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RESULTS AND ANALYSIS
OF THE
APPR-1 ZERO POWER EXPERIMENTS

PART I

CONTRACT NO. AT (11-1) - 318

ALCO PRODUCTS, INC.
POST OFFICE BOX 414
SCHENECTADY, N. Y.

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RESULTS AND ANALYSIS
OF THE
APPR-1 ZERO POWER EXPERIMENTS

PART 1

CONTRACT NO. AT (11-1) - 318

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ABSTRACT

This report contains the results of the initial experiments performed on the APPR-1 core at the Alco Critical Facility, an interpretation of the experimental measurements, and a plan of operation for the APPR-1.

An analysis of measurements made in the APPR-1 zero power experiments has indicated more than 15% excess reactivity in the cold clean core. Extrapolation of temperature coefficient data to 450° F predicts a temperature coefficient more negative than $-2 \times 10^{-4}\ \Delta K/^{\circ}F$.

It is concluded that the APPR-1 may be operated safely on a five rod shim bank without a modification to the original boron-10 specification.

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RESULTS AND ANALYSIS OF THE APPR-1 ZERO POWER EXPERIMENTS
PART I

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CHAPTER I
RESULTS OF ZERO POWER EXPERIMENT

This chapter is devoted to a compilation of data taken during the initial part of the APPR-1 Zero Power Experiments. The data as reported in this chapter were used in Alco's decision to make no change in the boron-10 loading for the APPR-1 core. The results of these measurements are reported and include the basic data on the following:

A. Initial Criticality
B. Buildup to 7 x 7 APPR-1 Array
C. Critical Water Height
D. Temperature Coefficient
E. Shutdown Position of Control Rods
F. Uniform Poison Addition
G. Poison Additions to Center 25 Fuel Elements

A. Initial Criticality

Seventeen fuel elements were required for criticality and were positioned as illustrated in Figure 1. (See Figure 2 for complete core cross section). All of the control rods had their fuel sections attached. The core contained 8.072 Kg U-235 and 7.50 gram B-10.

The configuration shown in Figure 1 was actually supercritical and did not permit complete withdrawal of all the control rods. Table 1 indicates the critical position of the control rods.

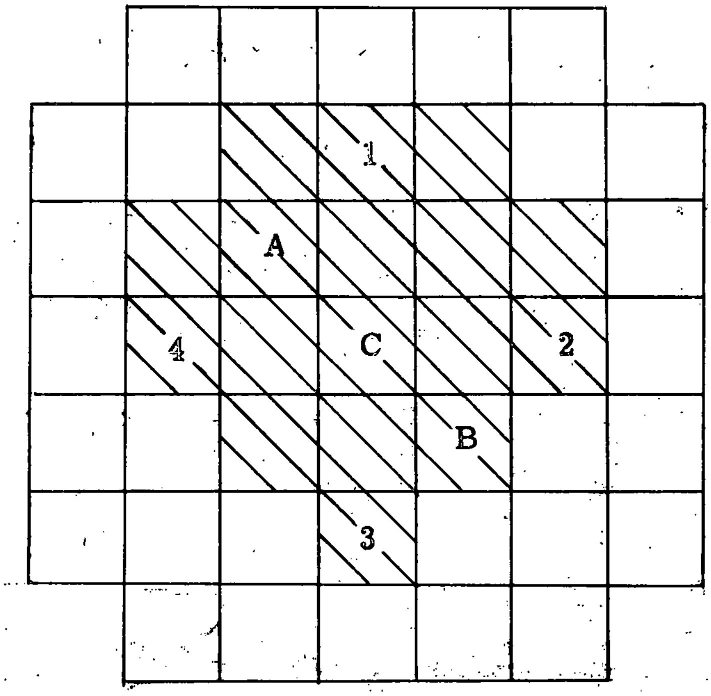
TABLE I
ROD WITHDRAWAL FOR INITIAL CRITICALITY
(All Rods Full Out - 22 Inches - Except as Indicated)

Case	Rod Partially Withdrawn	Inches Withdrawn
1	C	17.00
2	3	10.14
3	3 and 4	14.88 and 15.08 respectively

B. Buildup to 7 x 7 APPR-1 Array

After the initial criticality with 17 elements was determined, the core was assembled element by element with the five rod bank, rods 1, 2, 3, 4 and C, balancing the added reactivity. After 33 elements were in the core, rods A and B were inserted first half in and then full in. Half insertion of

FIGURE 1
CONFIGURATION FOR INITIAL CRITICALITY



Initial criticality established with fuel elements in shaded area only.

Letters and numbers identify control rods.

7 rod bank is defined as all 7 rods.

5 rod bank is defined as rods 1, 2, 3, 4 and C with absorber section of rods A and B full out.

NOTE: For a complete description of the APPR-1 core see reference (1).

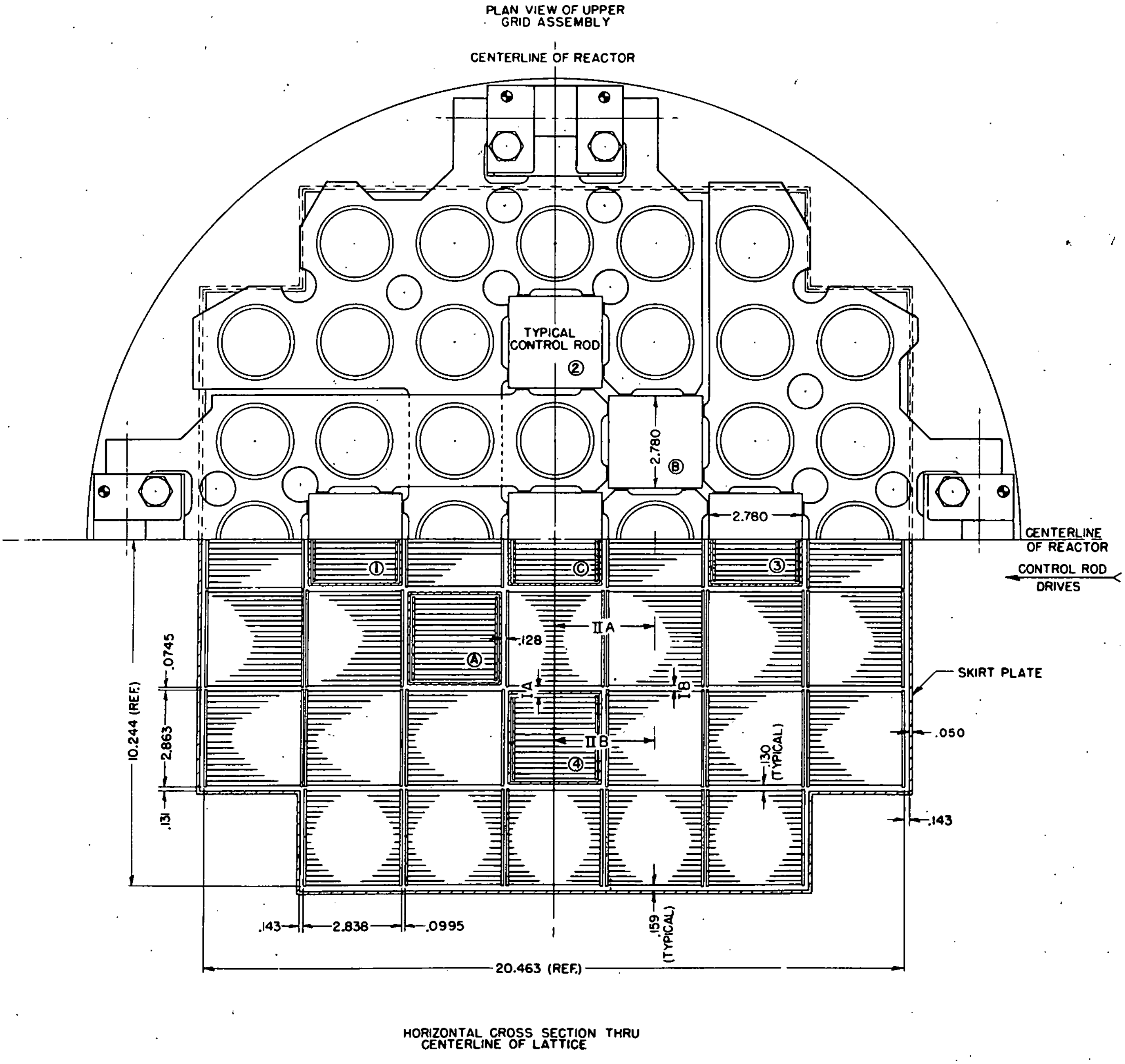


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FIG. 2 - CROSS-SECTION OF APPR-1 CORE

rods A and B in the five rod bank had little effect on the bank position since they were shielded to a large extent by the five rod bank. Rods A and B were then fully inserted for safety as the core was being assembled. After all of the elements (45) were present, the position of the five rod bank with rods A and B full out was determined. These data are plotted in Figure 3. The full APPR-1 core contains 22.5 Kg U-235 and 20.9 grams Boron-10

C. Critical Water Height

The critical water height was determined by step reduction of the water height and balancing with the five rod bank. Rods A and B were fully withdrawn. The critical water height was determined to be 9 inches from the bottom core reflector interface with all rods fully withdrawn.

D. Temperature Coefficient

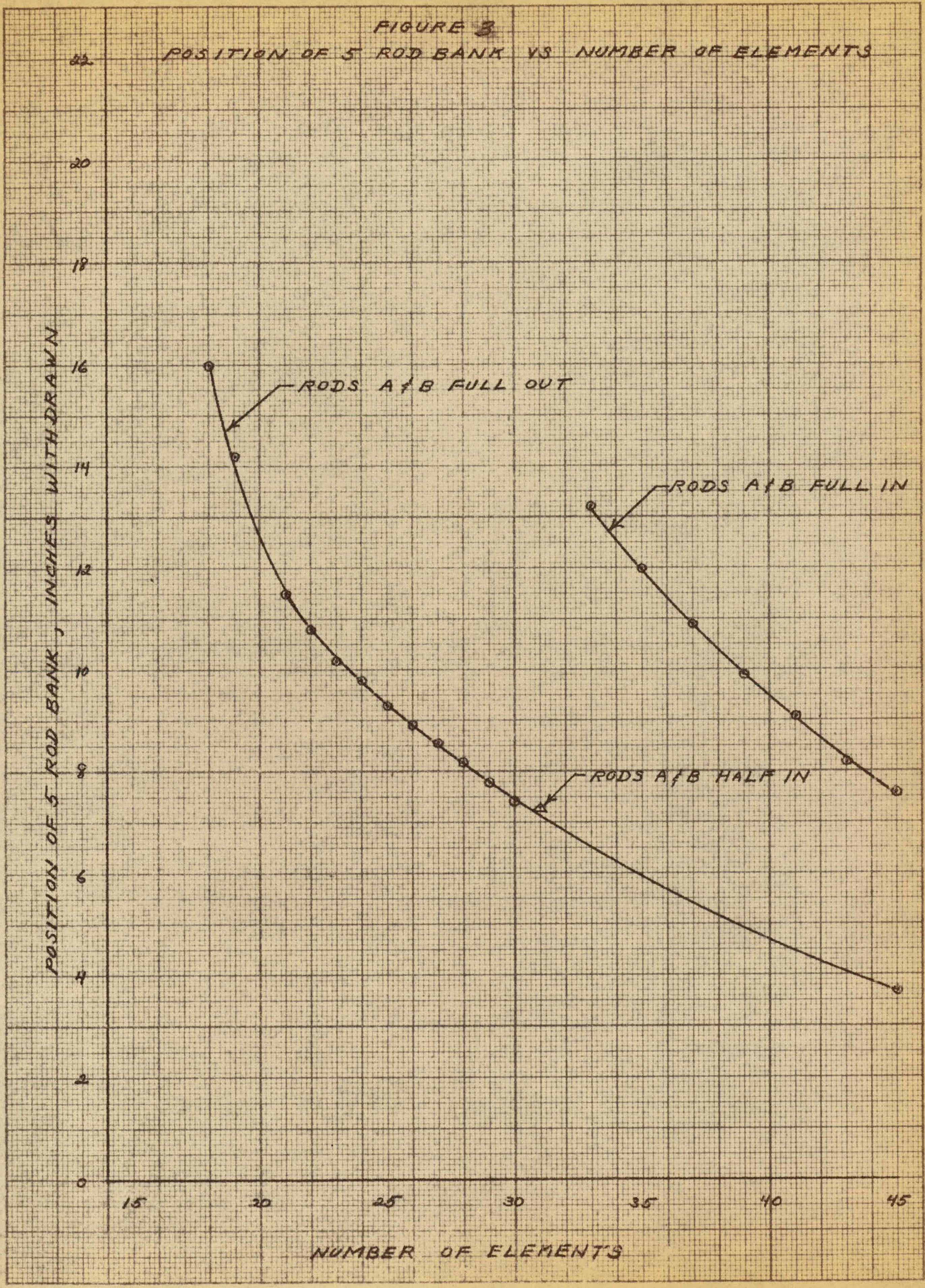
The temperature coefficient of reactivity was measured by heating the water to 200°F. Measurements were made at intervals corresponding to temperature changes of approximately 10°F. Rods A and B were fully withdrawn at all times. The position for criticality of the five rod shim bank was noted at certain temperatures. The position of an eccentric rod for criticality was noted at certain temperatures with the remaining four rods of the five rod shim bank in their positions for criticality at 71°F. Also, the position of the center rod for criticality was noted at each temperature with the remaining four rods of the five rod shim bank in their positions for criticality at 71°F. Period measurements were made at several temperatures for the five rod shim bank, the center rod or an eccentric rod.

Table 2 presents a summary of the average temperatures at which measurements were made and the positions of the five rods to establish criticality at these specific temperatures. The average temperature was determined as the average of six measurements given by thermocouples situated at various positions in the reactor.

Table 3 presents a tabulation of experimental measurements and the resultant calculated temperature coefficient of reactivity at various temperatures. The temperature coefficient was determined in the following manner:

For each period measurement the initial and final position of the rod moved to establish the period was noted. The worth in cents corresponding to this movement was determined from the measured period and the inhour relationship. The temperature difference corresponding to the rod movement was taken from the curves of temperature versus rod position presented in Figures 4, 5 and 6. The change from cents to reactivity was made by assuming a delayed neutron fraction of 0.0075, and the value of $\Delta\rho/\Delta T$ determined, where $\Delta\rho$ is the change in reactivity and ΔT is the temperature change in °F. Figure 7 presents a graph of temperature coefficient versus

FIGURE 3
POSITION OF 5 ROD BANK VS NUMBER OF ELEMENTS



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temperature. The values were plotted at the midpoints of the temperatures corresponding to the rod positions.

Figures 8 and 9 present graphs of rod worth in % ρ/inch versus rod position for the center rod and an eccentric rod, and the five rod shim bank respectively. Table 4 presents a tabulation of the data.

TABLE 2
SUMMARY OF TEMPERATURE COEFFICIENT DATA
(A and B Full Out)

Run	Avg. Temp. °F.	Rod Positions for Criticality in Inches 1	2	C	3	4
1-1	70.2	3.70	3.70	3.69	3.70	3.69
2-1	73.2	3.70	3.70	3.71	3.71	3.72
2-2	73.2	3.70	3.70	3.71	3.71	3.72
2-3	73.2	3.71	3.70	3.71	3.72	3.73
2-4	74.7	3.71	3.71	3.72	3.72	3.71
3-1	87.5	3.71	3.71	3.81	3.72	3.71
4-1	101.2	3.71	3.71	3.93	3.72	3.71
5-1	111.0	3.71	3.71	4.06	3.72	3.71
6-1	122.0	3.71	3.71	4.20	3.72	3.71
6-2	122.7	3.71	3.71	3.71	4.56	3.71
6-3	123.3	3.87	3.88	3.86	3.87	3.87
6-4	123.3	3.71	3.71	4.28	3.72	3.71
7-1	131.8	3.71	3.71	4.38	3.72	3.71
8-1	141.7	3.71	3.71	4.41	3.72	3.71
9-1	150.3	3.71	3.71	4.58	3.72	3.71
10-1	160.8	3.71	3.71	4.75	3.72	3.71
10-2	163.5	3.71	3.71	3.76	5.13	3.71
10-3	166.0	4.00	4.01	4.06	4.01	4.01
10-4	170.8	3.71	3.71	4.94	3.71	3.72
11-1	182.4	3.71	3.71	5.20	3.72	3.71
12-1	190.8	3.71	3.71	5.40	3.72	3.71
12-2	191.7	3.71	3.71	3.76	5.93	3.71
12-3	192.7	4.19	4.18	4.23	4.19	4.18
12-4	193.3	3.71	3.71	5.43	3.72	3.71
13-1	198.9	3.71	3.71	5.58	3.72	3.71
13-2	199.0	3.71	3.71	3.76	6.16	3.71
13-3	199.2	4.23	4.21	4.27	4.21	4.20
13-4	199.2	3.71	3.71	5.58	3.72	3.71
14-1	187.5	3.71	3.72	5.37	3.72	3.72
15-1	171.8	4.07	4.07	4.15	4.08	4.10
15-2	170.3	4.04	4.05	4.17	4.03	4.04
15-3	167.3	3.71	3.71	3.82	5.30	3.71
16-1	154.4	3.71	3.71	4.71	3.72	3.72
17-1	147.8	3.71	3.71	4.62	3.72	3.71
18-1	140.0	3.71	3.71	4.50	3.72	3.71
19-1	123.2	3.71	3.71	4.22	3.72	3.71
20-1	110.6	3.71	3.71	4.04	3.72	3.71
21-1	102.6	3.71	3.71	3.94	3.72	3.71
22-1	102.8	3.71	3.71	3.85	3.88	3.71
23-1	102.6	3.73	3.73	3.87	3.73	3.73
24-1	102.8	3.71	3.71	3.95	3.72	3.71

TABLE 3

SUMMARY OF TEMPERATURE COEFFICIENT DATA AND CALCULATED TEMPERATURE COEFFICIENTS

Rod Moved	Initial Position Inches	Final Position Inches	Worth From Period Measure, ¢	Temperature Difference From Curve °F.	°F	$\Delta\rho/\Delta T$ °F^{-1} x10^4
C	3.69	4.19	25.7	124 - 69	55	0.350
C	3.81	4.21	20.2	125 - 87	38	0.398
C	3.93	4.32	20.5	133 - 101	32	0.480
C	4.06	4.39	17.7	138 - 113	25	0.531
C	4.20	4.50	16.3	144 - 124	20	0.611
C	4.38	4.70	16.6	156 - 137	19	0.655
C	4.41	4.68	15.5	155 - 139	16	0.726
C	4.58	4.88	17.8	166 - 149	17	0.785
C	4.75	5.05	17.7	174 - 159	15	0.885
C	4.94	5.25	18.1	184 - 169	15	0.905
C	5.20	5.49	15.9	195 - 182	13	0.917
C	5.40	5.69	16.1	205 - 191	14	0.863
3	3.71	4.02	10.0	104 - 71	33	0.227
3	3.71	4.22	16.4	118.5 - 71	47.5	0.259
3	4.56	5.00	19.8	157 - 137.5	19.5	0.761
3	5.13	5.50	16.9	176 - 162	14	0.905
3	5.93	6.30	16.1	204 - 191	13	0.929
Bank	3.714	3.812	19.6	110 - 76.5	33.5	0.439
Bank	3.87	3.938	14.3	142 - 125.5	16.5	0.650
Bank	4.018	4.11	20.5	178 - 159	19	0.809
Bank	4.066	4.118	9.5	179.5 - 169	10.5	0.678

