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# PM-2A CORE II
# ZERO POWER EXPERIMENT

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## ABSTRACT

This report covers the zero power experiments performed on PM-2A Core II at the Alco Critical Facility. PM-2A Core II is the first replacement core for a portable pressurized reactor at Camp Century, Greenland. Core II is the same as Core I with the exception that Core II has an increased burnable poison (B-10) content. The zero power experiment consisted of fuel element uniformity test, core assembly test, development of an on-site loading procedure and an analysis of experimental data.

Physical characteristics determined include distribution of fuel and B-10 in the fuel plates, minimum critical mass, control rod bank calibration, and integral rod worth. The report concludes with an analysis of the experimental data including estimated uniform and non-uniform burnup rates.

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## SUMMARY

The PM-2A Core II zero power experiment consisted of (1) fuel element uniformity test and a quantitative estimate of the burnable poison content of the fuel elements, (2) core assembly and critical mass experiments, (3) development of core loading procedures for the PM-2A plant, (4) analysis of experimental data and estimate of burnup characteristics.

Results of the uniformity test indicated there was satisfactory distribution of fuel and poison in the fuel elements. In addition the stuck rod measurements demonstrated that criticality could not be attained by withdrawing any single rod, but required the partial withdrawal of a second rod.

An on-site loading procedure was developed using observed count rates of mockup conditions of the PM-2A site. This procedure insures safety and efficiency without an inverse multiplication approach to criticality.

The following tabulation summarizes the important data obtained for PM-2A Core II:

| | | |
|---|---|---|
| Number of stationary fuel elements | 32 | |
| Number of control rod fuel elements | 5 | |
| Number of europium absorber sections (from Core I) | 5 | |
| Mass U-235 per stationary fuel element | 542.34 | gm |
| Mass U-235 per control rod fuel element | 427.20 | gm |
| B-10 loading per stationary fuel element | 0.492 | gm |
| B-10 loading per control rod fuel element | 0.390 | gm |
| Total B-10 in Core II | 17.7 | gm |
| Five rod bank critical position | 7.303 | in. |
| Five rod bank critical PM-2A dial reading | 6.75 | in. |
| Minimum critical mass (U-235) | 8644.08 | gm |
| Five rod bank integral worth | 31 | dollars |
| Shutdown margin at critical bank position | 12.6 | dollars |
| Shutdown margin - rod #4 fully withdrawn | 0.9 | dollars |
| Estimated core life | 9.6 | MWYR |

# INTRODUCTION

The PM-2A is a portable pressurized water reactor with a net output of 1560 KWe, located at Camp Century, Greenland. The core contains enriched U-235 fuel and B-10 as a burnable poison. There are 32 stationary fuel elements, and 5 control rods containing an absorber and a fuel element follower that is equipped with integral flux suppressors at the top of the active meat.

This report describes the zero power experiment conducted on the PM-2A Core II at the Alco Products, Inc., Criticality Facility. This experiment was a part of Subtask 10.3 of the Program Plan for Engineering Support and Development of Army PWR Power Plants. The purpose was to establish uniformity of distribution of B-10 and U-235 and to estimate B-10 loading in the fuel elements. This test is necessitated by the loss of burnable poison in varying degrees from the fuel matrix during sintering, heating, and hot rolling processes of fuel plate fabrication.

Core assembly tests were performed to determine minimum critical mass, cold, clean five rod critical bank position and to formulate on-site initial core loading procedures. Stuck rod measurements were made to determine the minimum rod withdrawal to produce criticality and provide an estimate of the shutdown margins.

# 1.0 SYSTEM DESCRIPTION

## 1.1 INTRODUCTION

This chapter consists of a general description of Alco's Critical Facility, associated equipment related to this experiment, the PM-2A Core II and definitions of the system nomenclature. A detailed description of the experimental assembly is given in references (1), (2), and (3).

## 1.2 EXPERIMENTAL ASSEMBLY

### 1.2.1 Core Support Assembly

The core support assembly is a three-tiered stainless steel structure, consisting of the carrier plate, core support plate, and grid assembly, (Fig. 1.1). The support assembly is located in the reactor tank and centered over the tank floor. Tie rods and spacers provide structural support and assure alignment of the assembly.

Although PM-2A Core II is made up of 37 fuel elements, the Facility's core support assembly being experimentally flexible, can accommodate cores with as many as 89 fuel elements. Figure 1.2 shows an assembled PM-2A core in place in the reactor tank.

### 1.2.2 Control Rod Assembly

The control rod assemblies, Fig. 1.3, are the absorber-fuel element follower type. The lower section contains the enriched U-235 fuel plates, while the upper section consists of a box type absorber. The PM-2A Core II zero power experiments were performed with absorbers made of B-10 in iron which is clad in stainless steel. It is presently planned that the europium absorbers from Core I will be used with Core II. An europium absorber is worth approximately 21 cents less reactivity in comparison to the B-10 absorbers in the central position.[6] Therefore, where it is necessary, rod positions for the PM-2A site have been adjusted to account for this difference.

### 1.2.3 Fuel Element Assembly

The Core I and Core II fuel elements are the same except for the boron loading. A stationary fuel element, Fig. 1.4, consists of 18 fuel plates. Each fuel plate is composed of 30.13 gm of U-235 in the form of $UO_2$ contained in a matrix of 0.020-in. thick stainless steel. The matrix is clad with 0.005-in. stainless steel. The total U-235 loading of each stationary fuel element is 542.34 gm. Complete specifications for these fuel elements are given in[4].

