ENGINEERING DIVISION
U.S. ARMY ENGINEER REACTORS GROUP
CORPS OF ENGINEERS
FT. BELVOIR, VA. 22060

ED-7110

MH-1A CORE 3 PHYSICS TEST REPORT

S. A. HELMS
H. C. GIGNILLIAT

7 DECEMBER 1971

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ABSTRACT

This report contains the results of core physics testing on MH-1A Core 3. These tests were conducted during June 1971, immediately prior to power operation.

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MH-1A CORE 3 PHYSICS REPORT

I. INTRODUCTION

Core physics measurements were performed on the refueled MH-1A core in June 1971. The results are analyzed herein. Those parameters which are important in understanding core behavior (such as the temperature and power coefficients of reactivity, rod worths, xenon build-up, and critical bank position) are derived from the data. Comparisons are made with expected values of these quantities.

II. DISCUSSION

A. Core Configuration

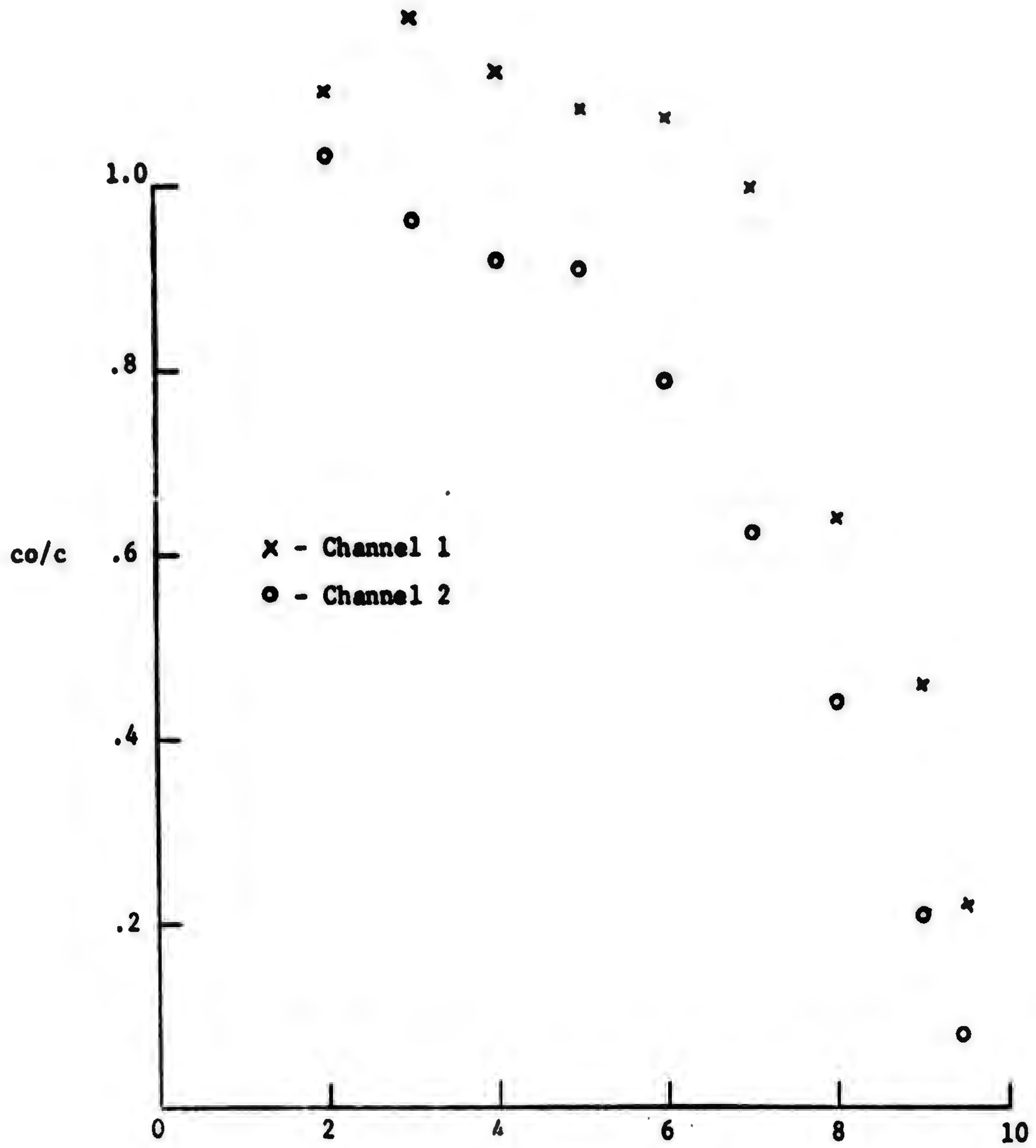
The control rods used in Core 2 were carefully inspected for signs of cracking and other indications that would preclude their use in Core 3. The rods were determined to be in excellent condition and all but one were re-installed in Core 3. A recently procured Type I modified control rod was installed in the #4 position.

The Type I modified rod differs from the original rods in that the stainless steel followers do not contain boron. The Type I modified rod was installed in Core 3 as a "lead rod" to gain early experience with this design.

B. Approach To Criticality

Initial approach to criticality after the second refueling of the MH-1A was conducted on 16 June 1971. Table I gives the data for the approach to criticality and Figure 1 gives the inverse multiplication curve. The first two counts taken on Channel 1 are considered statistically high. The curves for Channel 1 and Channel 2 predicted critical bank positions of 9.90 and 9.80 inches, respectively. The measured critical bank was 9.85 inches at a temperature of 146°F and a pressure of 350 psig.

The measured critical bank position of 9.85 inches compares unfavorably with the predicted value of 4.24 inches (Ref. #1). This calculational error is discussed in detail in Appendix A.



12-ROD WITHDRAWAL, INCHES
16 June 71

FIGURE 1

APPROACH TO CRITICALITY

TABLE I

Initial Approach to Criticality

12-Rod Bank Position (Inches)	Source Range Channel 1 (cpm)	Source Range Channel 2 (cpm)
0.00	1552	1031
2.00	1413	998
3.00	1313	1070
4.00	1387	1122
5.00	1437	1130
6.00	1447	1310
7.00	1556	1665
8.00	2427	2337
9.00	3335	4917
9.5	7121	12399

C. Stuck Rod Shutdown Margin

Signal from the forward intermediate range detector (Figure 2) was fed to the reactivity computer for this test and the following tests. This is the same detector position used in Core 2 physics testing, however the IRM detector was changed prior to criticality. The critical elevel rod bank for the Type I outer rod stuck full out was higher than that for an inner rod of similar design. The shutdown margin measurements for a stuck inner rod (#1) and an outer rod (#5) indicate that an inner rod resulted in a greater margin than did the outer rod. This phenomenon is attributed to special effects and was observed in the previous core physics test (Ref #2).

The results of the stuck rod shutdown measurement for Core 3 are listed in Table II. Similar data from Core 2 are shown in Table III. The inner rod/outer rod stuck rod margin ratio has decreased in Core 3 and indicates that power density is greater in the center elements. This is consistent with the prediction of Ref. #1.

TABLE II

Stuck Rod Shutdown Margin Measurements - Core 3

Control Rod #1	Position (inches)	11-Rod Bank (inches)	Shutdown Check ($)	Prim Temp (°F)	Prim Pres (psig)
1	35.78	7.88	-4.10	147	345
4	36.00	7.65	-3.50	149	340
5	36.00	8.38	-3.00	145	340
12	36.00	8.26	-3.60	147	350