TABLE 4
SUMMARY OF WORTH CALCULATIONS

Run	Rod Moved	Distance Moved Inches	Period Seconds	Worth ¢/inch	Worth %ρ/inch
1-1	C	0.50	22.80	51.40	0.385
2-1	3	0.31	94.44	32.26	0.242
2-2	3	0.51	48.85	32.16	0.241
2-3	Bank	0.098	36.91	200.00	1.500
3-1	C	0.40	34.74	50.50	0.379
4-1	C	0.39	33.65	52.56	0.394
5-1	C	0.33	43.42	53.64	0.402
6-1	C	0.30	49.94	54.33	0.407
6-2	3	0.44	35.82	45.00	0.337
6-3	Bank	0.068	59.71	210.29	1.577
7-1	C	0.32	43.50	55.00	0.412
8-1	C	0.27	53.19	57.41	0.431
9-1	C	0.30	42.33	59.33	0.445
10-1	C	0.30	43.42	59.00	0.442
10-2	3	0.37	46.70	45.68	0.343
10-3	Bank	0.092	33.70	222.83	1.671
10-4	C	0.31	40.17	58.39	0.438
11-1	C	0.29	51.02	54.83	0.411
12-1	C	0.29	49.93	55.52	0.416
12-2	3	0.37	49.93	43.51	0.326
12-3	Bank	0.086	33.65	237.21	1.779
13-1	C	0.32	45.59	53.75	0.403
13-2	3	0.40	43.42	44.25	0.332
13-3	Bank	0.11	23.90	227.27	1.704
13-4	C	0.22	78.20	53.18	0.399
15-2	Bank	0.052	102.80	182.69	1.370

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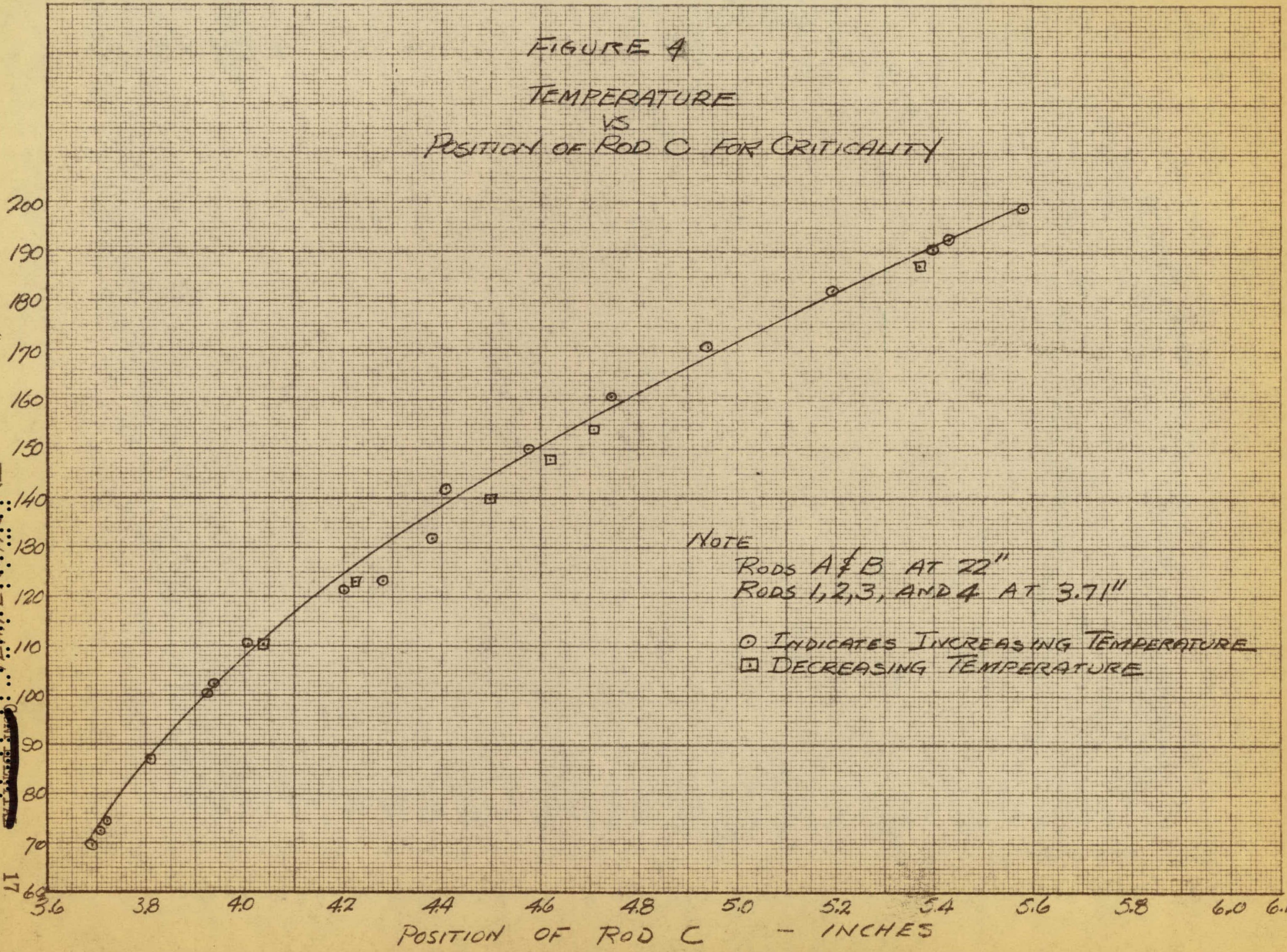

FIGURE 4

TEMPERATURE
VS
POSITION OF ROD C FOR CRITICALITY

NOTE
RODS A & B AT 22"
RODS 1,2,3, AND 4 AT 3.71"

⊙ INDICATES INCREASING TEMPERATURE
⊡ DECREASING TEMPERATURE

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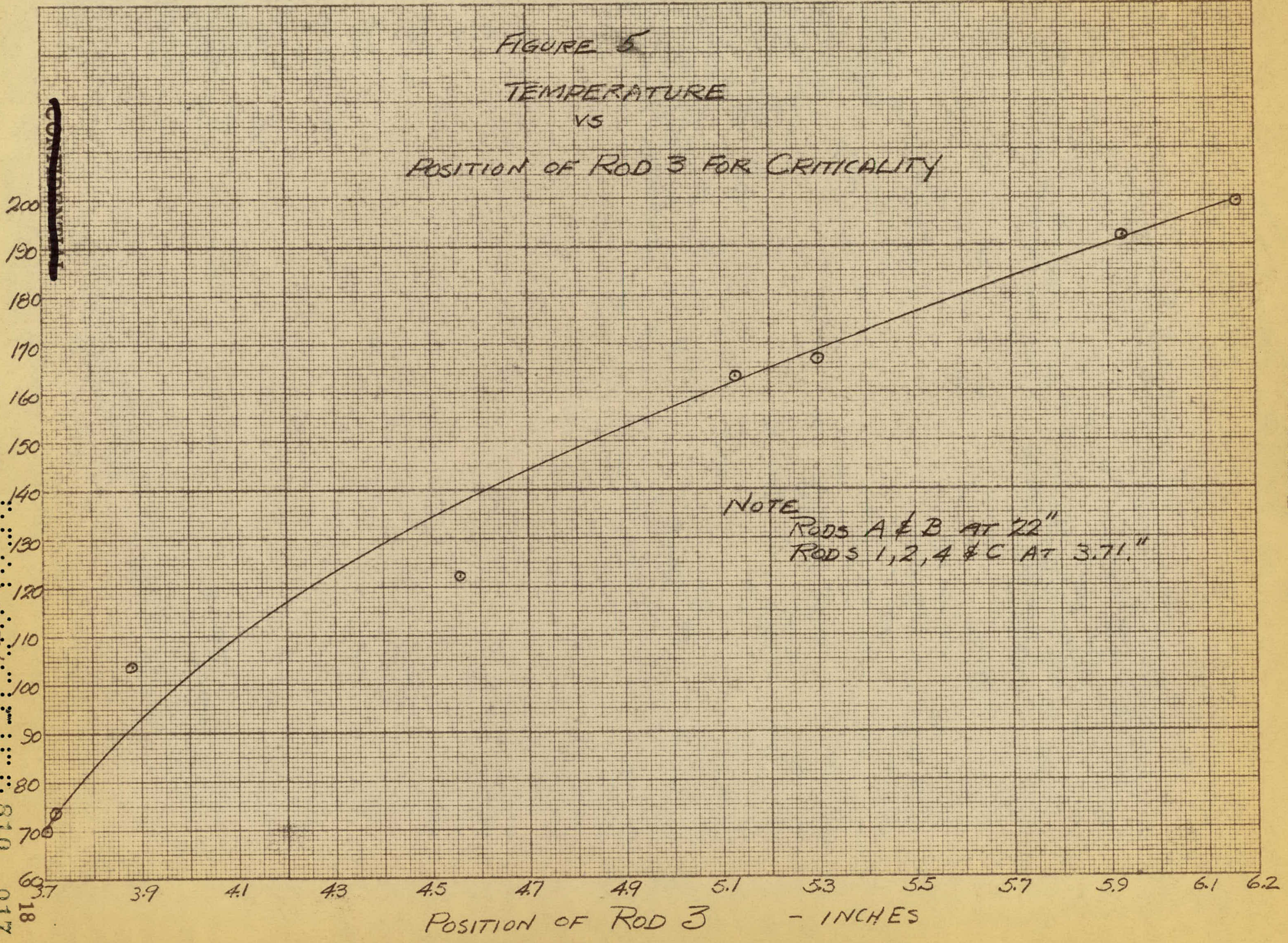

FIGURE 5

TEMPERATURE VS POSITION OF ROD 3 FOR CRITICALITY

NOTE
RODS A & B AT 22"
RODS 1, 2, 4 & C AT 3.71"

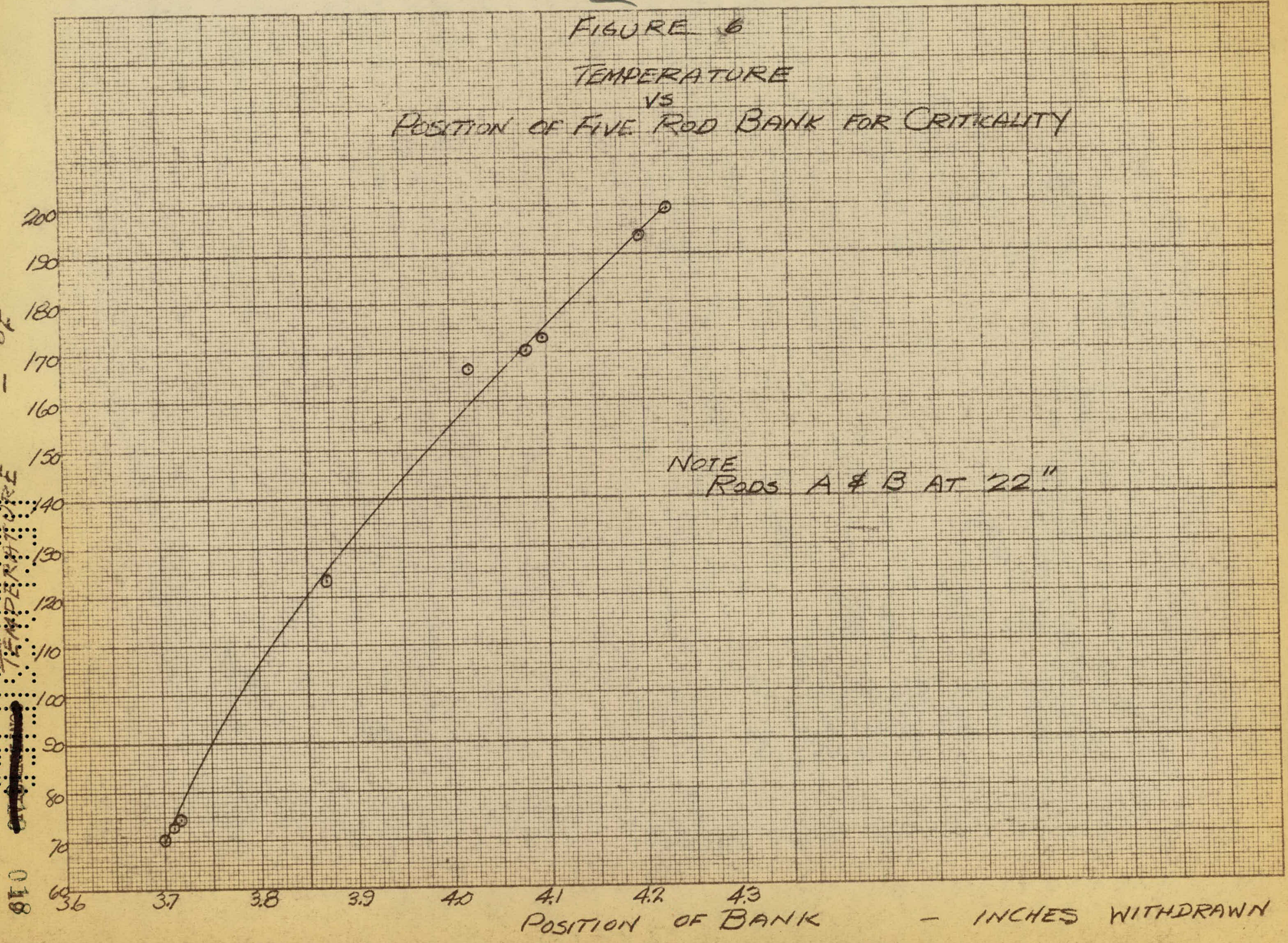

FIGURE 6

TEMPERATURE
VS
POSITION OF FIVE ROD BANK FOR CRITICALITY

NOTE
RODS A & B AT 22"

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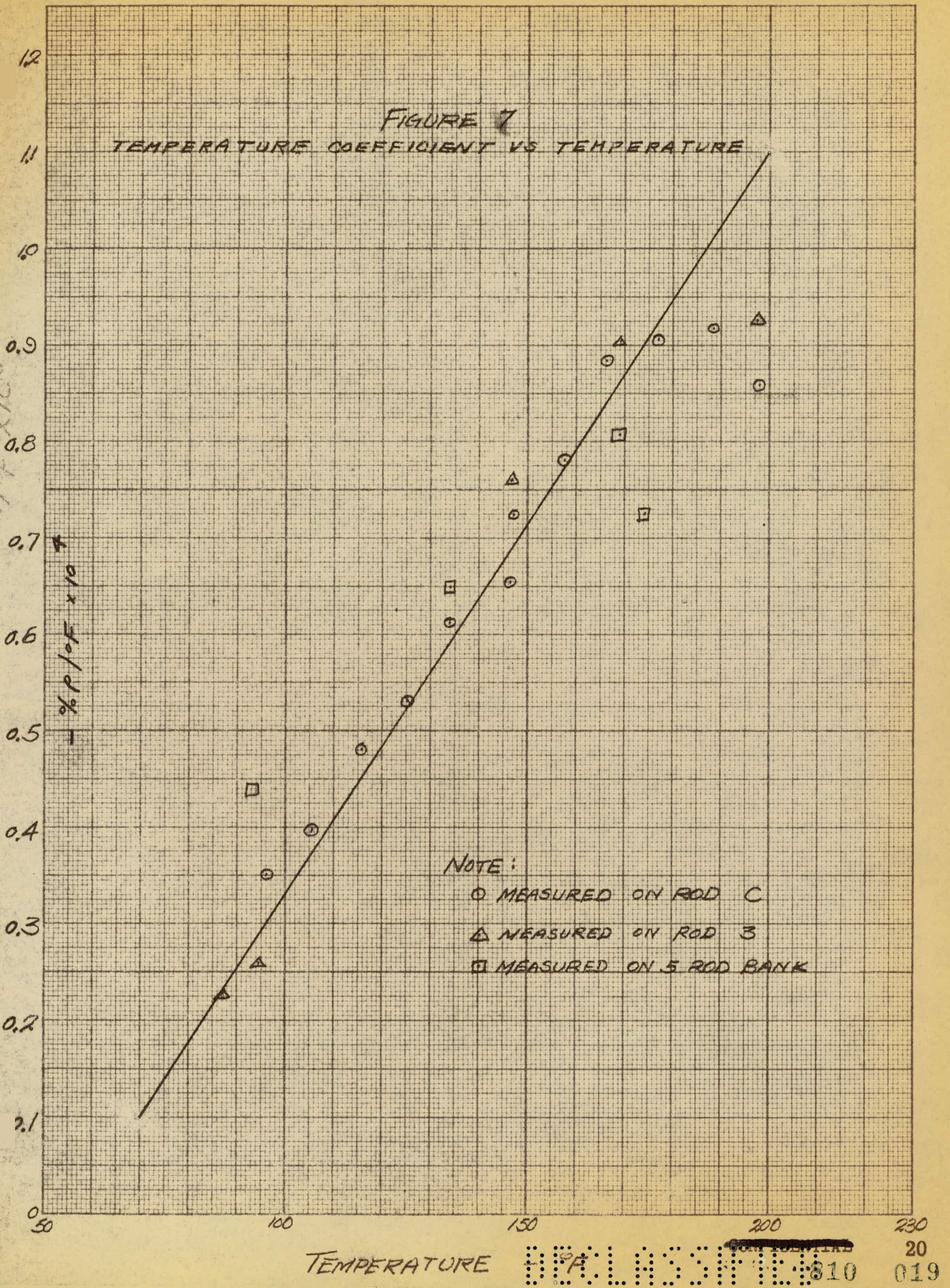
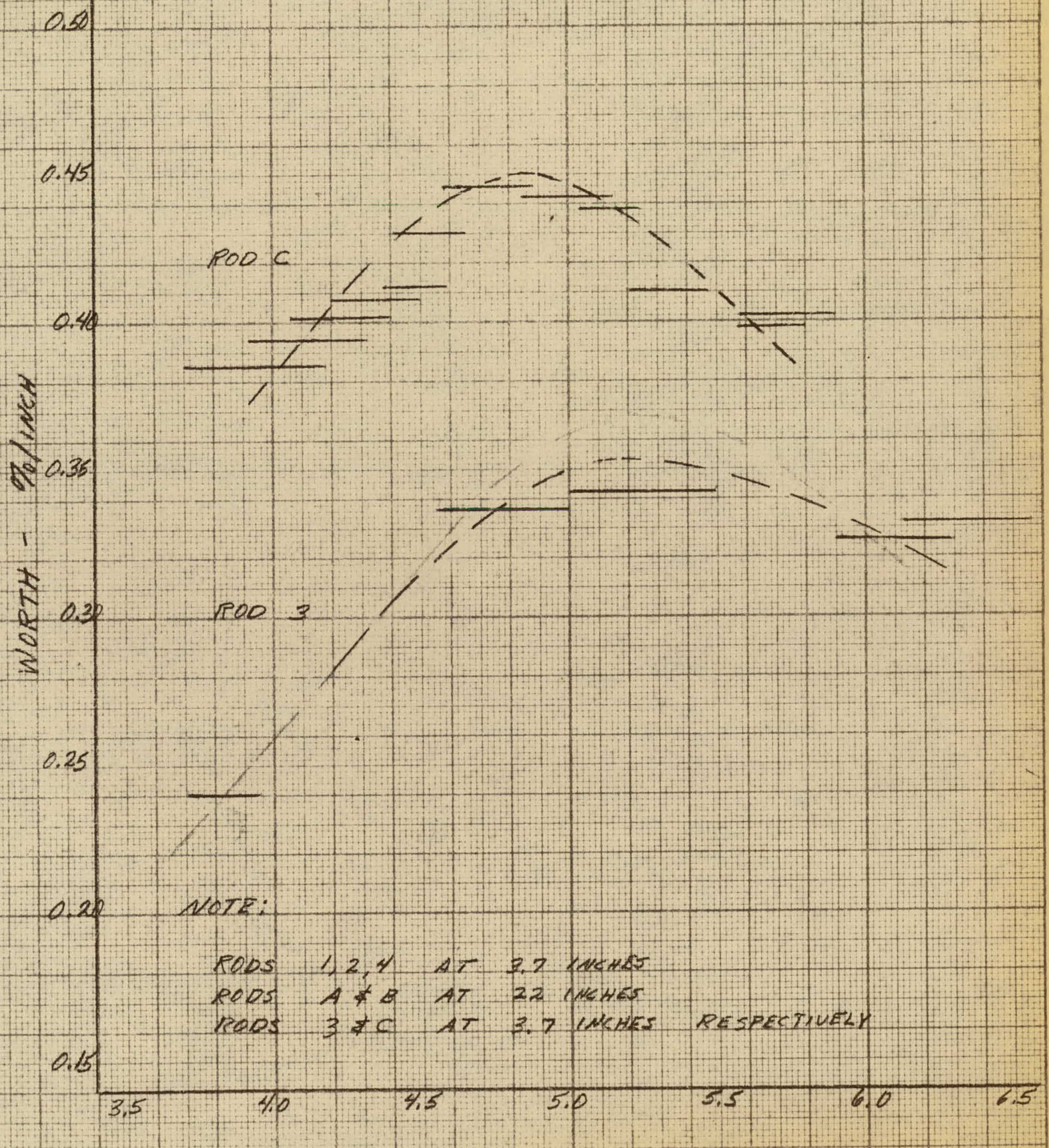