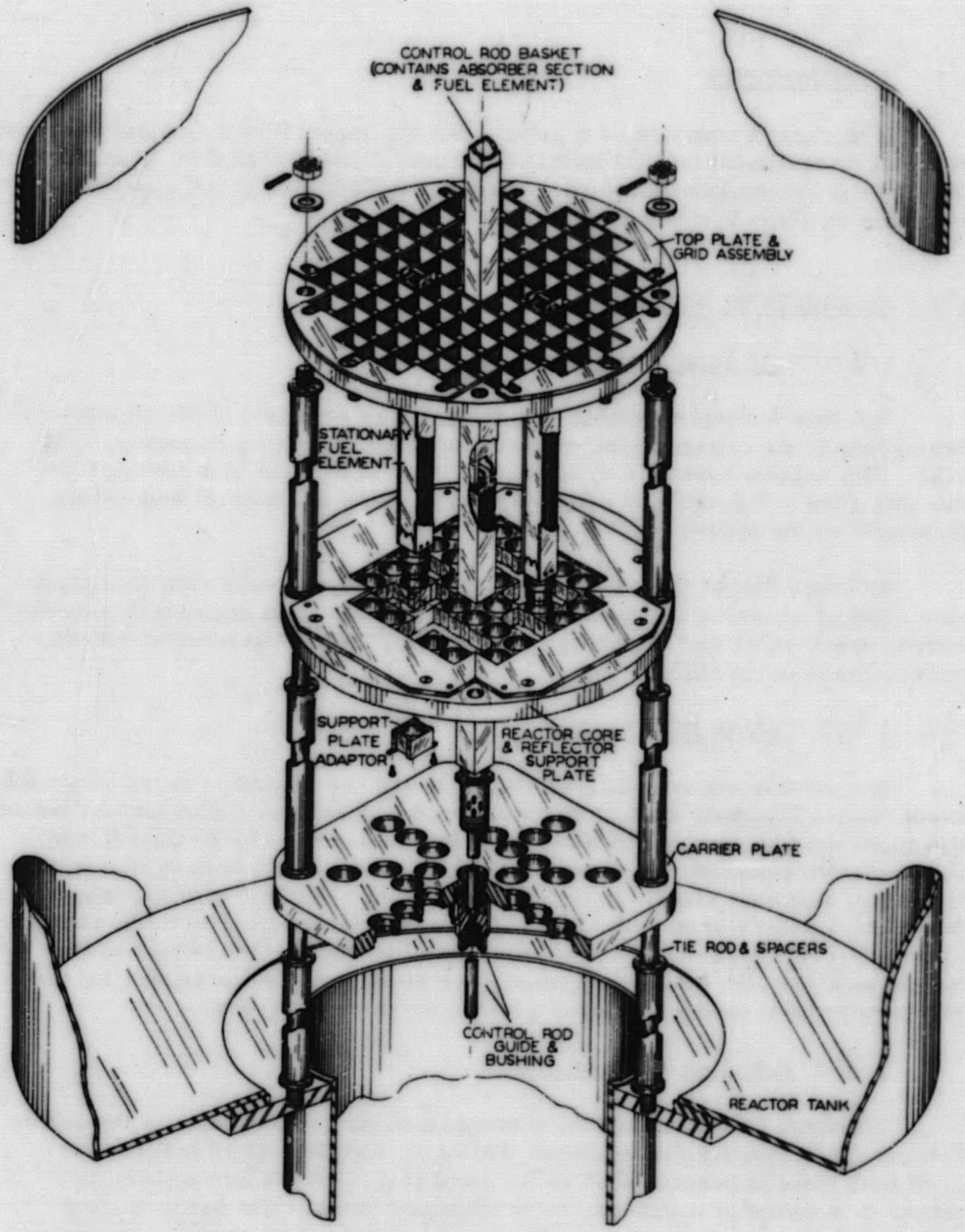



Figure 1.1. Core Support Structure

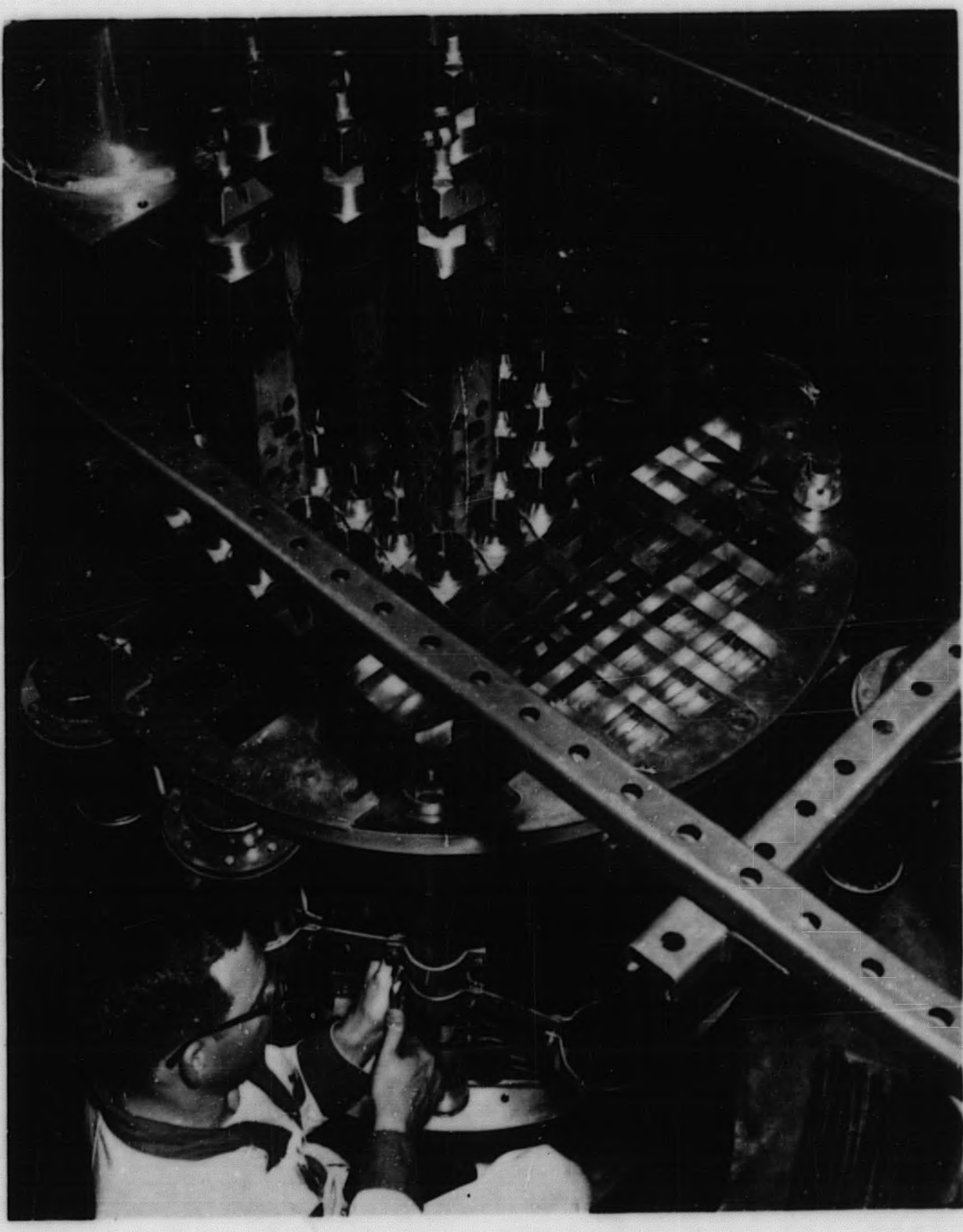


Figure 1.2. PM-2A Core In Reactor Tank

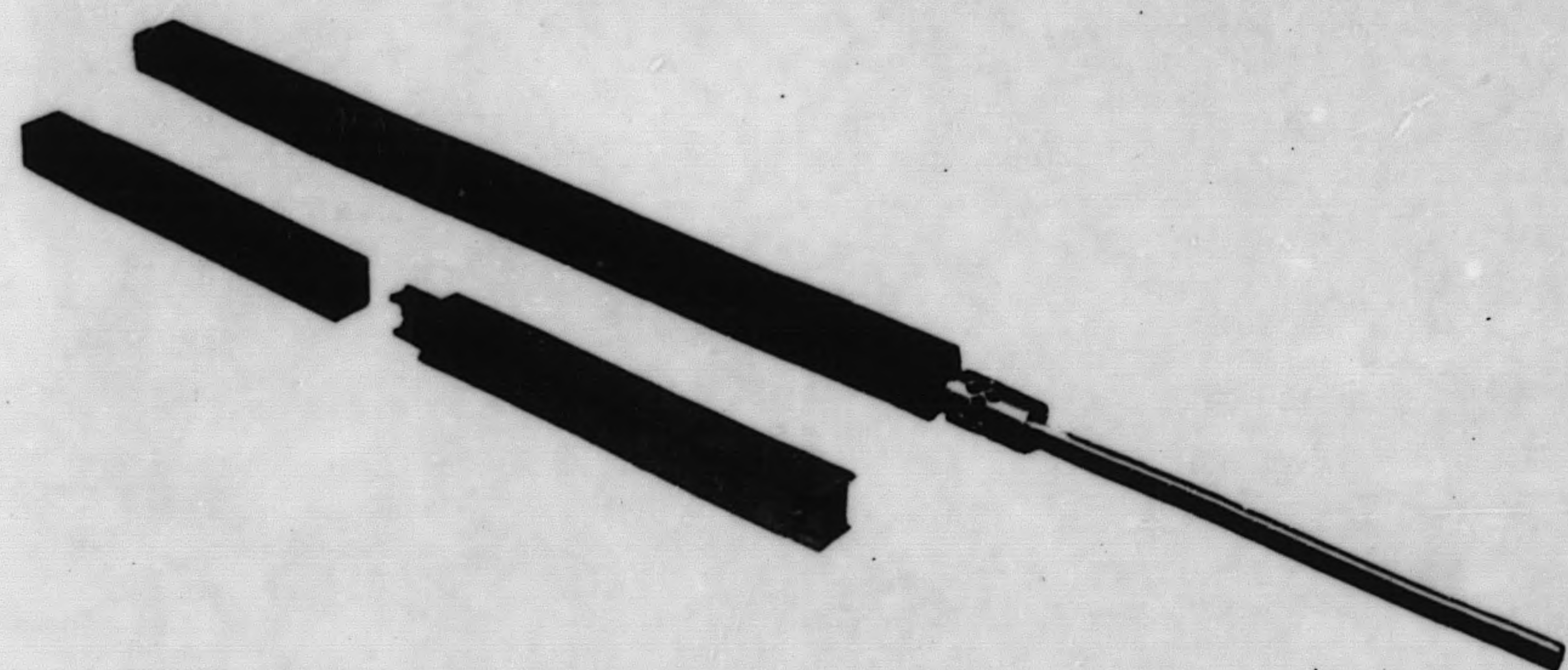


Figure 1.3. Control Rod Assembly

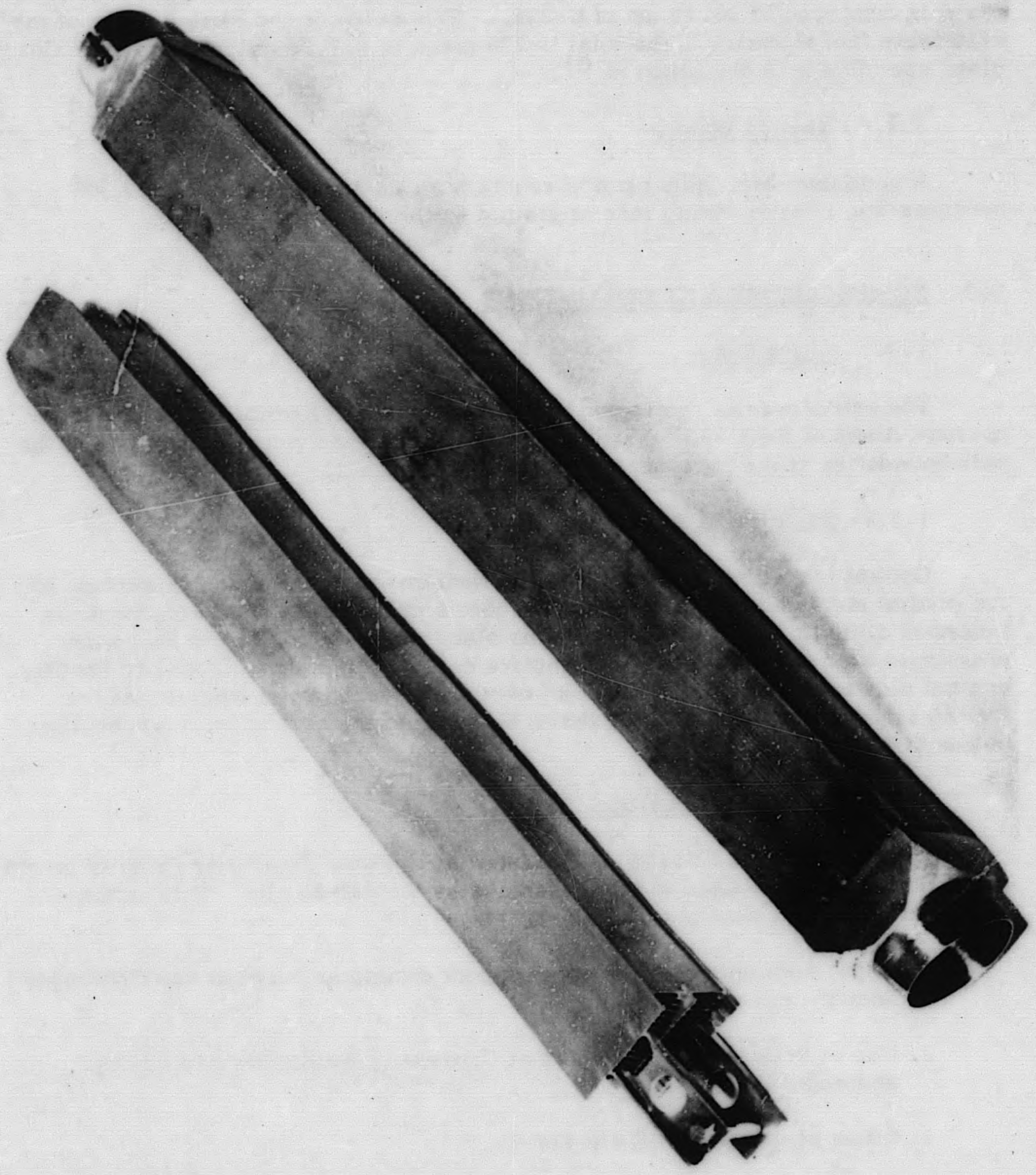


Figure 1.4. Stationary (Right) and Control Rod Fuel Element

A control rod fuel element, Fig. 1.4, consists of 16 fuel plates. Each fuel plate is composed of 26.70 gm of U-235. The matrix is the same as that of the stationary fuel elements. The total U-235 mass is 427.20 gm per element. Complete specifications are given in [5].

### 1.2.4 Neutron Source

A plutonium-beryllium neutron source with an emission rate of $8 \times 10^6$ neutrons/sec is used during reactor startup at the Criticality Facility.

## 1.3 NOMENCLATURE AND EXPLANATIONS

### 1.3.1 Active Core

The active core is the region within the boundaries of the upper and lower average limits of the U-235 distributions in the stationary-fuel elements and the cell boundaries of the outer row of stationary elements.

### 1.3.2 Control Rod Withdrawal

Control rod withdrawal refers to the withdrawal of the absorber section of the control rod assembly from the active core and the consequent simultaneous insertion of fuel. Insertion of fuel takes place when the top of the flux suppressor is even with the meat of the active core. At the Alco Criticality Facility, control rods are withdrawn by means of overhead mechanisms, whereas at the PM-2A site, control rods are withdrawn by pushing the rods up with mechanisms below thie core.

### 1.3.3 Control Rod Position

The cold clean rod positions measured at the Alco Criticality Facility do not coincide with the expected rod dial readings at the PM-2A site. This difference is due to three main reasons:

1. Slight differences in the core support structures between the Criticality Facility and PM-2A.

2. Use of B-10 in iron absorbers at Criticality Facility vs use of $Eu_2O_3$ absorbers at PM-2A.

3. Effect of thermal shield at PM-2A.

At the Alco Criticality Facility, the top of the integral flux suppressor in the control rod fuel element is aligned even with the bottom of the meat of the stationary fuel elements. This is the zero position at the Criticality Facility and is the reference position for analytical purposes. In contrast, at PM-2A site, the tops of the integral flux suppressors are located approximately 0.20 in. above the bottom of the meat of the stationary fuel elements. This rod position at PM-2A is calibrated as the zero rod dial reading. Therefore, 0.20 in. is subtracted from the Criticality Facility rod positions to compensate for PM-2A rod dial readings.

As noted in Section 1.2.2, the Criticality Facility used "B-10 in iron" absorbers for the zero power experiment, whereas at the PM-2A site, $Eu_2O_3$ absorbers are used. The boron absorbers are 21 cents more effective in the central position and approximately 14 cents per absorber more effective for eccentric positions than the $Eu_2O_3$ absorbers. Therefore, the Criticality Facility rod positions must be decreased by a proportional amount determined by the amount of absorber in the core.

The Criticality Facility used a mockup of the PM-2A thermal shield only to determine count rates during core loading. The PM-2A thermal shield is estimated to be worth about 46 cents. The Criticality Facility rod position, therefore, must be decreased by this amount to agree with the PM-2A rod dial readings.

All rod positions in this report are as measured at the Criticality Facility and can be used without correction for analytical purposes. Where PM-2A site dial readings are also given for comparison, they are so designated.

### 1.3.4 Temperature

All measurements were taken at 68$^{\circ}$F, unless otherwise stated.