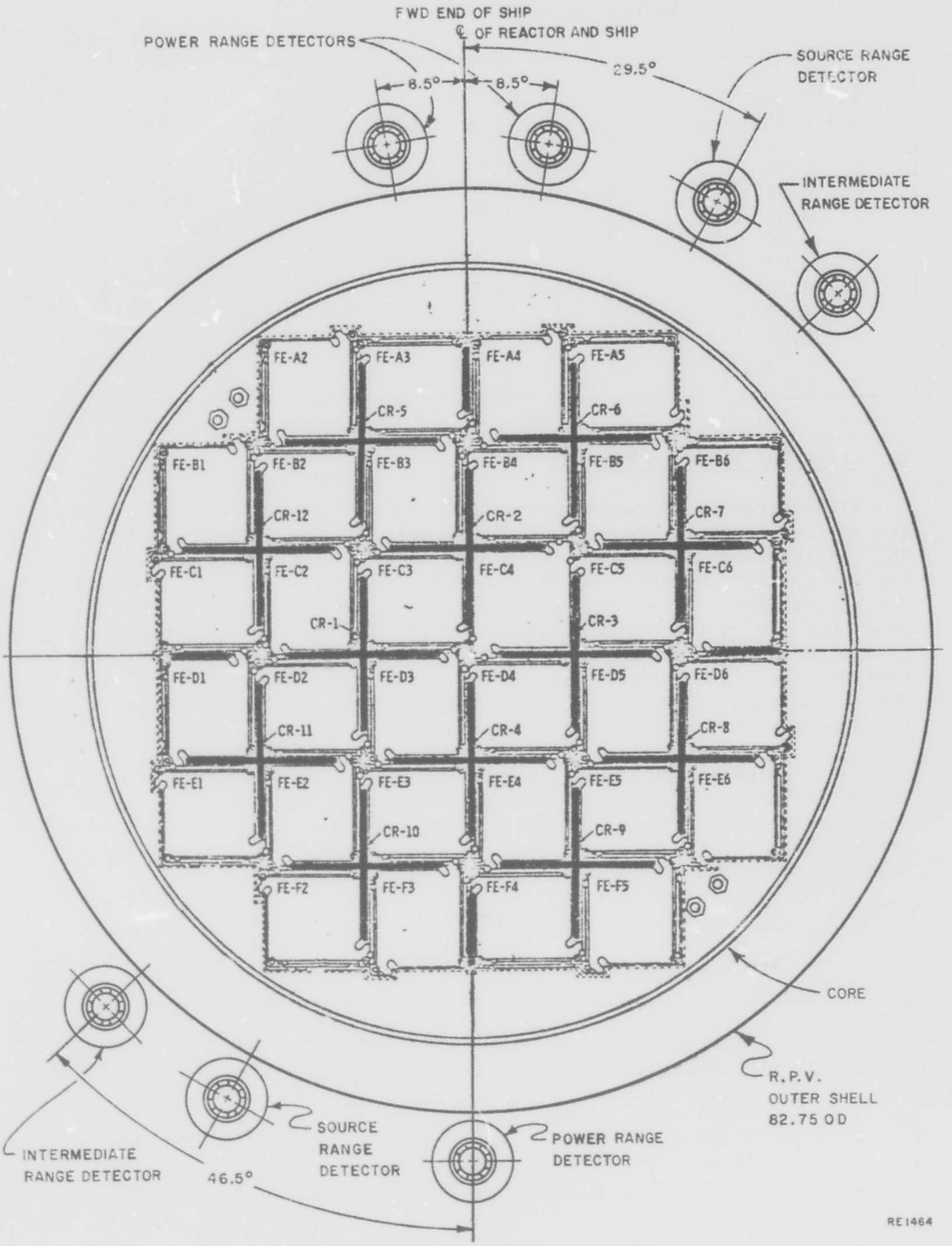


FIGURE 2. CORE – DETECTOR ORIENTATION

TABLE III

Stuck Rod Shutdown Margin Measurements - Core 2
(from Reference #2)

Control Rod #1	Position (inches)	11-Rod Bank (inches)	Shutdown Check($)	Prim Temp(°F)	Prim Pres(psig)
2	35.84	9.89	- - -	152	319
1	35.73	9.89	-4.00	150	330
8	35.89	10.18	- - -	145	345
5	36.10	10.10	-2.60	147	340
12	35.96	10.00	-3.60	147	320

D. Control Rod Calibrations

The calibrations of control rods #1, #4, and #12 were performed on 16 and 17 June 1971. Each rod was calibrated singly against the 11-rod bank of the remaining rods. The rod being calibrated was withdrawn an amount sufficient to produce a desired positive reactivity insertion. The magnitude of the insertion was then read from the reactivity computer. After the reading was completed, the 11-rod bank was moved so as to make the reactor slightly subcritical, and the negative reactivity inserted was determined by the computer. This process was repeated until the rod being calibrated was fully withdrawn.

The integral worth curves are shown in Figures 3, 4, and 5. Table IV compares the fully withdrawn integral worths for rods #1, #4, and #12 for this core and its predecessors (Ref 2). Since the cores investigated for each of the tests are different, it is difficult to draw any conclusions or comparisons between actual numerical values. Figures 3, 4, and 5 indicate the values of integral rod worth as a function of rod position.

It is worth noting that the integral worths of rod #1 and #4 are nearly identical. This indicates that the boron in the followers was essentially depleted during exposure in Core 2.

TABLE IV

Fully Withdrawn Integral Rod Worths

	Rod #1	Rod #4	Rod #5	Rod #12
June 1971	$3.21 (493°F)	$3.25 (492°F)		$1.38 (491°F)
Nov 1969	2.84 (484°F)			1.53 (489°F)
Oct 1968	1.92 (479°F)		$1.15 (479°F)	
June 1971	4.23 (145°F)	4.44 (145°F)		2.91 (146°F)
Nov 1969	3.18 (147°F)			2.33 (147°F)
Oct 1968	3.70 (101°F)		2.78 (101°F)	