FIGURE 7
TEMPERATURE COEFFICIENT VS TEMPERATURE

FIGURE 8

ROD WORTH VERSUS ROD POSITION - FOR RODS C & 3



NOTE:

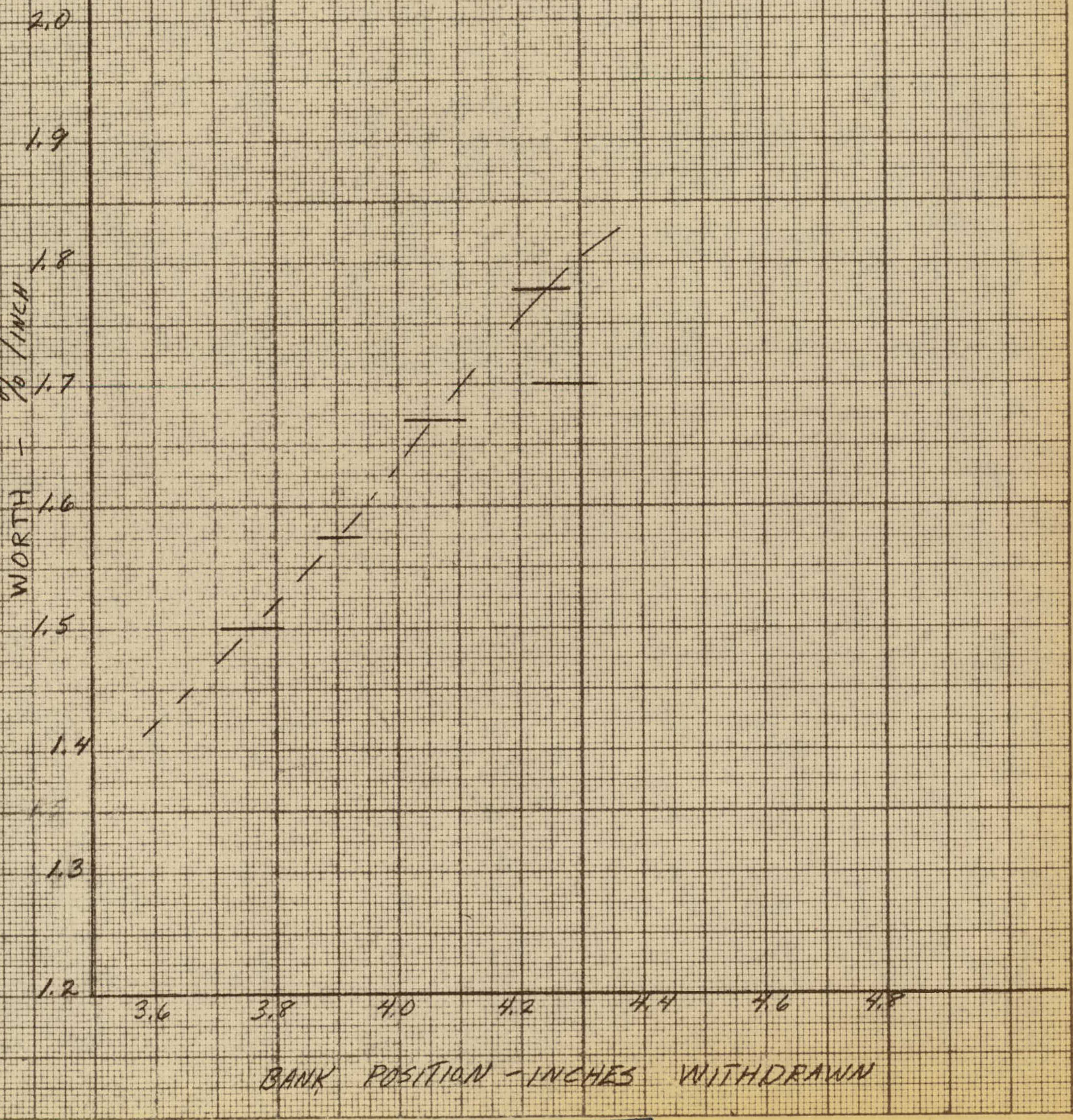
RODS 1, 2, 4 AT 3.7 INCHES
RODS A & B AT 22 INCHES
RODS 3 & C AT 3.7 INCHES RESPECTIVELY

FIGURE 9

BANK WORTH VERSUS

BANK POSITION

FOR 5 ROD BANK



E. Shutdown Position of Control Rods

The shutdown position of the control rods in various combinations has been measured. In some cases two rods can be fully withdrawn, while in other cases only one rod can be fully withdrawn. The data are reported as rods fully withdrawn, rods fully inserted, and rods partially withdrawn in Table 5.

TABLE 5
SHUTDOWN POSITION OF CONTROL RODS

Case	Rods Fully Withdrawn	Rods Fully Inserted	Rods Partially Withdrawn	Inches Withdrawn
1	C	1, 2, 4, A, B	3	16.21
2	3	1, 2, 4, A, B	C	13.87
3	A	2, 3, 4, B, C	1	11.97
4	1	3, 4, A, B, C	2	10.09
5	1	2, 3, A, B, C	4	15.06
6	1	2, 3, 4, B, C	A	9.5 ± 0.2
7	A, B	1, 2, 3, 4	C	9.98
8	A, B	1, 2, 4, C	3	9.84
9	A, C	2, 3, 4, B	1	3.36
10	A, 3	1, 2, 4, B, C	Subcritical	
11	1, 3	2, 4, A, B, C	Subcritical	

Period measurements were also made on the partially inserted rod about the point of insertion, Table 6. The basic core configuration was maintained as close as possible by withdrawal of a rod most distant from the calibrated rod.

TABLE 6
PERIOD CALIBRATION OF PARTIALLY WITHDRAWN ROD

Case	Rod Calibrated	Initial Position Inches	Final Position Withdrawn	Worth Cents	Worth %ρ/inch
1	3	16.21	16.66	12.3	0.205
		15.66	16.24	16.2	0.209
		15.21	15.66	12.2	0.203
		14.75	15.25	15.1	0.226
		13.99	14.30	11.6	0.281
		12.99	13.30	10.8	0.261
		11.99	12.30	9.7	0.235
2	C	13.87	14.26	9.0	0.173
		13.00	14.03	22.6	0.165
		12.00	12.60	13.2	0.165
		11.00	11.59	16.0	0.203
		9.00	9.59	17.2	0.219
3	1	11.97	12.23	14.8	0.427
		10.97	11.26	18.4	0.476
		10.97	11.27	18.0	0.450
4	2	10.09	10.40	12.4	0.300
		8.99	9.49	19.2	0.288
		7.99	8.49	15.7	0.235
5	4	15.06	15.66	14.4	0.180
		14.02	14.77	15.7	0.157
		12.02	12.77	17.7	0.177
7	C	9.98	10.32	17.2	0.379
		7.99	7.65	17.9	0.395
		4.99	4.68	16.6	0.402
		2.99	2.51	14.3	0.223
		0	0.99	12.9	0.098
8	3	9.84	9.60	12.9	0.403
		8.74	8.99	14.3	0.429
		7.40	7.66	16.6	0.479
		4.31	4.74	17.9	0.312

F. Uniform Poison Addition

Poison was added to the reactor in the form of boron - steel strips. Measurements were made of the positions of the five rod and seven rod banks for criticality for each poison addition. Period measurements were made for the five rod bank, the center rod or an eccentric rod. The strips were 23 inches long, 1/2 inch wide and 0.020 inches thick. The weight percent of boron was 1.01% corresponding to 0.0498 grams of boron-10 per strip. Poisoning was accomplished by adding 45 strips, one strip per element. This corresponds to an addition of 2.241 grams of boron-10.

Table 7 presents a summary of the experimental data on bank positions. Table 8 presents experimental period measurements and corresponding calculated worth values.

Figure 10 presents a curve of total additional boron-10 content versus five rod and seven rod bank positions. Figure 11 presents a curve of worth per inch versus position for rod C and rod 3 with criticality established with the five rod bank. Figure 12 presents a similar curve with criticality established with the seven rod bank. Figure 13 presents curves of worth per inch versus the position of the five rod bank. In Figure 14 the integrated curves for the five rod bank are given. Two theoretical curves and one experimental curve are presented.

In addition to calculating the excess reactivity present in the core and the shim bank worth by integrating the period measurements, another method based on the change in thermal utilization was used. (2) In this technique the addition of the boron strips was assumed to cause a change only in the thermal utilization. Bank position measurements were made at each boron strip loading. The change in the bank position can be related to the quantity of uniform poison added to the core. In this technique, the excess reactivity introduced into the core by the bank movement is assumed to be equal to $\Sigma_p/\Sigma_a + \Sigma_p$ where Σ_p is the uniform poison cross section and Σ a is the core absorption cross section exclusive of the poison. In this method the integrated bank worth can be calculated directly. The differential worth can be calculated from the slope of the integrated curve or by the change in poison corresponding to a measured bank movement, $\Delta\Sigma_p/\Sigma_a + \Sigma_p$. Since the bank movement was relatively small for each poison addition, and was relatively linear over the interval, the latter method was used in obtaining the differential worth.

The core absorption cross section was taken as 0.28658 cm^{-1} (1). Based on the absorption cross section of the boron steel strips a uniform poison cross section of 0.00347 was used for the addition of 1 strip to each element. The neutron flux on the surface of the strip was assumed to be 1.0. A self shielding factor of 0.9455 was used based on $F=1-.321\,\Sigma at$, where $\Sigma a = 3.344\ cm^{-1}$ and $t = .0508$ cm.

In Figure 13 calculated points based on the uniform poison method are presented for a comparison of the period measurements, in determining the worth per inch of the five rod bank.

In Figure 15 the differential worth per inch for the five and seven rod banks is presented. In Figure 16 the integrated worth for the five and seven rod banks is given. The APPR-1 has 15.4% excess reactivity in the cold clean core. The total worth of the five rod bank was found to be 19.4% and of the seven rod bank 24.6%.

TABLE 7
BORON CONTENT AND BANK POSITIONS

Run	Boron-10 Content Grams	5 Rod Bank Position Inches	7 Rod Bank Position Inches
1-1	0.000	3.73	
1-2	0.000	3.72	
1-3	0.000	3.72	
5-1	0.000		5.31
5-2	0.000		5.31
6-1	2.241	4.41	
6-2	2.241	4.41	
6-3	2.241	4.42	
6-4	2.241		5.80
7-1	2.241		5.80
8-1	4.482	5.02	
8-2	4.482	5.01	
8-3	4.482	5.01	
9-1	4.482		6.29
9-2	4.482		6.29
11-1	6.723	5.65	
11-2	6.723	5.65	
11-3	6.723	5.66	
12-1	6.723		6.79
12-2	6.723		6.79
13-1	8.964	6.29	
13-2	8.964	6.29	
13-3	8.964	6.29	
14-1	8.964		7.35
14-2	8.964		7.35
15-1	11.205	6.97	
15-2	11.205	6.97	
15-3	11.205	6.98	
15-4	11.205	6.98	
15-5	11.205	6.98	
16-1	13.446	7.61	
16-2	13.446	7.61	
16-3	13.446	7.61	
16-4	13.446	7.61	
17-1	13.446	7.61	
17-2	13.446	7.61	
17-3	13.446	7.61	
17-4	13.446	7.61	
18-1	13.446		8.53
18-2	13.446		8.53
19-1	15.687	8.33	

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TABLE 7 (CONT'D)

Run	Boron-10 Content Grams	5 Rod Bank Position Inches	7 Rod Bank Position Inches
19-2	15.687	8.33	
19-3	15.687	8.32	
19-4	15.687	8.32	
19-5	15.687	8.32	
19-6	15.687	8.32	
19-7	15.687	8.32	
20-1	15.687		9.17
20-2	15.687		9.17
21-1	17.928	9.13	
21-2	17.928	9.13	
21-3	17.928	9.13	
21-4	17.928	9.13	
15-6	11.205		7.93
21-5	17.928		9.94
21-6	17.928		9.94
22-1	20.169	9.99	
22-2	20.169	9.99	
22-3	20.169	9.99	
22-4	20.169	9.99	
23-1	20.169		10.76
23-2	20.169		10.76
24-1	24.651	12.03	
24-2	24.651	12.03	
24-3	24.651	12.03	
24-4	24.651	12.03	
25-1	24.651		12.82
25-2	24.651		12.82
26-1	29.133	14.57	
26-2	29.133	14.57	
26-3	29.133	14.57	
26-4	29.133	14.57	
27-1	29.133		15.16
27-2	29.133		15.16

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TABLE 8
PERIOD MEASUREMENTS AND CALCULATED WORTHS

Run	Rod(s) Moved	Distance Moved Inches	Period Seconds	Worth % ρ/inch
1-1	3	0.47	45.59	0.2729
5-2	3	0.36	65.13	0.2792
6-2	3	0.40	53.19	0.2888
7-1	3	0.37	56.44	0.2990
8-2	3	0.27	77.07	0.3929
9-2	3	0.40	65.13	0.2513
11-2	3	0.33	61.88	0.3148
12-2	3	0.60	35.82	0.2488
13-2	3	0.31	80.33	0.2782
14-2	3	0.40	62.96	0.2569
15-2	3	0.33	78.16	0.2671
16-2	3	0.47	40.30	0.2959
17-2	3	0.41	52.11	0.2861
18-2	3	0.65	47.76	0.1920
19-2	3	0.46	54.71	0.2462
19-4	3	0.38	73.80	0.2428
20-2	3	0.56	64.05	0.1808
21-2	3	0.40	78.20	0.2205
21-6	3	0.68	52.11	0.1721
22-2	3	0.50	62.96	0.2055
23-2	3	0.59	71.65	0.1595
24-2	3	0.71	67.30	0.1384
25-2	3	0.89	67.30	0.1104
26-2	3	1.01	68.40	0.0962
27-2	3	2.23	43.40	0.0595
1-2	C	0.39	35.80	0.3928
5-1	C	0.34	48.85	0.3600
6-1	C	0.26	54.28	0.4385
6-4	C	0.31	55.36	0.3629
8-1	C	0.27	47.76	0.4611
9-1	C	0.30	52.11	0.3900
11-1	C	0.36	33.65	0.4313
12-1	C	0.41	32.56	0.3860
13-1	C	0.23	68.39	0.4223
14-1	C	0.31	52.11	0.3774
15-1	C	0.15	102.04	0.4800
15-6	C	0.28	57.53	0.3911
16-1	C	0.27	50.60	0.4428
17-1	C	0.17	97.70	0.4365
18-1	C	0.36	66.22	0.2753

TABLE 8 (CONT'D)

Run	Rod(s) Moved	Distance Moved Inches	Period Seconds	Worth % ρ/inch
19-1	C	0.32	49.94	0.3773
19-3	C	0.20	108.60	0.3431
20-1	C	0.37	62.96	0.2777
21-1	C	0.26	74.90	0.3505
21-5	C	0.53	54.28	0.2151
22-1	C	0.26	78.16	0.3519
23-1	C	0.34	82.50	0.2492
24-1	C	0.48	57.53	0.2282
25-1	C	0.44	84.67	0.1892
26-1	C	0.54	77.10	0.1653
27-1	C	1.12	51.00	0.1058
1-3	5 Bank	0.076	48.95	1.6088
6-3	5 Bank	0.078	45.59	1.6343
8-3	5 Bank	0.080	37.99	1.8465
11-3	5 Bank	0.074	44.51	1.7633
13-3	5 Bank	0.062	65.13	1.6748
15-3	5 Bank	0.048	60.79	2.1825
15-4	5 Bank	0.060	51.02	1.9815
15-5	5 Bank	0.058	54.28	1.9658
16-3	5 Bank	0.064	65.30	1.5645
16-4	5 Bank	0.076	54.90	1.4865
17-3	5 Bank	0.094	40.60	1.4760
17-4	5 Bank	0.078	57.10	1.4085
19-5	5 Bank	0.078	62.31	1.3268
19-6	5 Bank	0.078	73.80	1.1828
19-7	5 Bank	0.080	60.14	1.3223
21-3	5 Bank	0.078	64.05	1.2983
21-4	5 Bank	0.082	59.71	1.3035
22-3	5 Bank	0.09	58.62	1.2000
22-4	5 Bank	0.10	45.59	1.2825
24-3	5 Bank	0.078	134.61	0.7403
24-4	5 Bank	0.128	59.70	0.8318
26-3	5 Bank	0.212	44.50	0.6155
26-4	5 Bank	0.176	62.30	0.5881

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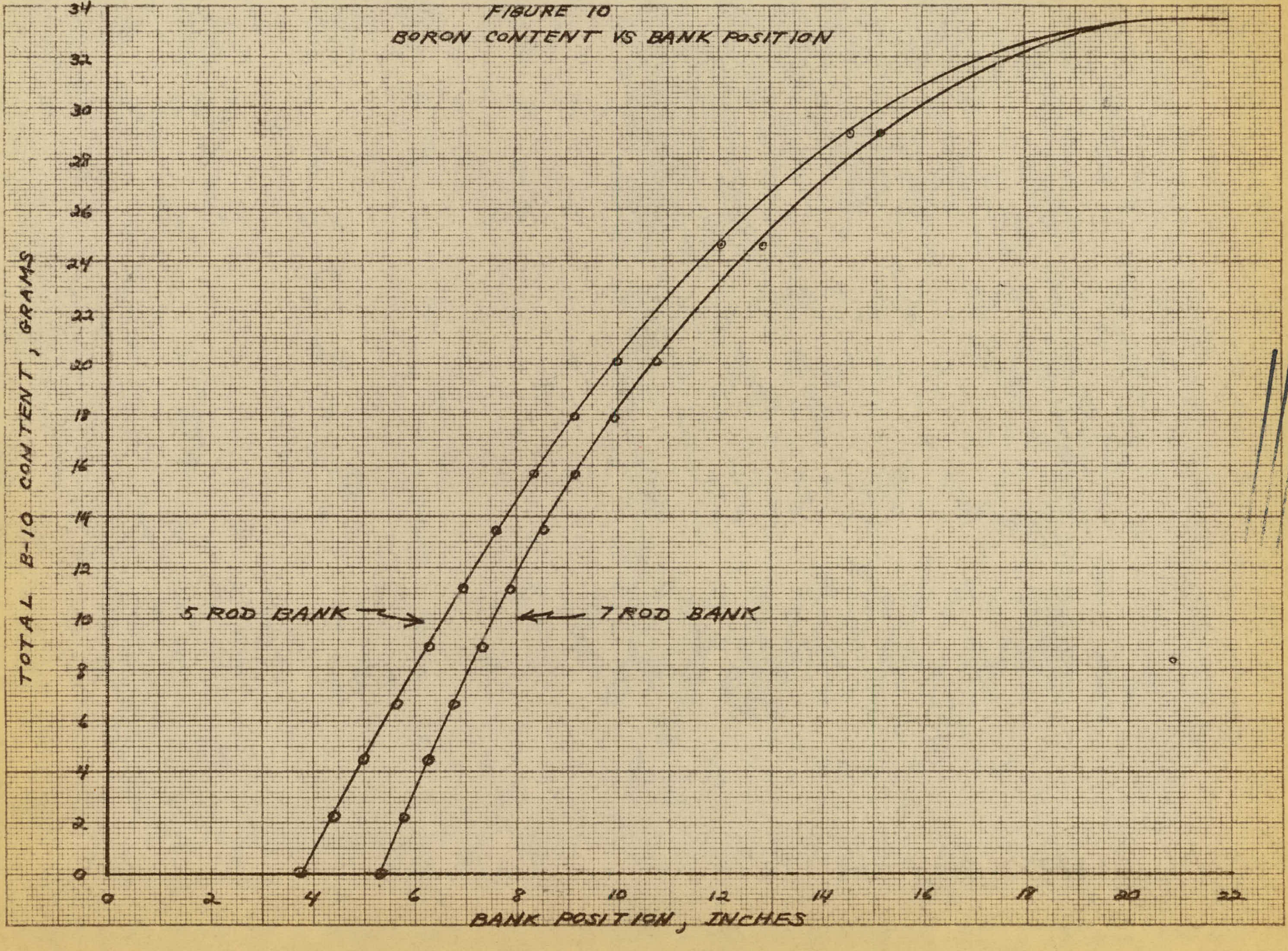
FIGURE 10
BORON CONTENT VS BANK POSITION



