]
COMBINATION LATTICES OF 1.66 INCH AND 0.925 INCH DIAMETERS, 44 INCH LENGTH

Date	Exp. No.	Lattice Spacing (inches)	H_2O/U (vol)	No. Tubes .925	No. Tubes 1.66	b_{11} (cm)	λ (cm)	Combination Buckling ($10^{-6}cm^{-2}$)	1.66 inch Buckling	.925 inch Buckling
5-21-58	68	1.80	0.86	44	43	14.45	8.19	1396	1639	1377
2-6-58	49a	1.95	1.20	44	41	17.60	7.25	2524	2640	2440
1-17-58	46	2.05	1.45	44	41	18.23	6.87	2606	2700	3130
2-3-58	48	2.20	1.84	44	41	18.18	6.61	2078	2230	3440



Buckling vs. H_2O/U Ratio
(1.007% U-235 - Combination Lattices of 1.66" & 0.925" Diameters)

BUCKLING MEASUREMENTS FOR FUEL ELEMENTS IN A RANDOM ARRAY VS A UNIFORM ARRAY [6,8,9]

A series of buckling measurements had previously been taken with random arrays of fuel elements to see if such configurations would have bucklings significantly less than those resulting from a uniform distribution of fuel elements. The results of these measurements, together with the error limits, are summarized in the following table.

The average value of the measured bucklings are less in all three cases for the random arrays, but, in view of the 95 percent confidence limits predicted from the t distribution, it is not advisable to increase the safe critical mass limits for the fuel elements in a random distribution over the critical mass based on the most reactive uniform rod lattice. Large errors are inherent in the reduction of data from this type of exponential experiment because of local perturbations in the neutron flux caused by local variations in the H_2O/U volume ratio. The error limits, predicted by student t distribution, were determined by personnel of the Research and Synthesis Operation.

SUMMARY OF BUCKLING VALUES FOR FUEL ELEMENTS IN RANDOM ARRAYS

Bare Fuel Elements
1.007% Enriched
0.925-inch Diameter
4 Inches in Length

Exp. No.	H_2O/U (by volume)	Measured Buckling for Random Array	Difference from Average	95% Confidence Limits Predicted From t Distribution	Corresponding Buckling of Fuel Elements in Uniform Array (Hexagonal Lattice)
32	0.86	$-113 \times 10^{-6} cm^{-2}$	$-231 \times 10^{-6} cm^{-2}$	(Upper, Lower Limit of Buckling)	
33	0.87	-727	-845		
35	0.86	744	+626		
36	0.86	568	+450	$1166.05 \times 10^{-6} cm^{-2}$	
	Avg. 0.86	Avg. $118 \times 10^{-6} cm^{-2}$		$-979 \times 10^{-6} cm^{-2}$	$1377 \times 10^{-6} cm^{-2}$

Bare Fuel Elements
1.007% Enriched
1.66 Inches O.D., 0.94 Inches I.D.
4 Inches in Length

38	1.49	$2139 \times 10^{-6} cm^{-2}$	$+90 \times 10^{-6} cm^{-2}$		
39	1.51	2149	+100		
40	1.46	2428	+379		
41	1.47	1418	-569	$2651 \times 10^{-6} cm^{-2}$	
	Avg. 1.48	Avg. $2049 \times 10^{-6} cm^{-2}$		$1388 \times 10^{-6} cm^{-2}$	$3075 \times 10^{-6} cm^{-2}$

Aluminum Clad Fuel Elements
1.44% Enriched

Clad Dimensions	Bare Dimensions
1.47-Inch O.D., 0.37-Inch I.D.	1.37-Inch O.D., 0.48-inch I.D.
8.6 Inches in Length	8 Inches in Length

42	1.78	$3271 \times 10^{-6} cm^{-2}$	$-96 \times 10^{-6} cm^{-2}$		
43	1.78	3225	-142		
44	1.80	3785	+418		
45	1.74	3777	+410		
50	1.93	2775	-592	$3901 \times 10^{-6} cm^{-2}$	
	Avg. 1.81	Avg. $3367 \times 10^{-6} cm^{-2}$		$2798 \times 10^{-6} cm^{-2}$	$5850 \times 10^{-6} cm^{-2}$

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM

UNH (0.68%) REFLECTED ASSEMBLIES - 0.925 INCH DIAMETER
(1.5 inch lattice spacing - water moderator)

Date	Experiment	.68% U-235 - Reflector	Relaxation Length (cm)	λ(cm)
10-55	Bathtub	536 gm/l	14.7	8.10 ± .2
10-55	"	188 gm/l	14.3	7.64
10-55	"	H_2O	13.9	7.25 - BNL data

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM[5] UNH (1.007%) REFLECTED ASSEMBLIES - 0.925 INCH DIAMETER

Exp. No.	Lattice Spacing Inches	Moderator Solution gms Uranium per Liter of Water	Reflector Solution gms Uranium per Liter of Water	Reflector Thickness cm	Relaxation Length (b_1) cm	Error[(b)] in b_1 (S_{b_1}) cm	Nitric Acid Content of Uranyl Nitrate gm/Liter	Exponential Assembly Conditions
3	1.4	zero	502	43.8	13.02	0.03	50.3	1/16-inch stainless steel lattice tank
12	1.4	"	406	43.8	12.81	0.03	54.8	" "
13	1.4	"	zero	43.8	12.00	0.04	--	" "
14	1.4	"	zero	43.8	12.37	0.03	--	No stainless steel tank
4	1.5	"	495[(a)]	42.5	14.22	0.04	50	1/16-inch stainless steel lattice tank
5	1.5	"	zero	42.5	13.07	0.03	--	" "
6	1.5	"	486	12.0	14.11	0.04	50.3	" "
7	1.5	"	490	22.2	14.31	0.03	50.3	" "
8	1.5	"	406	22.2	14.05	0.04	41.0	" "
9	1.5	"	203	22.2	13.58	0.04	16.2	" "
10	1.5	"	203	42.5	13.36	0.05	37.6	" "
11	1.5	"	406	42.5	13.90	0.04	45.3	" "
21	1.5	"	179	12.0	13.44	0.05	34.7	" "

(a) Estimated from values for experiments 3 and 6.

(b) The degrees of freedom for all experiments are four.

Exp. No.	Lattice Spacing inches	Moderator Solution gms Uranium per Liter of Water	Reflector Solution gms Uranium per Liter of Water	Reflector Thickness cm	Relaxation Length (b_1) cm	Error[b] in b_1 (S_{b_1}) cm	Nitric Acid Content of Uranyl Nitrate gm/liter	Exponential Assembly Conditions
23	1.5	431	zero	12.0	11.19	0.03	18.7	1/16-inch stainless steel lattice tank
2	1.6	zero	526	41.3	15.20	0.08	61.4	" "
16	1.6	zero	405	41.3	14.92	0.02	47.8	" "
17	1.6	zero	zero	41.3	13.93	0.03	--	" "
18	1.6	zero	zero	41.3	13.57	0.04	--	3/16-inch stainless steel lattice tank
19	1.6	zero	zero	41.3	14.46	0.07	--	No stainless steel tank
22	1.6	zero	zero	41.3	14.44	0.06	--	" "

(b) The degrees of freedom for all experiments are four.

Cylindrical radii of lattice cores: 1.4-inch lattice 17.21 cm, 1.5-inch lattice 18.44 cm, 1.6-inch lattice 19.67 cm.

EFFECTIVE URANYL-NITRATE REFLECTOR SAVINGS VS. URANIUM CONCENTRATION(a)

Experiment Number	Reflector Concentration Grams Uranium Per Liter of Water	Reflector Thickness (cm)	Reflector Savings (cm)(b)
9	203	22.20	7.18
8	406	22.20	7.72
7	490	22.20	8.01
21	179	12.04	7.08
6	486	12.04	7.78
5	H_2O	47.52	6.58(c)

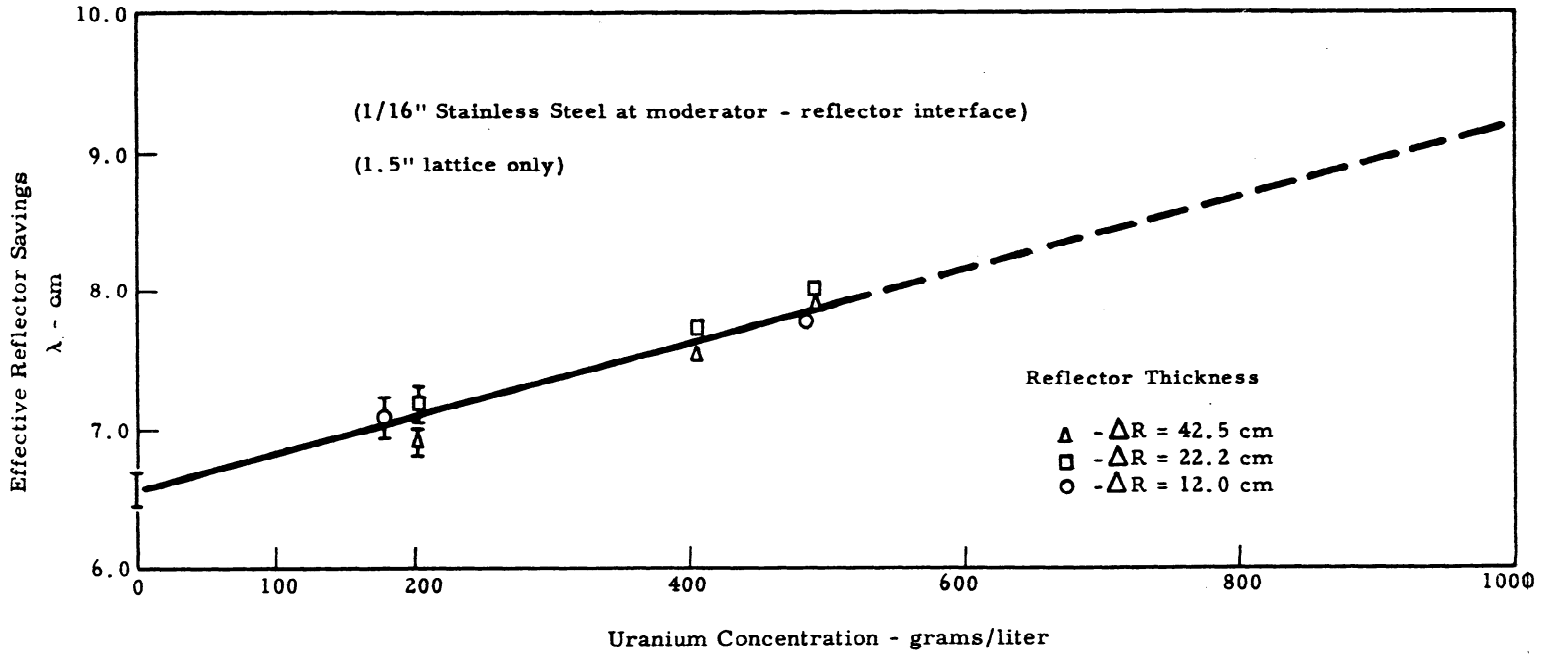
(a) Data are plotted in figure following.

Lattice spacing for all experiments is 1.5 inches and

$B_m^2 = 3386 \times 10^{-6} cm^{-2}$

(b) Reflector savings uncertainties 0.1 to 0.25 cm.

(c) Same for all three reflector thicknesses.