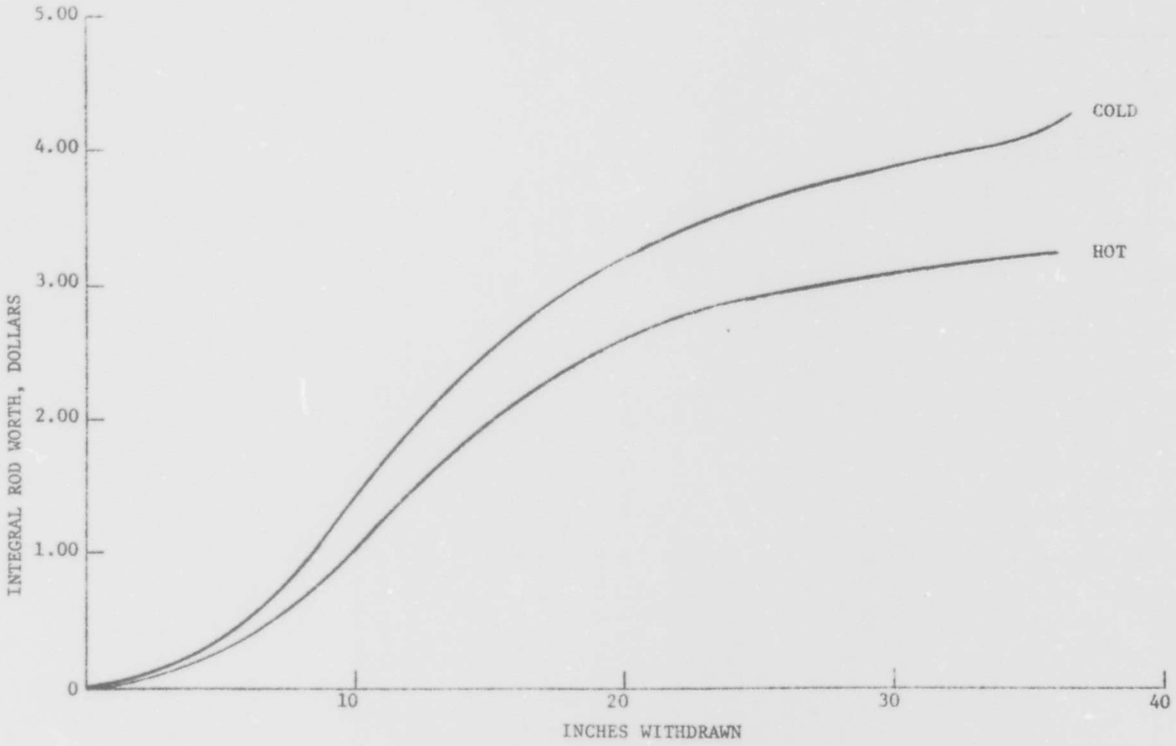


FIGURE 3

INTEGRAL ROD WORTH CURVES - ROD #1

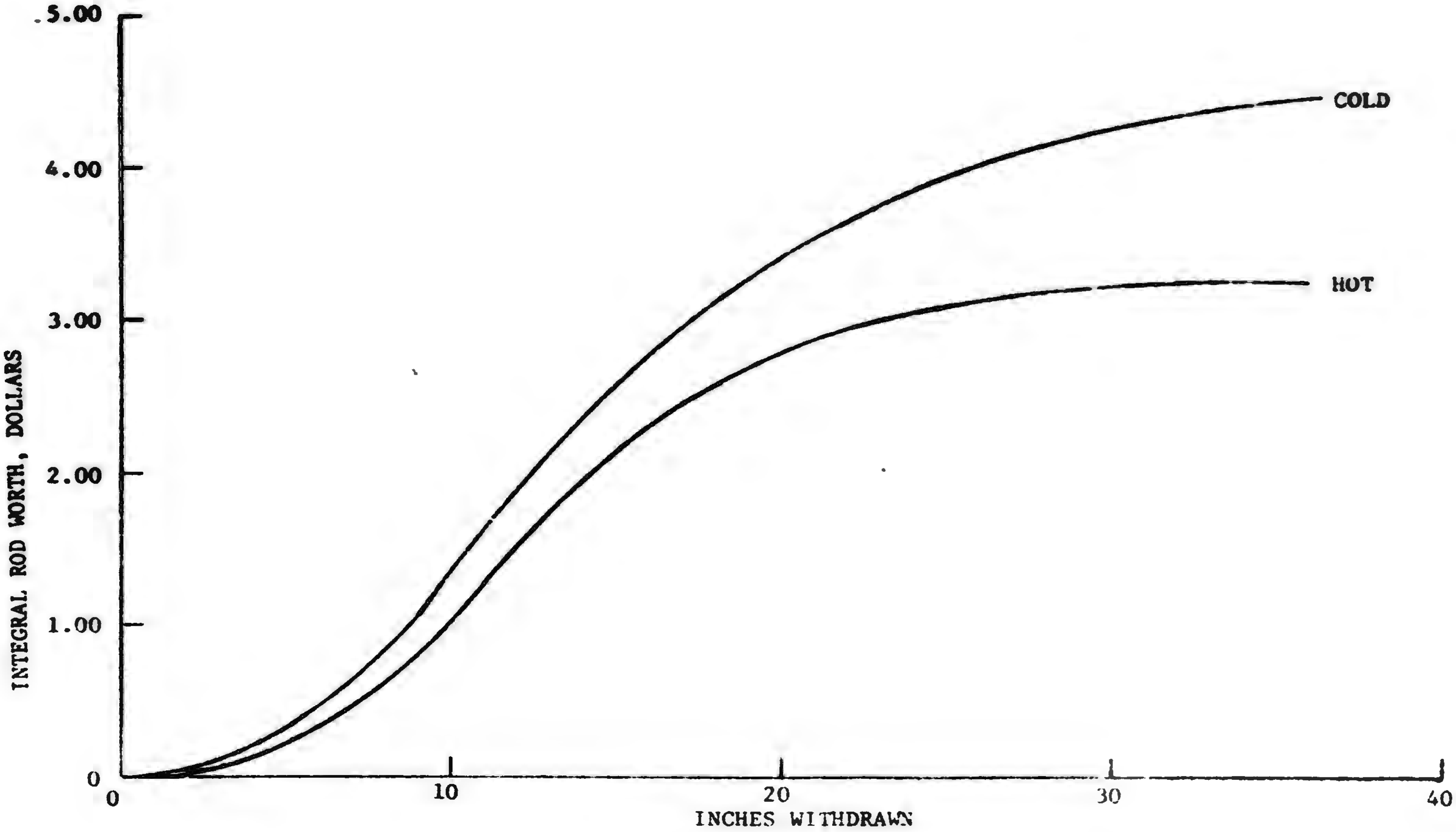


FIGURE 4

INTEGRAL ROD WORTH CURVES - ROD #4

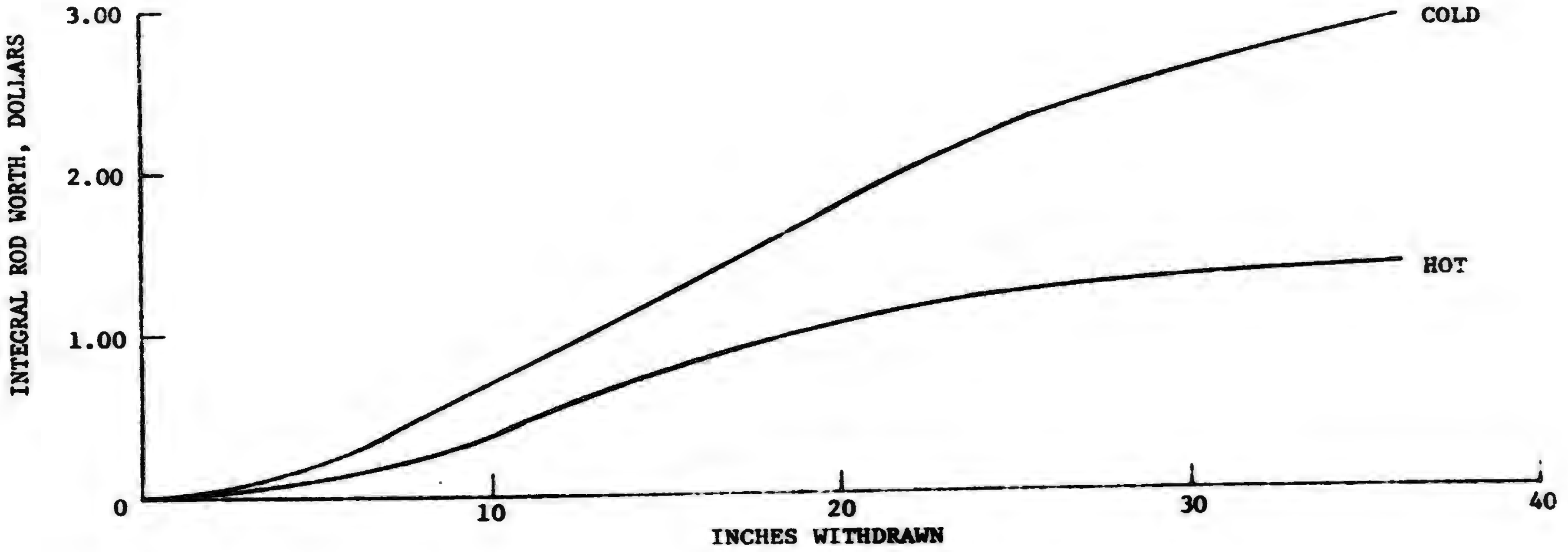


FIGURE 5

INTEGRAL ROD WORTH CURVES - ROD #12

E. Temperature Coefficient of Reactivity

The temperature coefficient measurement was performed on 16 and 17 June 1971. The data are plotted in Figures 6 and 7. Tables V and VI summarize data from this and previous cores.

TABLE V

Temperature Coefficient (%ΔK/K °F)

	Experimental			Calculated	
Temp.	Core 1	Core 2	Core 3	Core 2	Core 3
68°F	3.0×10^{-5}	8.10×10^{-5}		3.3×10^{-5}	
200°F			1.26×10^{-4}		9.1×10^{-5}
490°F	2.95×10^{-4}	2.45×10^{-4}	2.25×10^{-4}	2.7×10^{-4}	2.05×10^{-4}

TABLE VI

Temperature Defect

Experimental			Calculated	
Core 1*	Core 2*	Core 3***	Core 2*	Core 3**
6.4%Δρ	6.47%	5.84%	4.8%Δρ	5.3% (Rods In) 11.5% (Rods Out)

*from 68-490°F
**from 100-490°F
***from 147-490°F

F. Power Coefficient Test

The purpose of the power coefficient test is to determine the reactivity per megawatt that is lost due to doppler. This determination is made by taking on load in increments of 10 to 20 percent, allowing the system to stabilize briefly and recording average primary coolant temperature and power. The reactivity per megawatt can be calculated by use of the previously determined negative temperature coefficient.