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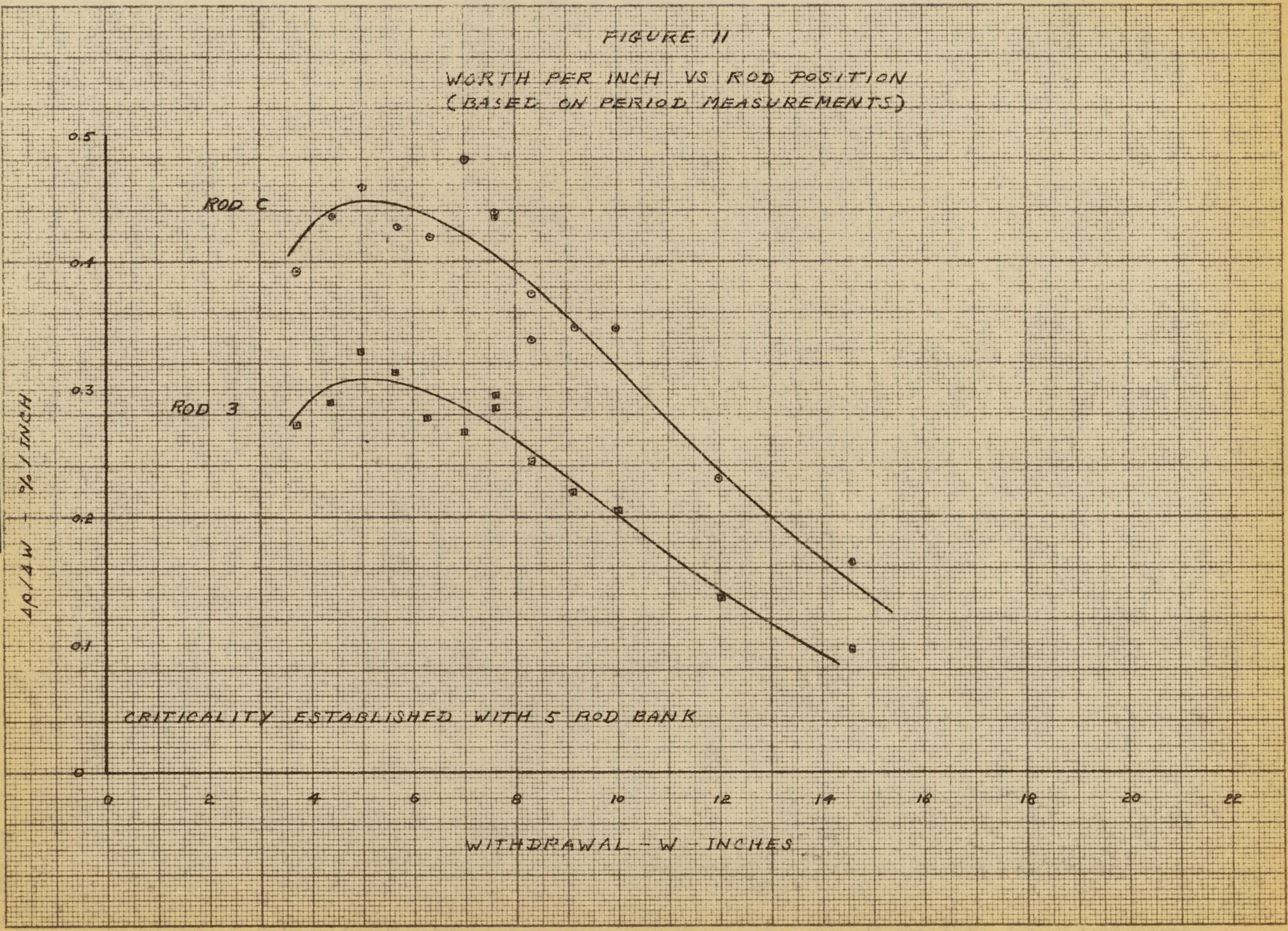

FIGURE 11

WORTH PER INCH VS ROD POSITION
(BASED ON PERIOD MEASUREMENTS)

CRITICALITY ESTABLISHED WITH 5 ROD BANK

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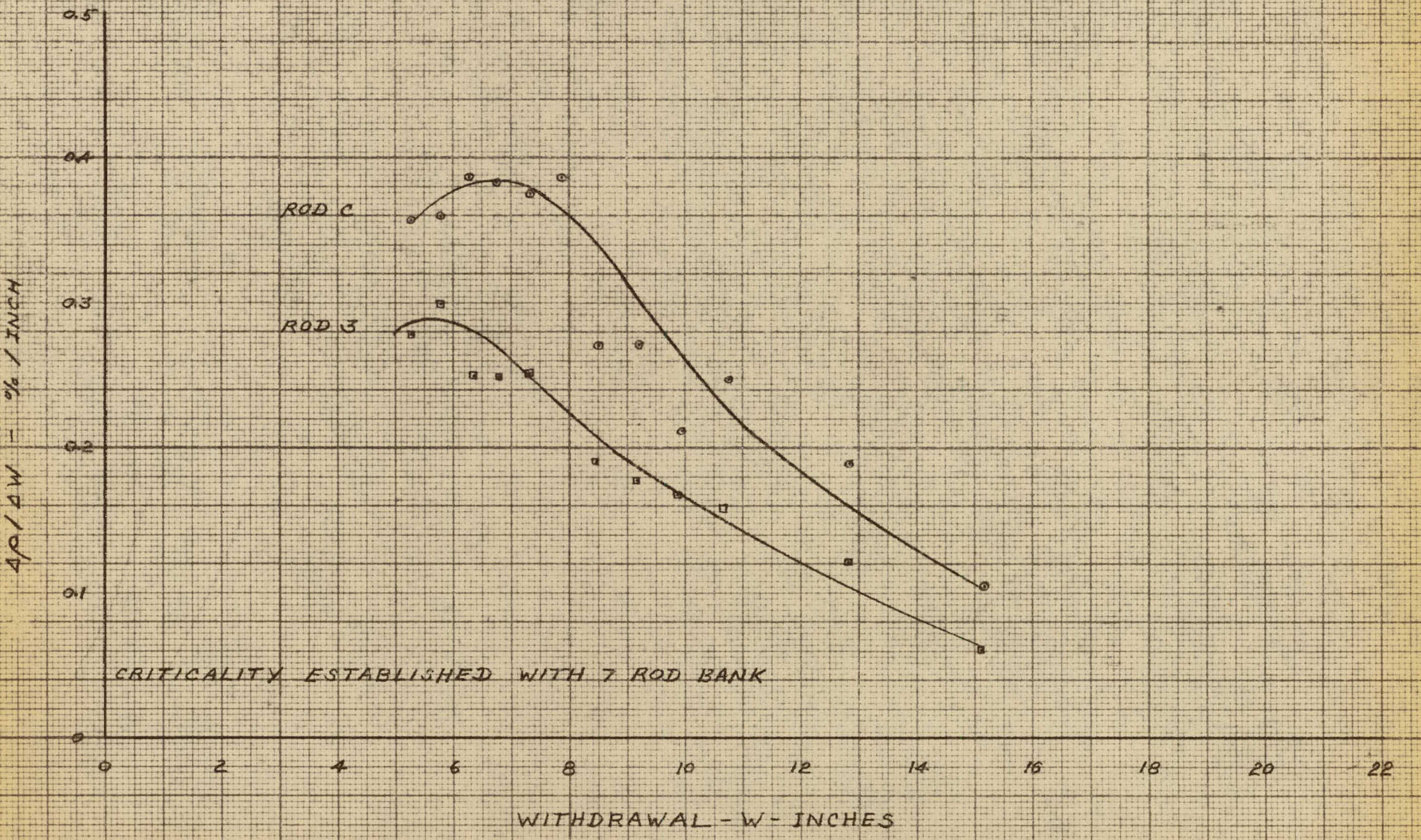
FIGURE 12

WORTH PER INCH VS ROD POSITION
(BASED ON PERIOD MEASUREMENTS)



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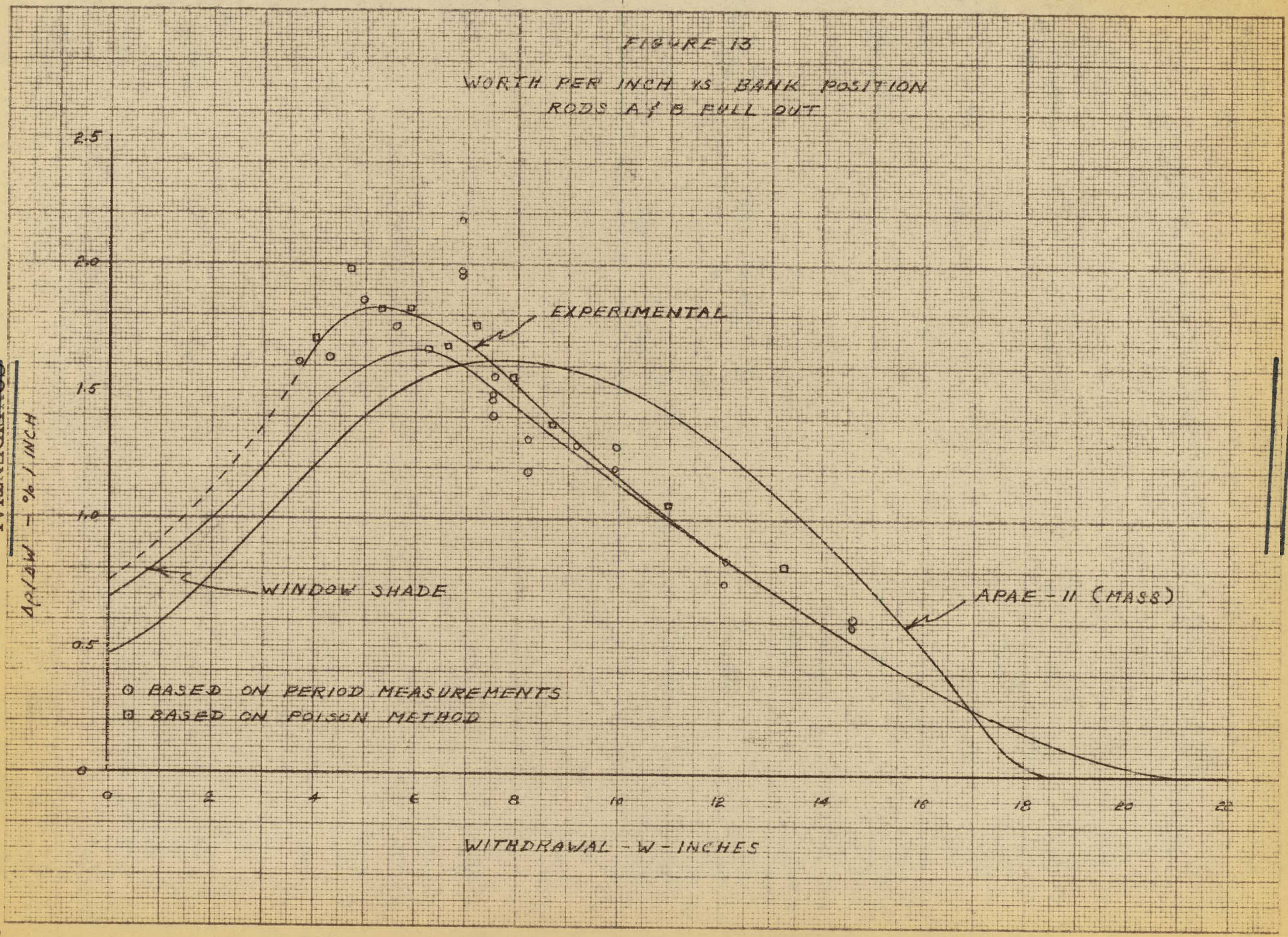

FIGURE 13

WORTH PER INCH vs BANK POSITION
RODS A & B FULL OUT

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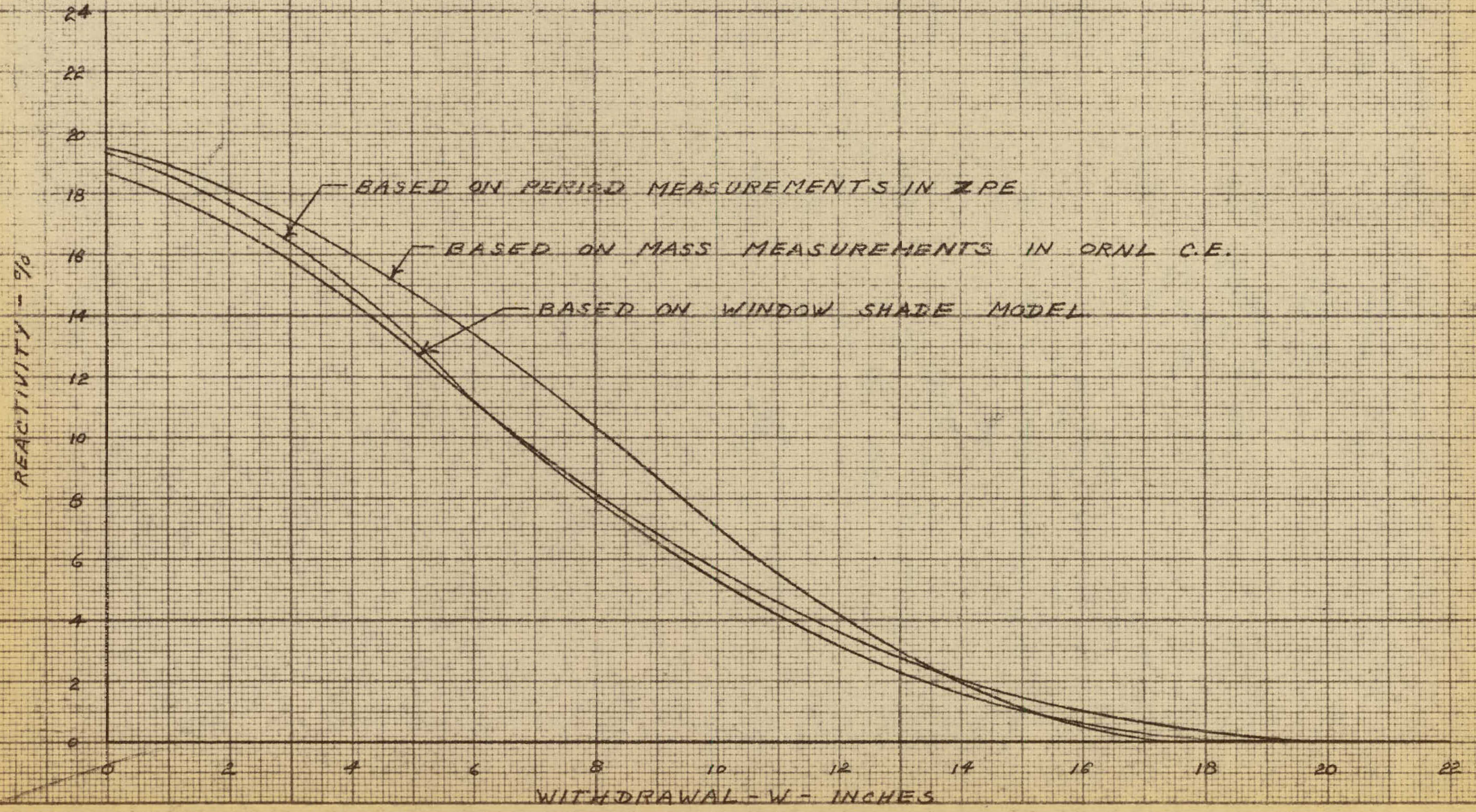
FIGURE 14

BANK WORTH VS POSITION
(5 ROD BANK)



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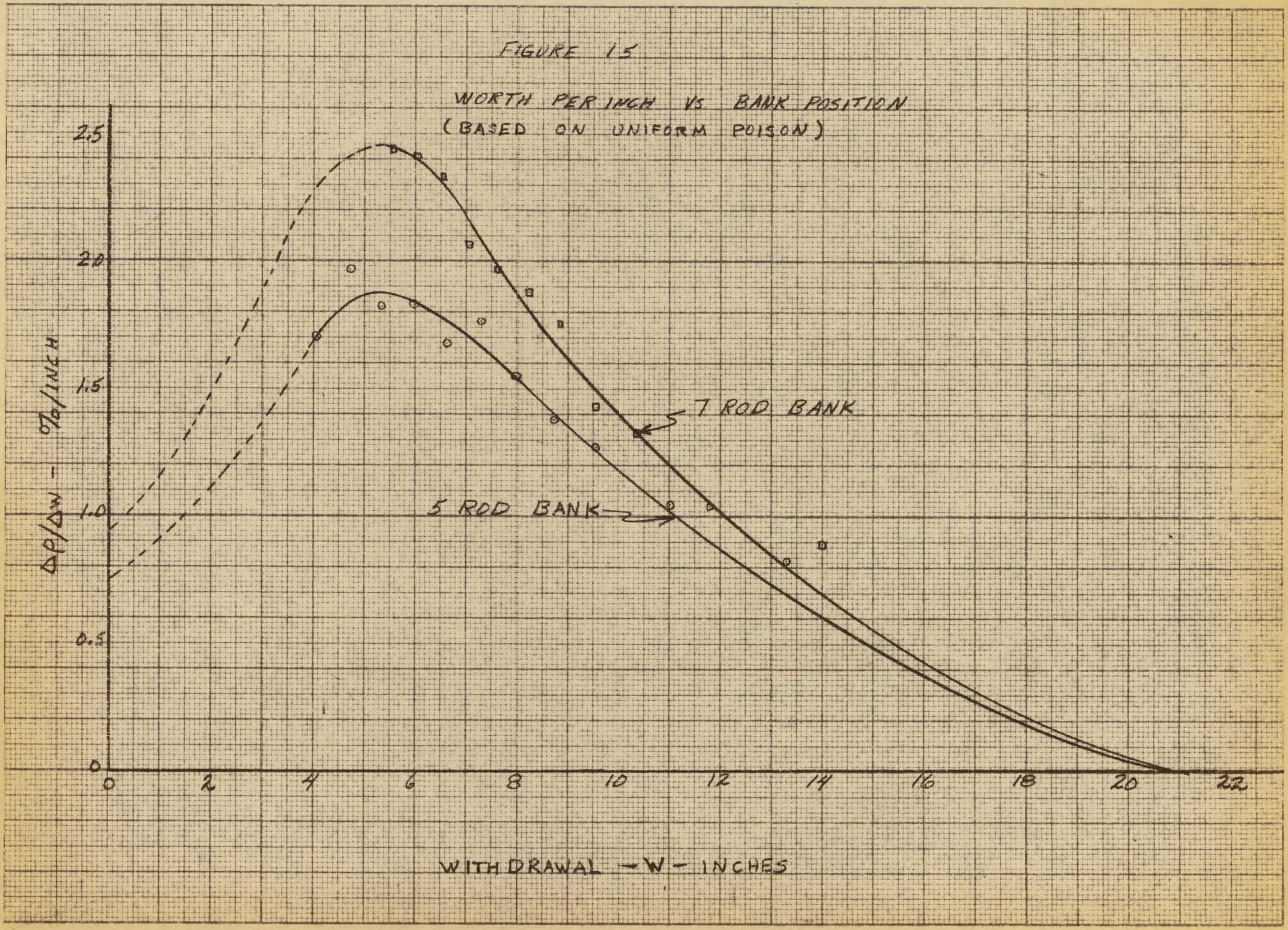

FIGURE 15

WORTH PER INCH VS BANK POSITION
(BASED ON UNIFORM POISON)