## 2.0 FUEL-ELEMENT UNIFORMITY AND B-10 CONTENT EXPERIMENTS

### 2.1 INTRODUCTION

In order to provide an estimate of burnable poison (B-10) contained in each PM-2A Core II stationary fuel element, the PM-2A elements were compared in terms of reactivity differentials to an SM-1 Core I standard element of experimentally determined composition. PM-2A control rod fuel elements were compared with each other for uniformity. These tests will also detect a depleted uranium or boron free fuel plate.

### 2.2 PM-2A CORE II STATIONARY FUEL ELEMENT

#### 2.2.1 Introduction

Reactivity measurements of the PM-2A Core II stationary fuel elements were made relative to an SM-1 Core I standard element and correlated to the B-10 loading of each element.

#### 2.2.2 Procedure

The PM-2A Core II stationary-fuel elements and one SM-1 element were substituted, one at a time, into the SM-2 mockup core loading 53A[7]. Lattice position 22 was selected for the fuel element substitution, and control Rod F adjacent to position 22 was fully withdrawn in order that this absorber section would not affect measurements in this quadrant. In addition, Rods A, B, C, D and G were kept at a bank position of 5.883 in.; and reactivity differences, measured on calibrated control Rod E. Using this bank position, control Rod E had a critical position in the range of 11 to 13 in., where it was known from previous experiments to have a smooth and essentially linear calibration curve. From these total reactivity differences, an estimate can be made of the uniformity of the fuel and boron loading.

As a counter check to the above uniformity experiment, four elements were rotated 180 degrees, and a comparison made of the relative change in the worth. This comparison would reveal any non-uniformities within the element itself with the exception of having a non-uniformity symmetrical to the centerline axis, which would be highly improbable.

#### 2.2.3 Sample Calculation

##### 2.2.3.1 Reactivity Differential Due to B-10

Let $\Delta K_B$ represent the reactivity change due to the difference in the amount of B-10 in the PM-2A element and the standard SM-1 element. $\Delta K_B$ is equal to the difference in the total reactivity change and the reactivity change attributed to the differential U-235 loading. This is expressed as

$$\Delta K_B = \Delta K_T - \Delta K_u$$

where:

$\Delta K_T$ = Total reactivity change of the PM-2A element as compared to the SM-1 standard.

$\Delta K_u$ = Estimated reactivity change due to the additional U-235 loading of the PM-2A element.

= 7.97 cents per element. (6)

$\Delta K_T$ is determined simply by multiplying the worth per inch of some calibrated control rod and the distance travelled by this rod between its critical height using the SM-1 standard and its critical height using the PM-2A element.

2.2.3.2 Difference in B-10 Loading

The difference in the amount of B-10 in the PM-2A element and in the standard element is $\Delta K_B$ divided by the worth of B-10 per gram. This is expressed as

$$\Delta M_B = \frac{\Delta K_B}{W_B}$$

where:

$\Delta M_B$ = Mass difference of the amount of B-10 in the PM-2A and the SM-1 element.

$W_B$ = Worth of B-10 per gram. Ref. (8)

= 117 cents/gm using same configuration as Ref. (8)

Since the SM-1 element is estimated to have 0.363 gm of B-10, Ref. (7), the total B-10 contained in a PM-2A element would be $\Delta M_B$ + 0.363 gm.

2.2.4 Data

The experimentally determined reactivity differences between the PM-2A Core II and the SM-1 standard are tabulated in Table 2.1. This reactivity differential is the total change between the elements and the standard due to differences in U-235 and B-10 loadings. To determine the differential reactivity due to B-10, the U-235 worth, 7.97 cents per element, was subtracted from the total reactivity change and is tabulated in the column headed as $\Delta K_B$ of Table 2.1 From these values of $\Delta K_B$, the estimated B-10 loading per element was computed and also shown in Table 2.1.