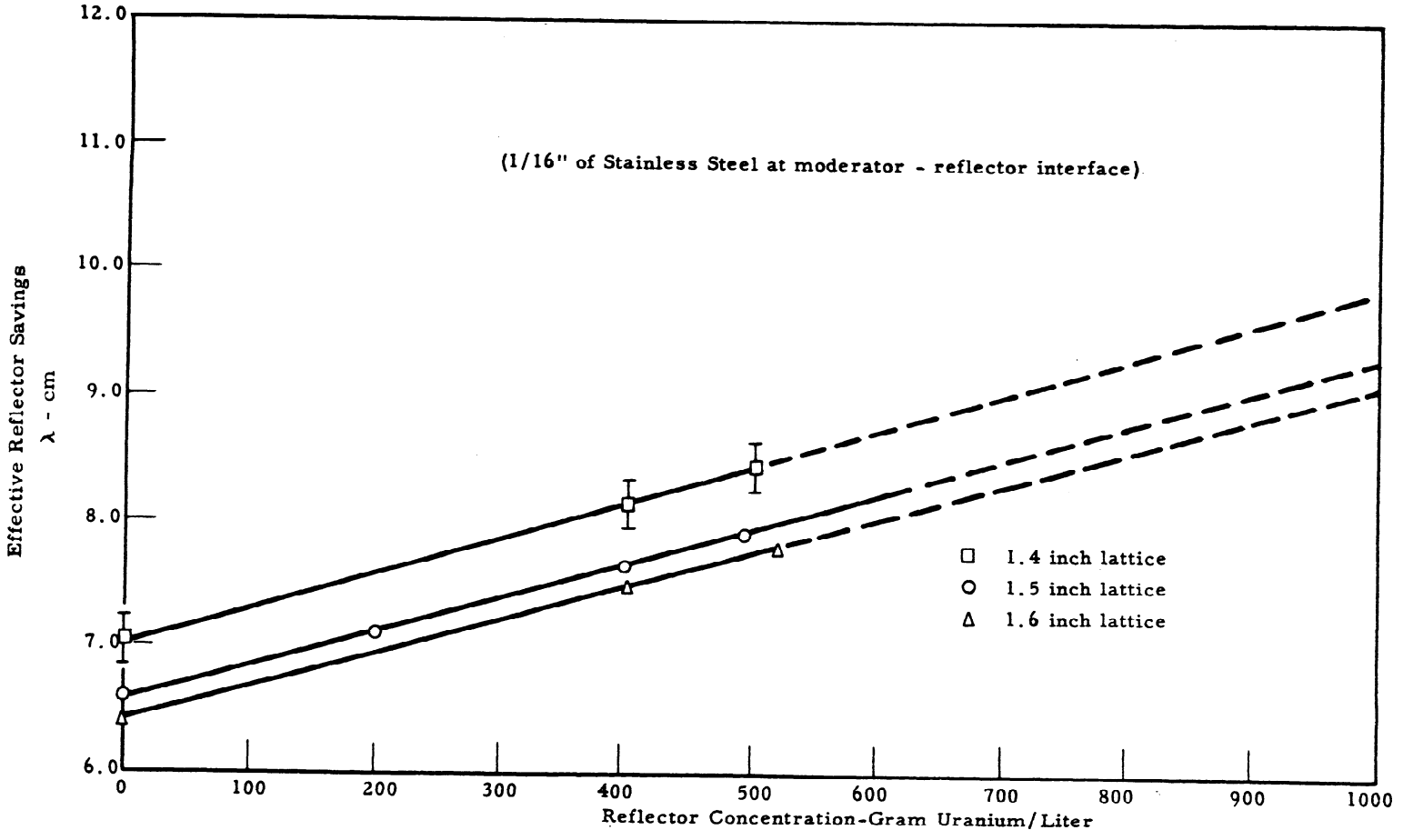
Effective Uranyl-Nitrate Reflector Savings vs Uranium Concentration
for Reflector Thicknesses 12.0, 22.2, 42.5 cm

EFFECTIVE[(a)] URANYL NITRATE REFLECTOR SAVINGS VS. URANIUM CONCENTRATION[(b)]

Experiment Number	Lattice Spacing Inches	Reflector Concentration Gram of Uranium per Liter of Water	Reflector Thickness (cm)	$\lambda + R$ (cm)	λ_{UNH}	Miscellaneous
13	1.4	zero	43.75	24.24	7.03	B_m^2 = 2869 μb
12	1.4	406	43.75	25.36	8.15	R = 17.21 cm
3	1.4	502	43.75	25.64	8.43	
5	1.5	zero	42.52	25.02	6.58	B_m^2 = 3386 μb
10	1.5	203	42.52	25.37	6.93	R= 18.44 cm
11	1.5	406	42.52	25.99	7.55	
4	1.5	495	42.52	26.35	7.91	
17	1.6	zero	41.29	26.11	6.43	B_m^2 = 3336 μb
16	1.6	405	41.29	27.19	7.52	R= 19.67 cm
2	1.6	526	41.29	27.48	7.81	

(a) These data are plotted in figure following.

(b) These are effective values, due to the stainless steel at moderator-reflector interface.



Effective Uranyl Nitrate Reflector Savings
vs Uranium Concentration

EXPONENTIAL MEASUREMENTS OF 1.007 PERCENT ENRICHED URANIUM[3,4]
COMPARISON OF AIR AND WATER REFLECTOR

(1.55" lattice, .925" diameter, 44" length, $H_2O/U = 1.94$)

Date	Condition	b_{11}(cm)	λ(cm)
11-55	H_2O Reflector - 1/8" Al Tank	14.6	7.14
11-55	H_2O Reflector - Cd cover tank	12.7	
11-55	No Reflector - Cd cover tank	11.6	3.4 ± 0.2

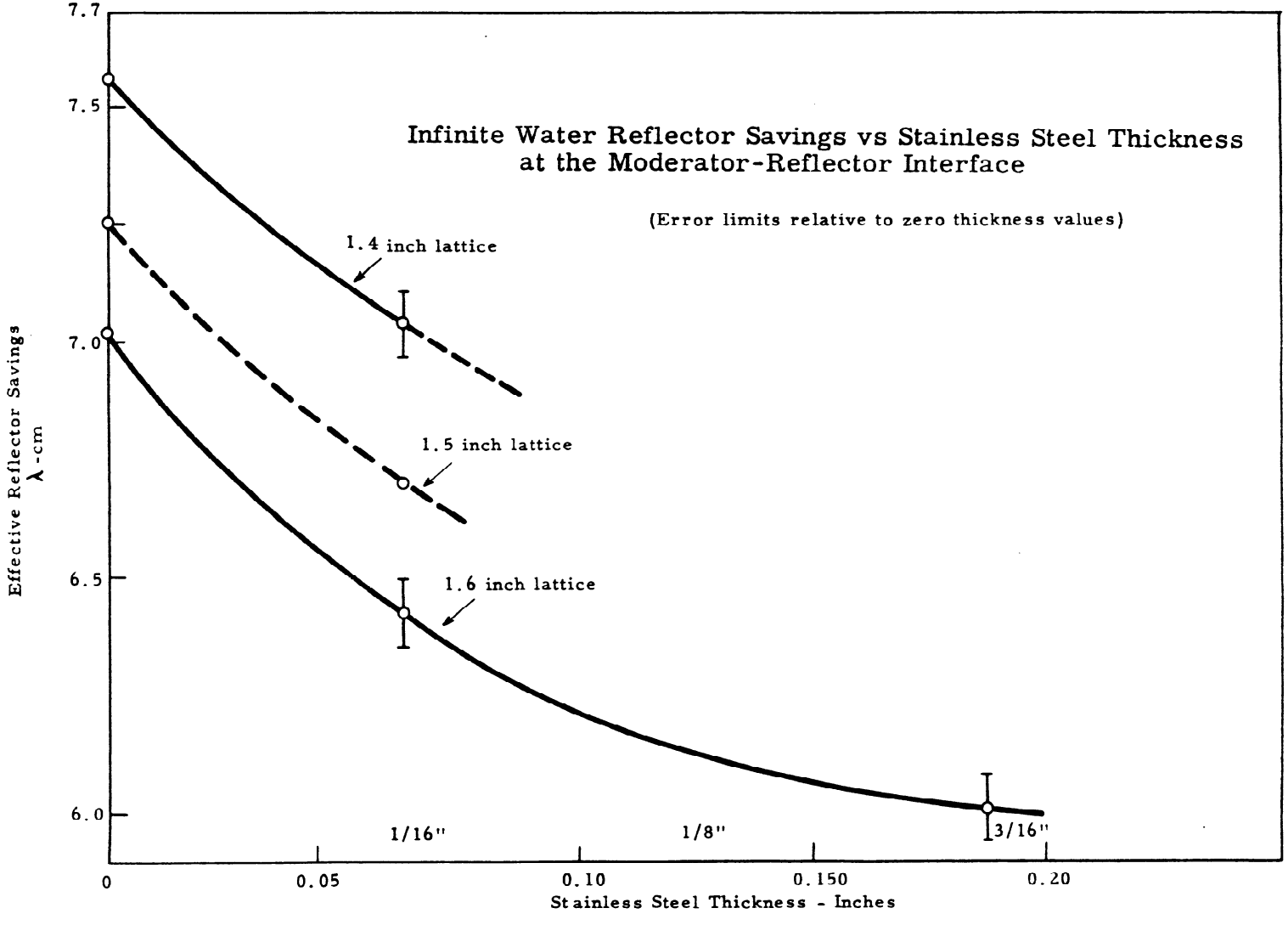
INFINITE WATER REFLECTOR SAVINGS VS. STAINLESS STEEL THICKNESS AT THE MODERATOR - REFLECTOR INTERFACE

Experiment Number	Lattice Spacing (inches)	Stainless Steel Thickness (inches)	Reflector Savings λ (cm)	Standard Error in S_λ (cm)
14	1.4	0	7.56	0.05 to 0.25[a]
13	1.4	1/16	7.04	0.1 to 0.25
19 and 22	1.6	0	7.02	0.05 to 0.25[a]
17	1.6	1/16	6.43	0.1 to 0.25
18	1.6	3/16	6.01	0.1 to 0.25
x[b]	1.5	0	7.25	0.05 to 0.25[a]
5	1.5	1/16	6.70[c]	

(a) Zero thickness-Stainless steel reflector savings and errors obtained from BNL data.

(b) Experiment not done.