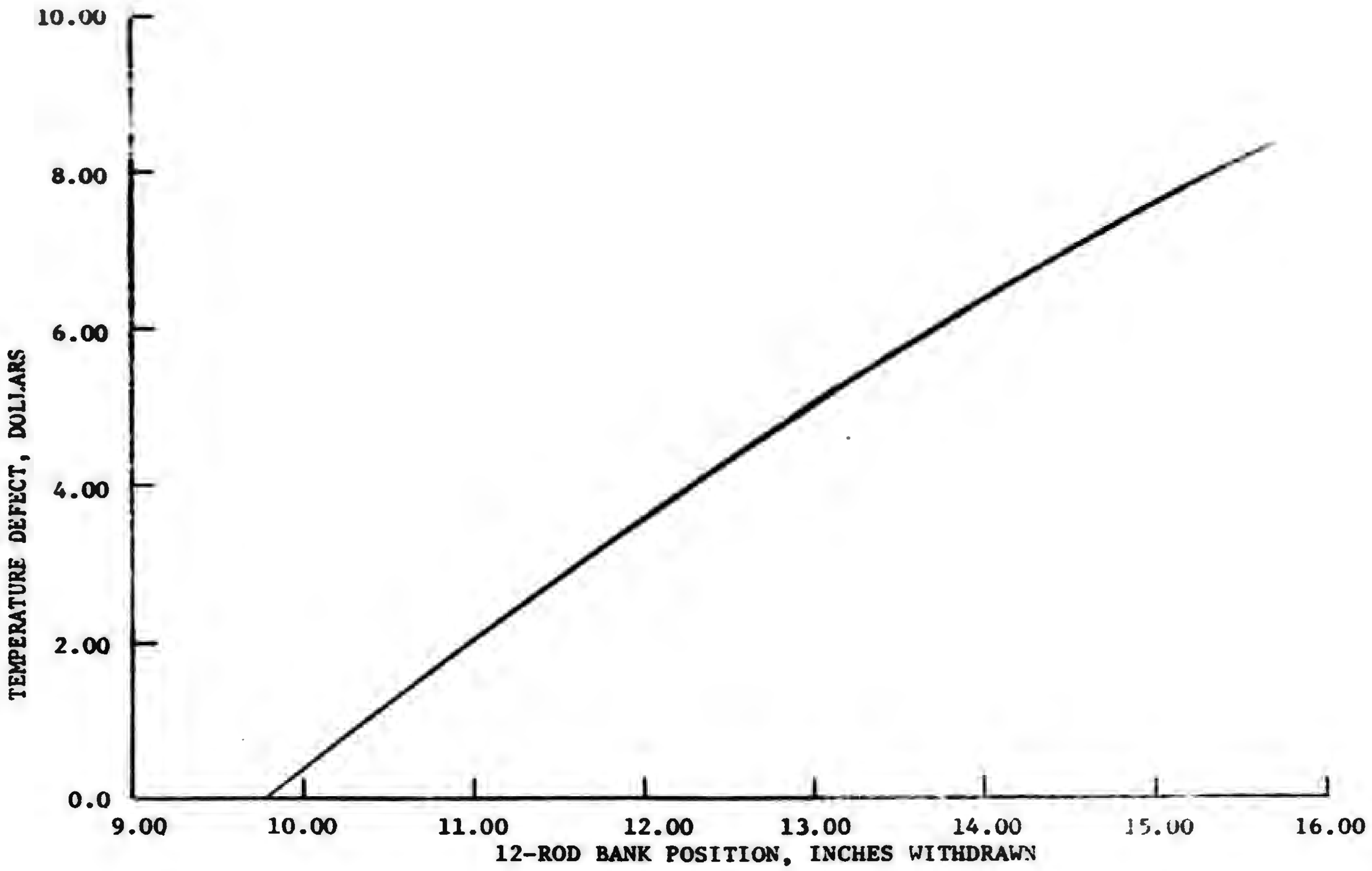


FIGURE 6

TEMPERATURE DEFECT VS BANK POSITION

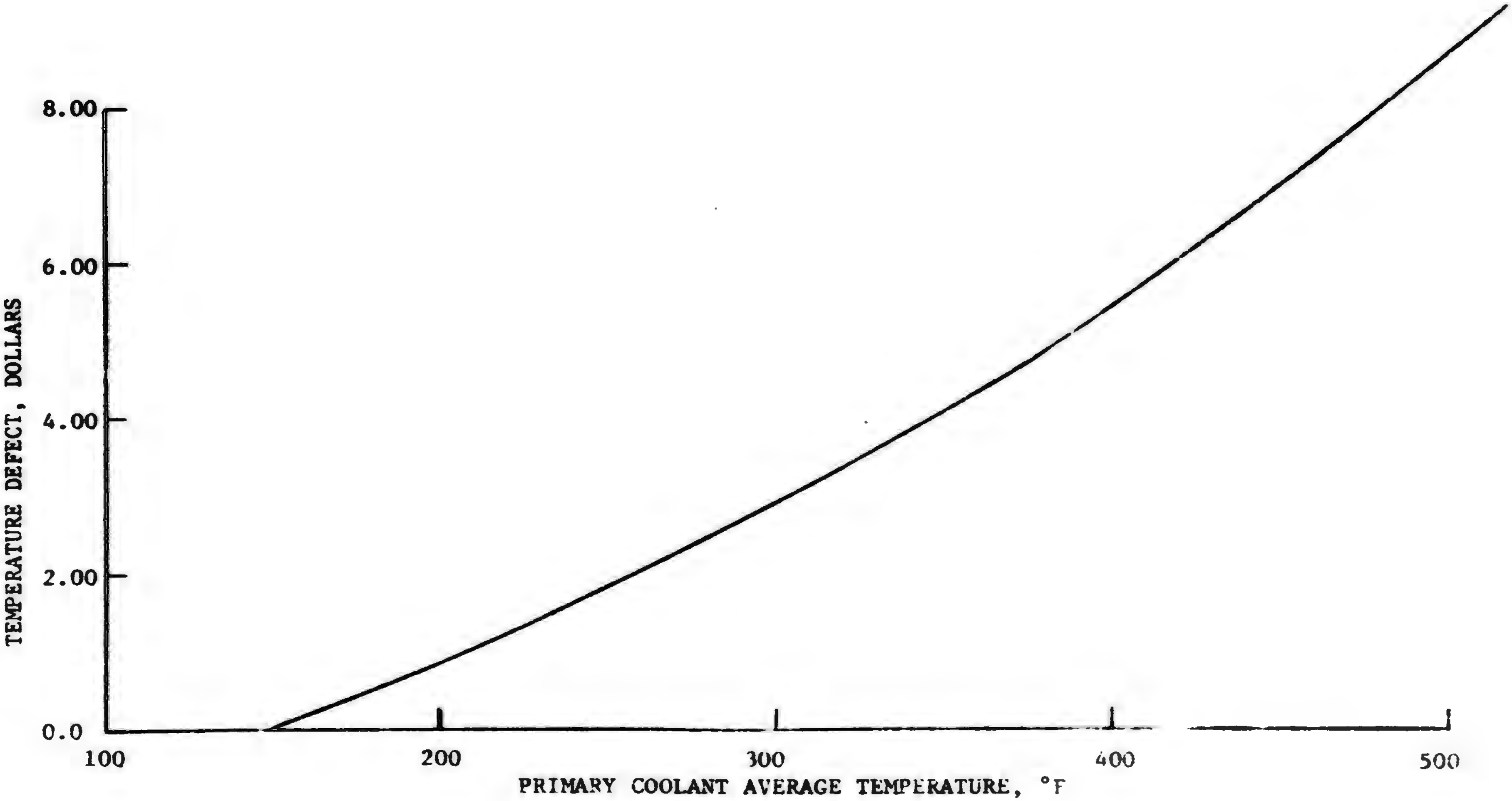


FIGURE 7

TEMPERATURE DEFECT VS PRIMARY COOLANT AVERAGE TEMPERATURE

The power coefficient data obtained during core physics testing of Core 2 was widely scattered, and the data obtained from Core 3 testing is not consistent. The difficulty arises because the operators cannot complete the tests before the Xenon build-up becomes significant. As presently written the operators must interrupt the test to increase average temperature (T_{ave}); otherwise steam conditions will deteriorate, and it will not be possible to produce 100 percent power.

During the power coefficient test on Core 3, plant management and nuclear test engineers were present in the control room. Despite the best efforts of the control room operators, the scheduled temperature adjustment and secondary system instrumentation problems stretched the power coefficient test to 3 hours. As previously stated, the data obtained during the test is not useful.

This test will be run at a later date using a revised test procedure. This new procedure will require that the initial T_{ave} (at zero power) be as high as practicable. The generator will be loaded as before but the T_{ave} will not be adjusted in the middle of the procedure. The test will be terminated whenever the limiting steam conditions are reached, or 100 percent load is achieved, whichever comes first.

The results of this test will be the subject of a separate report.

G. Equilibrium Xenon Defect

The equilibrium xenon measurements, with the reactor at near full power (96 ± 2 percent) were made during the period 18-22 June 1971. The power run began on 18 June at 1900 hours and was interrupted at 1643 hours on 19 June. At this point the reactor was shut down for calibration of instrumentation; the reactor was at power again on 21 June at 0110 hours. This interruption is shown graphically in Figure 8.

Xenon defect is plotted as a function of bank position in Figure 9. Table VII lists calculated and measured xenon defects for Core 2 and Core 3.