TABLE 2.1
STATIONARY ELEMENT UNIFORMITY EXPERIMENT
PM-2A CORE II ZPE VI

| Element Number | $\Delta K_T$, Cents | $\Delta K_B$, Cents | $\Delta M_B$ B-10 Mass Change from Standard, gm | Estimated B-10 Loading, gm |
|---|---|---|---|---|
| 1-1 | -7.59 | -15.56 | +0.133 | 0.496 |
| 1-2 | -7.15 | -15.12 | +0.129 | 0.492 |
| 1-4 | -9.02 | -16.99 | +0.145 | 0.508 |
| 1-6 | -6.90 | -14.87 | +0.127 | 0.490 |
| 1-7 | -8.54 | -16.51 | +0.141 | 0.504 |
| 1-8 | -8.91 | -16.88 | +0.144 | 0.507 |
| 1-9 | -7.34 | -15.31 | +0.131 | 0.494 |
| 1-10 | -3.22 | -11.19 | +0.096 | 0.459 |
| 1-11 | -5.57 | -13.56 | +0.116 | 0.479 |
| 1-12 | -6.15 | -14.12 | +0.121 | 0.484 |
| 1-13 | -6.77 | -14.74 | +0.126 | 0.489 |
| 1-14 | -7.52 | -15.49 | +0.132 | 0.495 |
| 1-15 | -7.25 | -15.22 | +0.130 | 0.493 |
| 1-16 | -7.56 | -15.53 | +0.133 | 0.496 |
| 1-17 | -7.40 | -15.37 | +0.131 | 0.494 |
| 1-18 | -5.75 | -13.72 | +0.117 | 0.480 |
| 1-19 | -5.38 | -13.35 | +0.114 | 0.477 |
| 1-20 | -4.30 | -12.27 | +0.105 | 0.468 |
| 1-21 | -6.93 | -14.90 | +0.127 | 0.490 |
| 1-22 | -7.06 | -15.03 | +0.128 | 0.491 |
| 1-23 | -5.26 | -13.23 | +0.113 | 0.476 |
| 1-24 | -10.15 | -18.12 | +0.155 | 0.518 |
| 1-25 | -7.15 | -15.12 | +0.129 | 0.492 |
| 1-26 | -7.03 | -15.00 | +0.128 | 0.491 |
| 1-27 | -9.74 | -17.71 | +0.151 | 0.514 |
| 1-28 | -10.82 | -18.79 | +0.161 | 0.524 |
| 1-29 | -9.26 | -17.23 | +0.147 | 0.510 |
| 1-30 | -6.58 | -14.55 | +0.124 | 0.487 |
| 1-31 | -2.84 | -10.81 | +0.092 | 0.455 |
| Total | -212.38 | -451.48 | +3.856 | 14.746 |
| Average | -7.079 | 15.05 | 0.129 | 0.492 ± 0.015 |

## 2.3 PM-2A CORE II CONTROL ROD FUEL ELEMENT

### 2.3.1 Introduction

To perform the control rod fuel element uniformity experiment, six control rods were loaded with SM-2 mockup control rod fuel elements. A seventh control rod was loaded with a PM-2A Core II control rod fuel element. The control rod containing the PM-2A fuel element was fully withdrawn and a reactivity difference measured on calibrated control Rod E, containing an SM-2 fuel element. Because there was no standard with which to compare the PM-2A Core II control rod fuel elements, it was necessary to use the method mentioned above of checking one element against another.

### 2.3.2 Procedure

Each of the PM-2A Core II control rod fuel elements was substituted in turn, in Rod F. The reactor was brought critical with control Rod F fully withdrawn and the five-rod bank position at 5.883 inches. The reactivity differences were measured on calibrated control Rod E.

The critical position and differential worth of Rod E for each of the five elements was tabulated and averaged. The difference between the differential worth and the average was then determined.

### 2.3.3 Data

The average critical position and worth of control Rod E at this position for the five control rod fuel elements was 10.907 in. and 28.68 cents per in., respectively. The resulting reactivity deviation from the average is given in Table 2.2.

TABLE 2.2
CONTROL ROD FUEL ELEMENT UNIFORMITY EXPERIMENT
PM-2A CORE II ZPE VI

| Control Rod No. | $\Delta K$ from Average, Cents |
|---|---|
| 2-1 | -1.43 |
| 2-2 | -1.81 |
| 2-3 | -1.14 |
| 2-4 | +2.92 |
| 2-5 | +1.44 |

## 2.4 SUMMARY

The uniformity test indicated that the fuel elements have an even distribution of fuel and poison. However, special cases in which the reactivity effects of fuel and poison are essentially compensating would not be apparent from these measurements, but manufacturing processes preclude these possibilities.

The comparative reactivity measurements indicated that the stationary fuel elements contain an average of 0.492 ± 0.015 gm of B-10 per element. This indicates a 26 percent fabrication loss of natural boron based on the original loadings of $B_4C$ at the start of the fabrication. Assuming the same percent of fabrication loss in the control rod fuel elements, they would contain 0.390 ± 0.015 gm of B-10 per element.

## 3.0 PM-2A CORE II ASSEMBLY AND CRITICAL MASS EXPERIMENTS

### 3.1 INTRODUCTION

The critical mass of the core and a worth calibration of the five rod bank are determined from a series of critical mass experiments. To determine the critical mass, PM-2A Core II fuel elements were consecutively loaded into the core assembly until the reactor became critical. The elements were then re-arranged to arrive at a geometry with a minimum surface-to-volume ratio. This arrangement yields the minimum critical mass.

To develop the calibration curve, worth measurements of the five rod bank were determined at the minimum critical mass and after each successive group loading consisting of four or less elements.

### 3.2 CRITICAL MASS

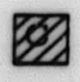
#### 3.2.1 Procedure

To eliminate the possibility of assembling a super-critical core with control rods inserted, a graphical plot was developed of the inverse multiplication, 1/M, as a function of the amount of fuel assembled in the core. As the fuel in the core increases, 1/M approaches zero. When 1/M becomes zero, the reactor is self-sustaining, or critical. After each addition of fuel, the graphical plot was extrapolated to zero in order to estimate the critical mass. Each fuel addition was then limited to 1/2 the difference between the extrapolated critical mass and the previous loading or four elements (approximately 2 Kg of U-235), whichever was smaller. Three instruments were used to monitor the count rates. These consisted of two $BF_3$ proportional counters and an ion chamber with a linear amplifier, Beckman No. 1. These chambers were placed as close to the core boundary as possible so there would be maximum instrument or neutron response.

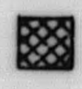
The fuel loadings consisted initially of the five control rod fuel elements with subsequent additions of stationary elements. The configuration of these loadings in their respective order is shown in Fig. 3.1.

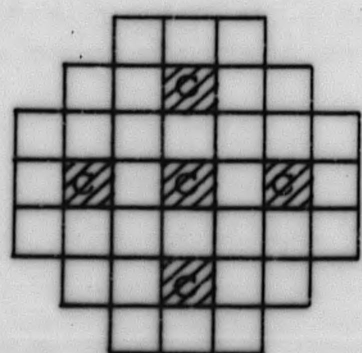
#### 3.2.2 Data

Table 3.1 is a tabulation of the U-235 mass in the core and the inverse multiplication. Criticality was attained with 17 fuel elements containing 8644.08 gm of U-235. With this critical mass the five rod critical position was 19.798 in. corresponding to a dial reading 18.5 in. at the PM-2A site.

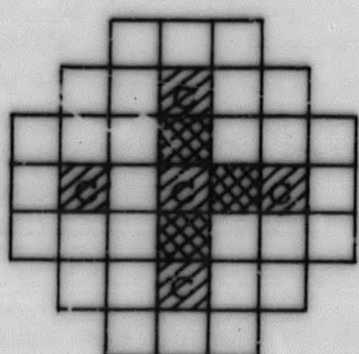
 Control Rod Fuel Element

 Stationary Fuel Element

 Fuel Element Added to Preceding Fuel Assembly

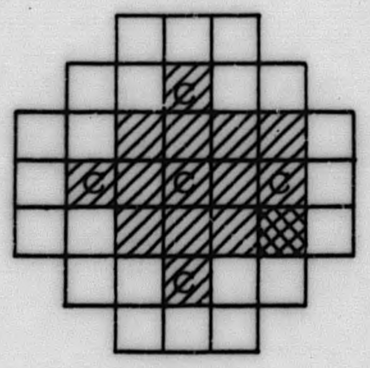


| | |
|---|---|
| Core Assembly #1 | Not Critical |
| Total Number of Elements | 5 |
| Total Mass of U-235 | 2136.00 gm |
| 1/M Using $BF_3$ Chamber (A) | 0.83 |
| 1/M Using $BF_3$ Chamber (B) | 0.67 |
| Five Rod Bank Position | Fully Withdrawn |

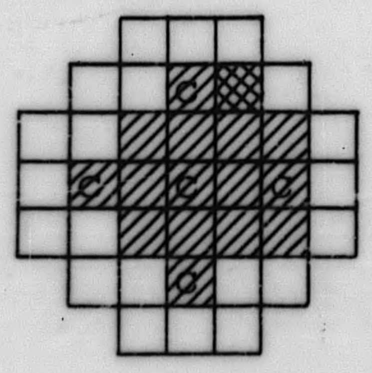


| | |
|---|---|
| Core Assembly #2 | Not Critical |
| Total Number of Elements | 8 |
| Total Mass of U-235 | 3763.02 gm |
| 1/M Using $BF_3$ Chamber (A) | 0.704 |
| 1/M Using $BF_3$ Chamber (B) | 0.368 |
| Five Rod Bank Position | Fully Withdrawn |