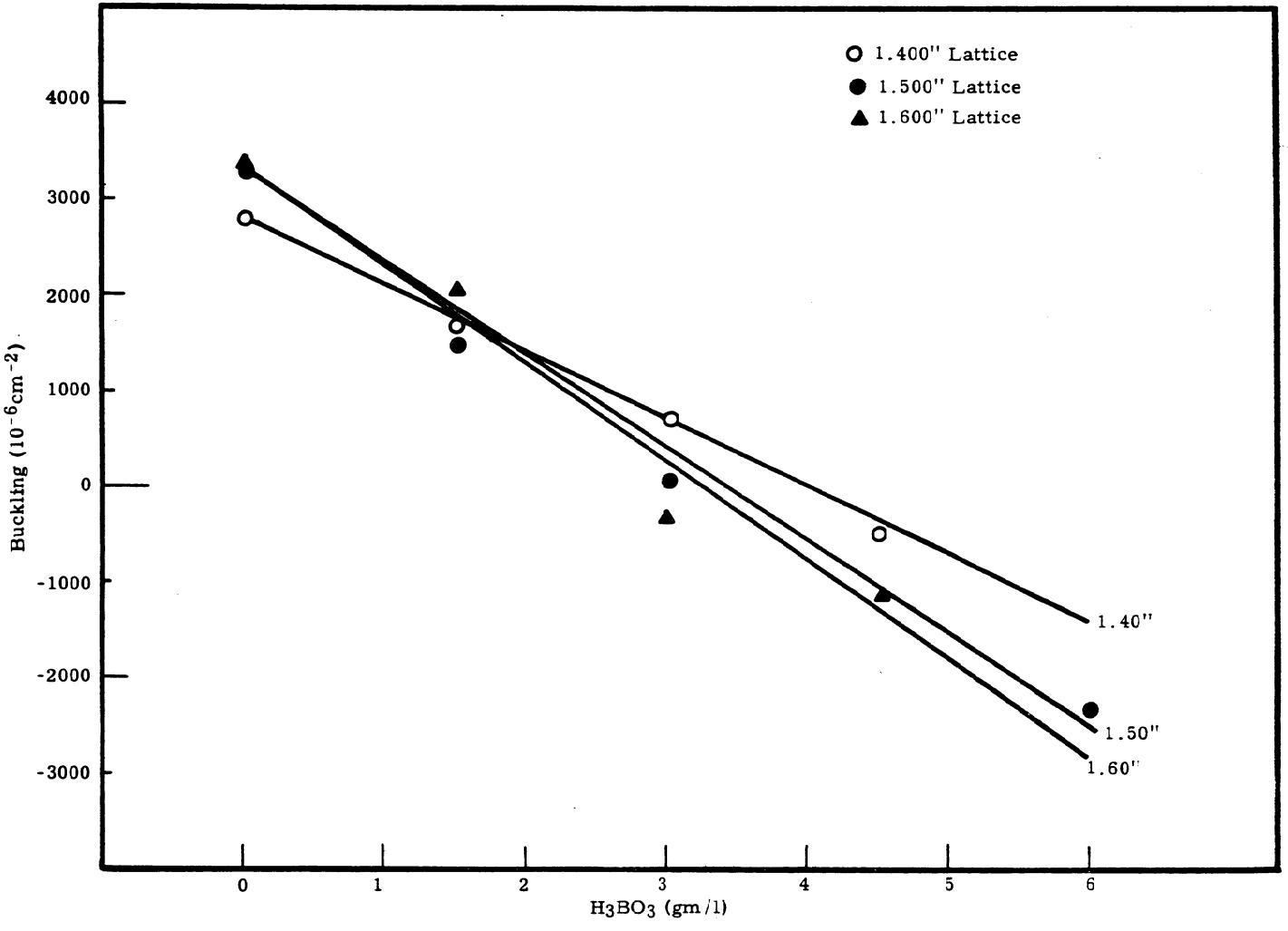
(c) Determined by linear interpolation between 1.4-inch and 1.6-inch lattices values.


Infinite Water Reflector Savings vs Stainless Steel Thickness
at the Moderator-Reflector Interface
(Error limits relative to zero thickness values)
1.4 inch lattice
1.5 inch lattice
1.6 inch lattice
Effective Reflector Savings
λ -cm
7.7
7.5
7.0
6.5
6.0
1/16"
1/8"
3/16"
0
0.05
0.10
0.150
0.20
Stainless Steel Thickness - Inches

EXPONENTIAL MEASUREMENT OF 1.007 PERCENT ENRICHED URANIUM WITH BORON POISONED MODERATOR
(0.925 inch Diameter, 44 inches Length)

Date	Exp. No.	Lattice Spacing (inches)	H_2O/U (volume)	Al/U (volume)	No. Tubes	R_{eff} (cm)	H_3BO_3 (gm/l)	Boron (gm/l)	b_{11} (cm)	λ^* (cm)	Buckling ($10^{-6}cm^{-2}$)	H_3BO_3 at $B^2 = 0$ (gm/l)
3-60	104	1.400	1.37	0.157	85	17.21	0	0	11.84	6.92	2794	
4-60	105	"	"	"	"	"	1.5	.26	10.99	"	1643	
4-60	106	"	"	"	"	"	3.0	.53	10.39	"	663	4.0 ± 0.3
4-60	107	"	"	"	"	"	4.5	.79	9.90	"	-269	
9-59	85, 86	1.500	1.74	"	"	18.44	0	0	13.03	6.65	3294	
9-59	89	"	"	"	"	"	1.5	.26	11.41	"	1502	
9-59	87	"	"	"	"	"	3.0	.53	10.49	"	97	3.4 ± 0.5
9-59	88	"	"	"	"	"	6.0	1.06	9.33	"	-2303	
12-59	97	1.600	2.15	"	"	19.67	0	0	13.94	6.43	3341	
2-60	98	"	"	"	"	"	1.5	.26	12.47	"	2061	
2-60	99	"	"	"	"	"	3.0	.53	10.66	"	-313	3.2 ± 0.5
3-60	100	"	"	"	"	"	4.5	.79	10.18	"	-1162	

*BNL-C-7592 values multiply by 0.916 to correct for 1/16" small stainless steel tank at the moderator-reflector interface.

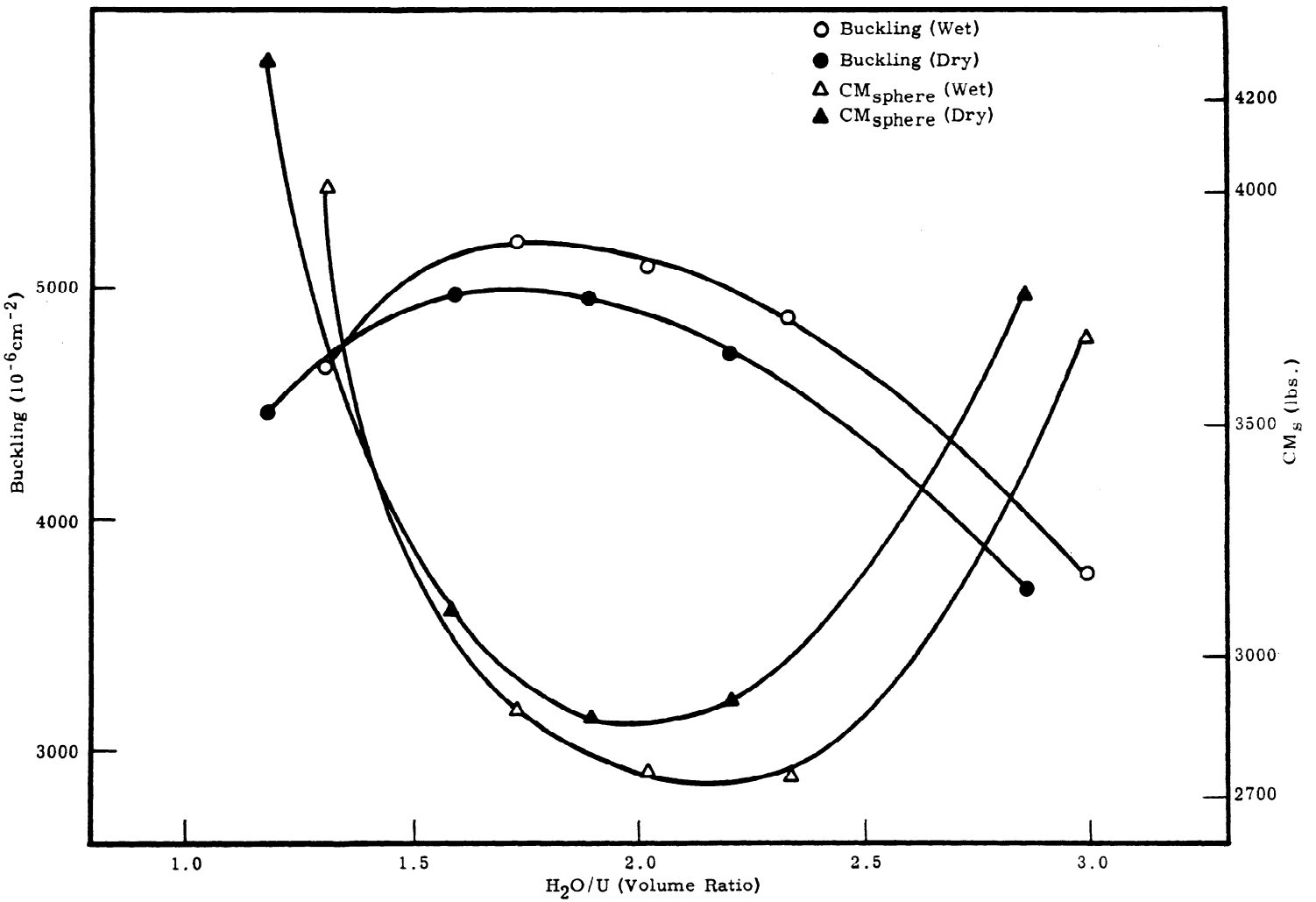


Buckling of 1.007 Per Cent Enriched Uranium vs. H_3BO_3 (gm/l) in Moderator

EXPONENTIAL MEASUREMENTS OF 1.25 PER CENT ENRICHED URANIUM[10]

1.336" O.D. 0.500" I.D.

Date	Exp. No.	Lattice Spacing (inches)	h (cm)	No. Tubes	Fuel Core Cond.	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (Liters)	CM_s (lbs)
3-59	84	1.85	114.14	55	Wet	.125	1.31	18.30	15.91	7.63	4650	± 19	38.44	238	4004
4-59	85	"	"	"	"	.125	1.31	"	15.90	"	4645	± 19	38.47	238	4011
3-59	83	"	"	"	Dry	.100	1.18	"	15.70	7.77	4450	± 35	39.33	255	4286
1-59	78	2.00	"	"	Wet	.125	1.73	19.78	19.26	7.29	5196	± 14	36.29	200	2883
1-59	79	"	"	"	Dry	.100	1.59	"	18.66	7.38	4969	± 23	37.19	215	3101
12-58	74	2.10	101.60	"	Wet	.125	2.02	20.77	20.93	7.115	5152	± 22	36.65	206	2641
1-59	75	"	114.14	"	"	.125	2.02	"	20.66	7.115	5092	± 3	36.91	211	2750
1-59	80	"	"	"	Dry	.100	1.89	"	20.24	7.19	4957	± 9	37.43	220	2868
11-58	72	2.20	101.60	"	Wet	.125	2.33	21.76	21.05	6.96	4755	± 68	38.60	241	2810
1-59	76	"	114.14	"	"	.125	2.33	"	21.63	6.96	4874	± 13	38.04	231	2743
2-59	81	"	"	"	Dry	.100	2.20	"	20.97	7.02	4709	± 10	38.76	244	2902
11-58	73	2.40	101.60	"	Wet	.125	2.99	23.74	19.72	6.72	3661	± 9	45.20	387	3792
1-59	77	"	114.14	"	"	.125	2.99	"	20.10	6.72	3757	± 10	44.53	370	3698
3-59	82	"	"	"	Dry	.100	2.86	"	19.92	6.76	3696	± 10	44.92	380	3794