TABLE VII

Xenon Defect, % ΔK/K

	Core 2	Core 3
Calculated	2.1%	2.5%
Measured	1.4%	2.3%

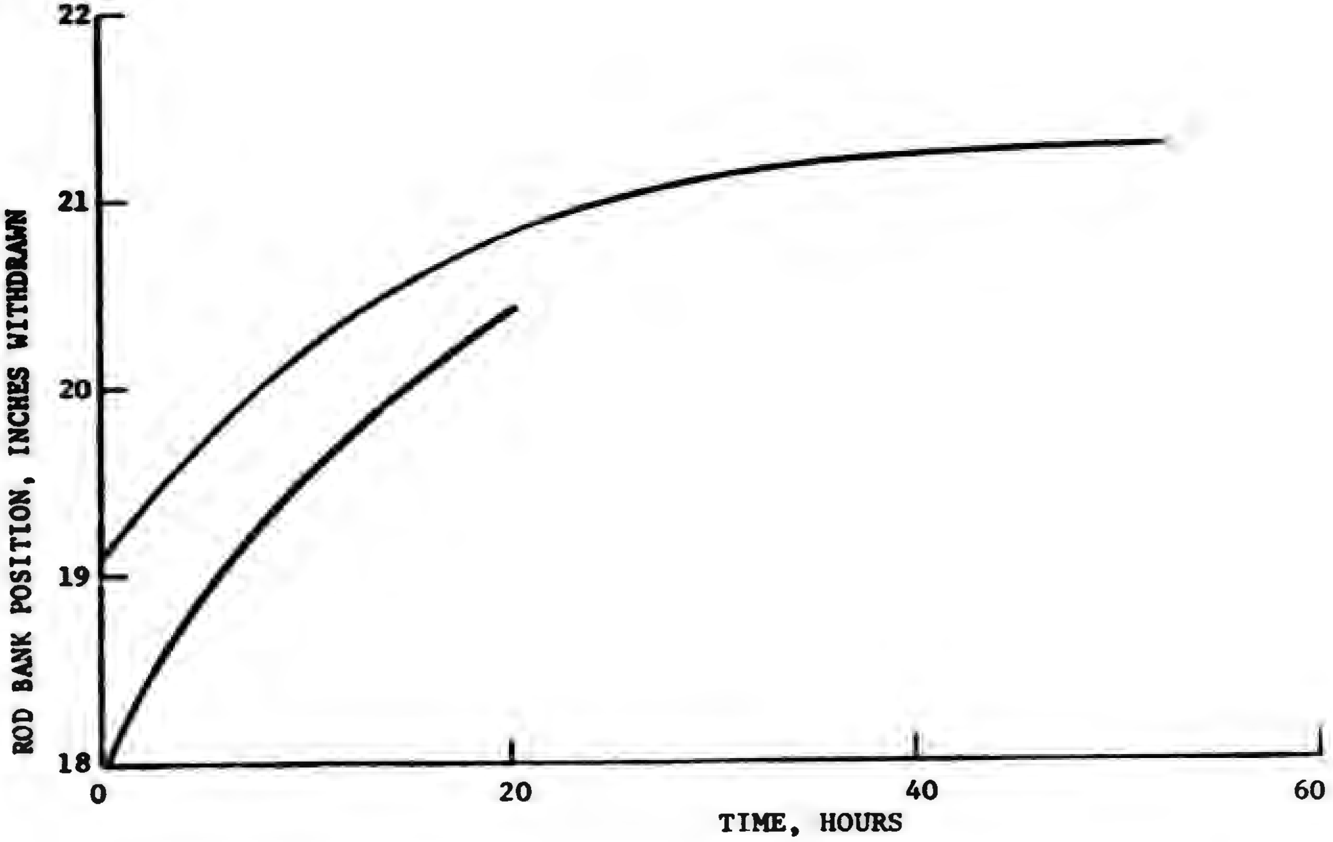


FIGURE 8

BANK POSITION VS TIME - XENON BUILD-UP

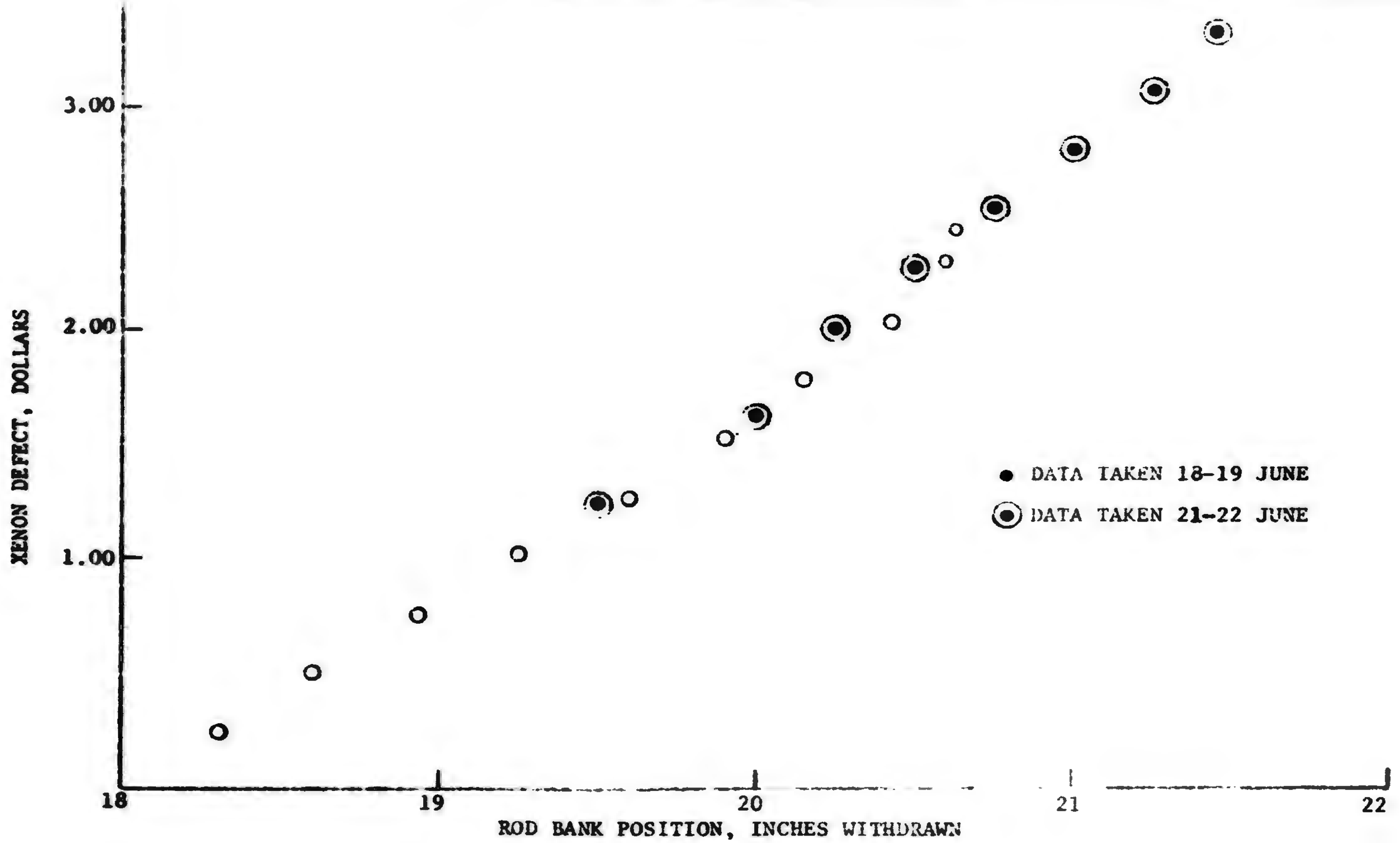


FIGURE 9

XENON DEFECT

III. REVIEW OF THE DATA

A. Critical Bank Positions

As previously noted, the measured critical bank position (9.85 inches) compares unfavorably with the predicted value of 4.24 inches. The calculational error is discussed in Appendix A. It is reasonable to question whether or not the error will influence other calculations, i. e., power distributions and core lifetime.

A one dimensional (axial) calculation, with MND cross-sections, was used to calculate the critical bank positions. As noted in Appendix A, application of the WW cross-sections would have predicted a much more accurate bank position. Since a two-dimensional model was used to calculate power distributions and lifetime, the critical bank position error does not feed back into other calculations.

B. Stuck Rod Margin

The critical 11-rod bank position and measured shutdown margins are shown in Table II. Based on the location of Rod #5 with respect to the neutron detector, the stuck rod margin of rod #5 is considered the closest to reality. Since the technical specifications require 1%Δ K ($1.42) shutdown with the most reactive rod stuck out at 68°F, the shutdown margin of rod #5 must be extrapolated back to 68°F from Figure 7, a conservative temperature coefficient between 68°F and 145°F is -.95¢/°F. Thus, the 68°F shutdown margin for rod #5 is: 3.00 -.0095 (145-68) = $2.28 or 1.6%ΔK.

From Figure VI-2, Ref. 1, the maximum differential 12-rod bank worth is approximately 1.2 percent per inch. The critical 11-rod bank positions (Table II), for rods #4 and #5, differ by .63 inches. Thus the stuck rod shutdown margin is greater than that required by the technical specifications.

C. Differential Bank Worths

The power range rod withdrawal transient is initiated by an uncontrolled withdrawal of the 12-rod bank at the maximum rate of 2 inches per minute. Ref. 3 assumed a maximum insertion rate of 4×10^{-4} ΔK/sec. This corresponds to a bank worth of 1.20×10^{-2} ΔK/in or $1.71 per inch. This is in good agreement with the $1.85 per inch one would calculate from Figure 6.

Ref. 3 assumed ~$1.43 would be inserted during the first 1-inch of bank motion following scram. This is conservative when compared to the core physics value of $1.85.

D. Ejected Rod Worths

The integral worth curve for control rod #4 is shown in Figure 4. Graphs of temperature defect and 12-rod bank position vs T_{ave} are shown as Figures 9 and 10, respectively.

From Figure 7, Ref. 4, it can be shown that the maximum ejected rod worth cannot exceed 1.86%ΔK for a critical bank position corresponding to 200°F T_{ave}; otherwise the peak enthalpy of the fuel will exceed 200 calories/gm (recall maximum peaking factor for Core 3 is 4.27). In other words, if the reactor is critical at 200°F, ejection of the maximum worth rod must not result in a reactivity insertion >1.86%ΔK.

From Figure 10, the 12-rod bank is at 10.3 inches for a primary temperature of 200°F. If it is conservatively assumed that the cold integral worth curve of rod #4 can be applied at 200°F, then ejection of rod #4 from 10.3 inches would result in a reactivity insertion of

$$4.44 - 1.45 = \$2.99$$

or

$$2.99 \times .00702 = 2.1\%\Delta K/K$$

This is not an acceptable situation.