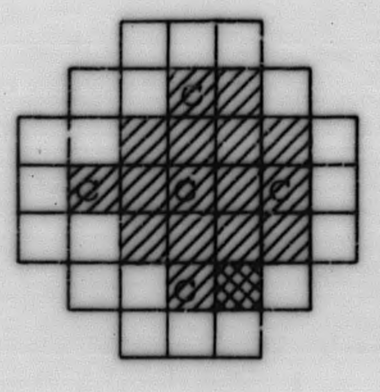
Figure 3.1. Core Assemblies for Initial Approach to Criticality-PM-2A Core II ZPE VI



| | |
|---|---|
| Core Assembly #6 | Not Critical |
| Total Number of Elements | 15 |
| Total Mass of U-235 | 7559.40 gm |
| 1/M Using $BF_3$ Chamber (A) | 0.135 |
| 1/M Using $BF_3$ Chamber (B) | 0.0188 |
| Five Rod Bank Position | Fully Withdrawn |



| | |
|---|---|
| Core Assembly #7 | Not Critical |
| Total Number of Elements | 16 |
| Total Mass of U-235 | 8101.74 gm |
| 1/M Using $BF_3$ Chamber (A) | 0.052 |
| 1/M Using $BF_3$ Chamber (B) | 0.00435 |
| Five Rod Bank Position | Fully Withdrawn |



| | |
|---|---|
| Core Assembly #8 | Critical |
| Total Number of Elements | 17 |
| Total Mass of U-235 | 8644.08 gm |
| 1/M Using $BF_3$ Chamber (A) | Critical |
| 1/M Using $BF_3$ Chamber (B) | Critical |
| Five Rod Bank Position | 19.798 inches |

Figure 3.1. (Continued)

TABLE 3.1
U-235 MASS VS INVERSE MULTIPLICATION
PM-2A CORE II ZPE VI

| U-235 Mass gm | No. of Fuel Elements | 1/M $BF_3$ A* | 1/M $BF_3$ B* | 1/M Beckman No. 1* |
|---|---|---|---|---|
| 0 | 0 | 1 | 1 | 1 |
| 2136.00 | 5 | 0.830 | 0.670 | 0.980 |
| 3763.02 | 8 | 0.704 | 0.368 | 0.944 |
| 5390.04 | 11 | 0.579 | 0.122 | 0.910 |
| 6474.72 | 13 | 0.375 | 0.0476 | 0.830 |
| 7017.06 | 14 | 0.242 | 0.0325 | 0.770 |
| 7559.40 | 15 | 0.135 | 0.0188 | 0.668 |
| 8101.74 | 16 | 0.052 | 0.00435 | 0.455 |
| 8644.08 | 17 | Critical | Critical | Critical |

* Initial detector response $BF_3$ (A) 1.49 cps, $BF_3$ (B) 0.18 cps, Beckman (No. 1) $5 \times 10^{-13}$ amp.

Figure 3.2 shows the graphical plot of 1/M vs U-235 mass for the three counting chambers used. Extrapolation of the three curves indicates a critical mass of 8450 gm to attain criticality.

The core geometry was rearranged to a 4 x 4 configuration; however, because of the reduced U-235 mass, this geometry failed to reach criticality. One control rod fuel element was added to the edge of the 4 x 4 assembly. Criticality was achieved with this geometry; however, the critical assembly consisted of 8759.22 gm of U-235. The configurations for these core assemblies are shown in Fig. 3.3.

## 3.3 FIVE ROD BANK CALIBRATION

Fuel elements in groups of four or less were added to the initial critical mass assembly until the core was fully loaded and contained 32 stationary fuel elements and the five control rods. The geometry after each of these fuel additions is shown progressively in Fig. 3.4.

After the addition of each fuel group, the reactor was brought critical with the five rod bank. These bank positions and U-235 mass are given in Table 3.2. A plot of bank position as a function of the number of fuel elements is shown in Fig. 3.5.

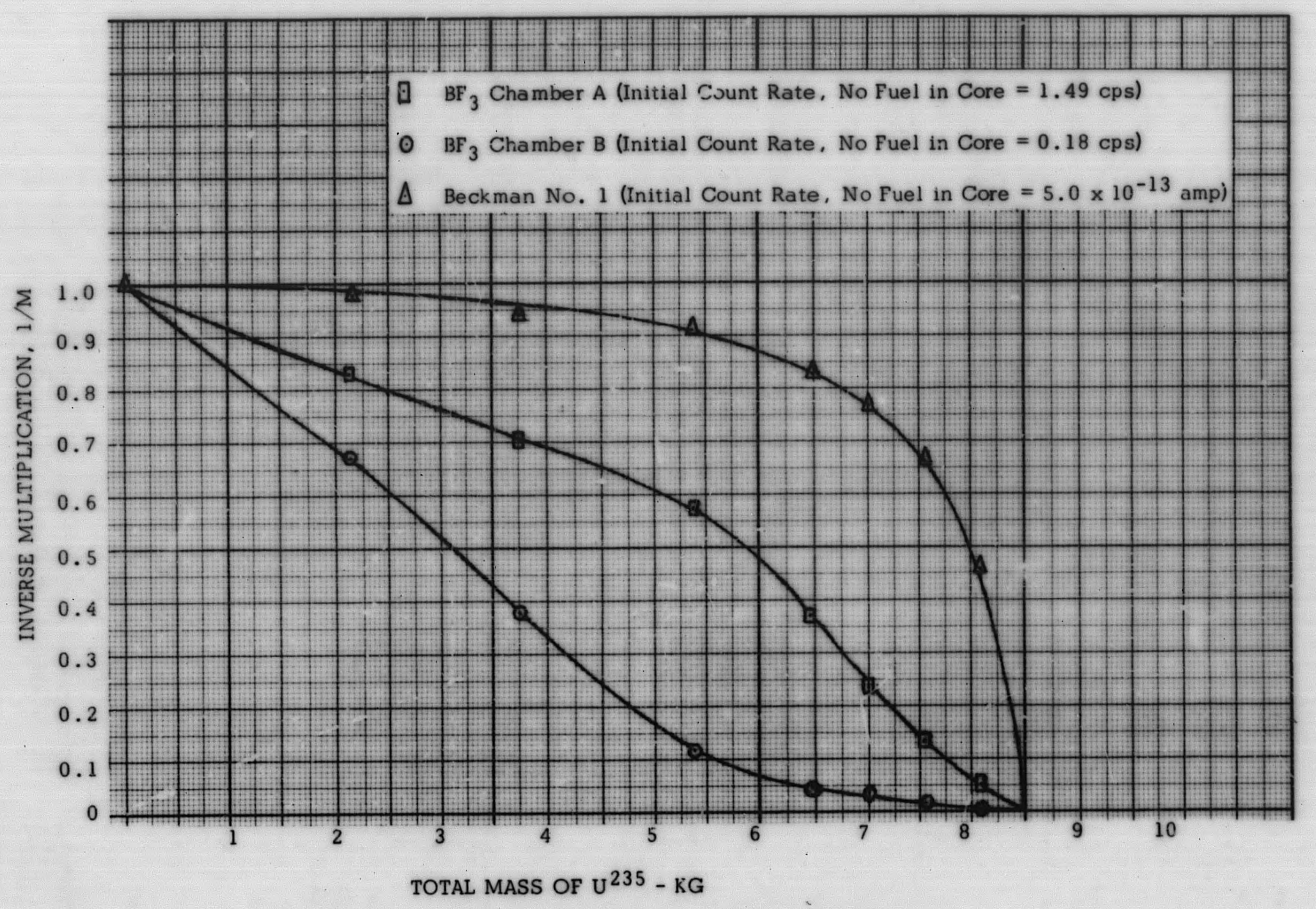
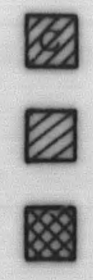


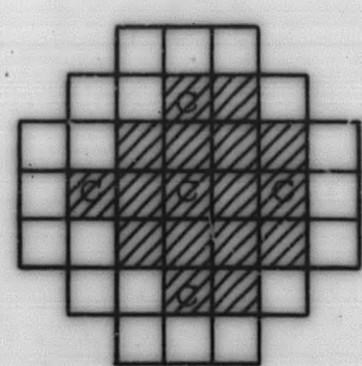

Figure 3.2. Inverse Multiplication Vs Total $U^{235}$ In Core PM-2A Core II ZPE VI