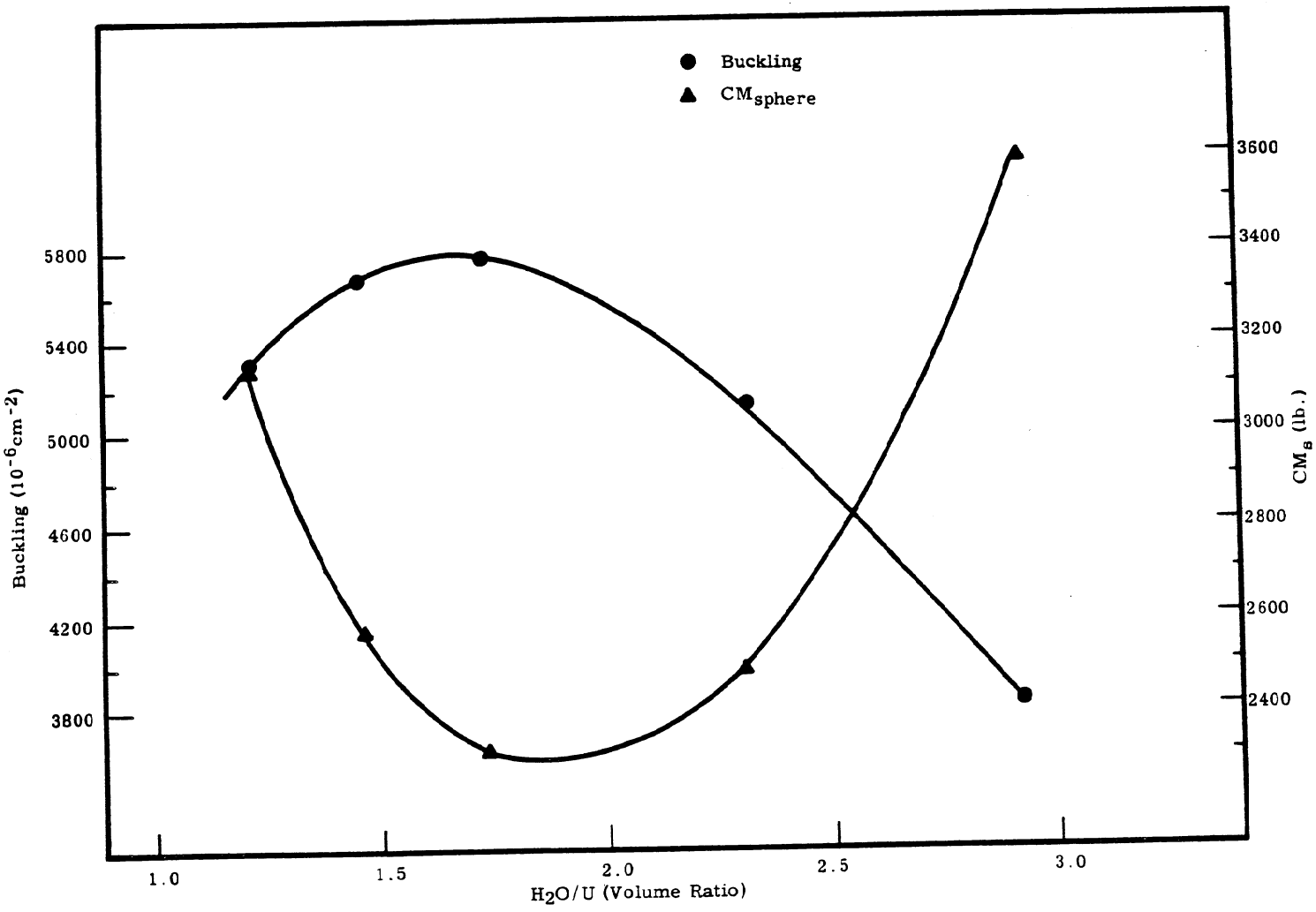


Buckling and Critical Mass vs. H_2O/U Ratio
(1.25% U-235 - 1.336" O.D. -
0.500" I.D.)

EXPONENTIAL MEASUREMENTS OF 1.44 PERCENT ENRICHED URANIUM[7]

1.336" diameter, 32" length

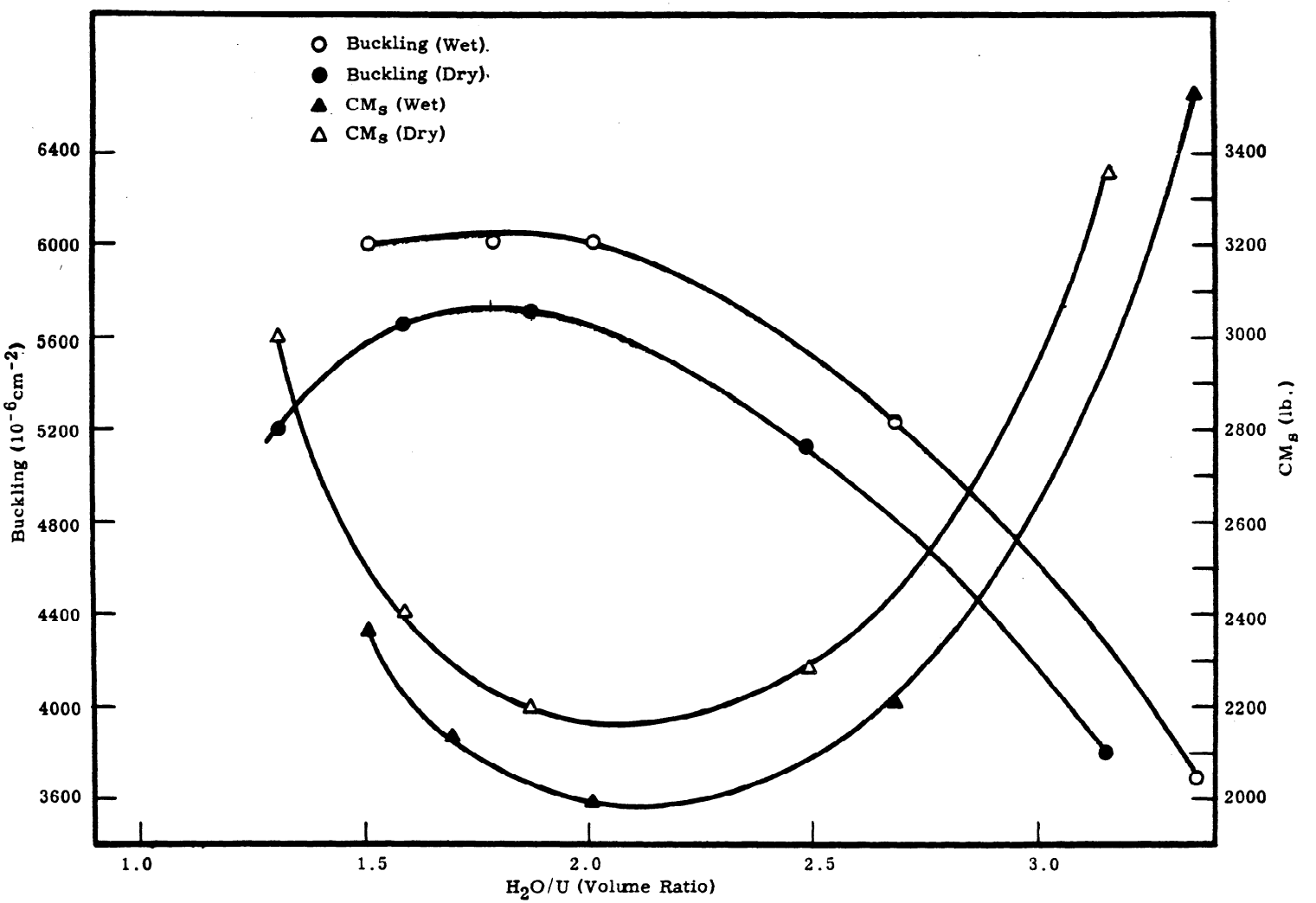
Date	Exp. No.	Lattice Spacing Inches	No. Tubes	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling (10^{-6} cm^{-2})	Std. Error	R_s (cm)	Vol_s (liters)	CM_s (lbs)
7-56	33-6	2.00	49	0.159	1.21	18.67	18.23	7.72	5294	±21	35.456	187	3148
6-56	33-4	2.10	52	"	1.46	20.20	21.21	7.45	5678	±27	34.243	168	2573
7-56	33-9	2.20	49	"	1.73	20.54	24.15	7.25	5774	±3	34.095	166	2314
7-56	33-7	2.40	49	"	2.30	22.40	25.01	6.95	5115	±5	36.977	212	2480
7-56	33-5	2.60	49	"	2.92	24.27	21.30	6.72	3818	±10	44.122	360	3590



Buckling and Critical Mass vs. H_2O/U Ratio
(1.44% U-235 - 1.336 Diameter)

EXPONENTIAL MEASUREMENTS OF 1.44 PERCENT ENRICHED URANIUM[11,12]
1.37 O.D., 0.48" I.D.

Date	Exp. No.	Lattice Spacing Inches	h (cm)	No. Tubes	Fuel Core Cond.	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (liters)	CM_s (Lbs)
4-56	32-6	2.00	101.60	49	Wet	0.172	1.51	18.67	20.28	7.44	6006	± 7	33.10	152	2364
4-56	32-1	2.00	81.28	"	Dry	"	1.31	18.67	17.76	7.61	5203	± 5	35.94	195	3025
4-56	32-7	2.10	101.60	"	Wet	"	1.79	19.60	22.72	7.23	6097	± 7	33.01	151	2126
4-56	32-10	2.10	"	"	Dry	"	1.59	19.60	21.10 21.09	7.37	5656	± 6	34.40	171	2407
4-56	32-5	2.20	"	45	Wet	"	2.07	19.68	22.18	7.07	6048	± 7	33.33	155	1994
4-56	32-2	2.20	"	"	Dry	"	1.87	19.68	20.79	7.17	5708	± 6	34.41	171	2195
4-56	32-4	2.40	"	49	Wet	"	2.69	22.40	25.49	6.81	5237	± 6	36.60	205	2219
4-56	32-3	2.40	"	43	Dry	"	2.49	20.99	20.81	6.89	5131	± 14	36.97	212	2286
4-56	32-8	2.60	"	49	Wet	"	3.36	24.27	20.57	6.63	3696	± 8	45.05	383	3525
4-56	32-9	2.60	"	"	Dry	"	3.16	24.27	21.09	6.66	3797	± 15	44.33	365	3358



Buckling and Critical Mass vs. H_2O/U Ratio
(1.44% U-235 - 1.37" O.D. - 0.48" I.D.)