Assume that the integral worth curve at 250°F lies between the two curves in Figure 4. Further assume that the reduction (when compared to 200°F) in rod worth is proportional to the temperature defect curve, Figure 7. Thus the integral worth of rod #4 at 250°F is calculated as follows:

$$4.44 - \frac{1.8}{8.0} \times (4.44 - 3.25) = \$4.17$$

Using the same argument, the integral worth of the rod at 10.8 inches (250°F) critical position is:

$$1.65 - \frac{1.8}{8.0} (1.65 - 1.27) = 1.56$$

The total reactivity inserted when control rod #4 is ejected from the 250°F critical bank position is:

$$4.17 - 1.56 = \$2.61$$

or

$$2.61 \times .00702 = 1.83\%\Delta K/K$$

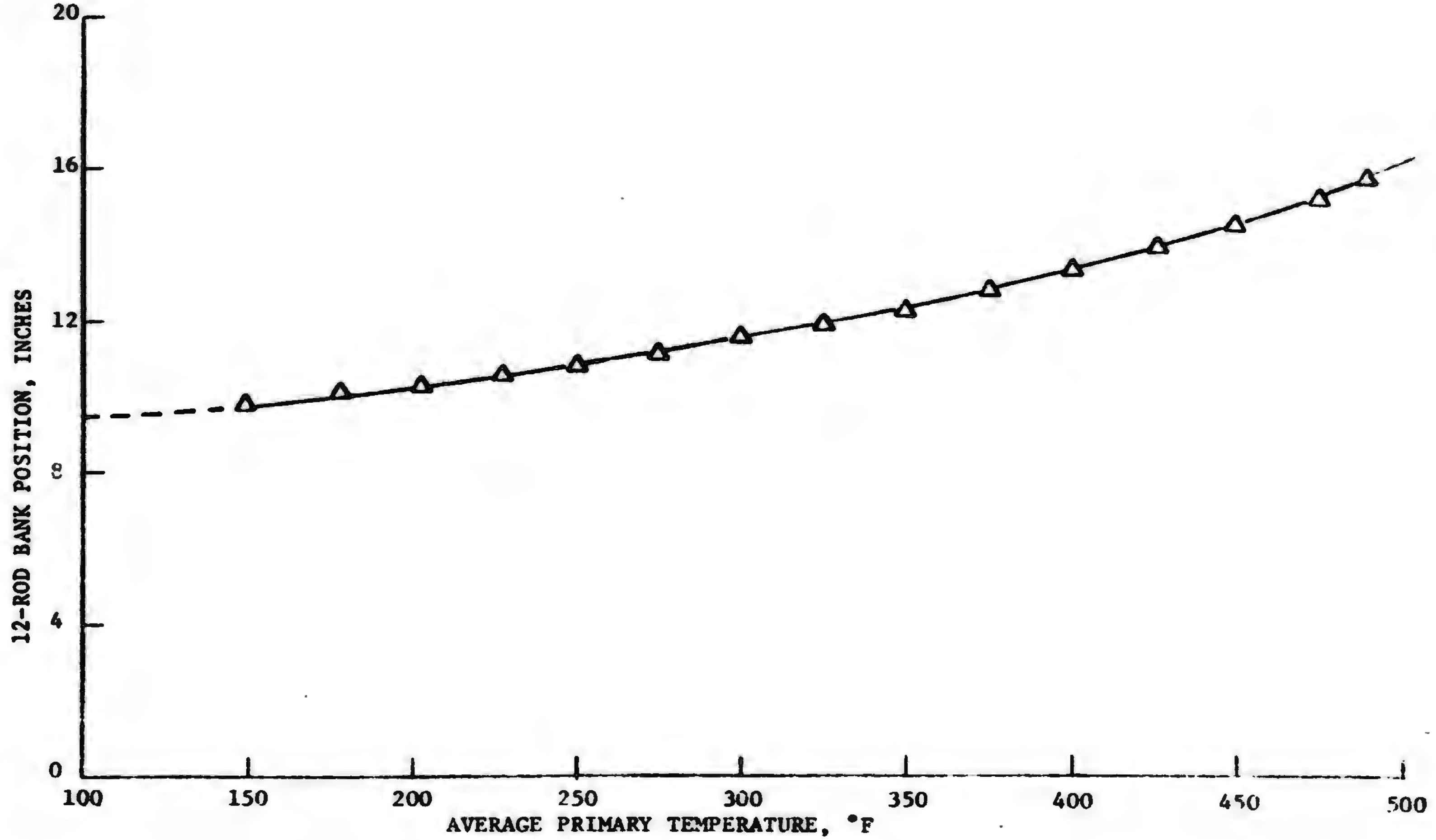


FIGURE 10

12-ROD BANK POSITION VS AVERAGE TEMPERATURE - CORE 3

From Figure 7, Ref. 4, the maximum permissible insertion at 250°F is 1.85%ΔK/K.

To recapitulate, if the primary system temperature is 250°F or greater, no fuel melting will occur during a rod ejection transient.

The rod calibration data for other control rods has been reviewed and rod #4 is the limiting rod.

E. Temperature Coefficient

Ref. #3 assumed a negative temperature coefficient of 3.7¢/°F and 3.1¢/°F for the main steam line rupture and power range rod withdrawal transients, respectively. The measured value of 3.2¢/°F is conservative in both cases.

IV. CONCLUSIONS

The core physics tests verify that MH-1A Core 3 can be operated in conformance with the technical specifications.

REFERENCES

1. Gregory, Michael V., et al, The Theoretical Nuclear Analysis of the MH-1A: Cores 2 & 3, ED 7102, 1 Mar 71

2. Sears, C. Frederick, et al, MH-1A Core Physics Test Report, ED 7002, 16 Mar 71

3. Gignilliat, Henry C., et al, MH-1A Core 3 Thermal-Hydraulic Design Analysis, ED 7103, 1 Mar 71

4. Gignilliat, Henry C., Engineering Support Study, Subject: Parametric Analysis of the MH-1A Rod Ejection Transient for the Shuffled Core and Extended Life Control Rods

APPENDIX A

AXIAL CALCULATIONS (CORE 3)

As a consequence of the discrepancy between predicted and measured BOL critical bank positions, the MH-1A Core 3 axial calculations were re-examined and calculated again (Figures A-1 to A-5). Evaluations of the results of the new calculations revealed values more nearly correct, but were not as conservative (i.e., bank positions were higher) as the earlier study. Much simpler, more comprehensive, and more accurate results ensued in light of the empirical results of the BOL measurements.

The methods previously employed and the results are given in Ref. 1. In the present calculations, the TURBO BOL cross-sections were again prepared as described in Ref. 1 but were input to PDQ-7 rather than CNCR-2. PDQ-7 output give the K_{eff}, percent reactivity, normalized power by point, and peak power for each rod bank position. The model employed is a four region (reflector, unrodded, rodded, and reflector), one-dimension axial calculation with a radial buckling input as the buckling to account for leakage in the radial direction. The source of the overly conservative critical bank positions is the value of the radial buckling used to describe the radial leakage and the mixed number densities (MND) cross-sections used for the hot case. Inputting a geometrical buckling results in a totally rodded K_{eff} that does not agree with the BOL TURBO two-dimensional K_{eff}. Thus, the leakage is not adequately described. However, if a buckling search is performed to obtain a buckling giving the TURBO K_{eff}, the radial leakage conforms to the two-dimensional calculation.

By using PDQ-7, all axial calculations may be combined into one run for each bank position and possibilities for the introduction of errors may be reduced. The mixed number density cross-sections do not adequately describe the system in the computational model for the initial K_{eff}. This starting point is critical in obtaining an accurate rod bank position. The cold case was analyzed by Wigner-Wilkins (WW) cross-sections, whereas no WW cross-sections were obtainable for the hot case. The cold bank position may be seen in Figure A-2 as the point where the reactivity from PDQ-7, using leakage corresponding to the 2-D K_{eff}, is zero. Using the geometrical buckling yields a very conservative bank position about 5 inches further into the core. The effect of the MND cross-sections may be seen in Figure A-4, where the hot critical bank positions are predicted as about 10.7 inches and 23 inches. The MND initial hot K_{eff} from TURBO deviates sufficiently to preclude any possibilities of utilizing rod bank data obtained in this fashion. This is discussed on page 73 of Ref. 1. Figure A-5 further confirms this when the integral curves for the hot and cold are compared. Here the MND hot and the WW cold almost coincide. The expected situation would be where the hot worth would be substantially larger than the cold worth.

As a consequence of the empirical data, it is recommended that WW multiplication constants be utilized to obtain critical rod bank positions from the reactivity calculated in a 1-D PDQ-7 using a buckling yielding leakage conforming to the 2-D model.