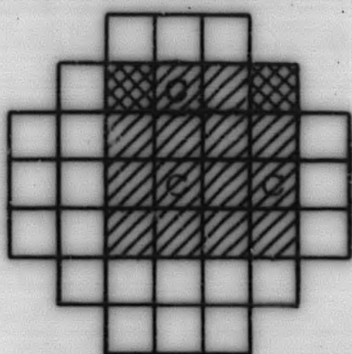
Control Rod Fuel Element

Stationary Fuel Element

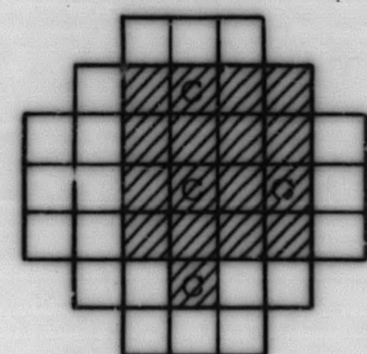
Fuel Element Added to Preceding Fuel Assembly



| | |
|---|---|
| Core Assembly #8 | Critical |
| Initial Criticality | |
| Total Number of Elements | 17 |
| Total Mass of U-235 | 8644.08 gm |
| Five Rod Bank Position | 19.798 inches |

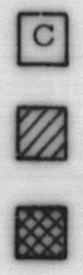


| | |
|---|---|
| Core Assembly #9A | Not Critical |
| 4 x 4 Configuration | |
| Total Number of Elements | 16 |
| Total Mass of U-235 | 8332.02 gm |
| Three Rod Bank Position | Fully Withdrawn |



| | |
|---|---|
| Core Assembly #9B | Critical |
| 4 x 4 plus one Control Rod | |
| Total Number of Elements | 17 |
| Total Mass of U-235 | 8759.22 gpm |
| Three Rod Bank Position | Fully Withdrawn |
| Rod #2 Position | 13.621 inches |

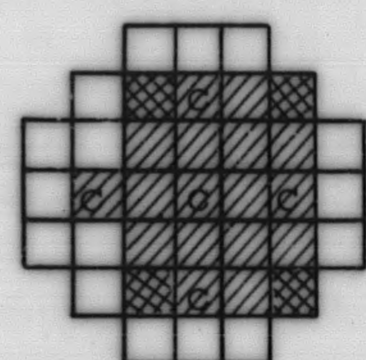
Figure 3.3. Core Assemblies to Determine Minimum Critical Mass PM-2A Core II ZPE VI



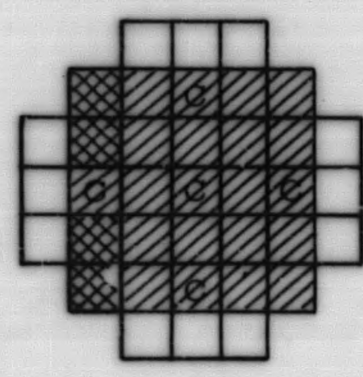
Control Rod Fuel Element

Stationary Fuel Element

Fuel Element Added to Preceding Fuel Assembly

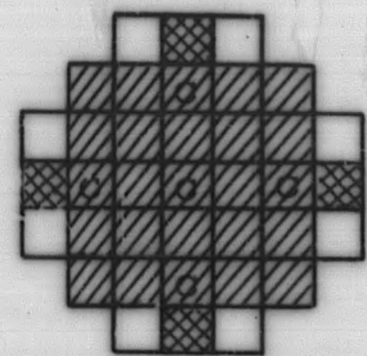


Core Assembly #10
Total Number of Elements 21
Total Mass of U-235 10.81 Kg
Five Rod Critical Bank Position 13.742 Inches

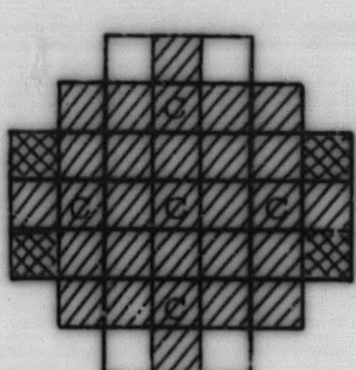


Core Assembly #11
Total Number of Elements 25
Total Mass of U-235 12.98 Kg
Five Rod Critical Bank Position 11.084 Inches

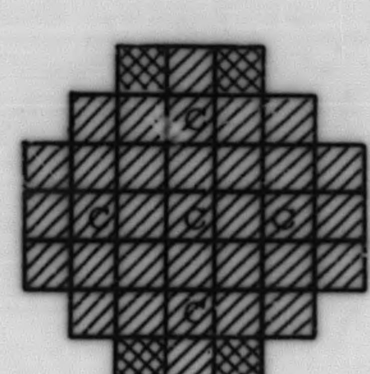
Figure 3.4. Core Assemblies from Initial Criticality to Fully Loaded Core PM-2A Core II ZPE VI



| | |
|---|---|
| Core Assembly #12 | |
| Total Number of Elements | 29 |
| Total Mass of U-235 | 15.15 Kg |
| Five Rod Critical Bank Position | 9.511 Inches |



| | |
|---|---|
| Core Assembly #13 | |
| Total Number of Elements | 33 |
| Total Mass of U-235 | 17.32 Kg |
| Five Rod Critical Bank Position | 8.342 Inches |



| | |
|---|---|
| Core Assembly #14 | |
| Total Number of Elements | 37 |
| Total Mass of U-235 | 19.49 Kg |
| Five Rod Critical Bank Position | 7.303 Inches |

Figure 3.4. (Continued)

TABLE 3.2
BANK POSITION VS U-235 MASS
PM-2A CORE II ZPE VI

(With S.S. Skirt)

| Five Rod Bank Position, In. | No. of Fuel Elements | U-235 Mass, gm |
|---|---|---|
| 19.798 | 17 | 8644.08 |
| 13.742 | 21 | 10813.44 |
| 11.084 | 25 | 12982.80 |
| 9.511 | 29 | 15152.16 |
| 8.342 | 33 | 17321.52 |
| 7.303 | 37 | 19490.88 |

Bank worths were determined by the period method and plotted as a function of bank position. (See Fig. 3.6.)

The cold clean critical bank position of the fully loaded PM-2A Core II, 37 elements, was 7.303 in. as compared to 6.605 in. for Core I. The corresponding PM-2A site dial readings are 6.75 and 6.3 in. respectively. The bank positions stated here for Core I include an adjustment of 50 cents to account for the stainless steel skirt, so that a comparison could be made between Core I and Core II.

TABLE 3.3
BANK POSITION VS. BANK WORTH
PM-2A CORE II ZPE VI

(With Skirt)

| No. of Fuel Elements | Five Rod Bank Position, In. | Worth, cents/inch |
|---|---|---|
| 17 | 20.058 | 37.36 |
| 21 | 13.829 | 120.34 |
| 25 | 11.141 | 174.78 |
| 29 | 9.558 | 224.36 |
| 33 | 8.385 | 253.20 |
| 37 | 7.339 | 255.07 |

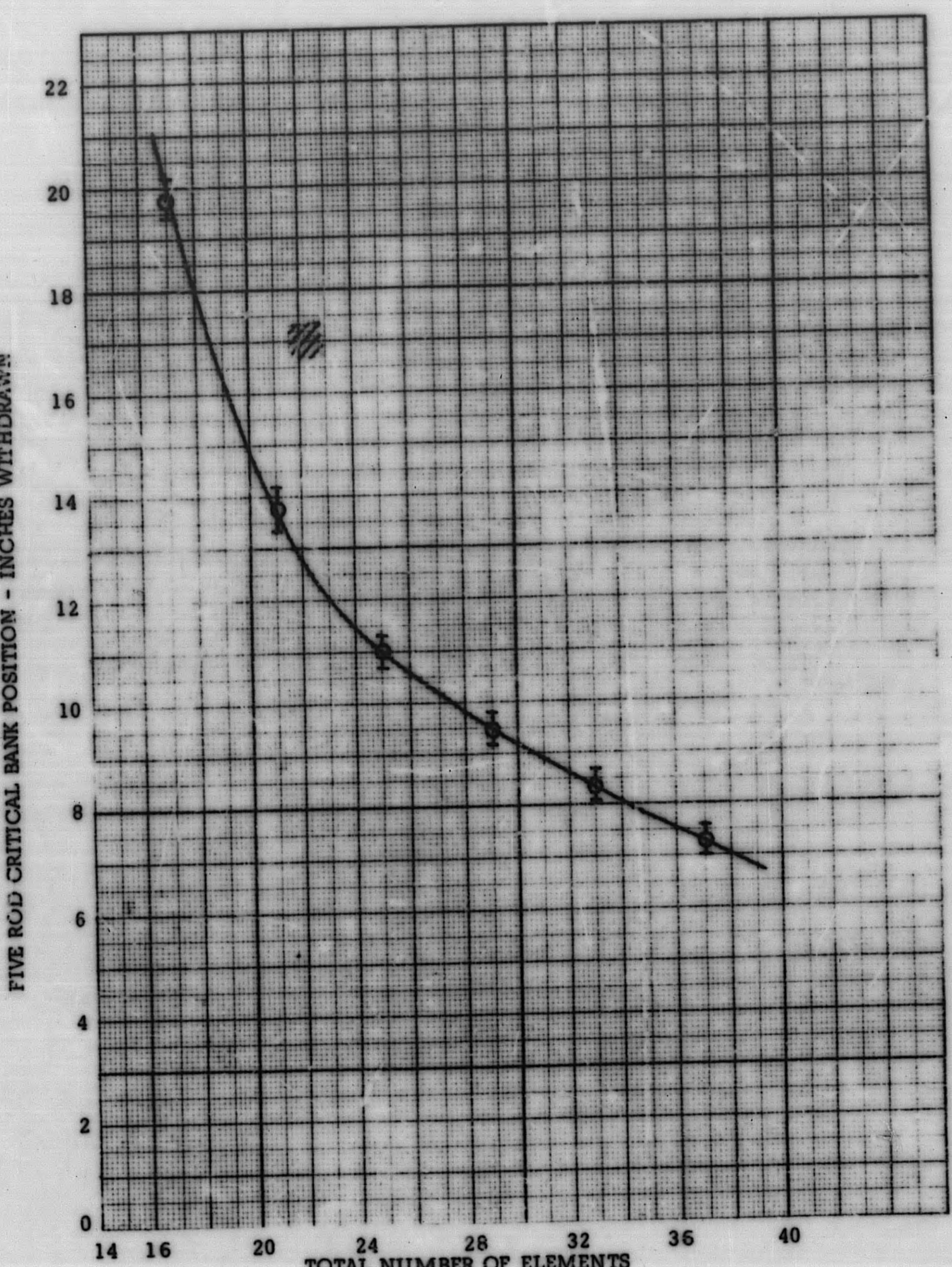



Figure 3.5. Five Rod Critical Bank Position Vs Total Number of Elements For Cold Approach To Operational Loading - PM-2A Core II ZPE VI