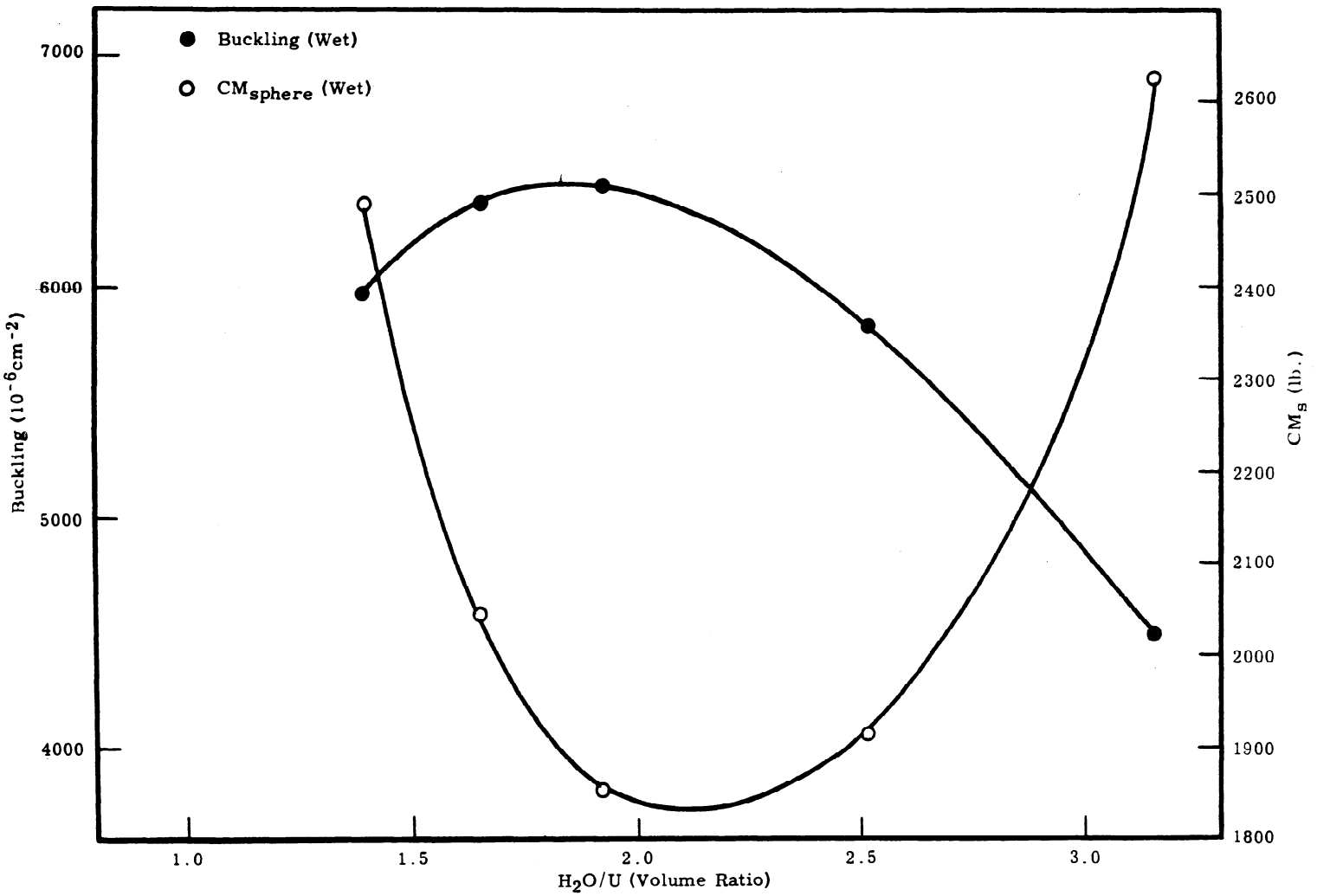
EXPONENTIAL MEASUREMENTS OF 1.44 PER CENT ENRICHED URANIUM[12]

Bismuth in Core of 1.37" O.D. 0.48" I.D., 40" Length

Date	Exp. No.	Lattice Spacing (inches)	No. Tubes	Fuel Core Cond.	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (Liters)	CM_s (lbs)
11-56	32-16	2.00	49	Dry	.173	1.312	18.67	18.06	7.61	5308	± 8	35.51	187.5	2917
11-56	32-15	2.00	49	Bi	"	1.312	18.67	17.90	7.61	5253	± 12	35.74	191.2	2974
11-56	32-14	2.20	45	Bi	"	1.875	19.68	20.96	7.17	5746	± 8	34.28	168.7	2169
11-56	32-13	2.20	49	Bi	"	1.875	20.54	23.56	7.17	5730	± 5	34.33	169.5	2179
11-56	32-12	2.20	49	Dry	"	1.875	20.54	23.63	7.17	5741	± 5	34.29	168.9	2172

EXPONENTIAL MEASUREMENTS OF 1.466 PERCENT ENRICHED URANIUM[13]
1.394" O.D., 0.464" I.D., 40" Length

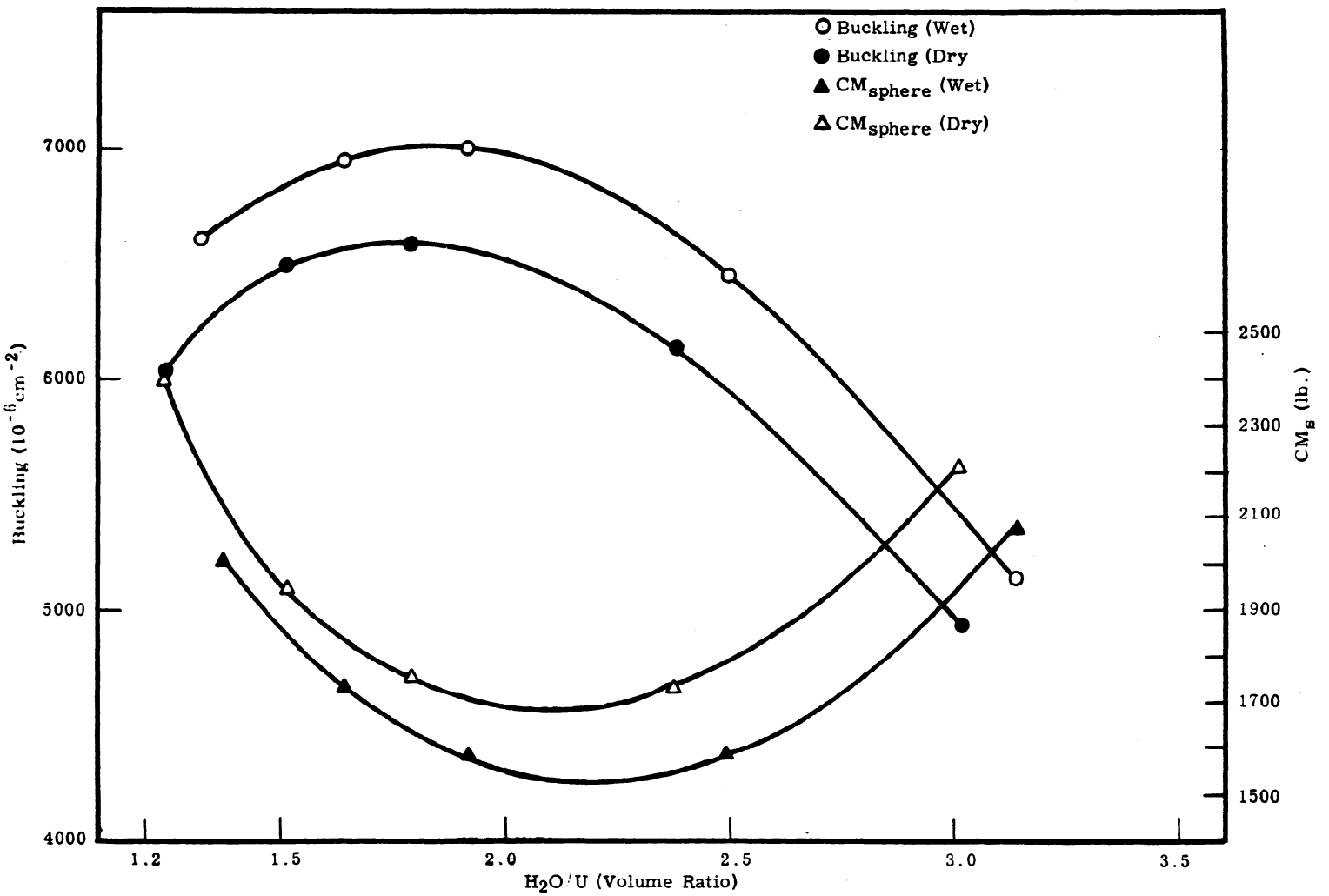
Date	Exp. No.	Lattice Spacing Inches	No. Tubes	Fuel Core Cond.	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (liters)	CM_s (lbs)
4-57	37-7	2.00	49	Wet	0.172	1.39	18.67	20.29	7.52	6003	± 14	33.03	151	2464
4-57	37-6	2.00	31	"	"	"	14.85	13.27	"	5876	± 20	33.46	157	2563
4-57	37-5	2.00	43	"	"	"	17.49	17.38	"	5936	± 10	33.26	154	2515
4-57	37-4	2.00	55	"	"	"	19.78	23.65	"	5971	± 4	33.14	152	2488
5-57	37-14	2.10	55	"	"	1.65	20.77	32.13	7.32	6360	± 5	32.07	138	2046
4-57	37-3	2.20	31	"	"	1.92	16.34	15.32	7.14	6229	± 15	32.66	146	1969
3-57	37-2	2.20	43	"	"	"	19.24	22.35	"	6307	± 3	32.42	143	1925
3-57	37-2	2.20	55	"	"	"	21.76	45.38	"	6438	± 3	32.01	137	1854
5-57	37-13	2.40	49	"	"	2.51	22.40	29.30	6.86	5590	± 6	35.16	182	2064
5-57	37-12	2.40	43	"	"	"	20.99	23.63	"	5666	± 7	34.88	178	2014
5-57	37-11	2.40	55	"	"	"	23.74	53.62	"	5828	± 4	34.29	169	1915
5-57	37-10	2.60	31	"	"	3.15	19.31	15.32	6.67	4306	± 19	41.21	293	2831
4-57	37-9	2.60	43	"	"	"	22.74	20.46	"	4296	± 12	41.26	294	2843
4-57	37-8	2.60	55	"	"	"	25.71	31.31	"	4495	± 21	40.19	272	2626



Buckling and Critical Mass vs. H_2O/U Ratio
(1.466% U-235 - 1.394" O.D. - 0.464" I.D.)

EXPONENTIAL MEASUREMENTS OF 1.6 PERCENT ENRICHED URANIUM[14]
1.394" O.D., 0.464" I.D., 40" Length

Date	Exp. No.	Lattice Spacing (inches)	No. Tubes	Fuel Core Cond.	Al/U (vol)	H_2O/U (vol)	R_{eff} (cm)	b_{11} (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	Std. Error	R_s (cm)	Vol_s (liters)	CM_s (lbs)
3-58	58	2.00	43	Wet	.165	1.375	17.49	19.49	7.53	6605	± 7	31.13	126	2055
4-58	59	2.00	43	Dry	"	1.25	17.49	17.91	7.65	6033	± 14	32.80	148	2405
3-58	54	2.10	43	Wet	"	1.637	18.36	23.52	7.35	6941	± 4	30.36	117	1730
3-58	53	2.10	43	Dry	"	1.512	18.36	21.33	7.45	6483	± 10	31.57	132	1945
3-58	55	2.20	43	Wet	"	1.91	19.24	27.62	7.14	7000	± 7	30.41	118	1584
3-58	51	2.20	31	Dry	"	1.79	16.34	16.21	7.25	6587	± 45	31.46	130	1754
6-58	69	2.20	55	"	"	1.79	21.76	59.81	7.25	6592	± 4	31.44	130	1751
3-58	52	2.20	43	"	"	1.79	19.24	24.59	7.25	6587	± 13	31.46	130	1754
3-58	56	2.40	43	Wet	"	2.497	20.99	31.70	6.88	6450	± 4	32.24	140	1586
4-58	61	2.40	43	Dry	"	2.373	20.99	27.92	6.93	6136	± 10	33.18	153	1728
3-58	57	2.60	43	Wet	"	3.135	22.74	25.35	6.68	5125	± 10	37.21	216	2078
4-58	60	2.60	43	Dry	"	3.011	22.74	24.00	6.70	4937	± 2	38.01	230	2216



Buckling and Critical Mass vs. H_2O/U Ratio
(1.6% U-235 - 1.394" O.D. - 0.464" I.D.)