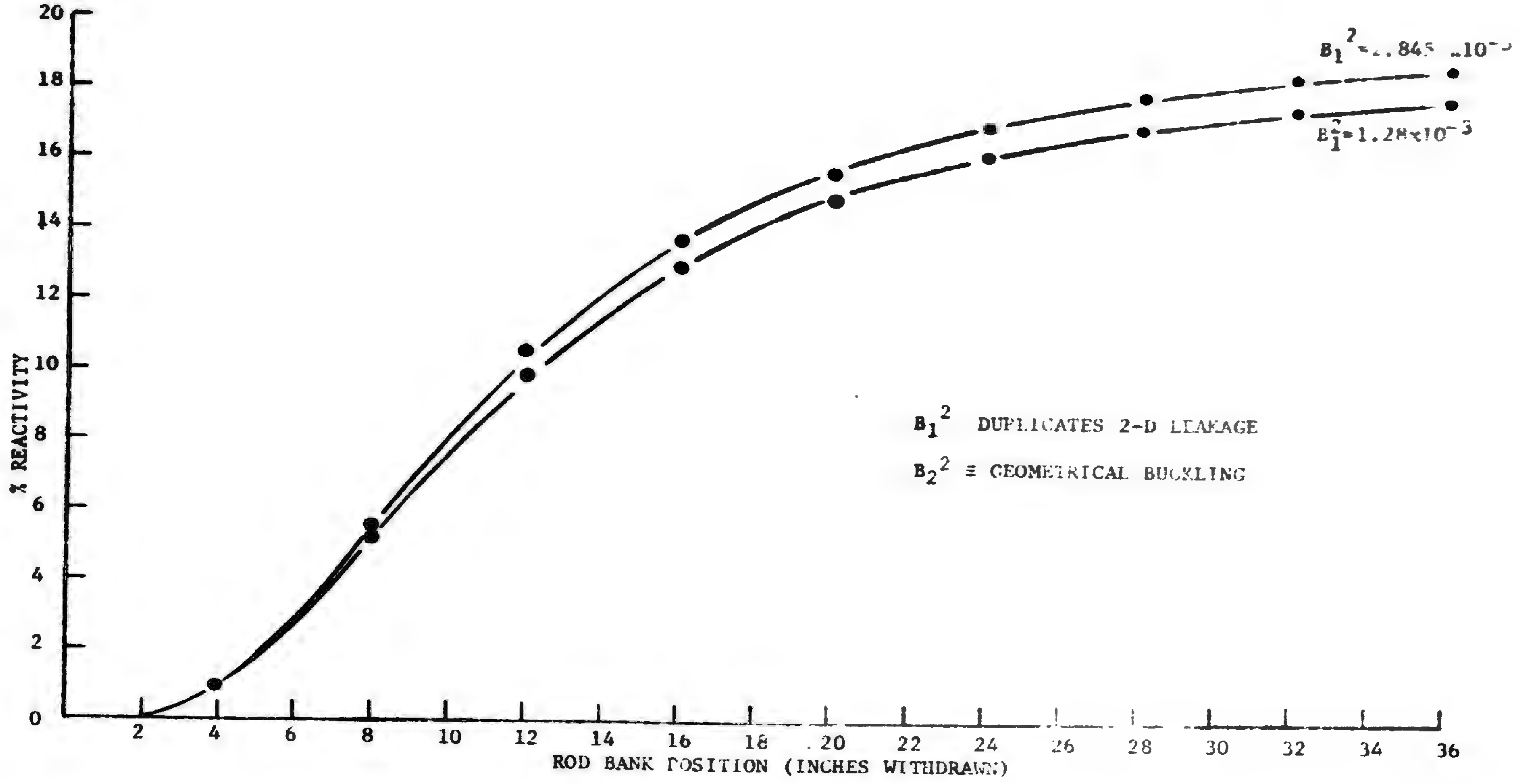


FIGURE A-1

CORE 3A COLD INTEGRAL WORTH

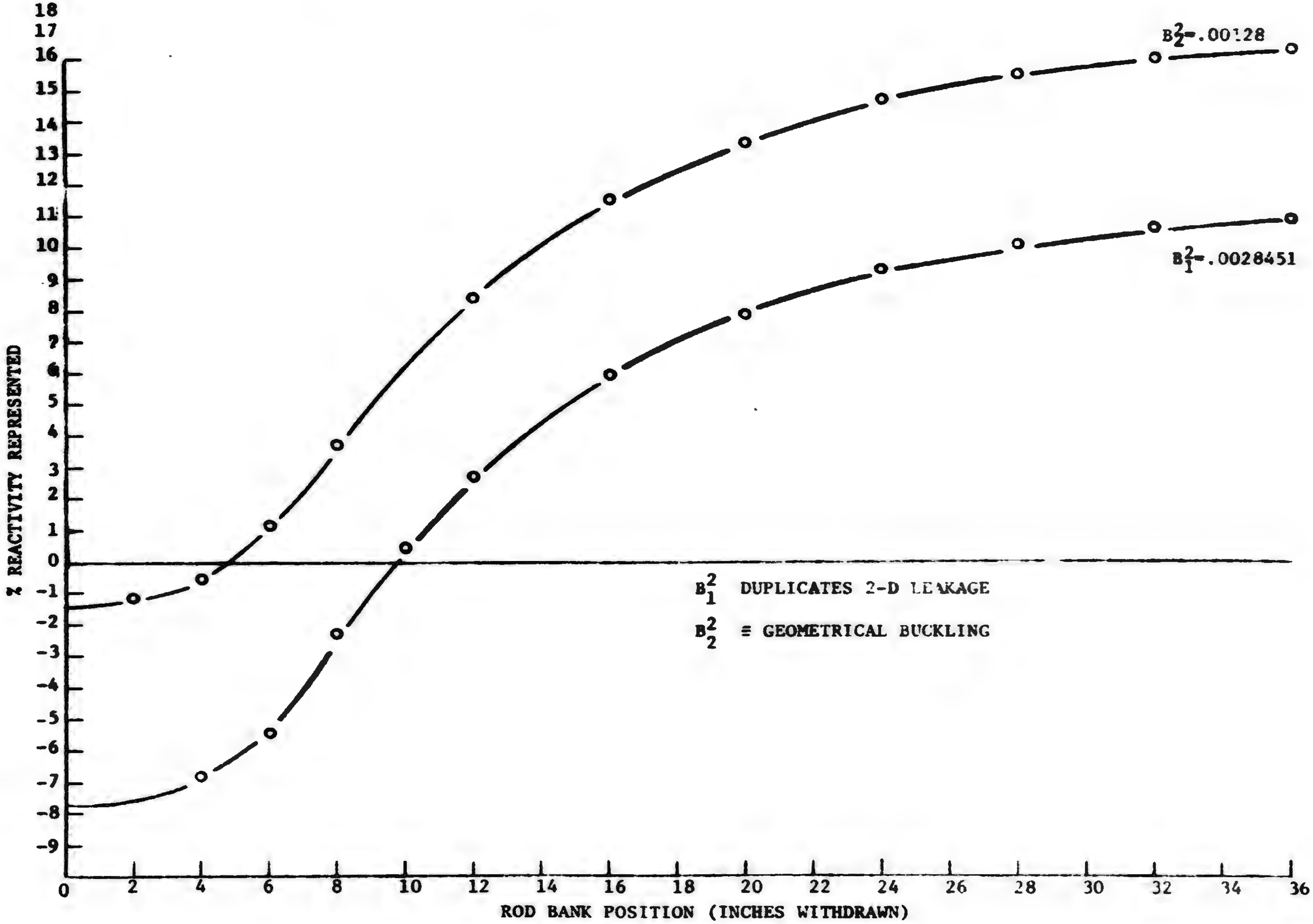


FIGURE A-2 CORE 3 COLD REACTIVITIES

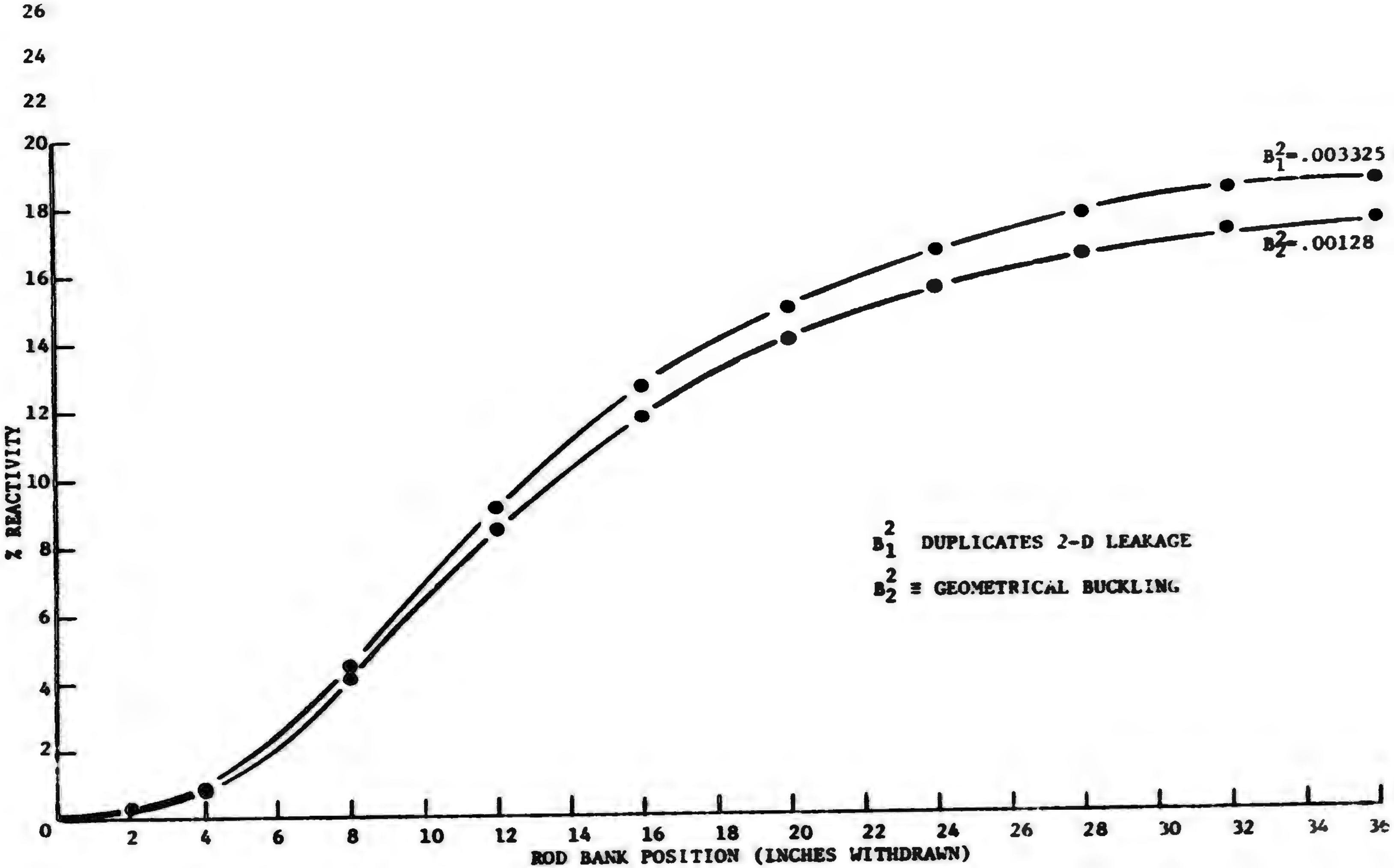