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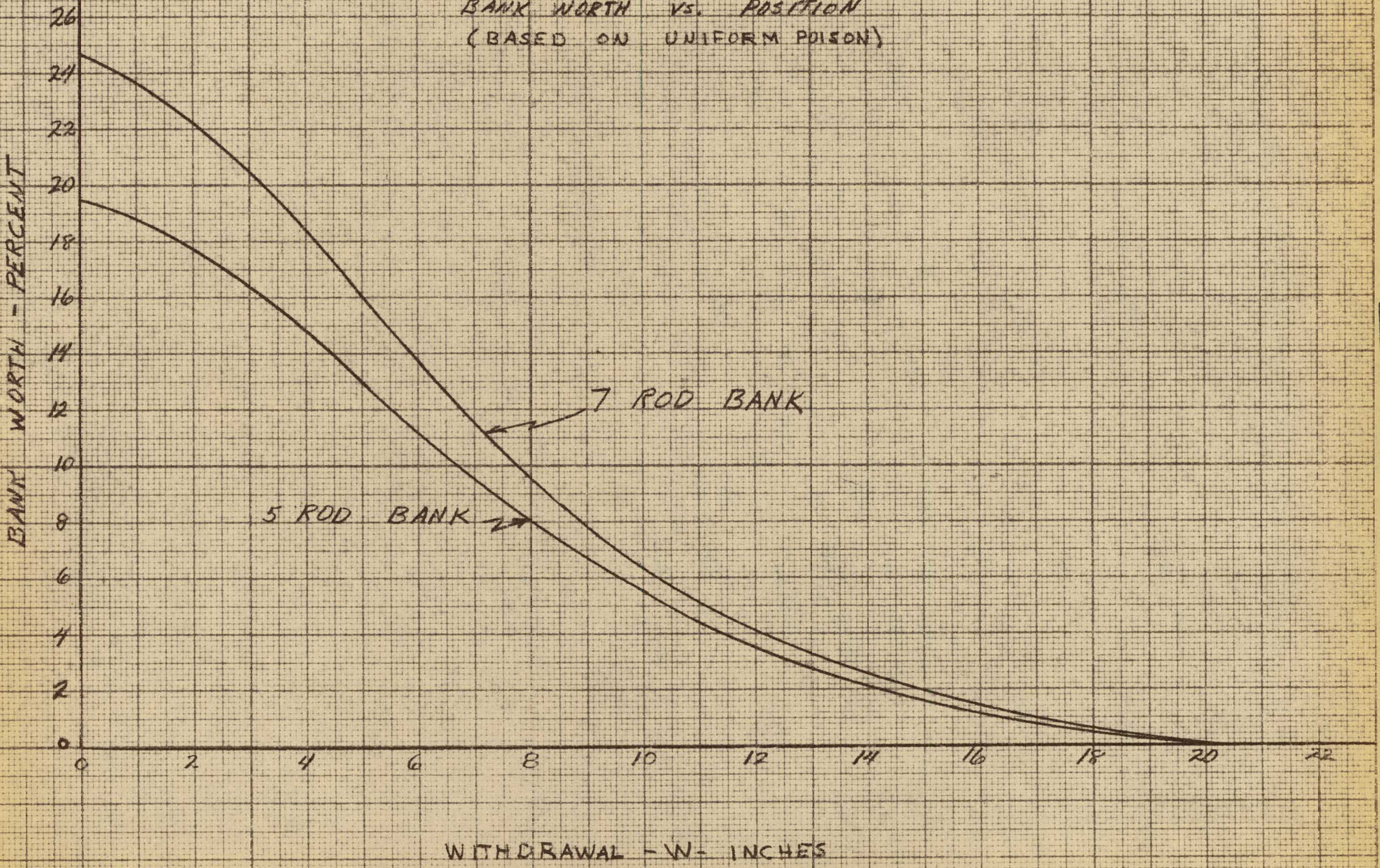
FIGURE 16

BANK WORTH vs. POSITION
(BASED ON UNIFORM POISON)



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G. Poison Additions to Center 25 Fuel Elements

The effect of distributing poison in the center 25 fuel elements of the reactor was determined. Runs were made with 3, 4 and 5 strips in position, thus varying the boron content, Criticality was established with the five rod bank and also with the center rod or an eccentric rod when certain rods of those remaining were fully withdrawn. Period measurements were made to determine the approximate worth of the final few inches of rod 1.

Table 9 contains a summary of the data for this experiment.

TABLE 9
SUMMARY OF POISON ADDITIONS TO CENTER 25 FUEL ELEMENTS

Run	Boron-10 Content grams	Control Rod Positions, Inches 1	2	C	3	4	A	B
1-1	6.225	22.00	0.00	5.58	0.00	0.00	22.00	22.00
1-2	6.225	8.08	0.00	22.00	0.00	0.00	22.00	22.00
1-3	6.225	6.32	6.33	6.23	6.31	6.36	22.00	22.00
1-4	6.225	22.00	0.00	9.72	0.00	0.00	22.00	0.00
2-1	4.980	19.53	0.00	0.00	0.00	0.00	22.00	22.00
2-2	4.980	5.80	5.84	5.73	5.85	5.84	22.00	22.00
2-3	4.980	5.85	0.00	22.01	0.00	0.00	22.00	22.00
2-4	4.980	22.00	0.00	6.47	0.00	0.00	22.00	0.00
3-1	3.750	5.16	5.20	5.00	5.16	5.22	22.00	22.00
3-2	3.750	0.28	0.24	17.70	0.24	0.20	22.00	22.00
3-3	3.750	19.66	0.24	0.10	0.24	0.19	22.00	0.00

NOTE: In run 2-1, Period established by moving rod 1 full out determined worth to be about 6¢.

In run 3-3, Period established by moving rod 1 full out determined worth to be about 4¢.

CHAPTER II
INTERPRETATION OF EXPERIMENTAL MEASUREMENTS

Comparisons between the experimental values and those derived analytically for characterization of the APPR-1 core are presented in this chapter together with postulations of the possible sources of the major discrepancies. A general comparison of predicted and experimental results indicate that the APPR-1 has approximately 5% more excess reactivity than that which was calculated. The discrepancy can, in some instances, be attributed to known differences between the APPR-1 core as built, and that on which calculations were based (1) (3). Some of the reasons for the discrepancy are yet to be measured and others can only be postulated. As a result of the additional excess reactivity present, the predicted initial critical size, critical water height, and shim bank position were in error by amounts essentially attributable to the additional excess reactivity present.

A. Comparison of Predicted and Experimental Values

1. Initial Critical Size

The initial critical size had been calculated to be 22 fuel elements. Experimentally only 17 elements were required to achieve criticality. Although the two group model can be expected to be more subject to error at small core sizes, the presence of additional reactivity over that calculated continued to exist at the full core loading.

2. Buildup to 7 x 7 APPR-1 Array

Throughout the buildup to the 7 x 7 APPR-1 the five rod bank was inserted more deeply than had been calculated in (3). In Figure 17 the predicted and actual shim bank position are plotted. The insertion at the full loading is approximately 3 inches greater than that calculated. The calculated curve of shim bank insertion vs. number of elements was based on the Σp for the bank established from the 7 x 7 (45 elements) reactor (3). Since the location of the control rods relative to the outside radius of the reactor changes, this assumption will overestimate the bank worth in the smaller cores.

3. Critical Water Height

The measured critical water height was 9 inches from the bottom core reflector interface compared to a calculated value of 13.6 inches. Part of this difference is due to the assumption that the reflector savings for the fuel, steel, and air region above the water filled core region was $0.71\,\lambda_{tr}$ of the core. Due to neutron leakage from the water filled core, the air fuel region is a multiplying medium and as a result contributes to the total core reactivity. However, the major difference is due to the additional excess reactivity in the water filled core.

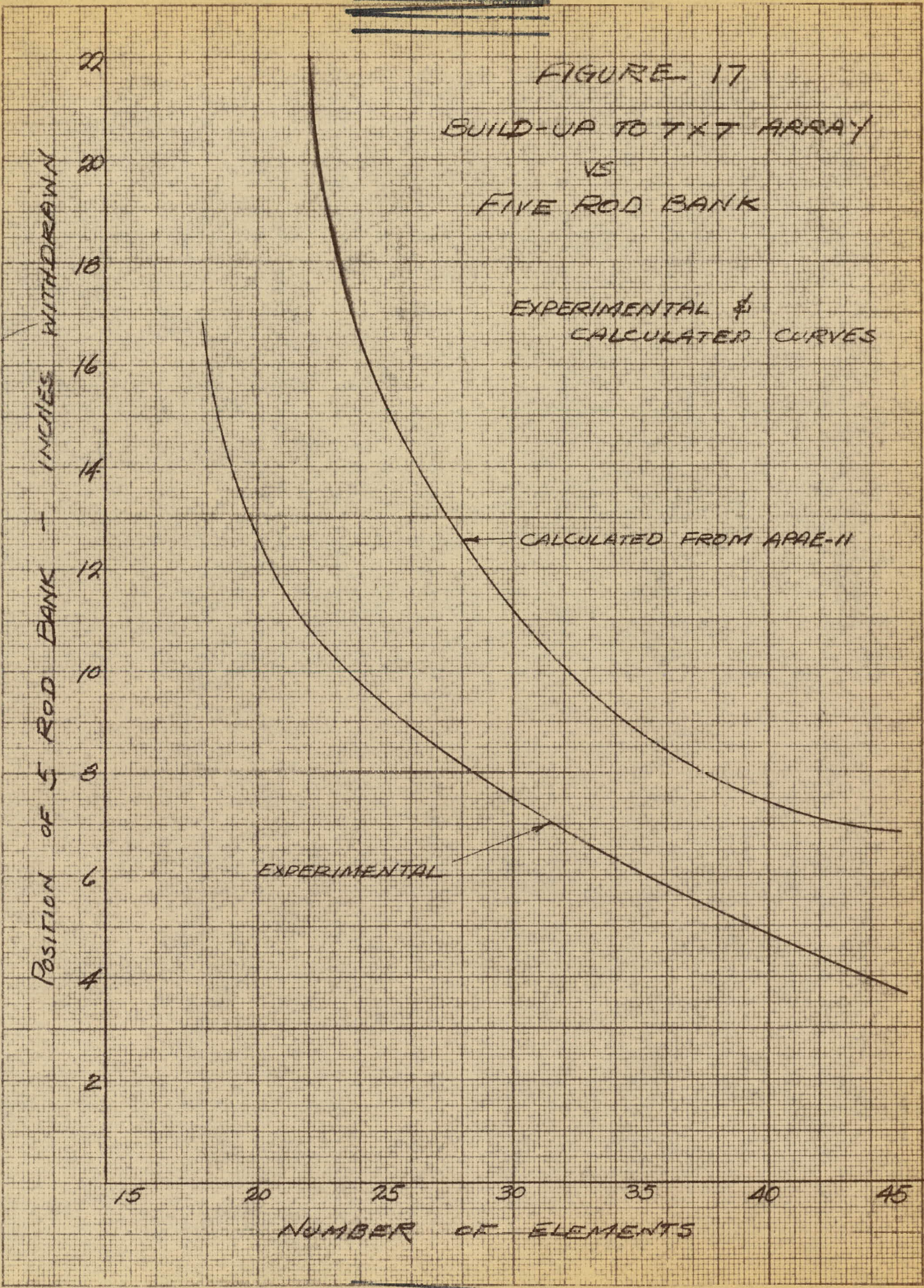

FIGURE 17

BUILD-UP TO 7×7 ARRAY VS FIVE ROD BANK

EXPERIMENTAL & CALCULATED CURVES

4. Bank Position versus Temperature

The position of the five rod shim bank for 68°F to 200°F has been measured. The measured and calculated positions differ from 3 to 3-1/2 inches from 68°F to 200°F with the measured position being more deeply inserted. In Figure 18 the calculated and experimental bank position is given. It is seen that the slopes of the two curves are nearly the same.

5. Temperature Coefficient versus Temperature

The temperature coefficient has been measured from 68°F to 200°F. In Figure 19 the calculated and experimental temperature coefficients are plotted. Although the measured coefficient is less negative at lower temperatures, its slope is greater. Extrapolation of the experimental points indicate a temperature coefficient more negative than -2×10^{-4} $\Delta K/^{\circ}F$.

B. Possible Sources of Additional Reactivity

Among the possible sources of the additional excess reactivity are lack of heterogeneity, reduced stainless steel content, loss of boron, the over-estimation of the poison due to the control rod fuel element characteristics and basket, and the calculational model. See Tables 11 and 12 for summary.

1. Heterogeneity

Previous calculations of the thermal multiplication factor included weighing and self shielding factors. In order to evaluate the effect of the heterogeneity, the multiplication factor has been calculated on the basis of a homogeneous mixture of core materials.

(a) Effect on Reactivity

The homogeneous calculation introduces additional reactivity in varying amounts when considered with respect to temperature and lifetime. Since weighing and self shielding factors were more severe at 68°F than at 450°F, more additional reactivity is calculated at 68°F. In addition the weighing and self shielding factors were a function of the fuel plate absorption, and, consequently, were more severe at 68°F than at 450°F.

In Table 10 a comparison of reactivities at 68°F and 450°F is made. (No Xe or Sm).

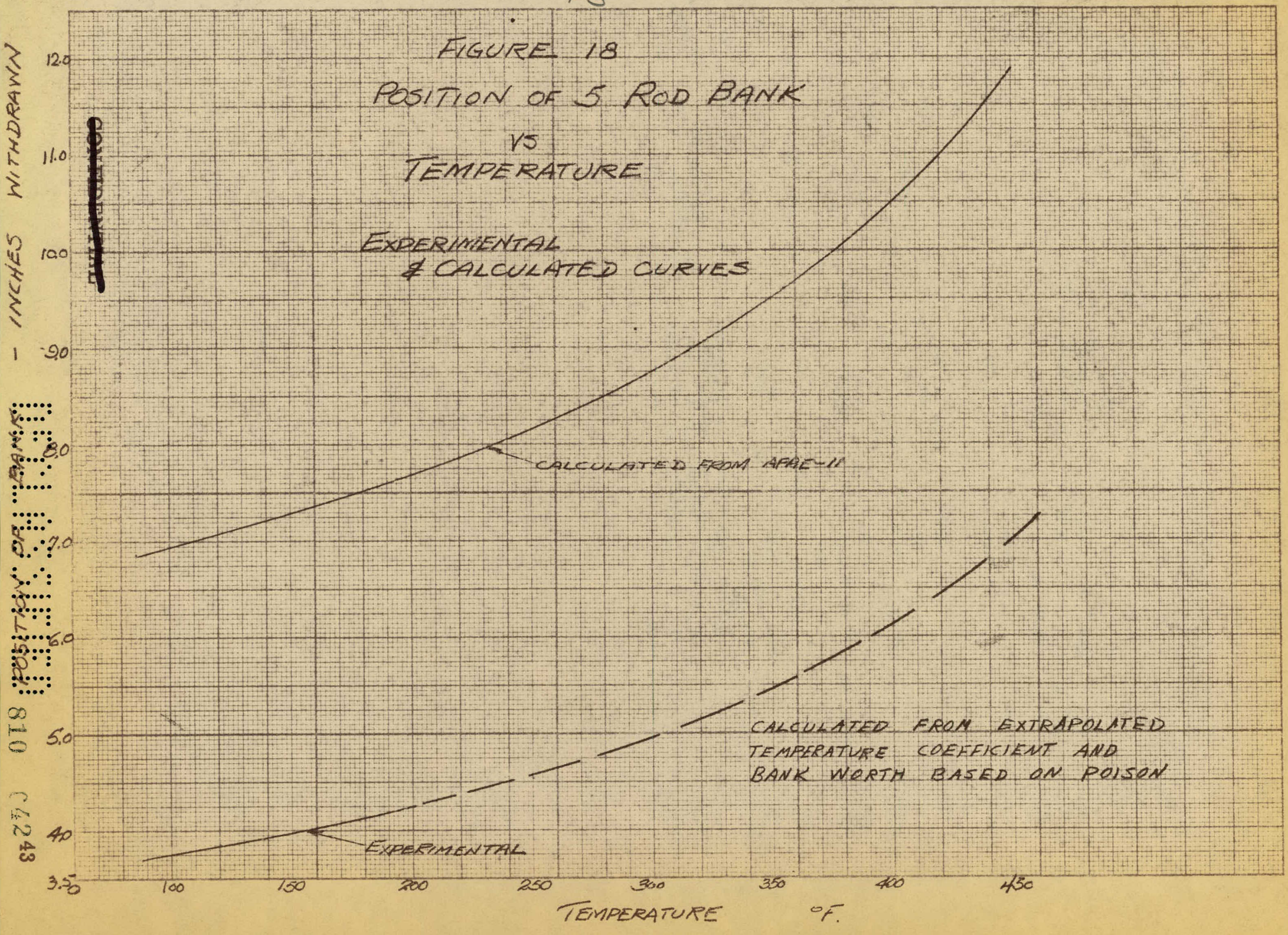

FIGURE 18
POSITION OF 5 ROD BANK
VS
TEMPERATURE

EXPERIMENTAL
& CALCULATED CURVES

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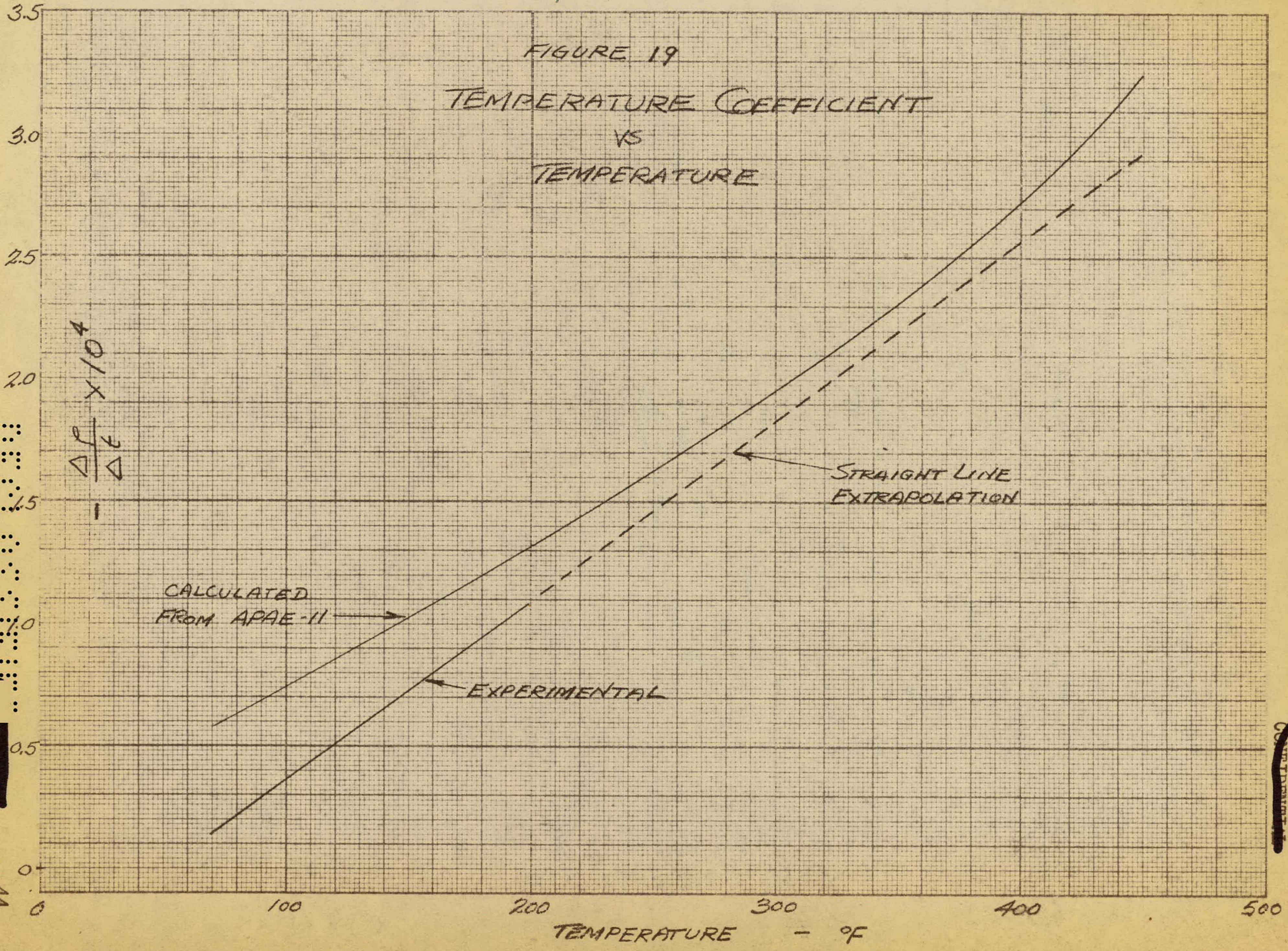


FIGURE 19

TEMPERATURE COEFFICIENT VS TEMPERATURE

[redacted] 810

C43 44

[redacted]

TABLE 10
COMPARISON OF HETEROGENEOUS AND HOMOGENEOUS REACTIVITIES

Temperature °F	Heterogeneous Reactivity %	Homogeneous Reactivity %	$\Delta\rho$ %
68	10.2	13.0	2.8
450	5.2	6.6	1.4

(b) Effect on Initial Critical Size

A homogeneous calculation of the initial critical size indicates criticality with 19 elements. This compares with 22 elements based on a heterogeneous model, and 17 elements found experimentally. For the 17 element core, $K_{eff} = 0.949$ and 0.977 for a heterogeneous and homogeneous calculation, respectively.