CRITICAL APPROACH MEASUREMENTS OF 1.6 PER CENT ENRICHED URANIUM[15]

(1.394" O.D., 0.464" I.D., 40" Length)

Date	Exp. No.	Lattice Spacing (inches)	H_2O/U (vol)	Ext. N Tubes	CM cyl. (lbs)	R_c (cm)	λ (cm)	Buckling ($10^{-6}cm^{-2}$)	R_s (cm)	Vol_s (liters)	CM_s (lbs)
7-58	0-1	2.20	1.91	60.58 ± .86	2221 ± 32	22.745	7.14	7210	29.858	111.5	1499
7-58	0-1a	2.20	1.91	59.09 ± .12	2183 ± 44	22.553	7.14	7294	29.644	109.1	1468
6-58	0-2	2.20	1.79	68.08 ± .78	2516 ± 29	24.208	7.25	6576	31.491	130.8	1759
6-58	0-2a	2.20	1.79	64.21 ± .47	2373 ± 17	23.510	7.25	6844	30.724	121.5	1634
6-58	0-3	2.40	2.50	57.43 ± 1.85	2122 ± 68	24.255	6.88	6707	31.480	130.7	1476
6-58	0-3a	2.40	2.50	58.11 ± 0.47	2147 ± 17	24.398	6.88	6653	31.636	132.6	1499
6-58	0-4	2.40	2.37	64.86 ± .38	2397 ± 14	25.776	6.93	6147	33.141	152.4	1723
6-58	0-4a	2.40	2.37	62.31 ± 1.2	2302 ± 44	25.265	6.93	6320	32.589	145.0	1638

The Al/U Volume Ratio for all above exp. was .165.

Type of plot to get Ext. N was N/CR.

Poison corrections were calculated for exp. 0-1. These amounted to 0.48 rod so were not made for others.

Exp. No. with (a) denotes back off, the others are approach measurements.

Variation in H_2O/U for the same lattice spacing is due to dry or wet center core.

EXPONENTIAL MEASUREMENTS OF 3.063 PER CENT ENRICHED URANIUM[17,18,19,20,21,22]

Date	Exp. No.	Slug Dia. (inches)	Lattice Spacing (inches)	H_2O/U (volume)	Height, h (cm)	No. Tubes	R_{eff} (cm)	Relaxation Length, b_{11} (cm)
11-58	12-c	0.925	1.950	3.89	81.28	31	14.48	23.67
11-58	12-b	"	"	"	60.96	"	"	24.91
6-59	42	0.600	1.000	2.06	81.28	97	13.13	39.24
6-59	44	"	1.100	2.71	"	73	12.53	30.40
7-59	46	"	1.200	3.41	"	67	13.10	35.66
7-59	47	"	1.300	4.18	"	61	13.54	35.07
7-59	50	"	1.420	5.18	"	61	14.79	41.10
7-59	52	"	1.600	6.84	"	65	17.20	37.87
3-59	21	0.300	0.500	2.06	81.28	289-1	11.34	15.88
5-59	35	"	0.600	3.41	"	253-1	12.73	43.87
4-59	23	"	0.700	5.00	"	187	12.77	32.38
4-59	25	"	0.800	6.84	"	163	13.62	31.58
5-59	27	"	0.900	8.92	"	163	15.32	35.08
12-59	71	0.175	0.300	2.24	59.69	781-1	11.18	14.01
1-60	74	"	0.375	4.06	"	611-1	12.86	38.40
10-59	61	"	0.450	6.29	"	433-1	12.49	24.27
10-59	57	"	0.500	8.00	"	279-1	12.98	23.00
10-59	59	"	0.550	9.89	"	379	14.28	27.17
10-59	63	"	0.600	11.96	"	379	15.58	28.18

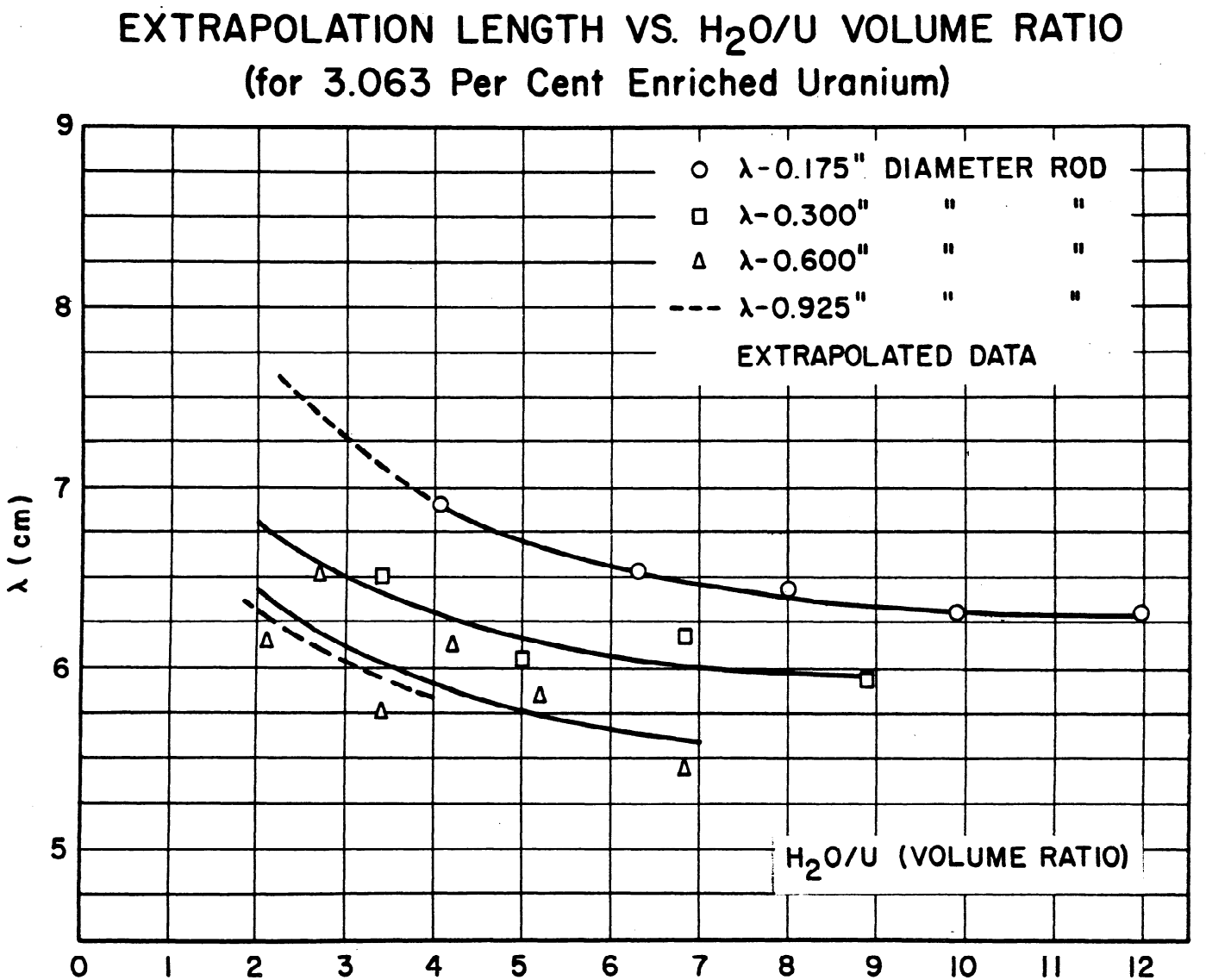
CRITICAL APPROACH MEASUREMENTS OF 3.063 PERCENT ENRICHED URANIUM[17,18,19,20,21,22]

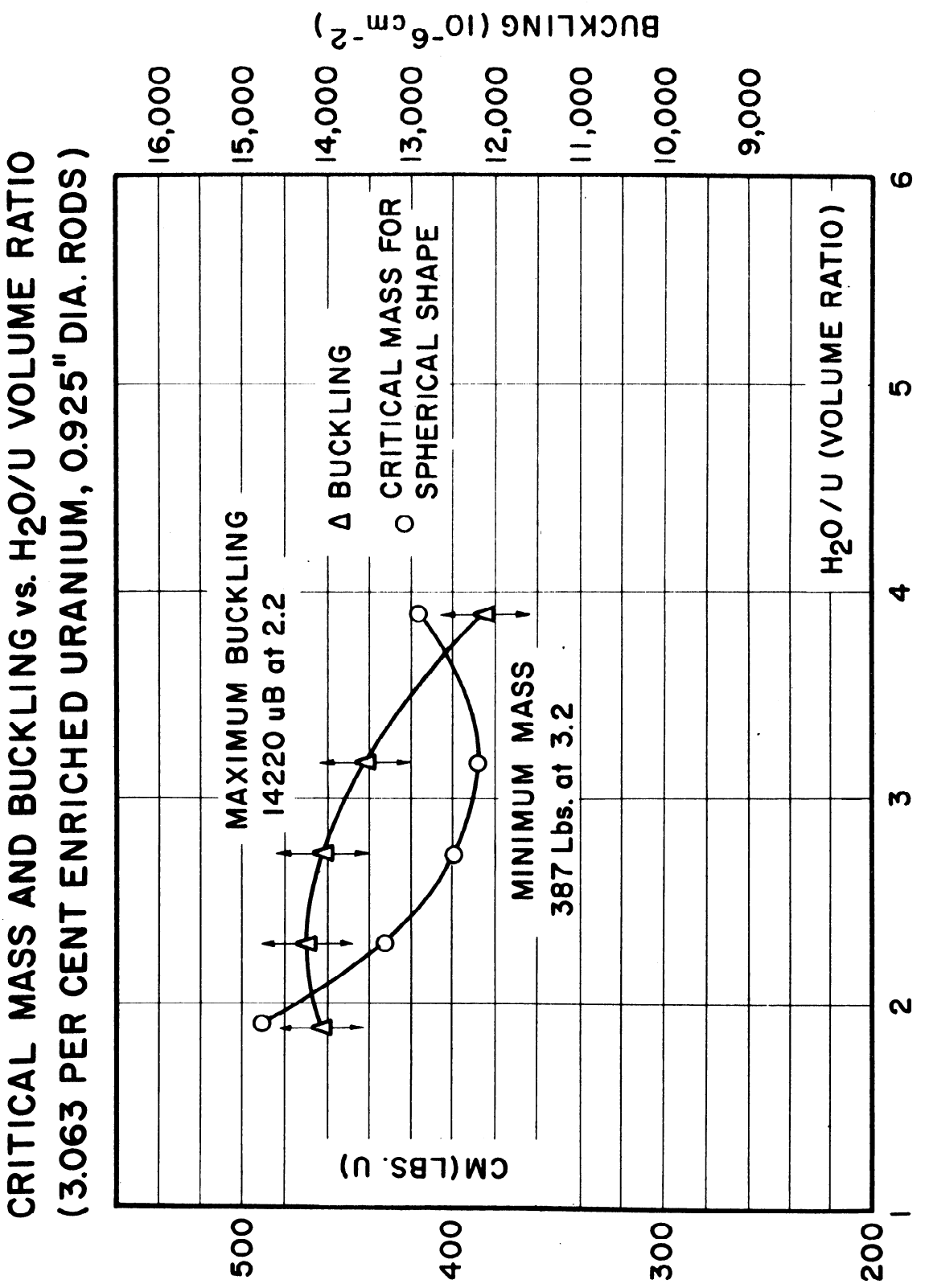
Date	Exp. No.	Slug Dia. (inches)	Lattice Spacing (inches)	h (cm)	H_2O/U (vol)	N_c (1) (rods)	R_c (cm)	C.M. Cylinder (lb)	λ (2) (cm)	Buckling ($10^{-6}cm^{-2}$)	C.M. Sphere (lb)
9-58	8	0.925	1.500	40.64	1.89	72.08	16.98	530.7	6.37	14068	497
7-58	2	"	"	60.96	"	60.0	15.50	662.6			
8-58	4	"	1.600	40.64	2.29	63.5	17.01	467.6	6.23	14212	437
7-58	3	"	"	60.96	"	52.4	15.45	578.8			
8-58	5	"	1.700	40.64	2.72	58.6	17.35	431.3	6.12	14027	403
7-58	1	"	"	60.96	"	49.2	15.90	543.1			
9-58	6	"	1.800	40.64	3.17	56.7	18.08	417.6	6.00	13536	392
9-58	7	"	"	60.96	"	46.9	16.44	518.1			
10-58	11	"	1.950	40.64	3.89	60.4	20.21	444.7	5.86	12108	421
11-58	12a	"	"	60.96	"	48.6	18.13	536.8			
12-58	15	0.600	1.000	40.64	2.06	152.1	16.45	471.2	6.16	14834	433
6-59	41	"	"	81.28	"	114.9	14.30	711.9			
10-58	10	"	1.100	40.64	2.71	118.6	15.97	367.4	6.52	14855	337
6-59	43	"	"	81.28	"	91.2	14.01	564.8			
9-58	9	"	1.200	40.64	3.41	104.5	16.36	323.7	5.77	15435	295
7-29	45	"	"	81.28	"	79.9	14.30	494.9			
12-58	13	"	1.300	40.64	4.18	98.9	17.24	306.4	6.13	14115	283
7-59	48	"	"	81.28	"	74.1	14.92	458.8			
12-58	14	"	1.420	40.64	5.18	100.3	18.97	310.7	5.86	12984	290
7-59	49	"	"	81.28	"	73.8	16.27	457.1			
12-58	16	"	1.600	40.64	6.84	122.0	23.57	378.0	5.46	10576	353
7-59	51	"	"	81.28	"	82.4	19.37	510.4			
3) 3-59	21	0.300	0.500	81.28	2.06	624	16.7	964	6.80	13607	465
2-59	19	"	0.600	40.64	3.41	387.5	15.75	299.2	6.51	15098	274
5-59	33	"	"	81.28	"	298.1	13.82	460.3			
2-59	18	"	0.700	40.64	5.00	296.9	16.09	229.2	6.05	15352	209
4-59	22	"	"	81.28	"	230.0	14.16	355.3			
2-59	17	"	0.800	40.64	6.84	271.9	17.59	209.9	6.17	13758	195
6-59	40	"	"	81.28	"	199.9	15.09	308.7			
2-59	20	"	0.900	40.64	8.92	285.7	20.29	220.6	5.94	11986	207
4-59	26	"	"	81.28	"	203.8	17.14	314.7			
3) 12-59	71	0.175	0.300	59.69	2.24	1786	16.9	689	7.5	11477	560
12-59	72	"	0.375	59.69	4.06	873.3	14.78	337.1	6.91	14121	257
10-59	60	"	0.450	59.69	6.29	628.3	15.04	242.5	6.53	14292	184
10-59	56	"	0.500	59.69	8.00	569.7	15.92	219.9	6.43	13458	171
10-59	58	"	0.550	59.69	9.89	554.2	17.27	213.9	6.30	12301	171
10-59	62	"	0.600	59.69	11.96	572.5	19.15	221.0	6.31	10809	184