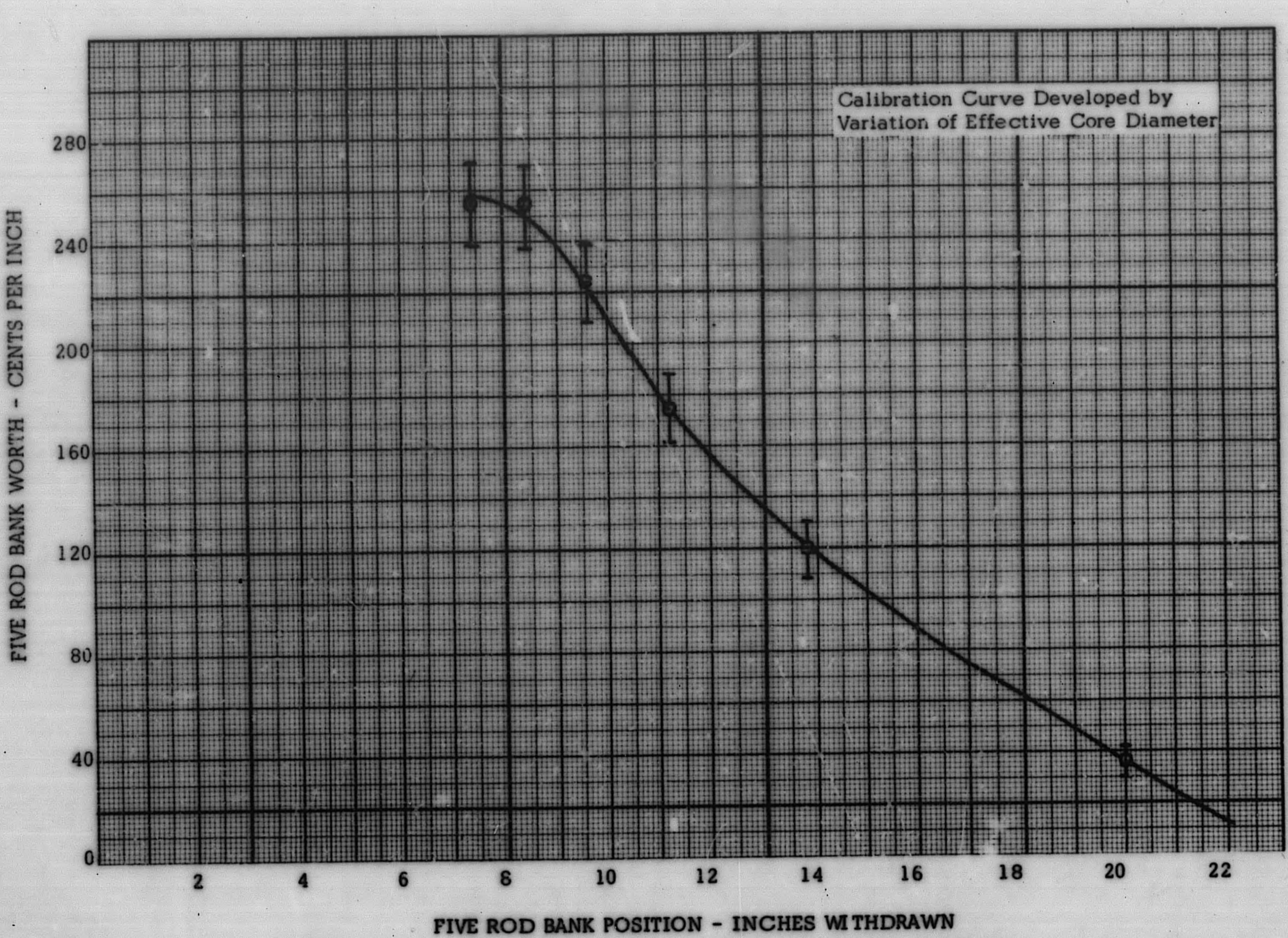



Figure 3.6. Bank Worth Vs Bank Position - PM-2A Core II ZPE VI

## 3.4 CONTROL ROD CALIBRATION

A calibration curve of control rod 4 is shown in Fig. 3.7. B-10 in iron absorber section was used and the four rod bank was adjusted between 4.122 to 9.497 in. to develop the curve.

## 3.5 STUCK ROD EXPERIMENTS

Stuck rod measurements were made on all five rods. These measurements were made with pairs of rods as well as single rods. The PM-2A Core II could not be brought critical by withdrawal of a single control rod. Partial withdrawal of a second control rod was necessary to attain criticality. Table 3.4 is a tabulation of the stuck rod measurements. Adjustments were made in the PM-2A dial readings to account for the $Eu_2O_3$ absorbers to be used at the site. From the stuck rod measurement the worth of the stainless steel skirt is found to be approximately 50 cents.

## 3.6 CRITICAL WATER HEIGHT

### 3.6.1 Introduction

Critical water height experiments were performed as a means of determining the excess reactivity of the PM-2A Core II. To determine the excess reactivity, the axial reflector savings must be evaluated. An estimate of the axial reflector savings can be made through variations of the water reflector worth at different critical water heights. This method is based on one-group theory of an effective bare core. The method assumes that radial flux distributions are independent of axial position and that axial-reflector savings are independent of the core height.

Differentiating the one group critical equations yields: [10]

$$\frac{d\rho}{dh} = \frac{2\pi^2 M^2}{k_\infty} \left[\frac{1}{(h + S_z)^3}\right] \qquad (3.1)$$

where

$\rho$ = reactivity
M = migration distance
h = core height
$S_z$ = axial reflector savings
$k_\infty$ = infinite multiplication factor