(c) Effect on Bank Position

The shim bank position has been reevaluated on a homogeneous model. The absorber insertion has been found to be 16.6 inches compared to 17.0 inches measured experimentally and 13.80 inches in the heterogeneous model.

In Figure 20 a comparison is shown of the shim bank worth on a homogeneous and heterogeneous basis. It is seen that the bank worth is less in the homogeneous model, since a constant window shade poison was used in both calculations. The control rod poison is less effective in the homogeneous core. The experimental bank worth is 19.4%.

The absorber insertion at 450°F with no xenon or samarium has been calculated as being 8.91 inches for a heterogeneous model and 10.34 inches for a homogeneous model.

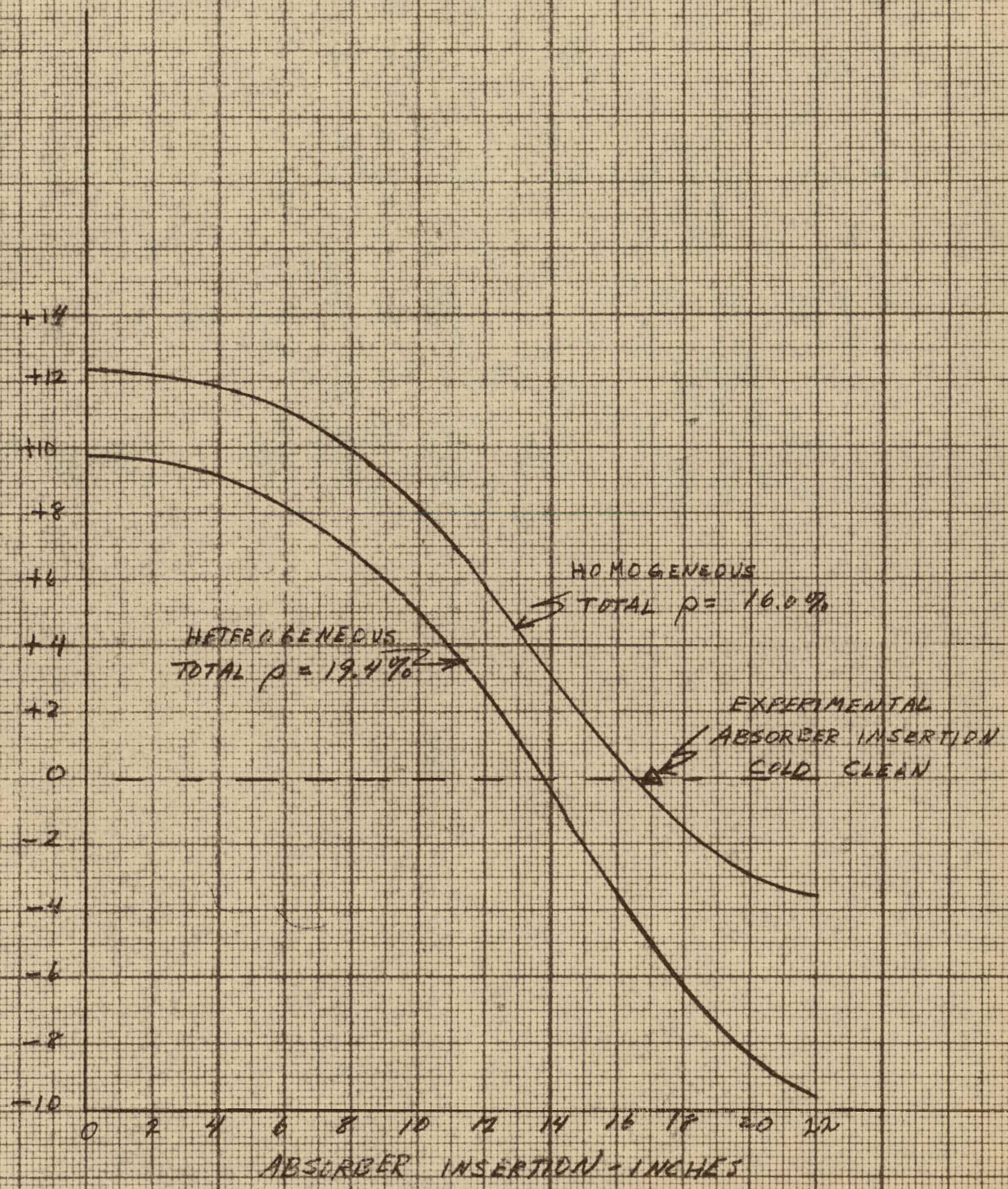
2. Reduced Stainless Steel Content

Calculations previously had assumed a volume percent for stainless steel in the core as being 18.5%. A review of ORNL specifications (to be published) for the APPR-1 elements indicated that the amount of stainless steel powder placed in the fuel bearing compact of a fixed fuel element plate is 99.8 gram. This compares to 118 gram used in the calculation. This difference amounts to 1.34% by volume of the steel content in the core. Reduction of the steel content from 18.5% to 17.16% results in an increase in excess reactivity of approximately 0.9% and causes the 5 rod shim bank to be inserted approximately 0.54 inches further than that calculated at 68°F in the heterogeneous model.

FIGURE 20

APPR-1

SHIM BANK CALCULATIONS



3. Loss of Boron in Sintering

Chemical analysis of the fuel compact after sintering has indicated a possible sintering loss of approximately 6% of the boron. This loss is estimated to be the maximum loss, since the chemical analysis has a degree of uncertainty. A loss of this amount of boron amounts to approximately 0.5% in added reactivity.

4. Overestimation of Poison due to Control Rod Fuel Element Characteristics

Calculations in (1) and (3) have used a uniform poison to account for characteristics of the control rod fuel element and basket. Omitting this poison increases the reactivity by approximately 1.2%.

5. Effect of Calculational Model on Reactivity of APPR-1

(a) Continuous Slowing Dowl Model

Calculations were made to determine the effect of calculational model on K_{eff}. A comparison was determined between the modified two group model and the continuous slowing down model.

For the modified two group model the expression for K_{eff} is, from (3):

$$K_{eff} = \frac{(1-p)\,K_f}{(1+\tau B^2)} + \frac{p\,K_{th}}{(1+\tau B^2)\,(1+L^2B^2)}$$

where K_f = Fast Multiplication Factor
K_{th} = Thermal Multiplication Factor
p = Resonance Escape Probability
τ = Age of Neutrons to Thermal
B^2 = Geometric Buckling
L^2 = Thermal Diffusion Length Squared

For the continuous slowing down model the expression is, from (4):

$$K_{eff} = \nu \int_0^{u_{th}} \frac{\Sigma_f(u)}{\xi \Sigma_T(u)}\, e^{-B^2 \int_0^{u} \frac{D(u')\,du'}{\xi \Sigma_T(u')}}\, e^{-\int_0^{u} \frac{\Sigma_a(u')\,du'}{\xi \Sigma_T(u')}}\, du$$

$$+ \frac{K_{th}\, p\, e^{-B^2\tau}}{1 + L^2 B^2}$$

where u = lethargy
Σ_f = macroscopic fission cross-section
ξ = average logarithmic energy decrement per collision
D = diffusion coefficient
Σ_T = macroscopic total cross-section
ν = neutrons per fission

In using the expression from the modified two group model the heavy critical experiment performed at ORNL was used to determine τ for criticality. Five energy groups were used. The five group cross-sections presented in (1) were used following verification that their use gave an age for water of 31.6 cm^2. K_{th}, L^2 and B^2 were taken from (1). τ was determined to be 39.008 cm^2. This age was used to find K_{eff} for the APPR-1 core. The K_{eff} so determined was 1.1130.

In using the expression for K_{eff} from the continuous slowing down model the data was adjusted to fit the heavy critical experiment. Adjustments were made in the first group (the high energy group, $0 \leq u \leq 4$). Criticality was realized by adjusting the average logarithmic energy decrement per collision in stainless steel from 0.0353 to 0.600 on the basis of information in (5) on the effect of inelastic scattering of iron and by adjusting the macroscopic scattering cross-section for stainless steel from 0.243 to 0.283 cm^{-1}. Using the adjusted data K_{eff} was determined for the APPR-1 to be 1.106.

The use of the more exact expression for K_{eff} results in a difference in $\Delta K = .007$.

(b) Two Region Calculations

All the calculations of the APPR-1 core were based on an equivalent bare model using a B^2 based on reflector savings estimated from experiments. (1) To determine the effect of the use of the equivalent bare model for calculation of K_{eff} for the APPR-1, a two region calculation was made using the core and reflector properties from (1). A value of ν/ν_c of 0.8975 when applied to K_f and K_{th} made the two region model critical. The K_{eff} for this model is then 1.114 compared to 1.1130 for the equivalent bare model, and 1.182 experimentally.

The radial reflector savings was 5.97 cm compared with 6.03 cm found from critical experiment data.

TABLE 11
EFFECT OF CALCULATIONAL MODEL ON REACTIVITY

Model	K_{eff} 68° clean
Modified two group, equivalent bare	1.113
Modified two group - two region	1.114
Continuous slowing down	1.106
Experimental	1.182

TABLE 12
SUMMARY OF POSSIBLE SOURCES OF ADDITIONAL REACTIVITY

Possible Source	% reactivity
Lack of Heterogeneity - maximum	+2.8
Reduce Stainless Steel content	+0.9
Loss of Boron in Sintering - maximum	+0.5
Over estimation of Control Rod Poison - maximum	+1.2
Total - maximum	+5.4

The calculated reactivity is 10.2% and the experimental is 15.4% or 5.2% greater.

CHAPTER III
ANALYSIS OF ADDITION OF POISON TO CENTER 25 FUEL ELEMENTS

As a result of the additional excess reactivity in the APPR-1 core, experiments have been made on the feasibility of adding additional boron to the center 25 fuel elements*. It was anticipated that the APPR-1 core could be poisoned sufficiently in the inner region to permit reactor shutdown with any two and possibly three rods stuck full out.

Originally the APPR-1 was to be controlled by five rods with shutdown accomplished by any four rods. Preliminary calculations in (6) indicated that the shutdown margin at midlife was marginal. As a result two additional rods were added.

In Table 5 it is seen that there are several cases where only one rod can remain stuck full out and still permit shutdown in the cold clean reactor. Depending on the quantity of boron-10 present in the core, the reactivity will increase to some degree and then decrease during the core life since the boron burns out much more rapidly than does the uranium.

It had been deemed desirable to be able to attain shutdown at any time during the core life with rods 1 and A full out and if possible with 1, A and B full out. Since the additional boron-10 would be added to the center 25 elements, the APPR-1 core was poisoned with boron steel strips in that region to determine how much additional boron-10 would be required to meet the above requirements. In Figure 21 a plot of percent reactivity overridden by additional one region and two region boron is given. The figure was evaluated from a cross plot of data in Figure 10 and Figure 16 for one region boron and from Table 9 for the two region boron. From Table 9 and Figure 21 it is seen that 2.7% reactivity must be overridden to move rods 1 and A full out and 3.8% reactivity must be overridden to move rods 1, A and B full out in the cold clean reactor. If the core has 15.4% excess reactivity, rods 2, 3, 4 and C then override 11.6% reactivity.

In Figure 22 the excess reactivity versus core energy is plotted for various uniform (one region) boron loadings as in (3).

In Figure 23 the changes in reactivity at 68°F and 450°F are plotted. Although the absolute reactivities in Figure 22 are different from those measured, the relative changes in Figure 23 are assumed valid.

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* Since ORNL is presently fabricating a second set of APPR-1 fuel elements for the Fort Belvoir installation, additional boron could be added to 25 elements.

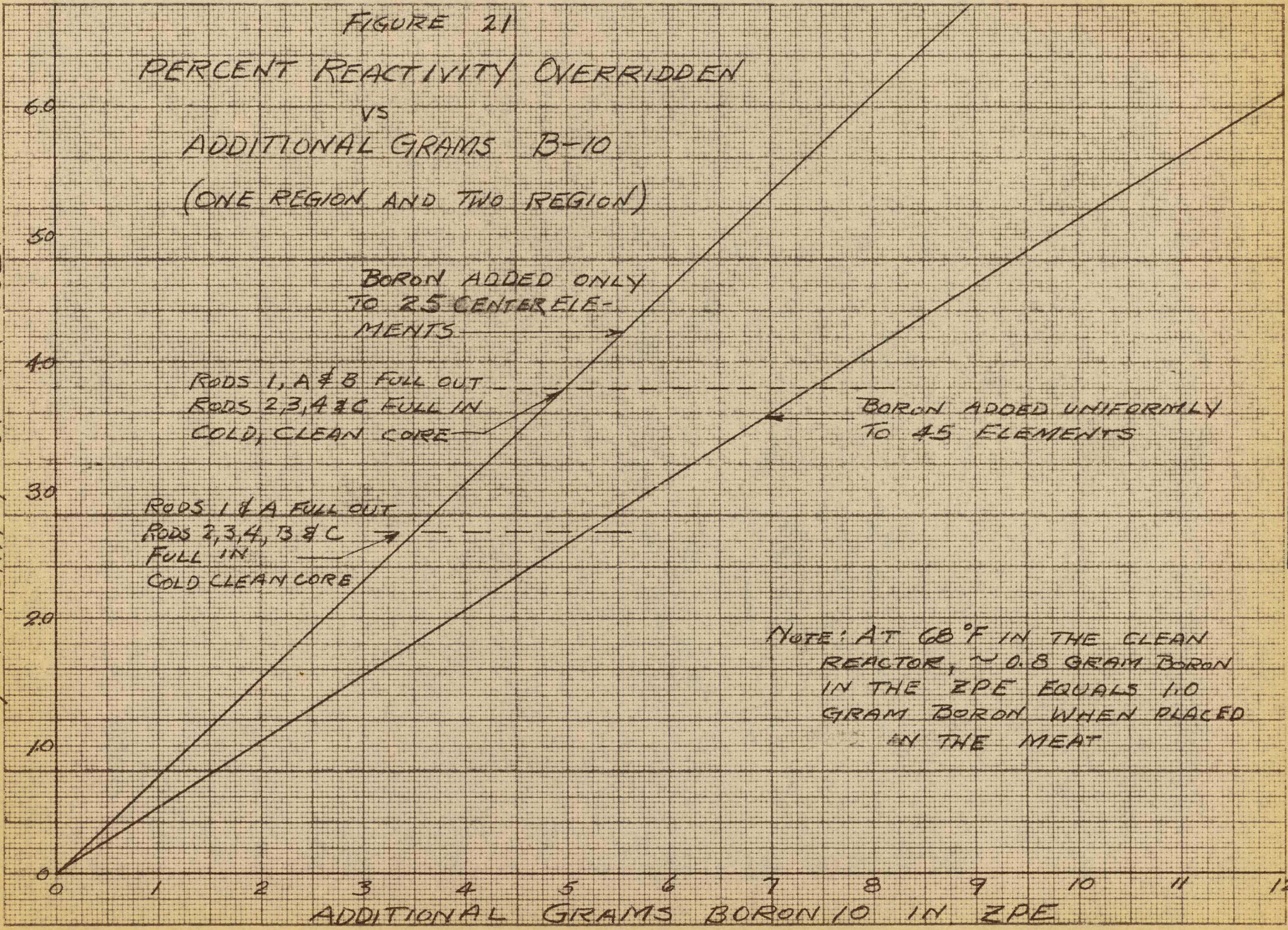


FIGURE 21

PERCENT REACTIVITY OVERRIDDEN
VS
ADDITIONAL GRAMS B-10
(ONE REGION AND TWO REGION)

BORON ADDED ONLY TO 25 CENTER ELEMENTS

RODS 1, A & B FULL OUT
RODS 2,3,4 & C FULL IN
COLD, CLEAN CORE

BORON ADDED UNIFORMLY TO 45 ELEMENTS

RODS 1 & A FULL OUT
RODS 2,3,4, B & C
FULL IN
COLD CLEAN CORE

NOTE: AT 68°F IN THE CLEAN REACTOR, ~0.8 GRAM BORON IN THE ZPE EQUALS 1.0 GRAM BORON WHEN PLACED IN THE MEAT

Due to the differences in weighing and self shielding factors in the ZPE boron strips and the boron in the APPR-1 fuel element, 0.8 grams of boron in the ZPE is assumed equal to 1.0 gram in the APPR-1. A comparison of the one and two region boron additions in Figure 21 indicates that approximately 0.7 gram boron in the inner region is equivalent to 1.0 gram over the whole core. The APPR-1 core contains 20.9 grams of B-10 within the fuel elements.

From Figure 23 it is seen that the addition of approximately 7 grams-Boron 10 to the APPR-1 uniformly (or 5 gram to the inner region) would permit shutdown with rods 1 and A full out only in the clean reactor. This addition amounts to 2.7% negative reactivity. The addition of approximately 9 grams-Boron 10 to the APPR-1 uniformly (or 6 grams to the inner region) would permit shutdown with rods 1, A and B full out, also, only in the clean reactor. This addition amounts to 3.8% negative reactivity. Since the boron burns out rapidly, the excess reactivity soon exceeds the permissable amount. In general for each percent reactivity overridden by boron in the clean reactor, only one-half of that amount will be present at midlife.

On the basis of this approximation, an extrapolation to meet the requirement that rods 1 and A can be stuck full out at midlife requires that boron be added in an amount to override 5.4%. For the case with rods 1, A and B full out an amount is required to override approximately 7.6%.

A reactivity balance for the APPR-1 core based on ZPE measurements, where applicable and calculations is given in Table 13.