FIGURE A-3

CORE 3A HOT ROD BANK INTEGRAL WORTH

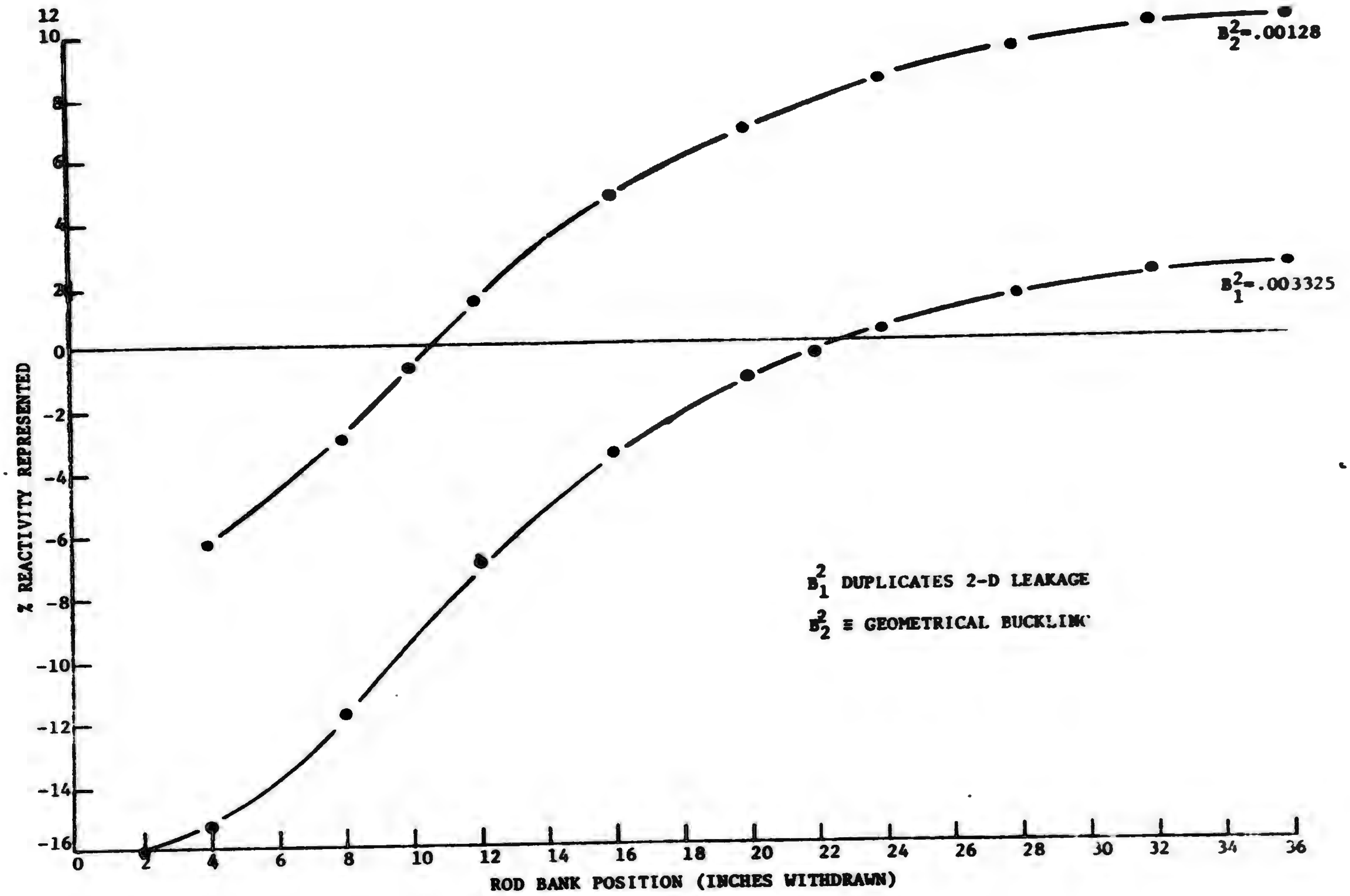


FIGURE A-4 CORE 3A HOT REACTIVITIES

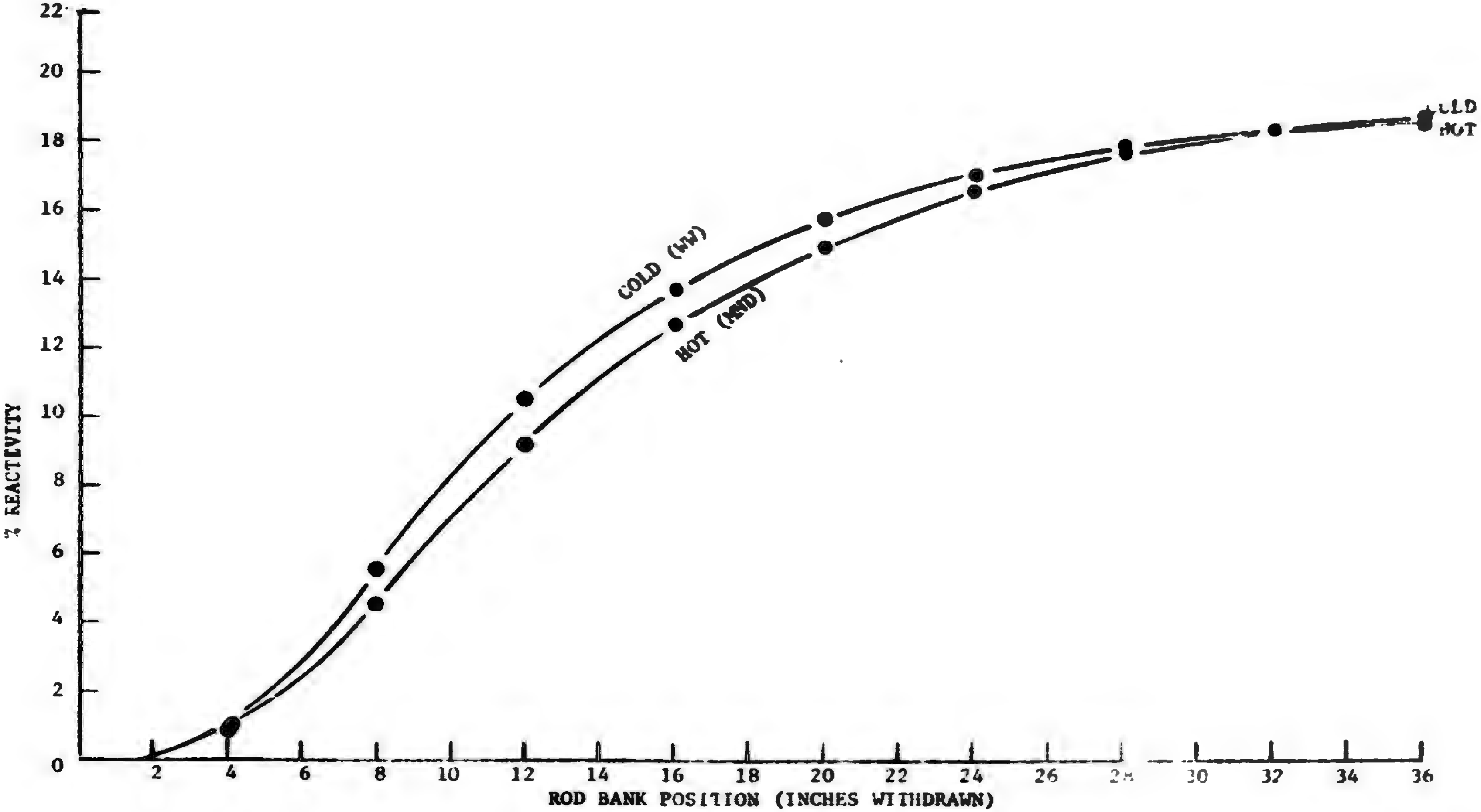


FIGURE A-5

CORE 3A INTEGRAL WORTHS