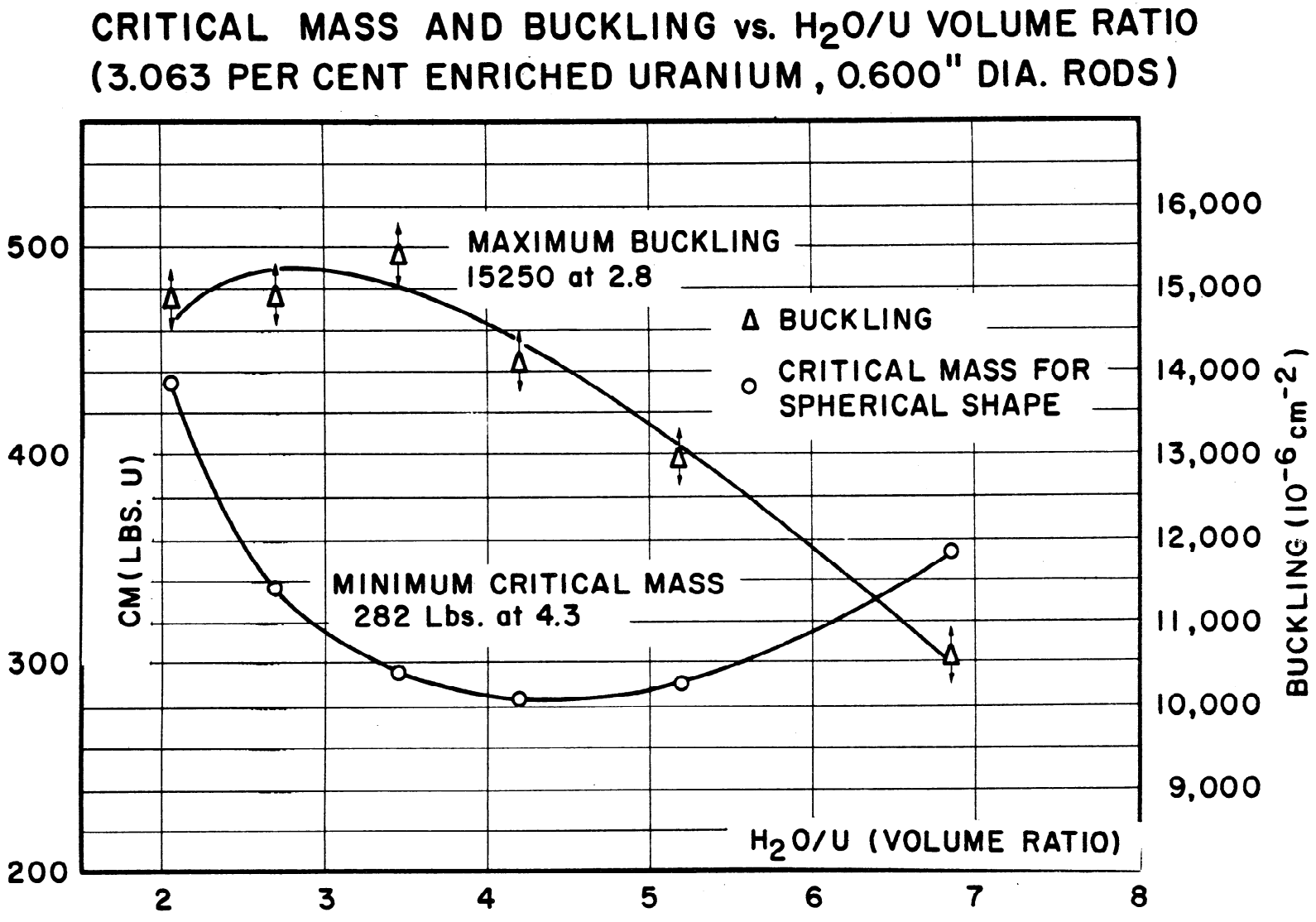
(1) N/CR vs N used to evaluate N_c.

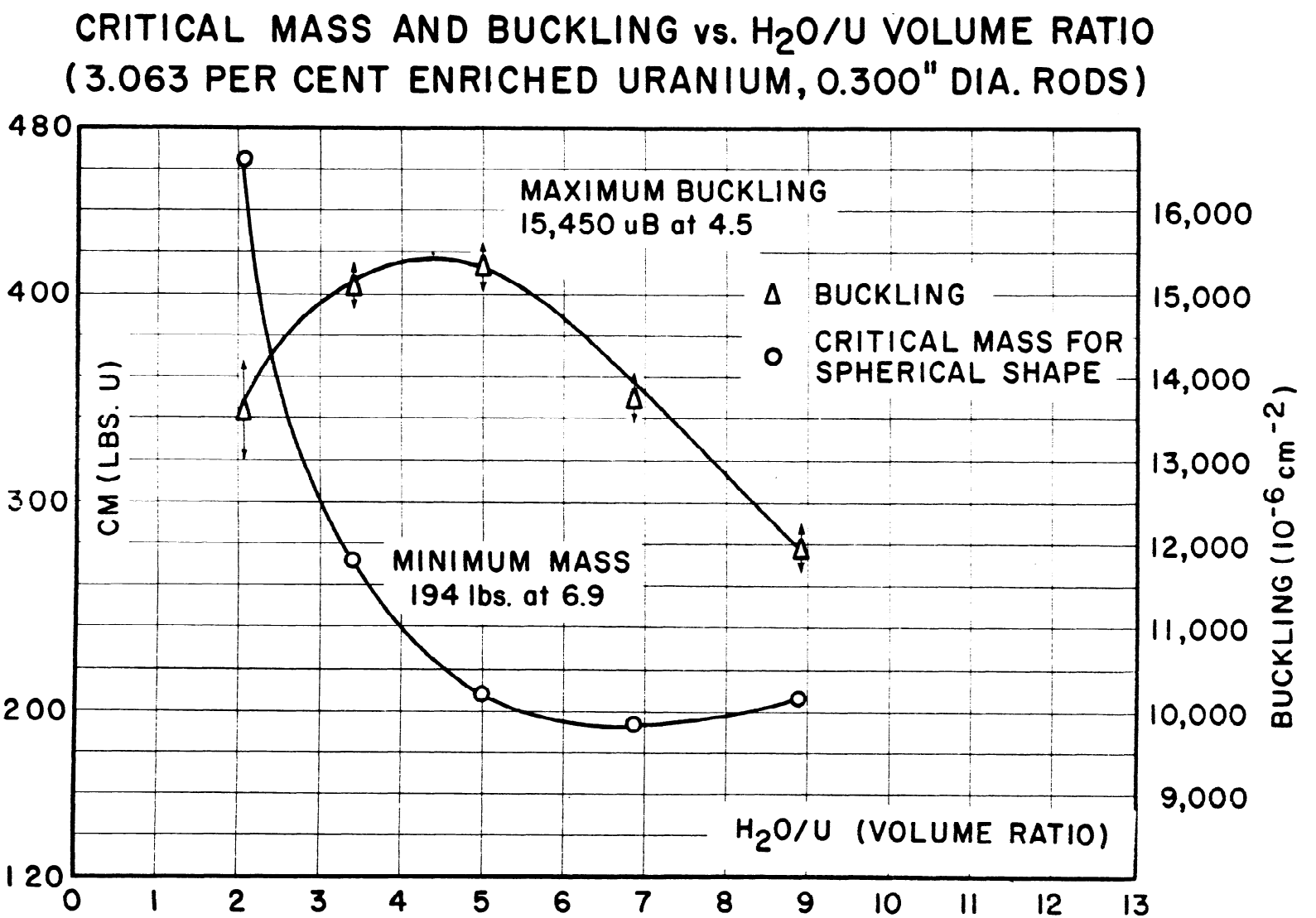
(2) λ for 0.925 diameter extrapolated from curves of λ vs rod diameter. λ calculated from setting values of buckling equal, when more than two measurements were made, a weighted average was taken.

(3) Exponential measurement only - λ from extrapolating measured λ curve.