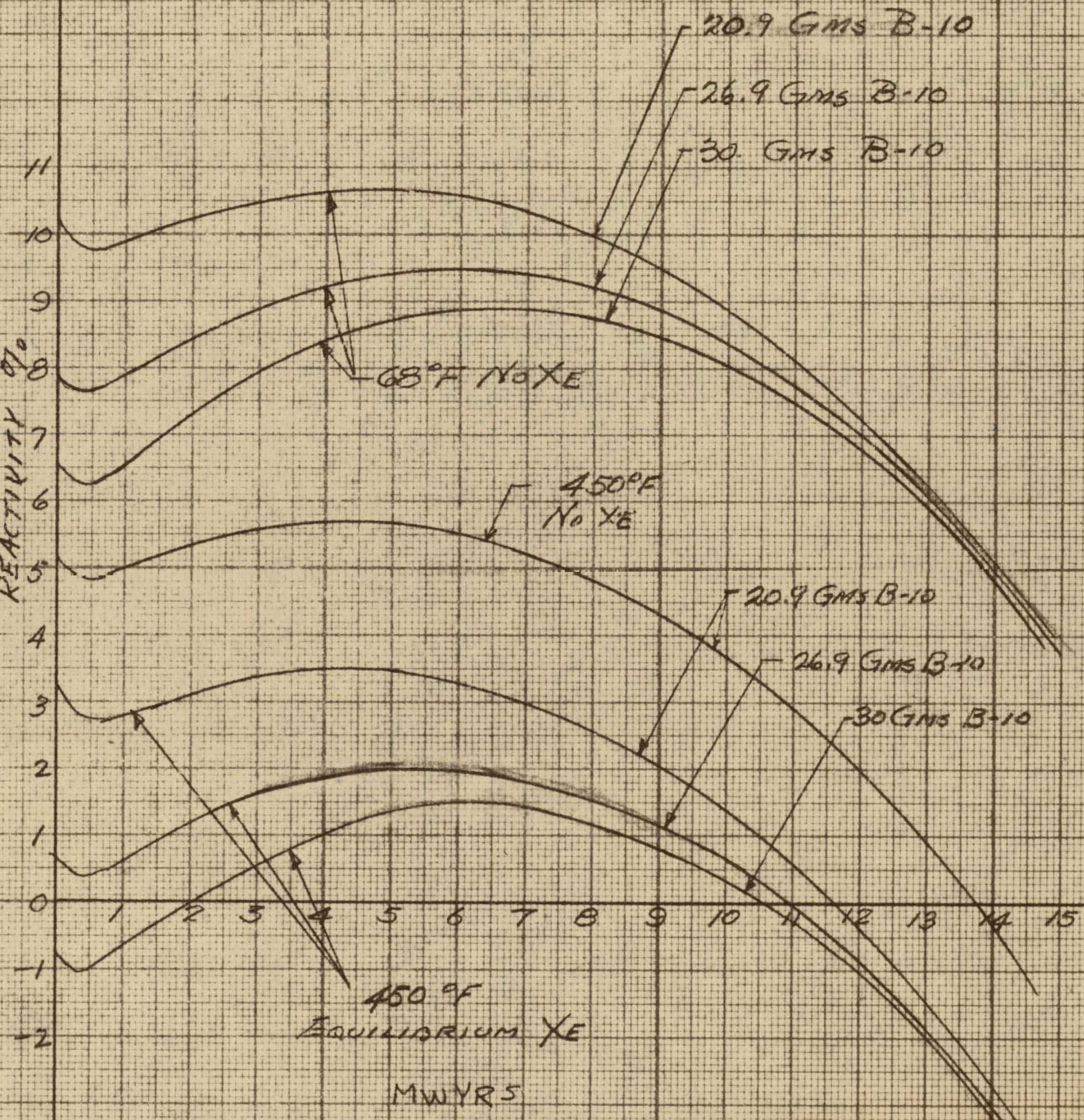
TABLE 13
REACTIVITY BALANCE

Condition	Change in Reactivity %	Net Reactivity Available %
Cold Clean Core 68°F		15.4
Cold to Hot Change	-5.8	
Hot Clean 450°F		9.6
Equilibrium Xenon	-2.0	
Hot with Equilibrium Xenon		7.6
Equilibrium Samarium (0.5 MW YR)	-0.5	
Hot with Equilibrium Xenon and Samarium		7.1
Peak Xenon (Over Equilibrium)	-0.4	
Hot with Peak Xenon, Equilibrium Samarium		6.7

FIGURE 22

APPR-1

REACTIVITY VS CORE ENERGY
(VARIABLE BORON CONTENT)



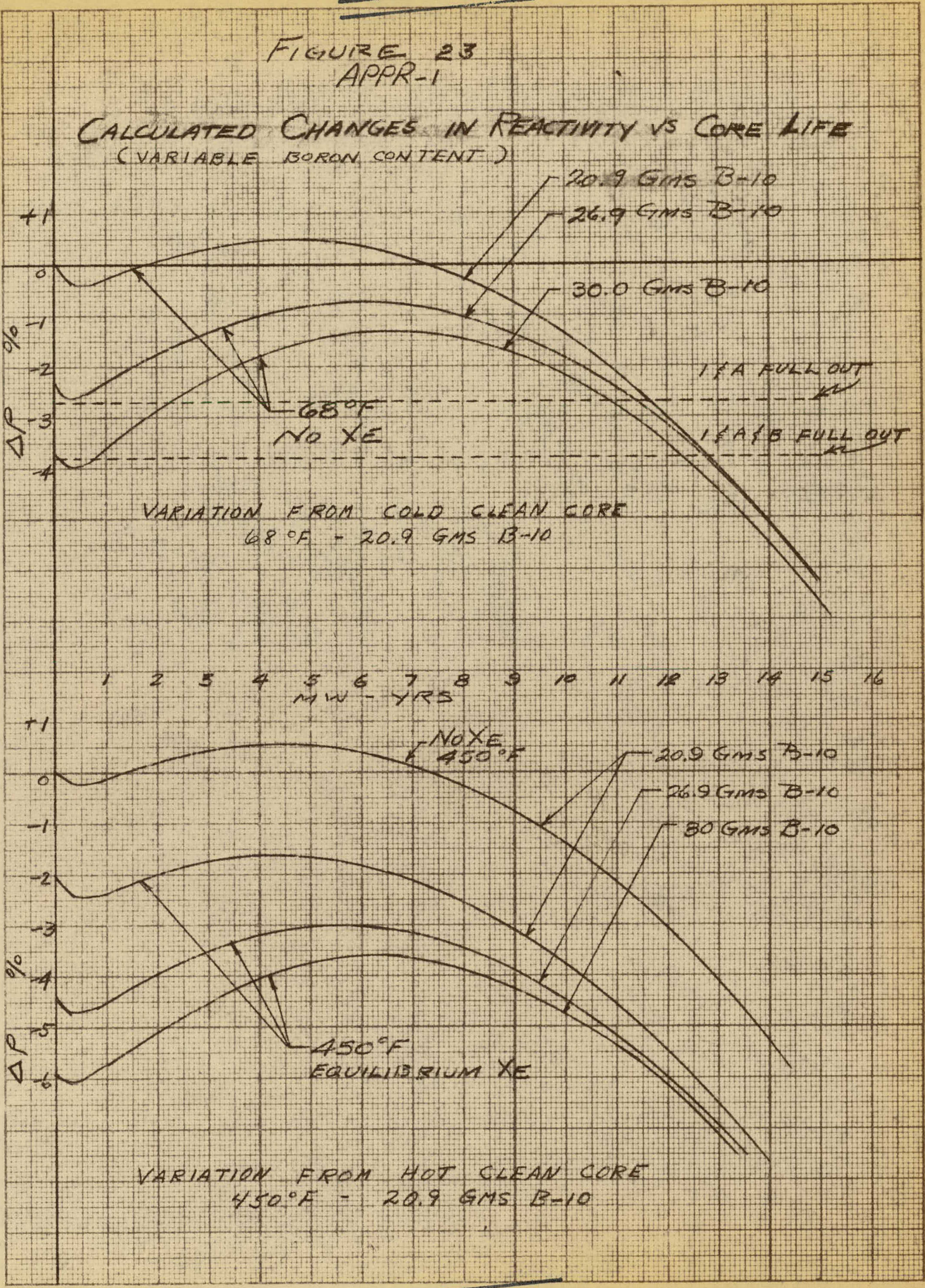


FIGURE 23
APPR-1

CALCULATED CHANGES IN REACTIVITY VS CORE LIFE
(VARIABLE BORON CONTENT)

On the basis of the extrapolated cold to hot change and calculated xenon and samarium reactivity worths, approximately 6.7% excess reactivity is present at 450°F with peak xenon and equilibrium samarium.

Due to uncertainties in the cold initial reactivity and the cold to hot change it is desirable to allow 2% reactivity to insure reactor operation at temperature. This leaves less than 5% excess reactivity than can safely be overridden. Since it is estimated that more than 5% excess reactivity must be overridden in the clean reactor to insure shutdown at any time with rods 1 and A stuck full out, it does not appear desirable to change the present APPR-1 loading to a loading which is two region in boron.

Unless the reactivity changes with respect to temperature, xenon and lifetime are considerably in error, it appears doubtful if the APPR-1 could be shutdown at all times during the life of the reactor with rods 1, A and B full out and still insure operation at 450°F with the present loading of 22.5 Kg U-235.

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CHAPTER IV
OPERATIONAL CHARACTERISTICS OF THE APPR-1

An analysis of the control rod worth as measured in the zero power experiments has been made to predict control rod movement as a function of temperature and lifetime. Various operating procedures are also presented.

A. Control Rod Worth

Two basic assumptions have been made with respect to control rod worth. First, the worth is independent of temperature; and second, the worth is independent of lifetime. These assumptions should be conservative since the core absorption decreases with an increase in temperature and lifetime.

1. Five Rod Bank Worth Measurements

The worth of the five rod bank has been evaluated by both period and poison measurements. The agreement between the two methods is within the experimental error of the period measurements and control rod positions. The excess reactivity based on the integrated period measurements and uniform poison additions is 15.4%. Extrapolation of the worth curve for the five rod bank to the full in position indicates a total worth of 19.4%. Figure 14.

2. Seven Rod Bank Worth Measurements

The worth of the 7 rod bank has been evaluated by the poison method since period measurements were not made. In view of the good agreement between the two methods for the five rod bank, it is believed to be a valid approach. Extrapolation of the worth curve for the seven rod bank indicates a total worth of 24.6%.

B. Position of the Shim Bank at 450°F

The position of the five and seven rod bank as a function of temperature has been calculated on the basis of the extrapolated temperature coefficient and the shim bank worth from the uniform poison additions. The hot to cold change is approximately 6% in reactivity. In Figure 24 the position of the five and seven rod bank as a function of temperature is presented.

C. Shim Bank Position as a Function of Lifetime

The shim bank position as a function of lifetime has been determined from calculated reactivity changes from the hot clean core.

In Figure 25 results of calculations of absolute reactivity versus lifetime based on uniform burnup are given. In Figure 26 the same is presented

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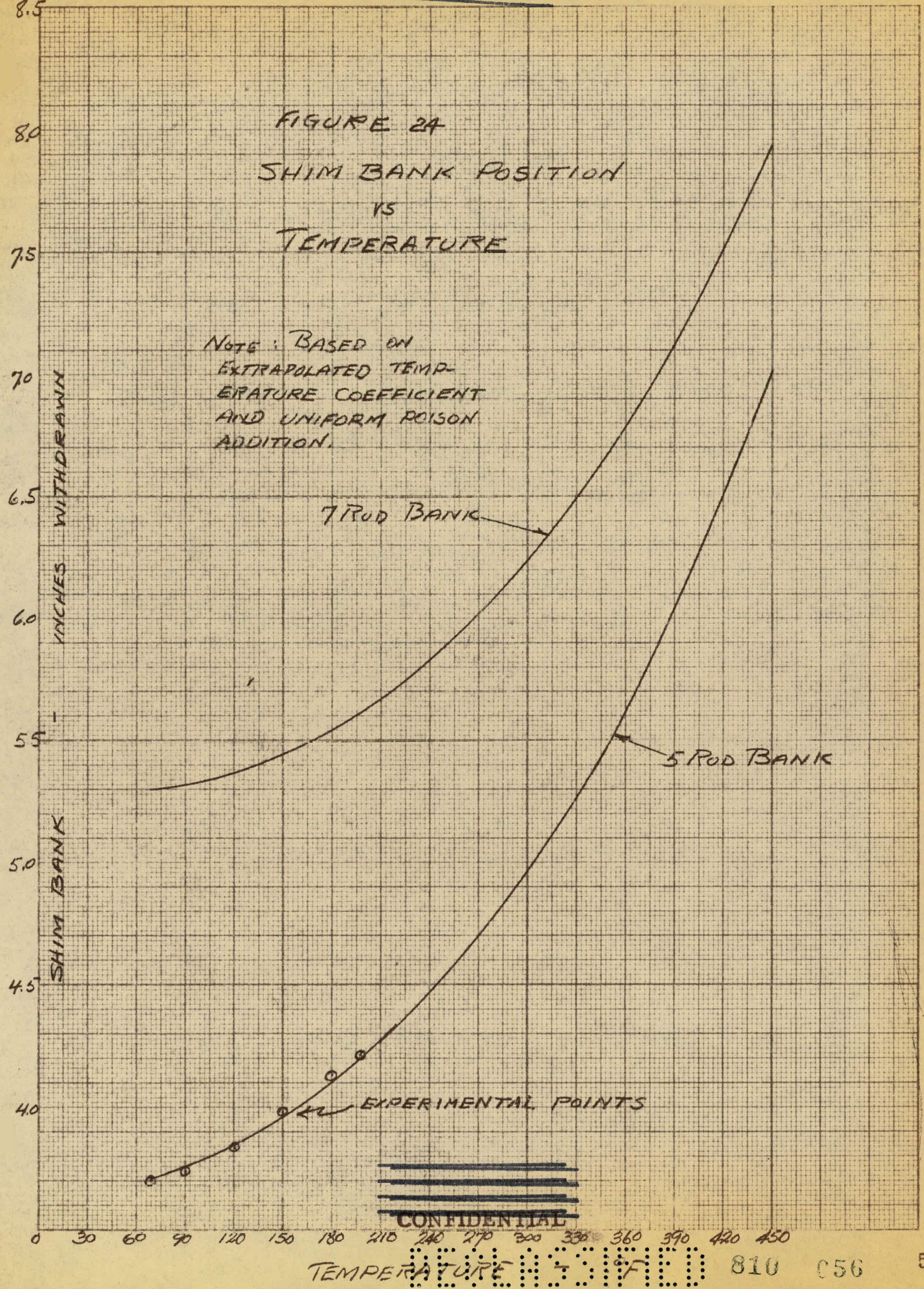


FIGURE 24

SHIM BANK POSITION VS TEMPERATURE

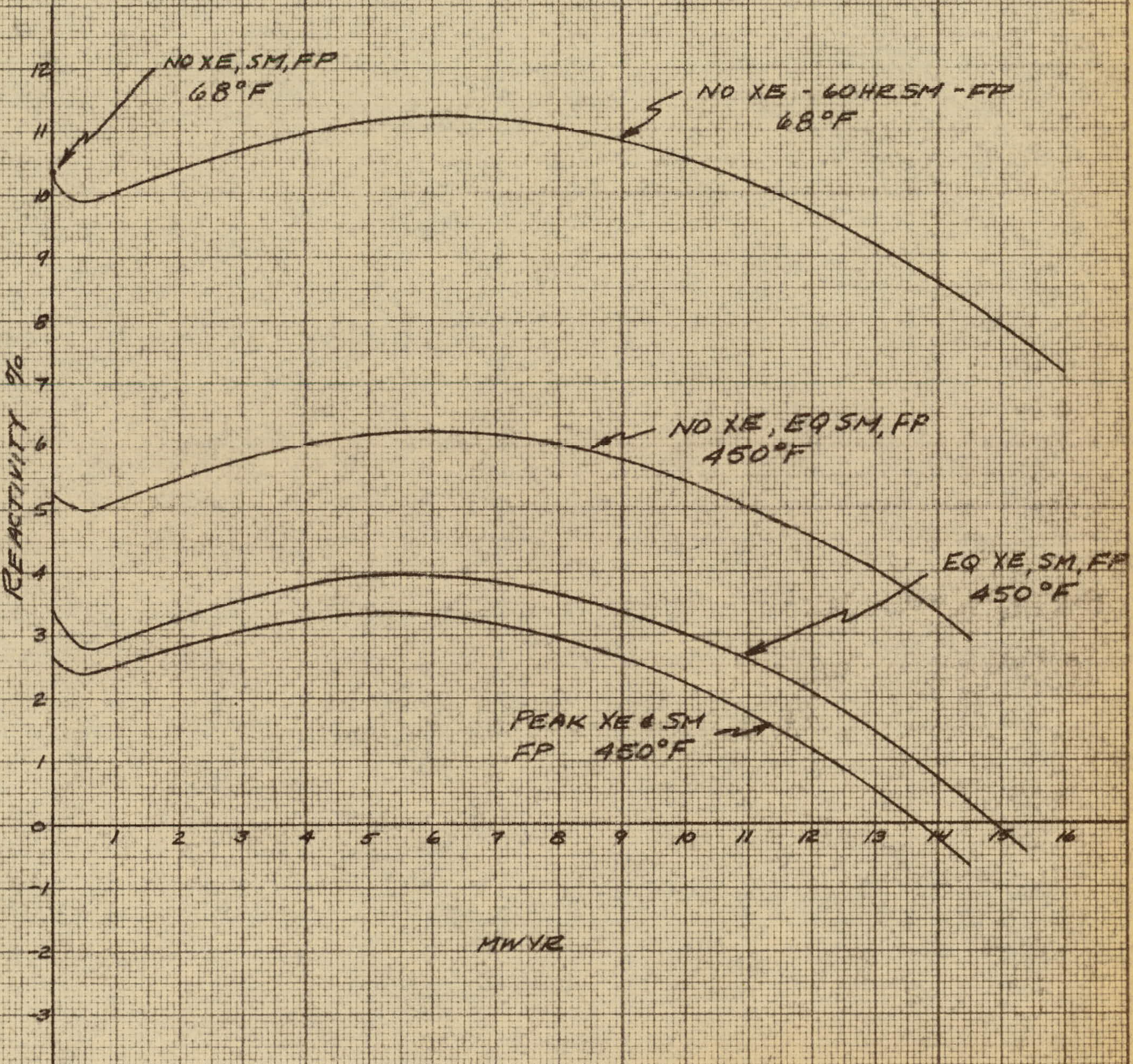
NOTE: BASED ON EXTRAPOLATED TEMPERATURE COEFFICIENT AND UNIFORM POISON ADDITION.

FIGURE 25

APPR-1

REACTIVITY VS CORE ENERGY

(UNIFORM BURNOUT)



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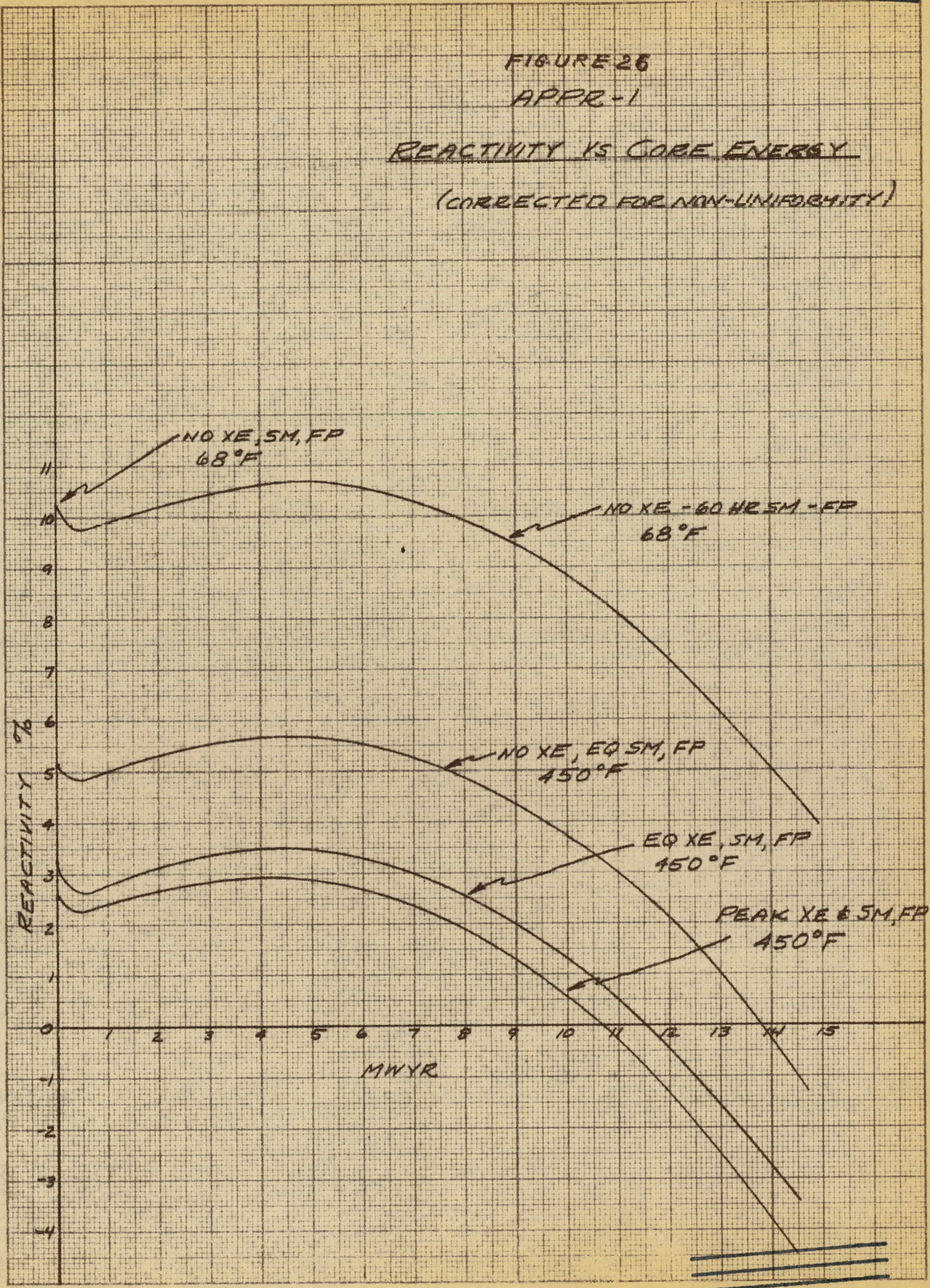