EXTRAPOLATION LENGTH VS. H_2O/U VOLUME RATIO
(for 3.063 Per Cent Enriched Uranium)
λ-0.175" DIAMETER ROD
λ-0.300" " "
λ-0.600" " "
λ-0.925" " "
EXTRAPOLATED DATA
λ (cm)
H_2O/U (VOLUME RATIO)
9
8
7
6
5
0
1
2
3
4
5
6
7
8
9
10
11
12

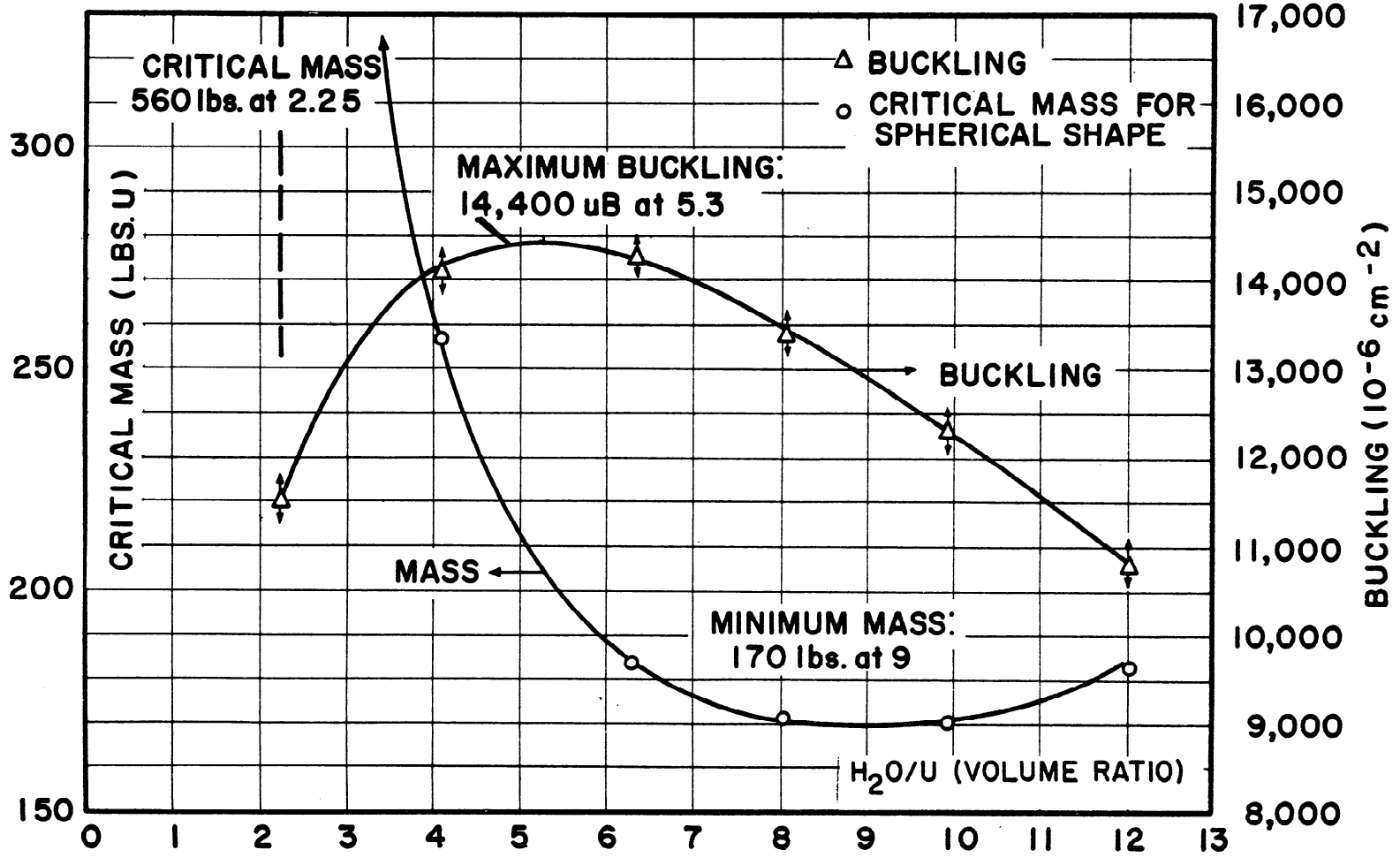

CRITICAL MASS AND BUCKLING vs. H2O/U VOLUME RATIO
(3.063 PER CENT ENRICHED URANIUM, 0.925" DIA. RODS)
BUCKLING (10⁻⁶ cm⁻²)
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
CM (LBS. U)
500
400
300
200
H2O/U (VOLUME RATIO)
1
2
3
4
5
6
MAXIMUM BUCKLING
14220 uB at 2.2
Δ BUCKLING
CRITICAL MASS FOR
SPHERICAL SHAPE
MINIMUM MASS
387 Lbs. at 3.2


CRITICAL MASS AND BUCKLING vs. H2O/U VOLUME RATIO
(3.063 PER CENT ENRICHED URANIUM, 0.600" DIA. RODS)
MAXIMUM BUCKLING
15250 at 2.8
Δ BUCKLING
CRITICAL MASS FOR
SPHERICAL SHAPE
MINIMUM CRITICAL MASS
282 Lbs. at 4.3
CM (LBS. U)
BUCKLING (10-6 cm-2)
H2O/U (VOLUME RATIO)
500
400
300
200
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
2
3
4
5
6
7
8

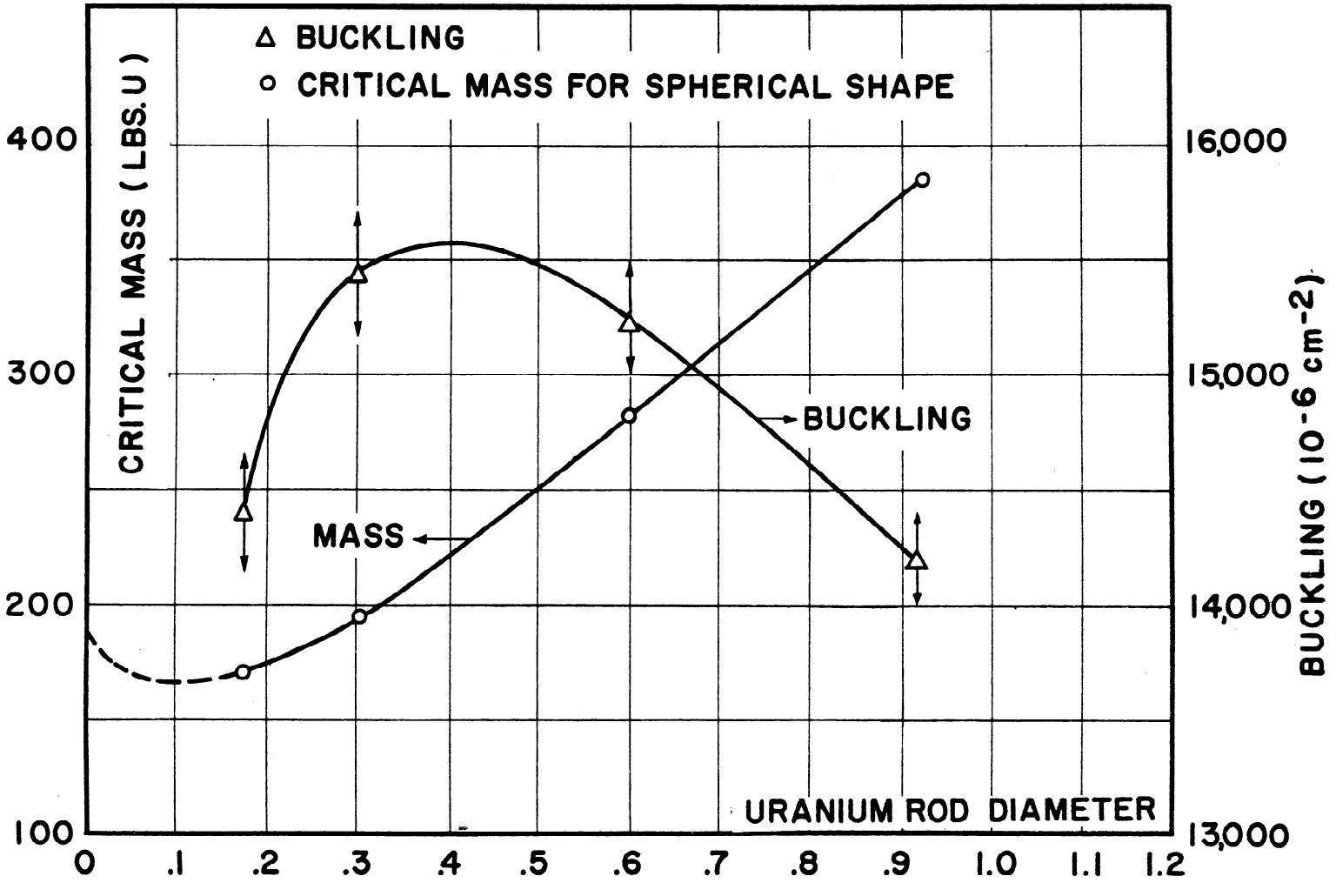

CRITICAL MASS AND BUCKLING vs. H_2O/U VOLUME RATIO
(3.063 PER CENT ENRICHED URANIUM, 0.300" DIA. RODS)
MAXIMUM BUCKLING
15,450 uB at 4.5
Δ BUCKLING
O CRITICAL MASS FOR SPHERICAL SHAPE
MINIMUM MASS
194 lbs. at 6.9
CM (LBS. U)
BUCKLING (10^{-6} cm^{-2})
H_2O/U (VOLUME RATIO)
480
400
300
200
120
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
0 1 2 3 4 5 6 7 8 9 10 11 12 13

HW-65552

CRITICAL MASS AND BUCKLING VS. H_2O/U VOLUME RATIO
(3.06 Per cent Enriched Uranium, 0.175-Inch Dia. Rods)



MAXIMUM BUCKLING AND MINIMUM MASS VS. ROD DIAMETER
(3.06 Per cent Enriched Uranium)



SHAPE PERTURBATIONS OF 3.063 PERCENT ENRICHED URANIUM[23,24,25]
(0.175" Diameter, 23.5" Length, 0.50" Lattice Spacing)

ELLIPTIC CYLINDERS

Date	Exp. No.	Eccentricity	Axis Semi-Major	Axis Semi-Minor	N_c (rods)	CM cyl. (lb.)	B^2 ($10^{-6}cm^{-2}$)	λ
11-19-59	69		15.88	15.88	567.3 ± 1	219.0 ± 0.4	13,530	6.4
11-9-59	64	.212 *(.224)	16.07 16.2	15.71 15.6	568.2 ± 1.5	219.3 ± 0.6	13,520	6.4
11-11-59	65	.465 (.480)	16.92	14.98	570.3 ± 2.5	220.1 ± 1.0	13,520	6.4
11-13-59	6.6	.647 (.624) (.74)	18.34 19.2 21.9	13.99 13.6 12.6	572.2 ± 1.5	222.8 ± 0.6	13,550	6.4

*Calculated values from (25), others calculated from measured moments.

RECTANUGLAR CYLINDERS

Date	Exp. No.	Critical Dimensions a (cm)	Critical Dimensions b (cm)	N_c (rods)	CM cyl. (lb)	B^2 ($10^{-6}cm^{-2}$)	λ (cm)
11-16-59	67	28.09	29.22	587.7 ± 0.6	226.9 ± 0.2	13,440	6.3
11-17-59	68	25.30	33.00	597.7 ± 1.5	230.7 ± 0.6	13,510	6.3

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