FIGURE 26
APPR-1
REACTIVITY VS CORE ENERGY
(CORRECTED FOR NON-UNIFORMITY)

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FIGURE 27
APPR-1

CALCULATED CHANGES IN REACTIVITY VS CORE LIFE

(BASED ON NON-UNIFORM BURNOUT)

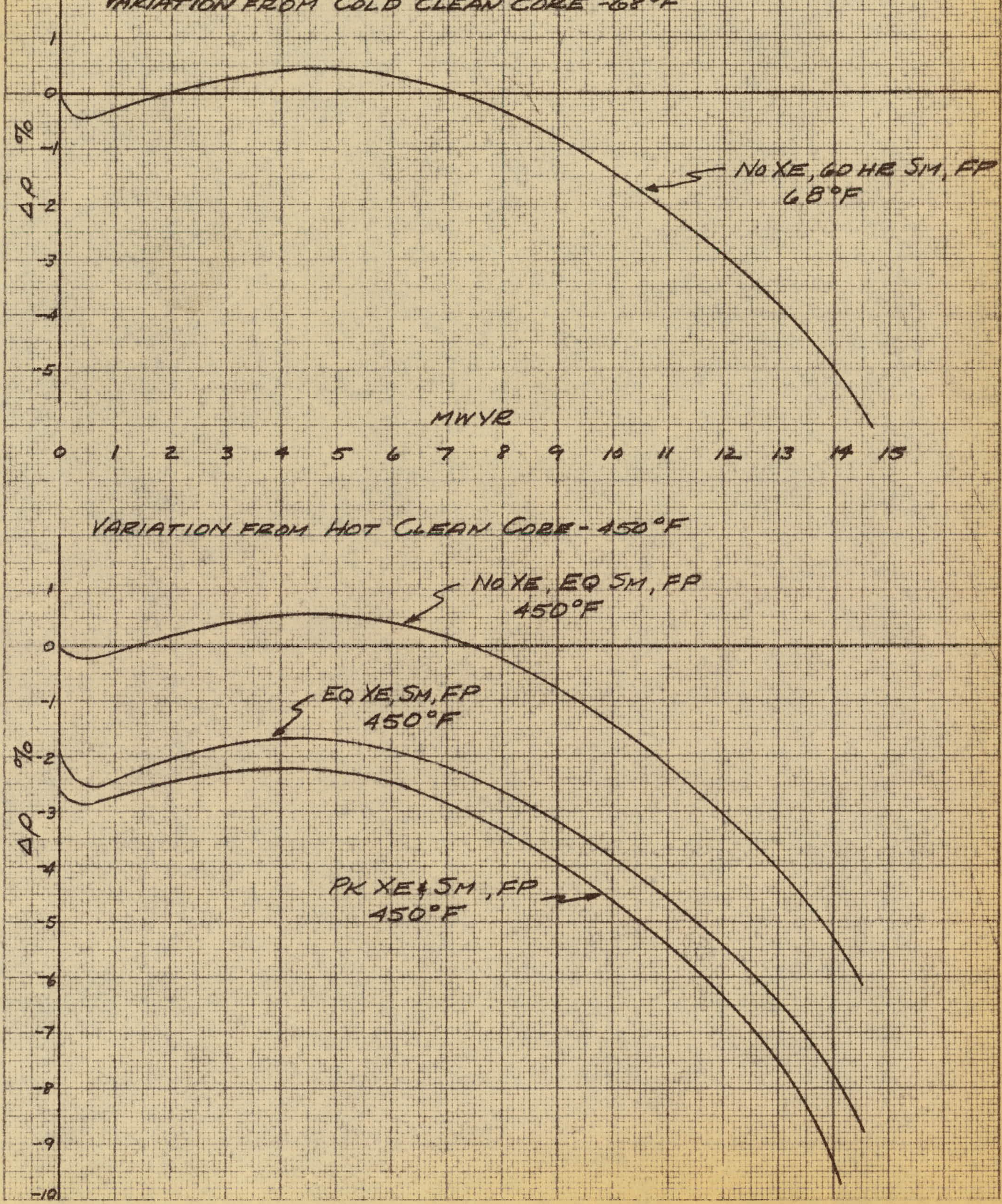

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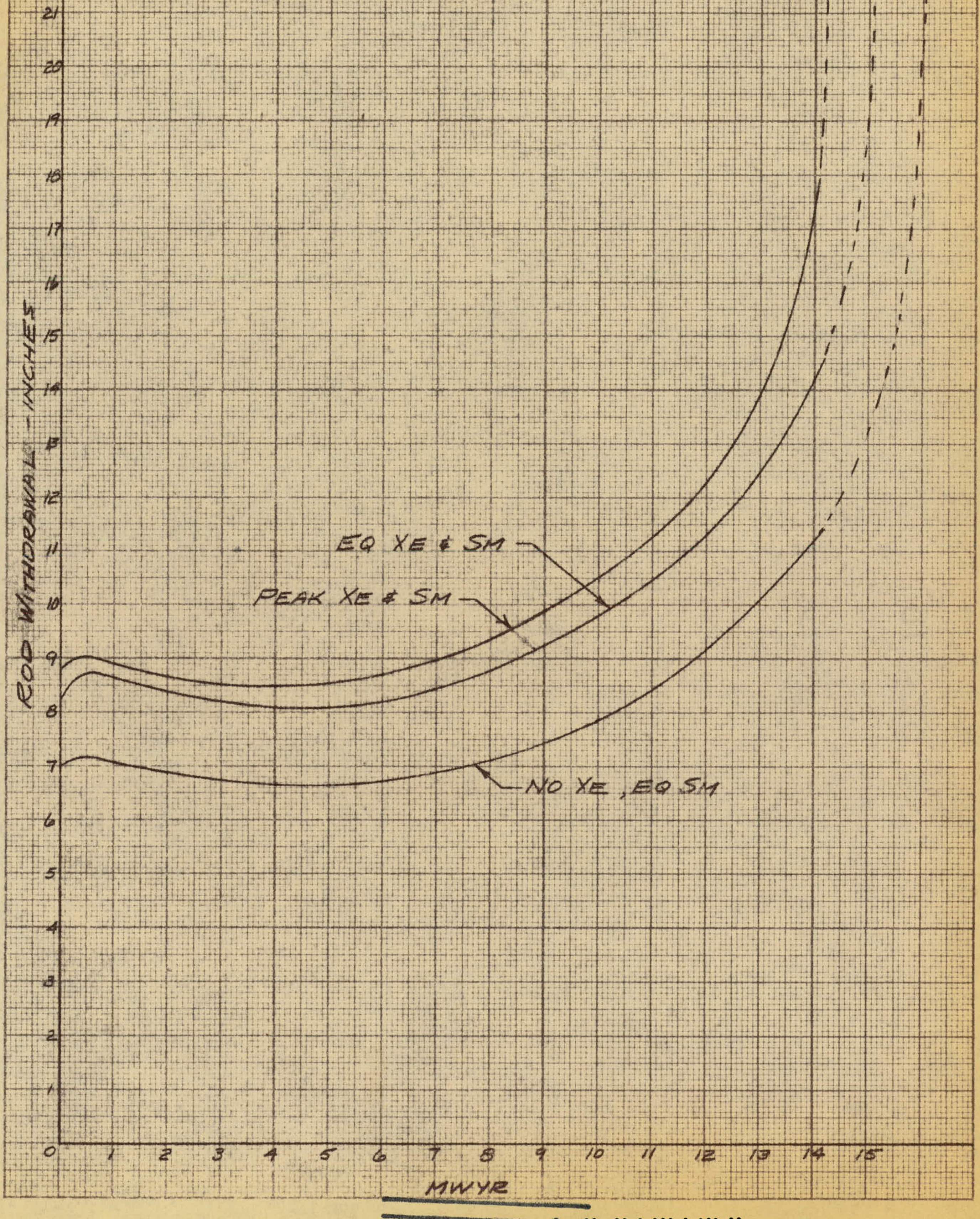
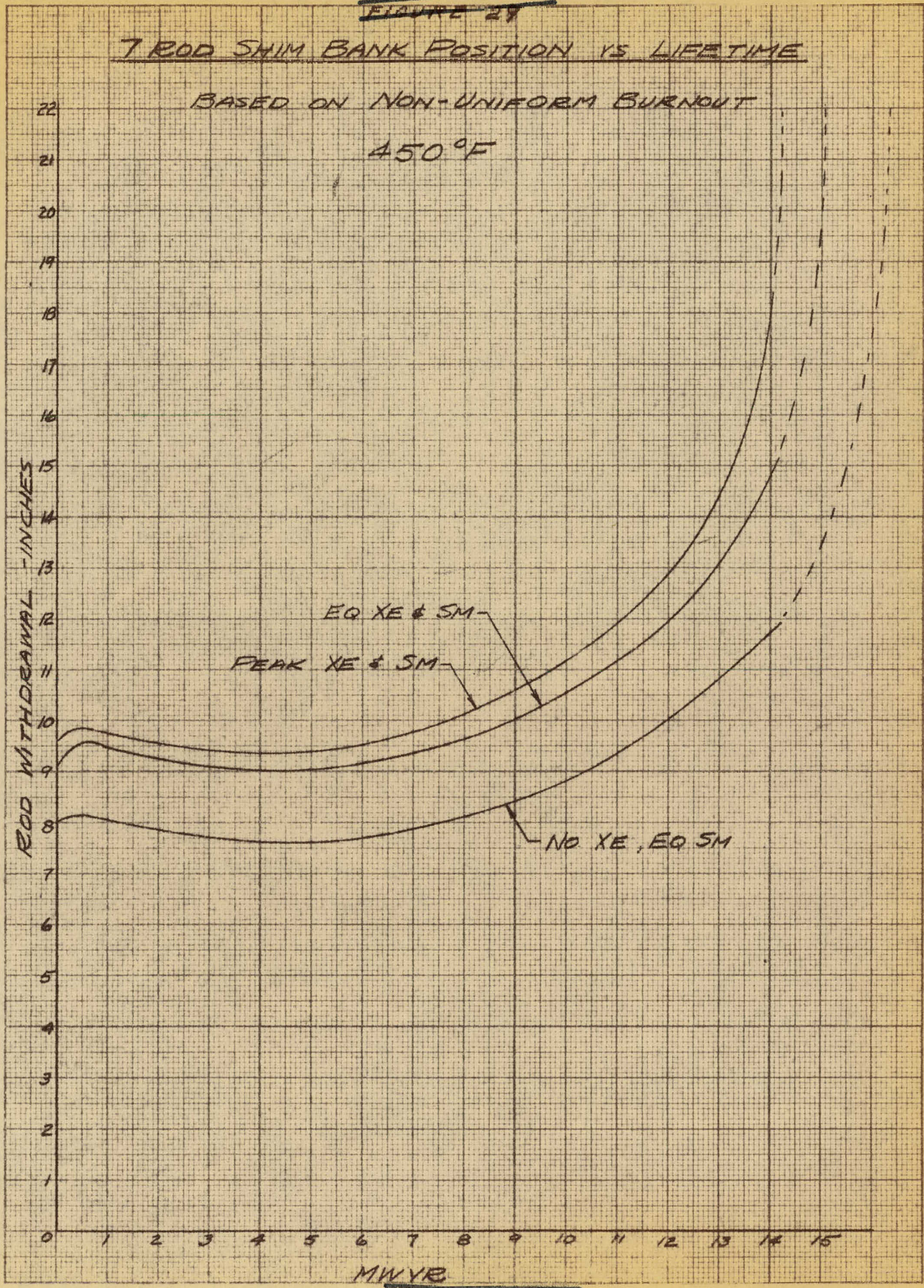
FIGURE 28

5 ROD SHIM BANK POSITION VS LIFETIME

BASED ON NON-UNIFORM BURNOUT

450°F





~~FIGURE 27~~

7 ROD SHIM BANK POSITION VS LIFETIME

BASED ON NON-UNIFORM BURNOUT

450°F

for non-uniform burnup. In Figure 27 the calculated reactivity changes from 68°F clean and 450°F clean are given for non-uniform burnup. Even though the absolute values of reactivity are different from those measured, the reactivity changes are assumed to be valid.

In Figure 28 the position of the five rod shim bank versus lifetime is given at 450°F under various xenon conditions. In Figure 29 the position of the seven rod shim bank is given under the same conditions.

D. Reactor Operation

In selecting an operating procedure the criteron has been maximum safety without jeopardizing the reactor performance. Experiments have been performed to determine the safest method of operation considering the remote possibility of one or several rods becoming inoperative in their maximum reactive position. The operating procedure has been confined to three areas:

1. Non-Bank Operation
2. Five Rod Bank Operation - A and B full out
3. Seven Rod Bank Operation

Each of the three methods is safe in varying degrees. The degree of safety increases as the reactor is operated with more rods in the core. In the zero power experiments on the APPR-1, the half reactor has been shown to be a major contributor to the reactivity when an eccentric rod sticks full out.

1. Non-Bank Operation

In Non-Bank operation it would be possible to operate the reactor with any two rods fully withdrawn. However, in many cases only one rod can stick and still permit shutdown. As a result non-bank operation does not offer a high degree of safety since only one rod can be assumed to stick.

2. Five Rod Bank Operation - A and B Full Out

In five rod bank operation, rods A and B are fully withdrawn at all times except at shutdown. In the shutdown condition, stuck rods are positioned at the point they were during the operation. That is, if A and, or B stick, they will remain fully withdrawn; and if 1, 2, 3, 4 or C stick, they will remain at the operating bank position. In five rod bank operation any two rods can stick and still permit shutdown under the stated conditions. The most marginal case here is with rod A stuck full out and rod 1 stuck at the bank operating condition. This condition has been evaluated at mid-life with peak xenon. From Figure 27 midlife reactivity is calculated to be 0.5% greater than startup at 68°F and no xenon. From Figure 28 the bank position is seen to be 8.5 inches withdrawn with peak xenon at 450°F. From Table 5 the clean cold shutdown position for this case is with rod 1 withdrawn 11.97 inches. From Table 6, case 3, the worth of rod 1 between 8.5 and

11.97 inches can be evaluated. As a conservative estimate 0.4%/inch is taken with a total worth of approximately 1.4% for that interval. The reactor in this condition at 68°F with no xenon will have a negative reactivity of approximately -0.9%. See Figure 30.

3. Seven Rod Bank Operation

In seven rod bank operation all of the rods are to be operated at the same position. Since rods A and B are shielded to a large extent by rods 1, 2, 3, 4 and C, the seven rod bank operates at approximately one inch greater withdrawal then the five rod bank.

A comparison of Figures 28 and 29 at the most reactive condition with the rods withdrawn the farthest indicates a withdrawal of 8.5 inches for the 5 rod bank and 9.4 inches for the 7 rod bank.

Experimental measurements have not been made on the stuck rod condition in the 7 bank operation. However, the shutdown margin in seven bank operation will be enhanced over the five bank operation, and it appears clear that the reactor will be subcritical at 68°F with any 3 rods stuck.

E. Planned Operating Procedure

In non-bank operation only one rod may be assumed to stick. Even though the reactor performance may be improved by flux flattening and reducing non-uniform effects in rod programming, there is less of a margin for reactor shutdown.

In seven rod bank operation the maximum in safety will be achieved since in this type of operation all the rods will be partially inserted. Since rods A and B are shielded to a large extent by the other five rods, the seven rod bank is inserted almost as far as the five rod bank (approximately one inch less). In the seven rod bank operation three rods could stick and still permit shutdown. Seven rod bank operation will possibly decrease the reactor performance with respect to five rod bank operation. In seven rod bank operation the top of the core will be blacked out considerably more than in five rod bank operation. As a result less power will be generated in the upper region where the bank is inserted. The positioning of the rods in the five rod bank is such that the flux is flattened in the upper absorber region but still is of sufficient magnitude to generate considerable power.

The hypothesis that any two rods can stick in five rod bank operation appears adequate from a safety viewpoint. With the increased power generation in the absorber region of the five rod bank over the seven rod bank, it is planned that five rod bank operation be utilized in the APPR-1. The plan to operate the APPR-1 with 5 control rods will provide valuable data for the operation of a reactor with a minimum number of control rods.

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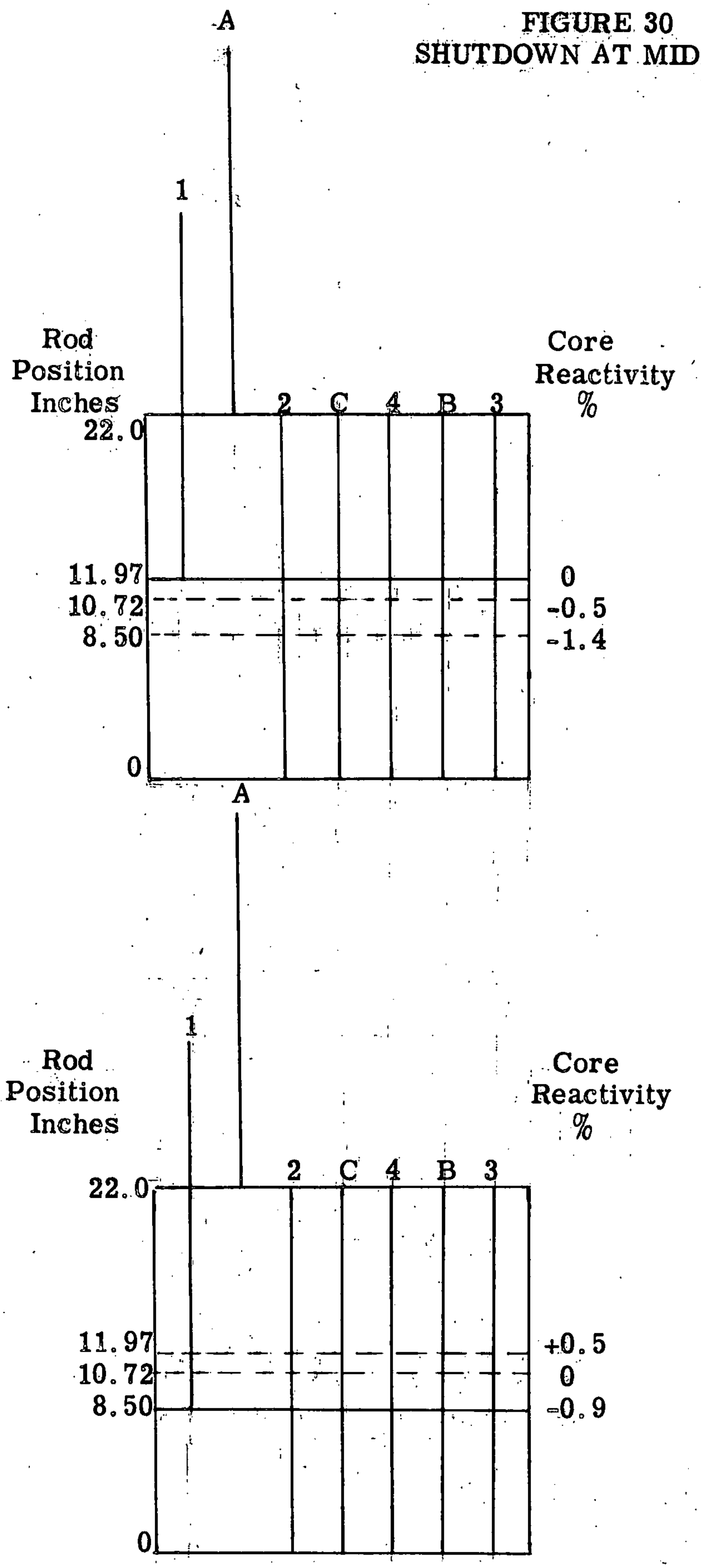
FIGURE 30
SHUTDOWN AT MIDLIFE



Conditions
68°F - Clean

Rods 2, C, 4, B, 3 full in
Rod A full out
Rod 1 out 11.97 inches

Conditions
68°F Midlife - no xenon

Rods 2, C, 4, B, 3 full in
Rod A full out
Rod 1 out 8.50 inches
(stuck at bank position at 450°F with peak xenon)

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