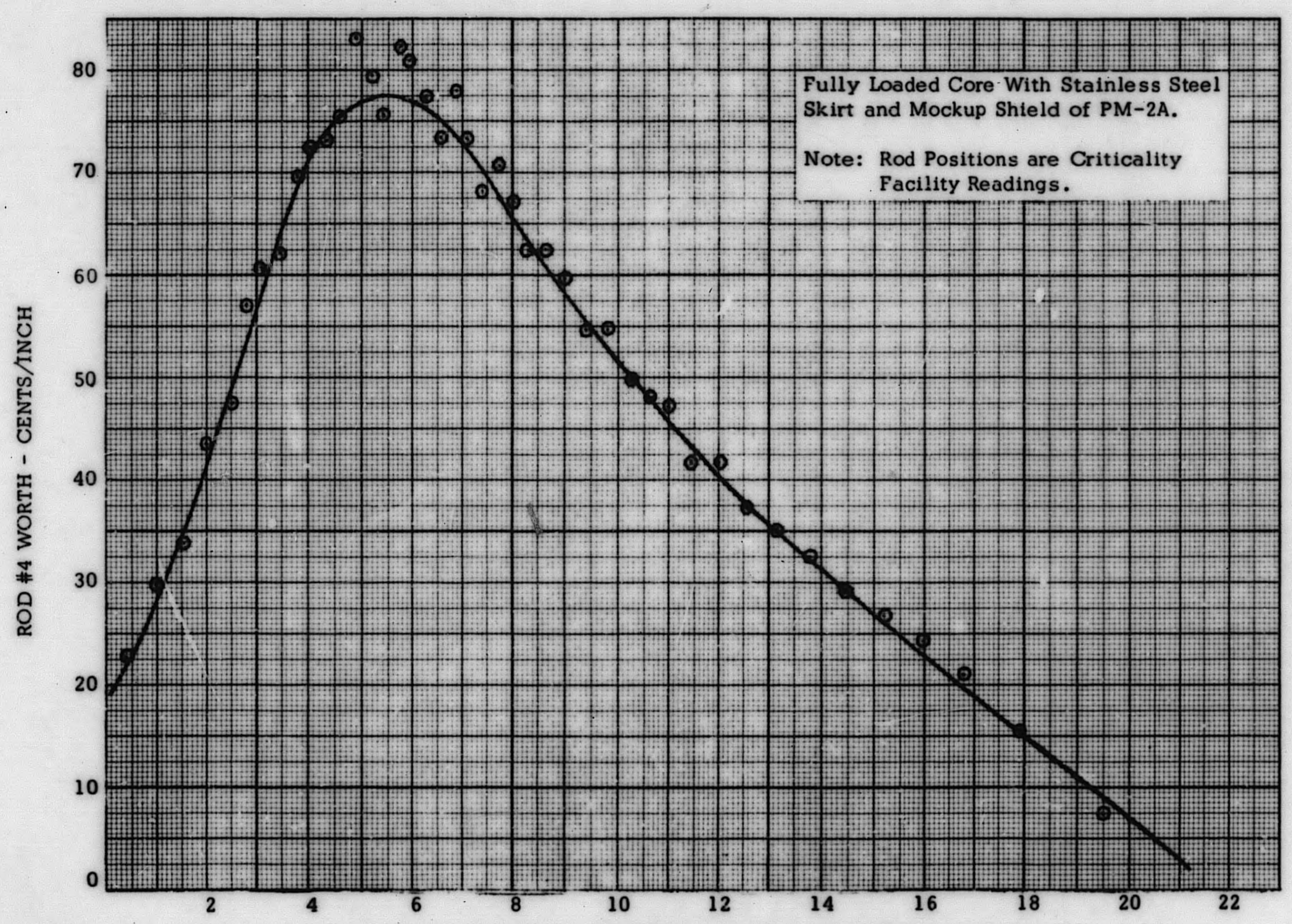



Figure 3.7. Rod #4 Calibration Curve Using B-10 Absorber - PM-2A Core II ZPE IV

## TABLE 3.4
## STUCK ROD MEASUREMENTS
## PM-2 CORE II ZPE VI

| | Rods Fully Inserted | Rods Full Out | Critical Rods | Critical Position, Inches | Dial Reading at PM-2A Site, Inches | Critical Rods Worth: Worth, Cents/In. | Critical Rods Worth: Position, Inches |
|---|---|---|---|---|---|---|---|
| With Skirt | 1,2,5 | 3 | 4 | 8.377 | 7.08 | 58.36 | 8.505 |
| | 2,3,5 | 1 | 4 | 8.585 | 7.29 | 60.17 | 8.759 |
| | 2,3,5 | | 1,4 | 12,383 | 11.48 | 102.39 | 12.477 |
| | 1,2,5 | | 3,4 | 12.283 | 11.38 | 107.89 | 12.378 |
| | 2,3,5 | 4 | 1 | 7.872 | 6.37 | 50.67 | 8.059 |
| | 1,2,5 | 4 | 3 | 7.714 | 5.98 | 51.47 | 7.908 |
| Without Skirt | 1,2,5 | 4 | 3 | 6.701 | 4.81 | 44.89 | 6.919 |
| | 2,3,5 | 4 | 1 | 6.905 | 5.02 | 45.66 | 7.164 |
| | 2,3,5 | 1 | 4 | 7.610 | 5.91 | 58.10 | 7.826 |
| | 2,4,5 | 1 | 3 | 9.744 | 7.84 | 42.38 | 10.000 |
| | 2,4,5 | 3 | 1 | 9.542 | 7.64 | 41.67 | 9.785 |
| | 1,2,5 | 3 | 4 | 7.405 | 5.70 | 54.13 | 7.601 |
| | 2,4,5 | | 1,3 | 13.816 | 12.70 | 80.53 | 13.965 |
| | 3,4,5 | | 1,2 | 16.231 | 14.68 | 50.10 | 16.483 |
| | 2,3,5 | | 1,4 | 11.921 | 11.02 | 111.61 | 12.033 |
| | 1,2,5 | | 3,4 | 11.815 | 10.91 | 116.85 | 11.907 |

Assuming that $M^2/k_\infty$ and $S_z$ are independent of h, then h is a function of $\left(\frac{dh}{d\rho}\right)^{1/3}$. Rearranging equation 3.1 and solving for h yields

$$h = -S_z + \left(\frac{2\pi^2 M^2}{k_\infty}\right)^{1/3} \left(\frac{dh}{d\rho}\right)^{1/3} \tag{3.2}$$

which is the slope intercept form of equation 3.1. The intercept is $-S_z$, the slope is

$$\left(\frac{2\pi^2 M^2}{k_\infty}\right)^{1/3}$$

and the two variables are h and

$$\left(\frac{dh}{d\rho}\right)^{1/3}.$$

Integration of equation 3.1 yields the reactivity between the limits of integration.

$$\int_{h_{water}}^{h_{core}} d\rho = 1/2 \left(\frac{2\pi^2 M^2}{k_\infty}\right) \left[\frac{1}{(h_{water} + S_z)^2} - \frac{1}{(h_{core} + S_z)^2}\right]$$

where

$h_{water}$ = critical water height
$h_{core}$ = core height

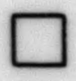
3.6.2 Procedure

Different critical water heights were determined by varying the effective core diameter through geometry changes. These various geometries are shown in Fig. 3.8. The five rod bank was maintained approximately 1.5 in. above the critical water height to maintain a constant axial reflector savings per element. Water worths were determined by the positive period method.

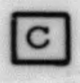
To measure the variations in water height, a sensitive electric probe was attached to a spare control rod drive mechanism. As a counter check, water heights were measured on a sight glass.

3.6.3 Data

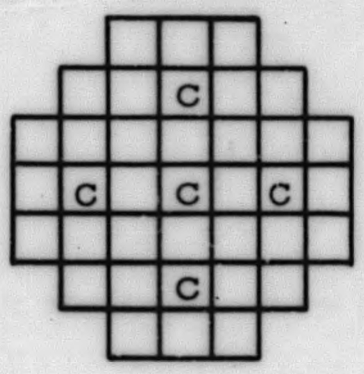
Table 3.5 gives the various configurations with the associated water worths and critical water heights. Figure 3.9 shows the critical water height as a function of $\left(\frac{dh}{d\rho}\right)^{1/3}$ the intercept of which is the negative reflector savings, $-S_z$. It should be noted, however, that the data was obtained from cores of different effective diameters.



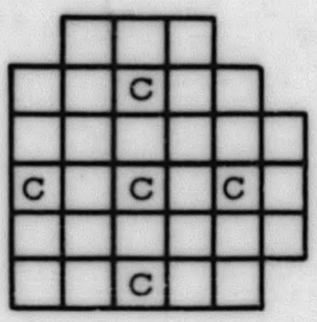
Stationary Fuel Elements



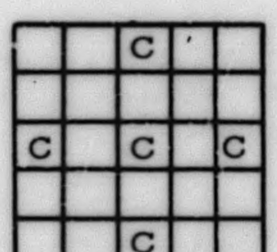
Control Rod Fuel Elements



7 x 7 Core Configuration
(PM-2A Fully Loaded Core)
Total Number of Elements 37

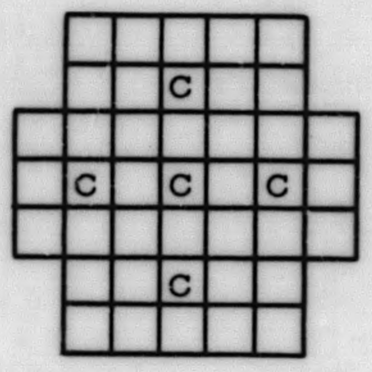


6 x 6 Core Configuration
Total Number of Elements 31

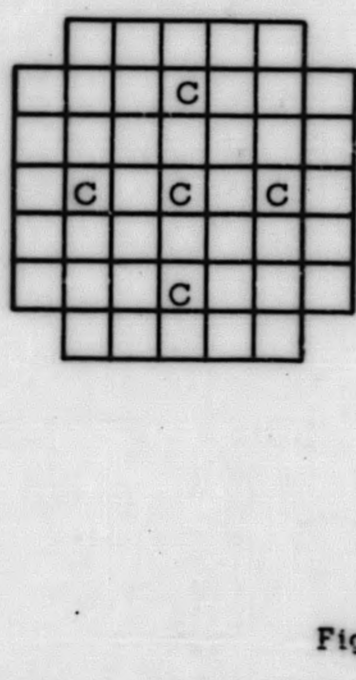


5 x 5 Core Configuration
Total Number of Elements 25

Figure 3.8. Critical Water Height Core Configurations
PM-2A Core II ZPE VI




7 x 7 plus 4 ElementsCore Configuration
Total Number of Elements - 41




7 x 7 plus 8 Elements Core Configuration
Total Number of Elements - 45

Figure 3.8. (Continued)

## TABLE 3.5
## CRITICAL WATER HEIGHT
## PM-2A CORE II ZPE VI

| Configuration | Critical Water Height, Inches | $\frac{\Delta\rho}{\Delta h}$ Dollars/Inch | $\left(\frac{\Delta h}{\Delta\rho}\right)^{1/3}$ |
|---|---|---|---|
| 5 x 5 | 12.728 | 1.185 | 0.948 |
| 6 x 6 | 10.765 | 1.610 | 0.855 |
| 7 x 7 | 9.640 | 2.060 | 0.788 |
| 7 x 7 | 9.733 | 1.859 | 0.815 |
| 7 x 7 + 4 elements | 9.350 | 2.185 | 0.773 |
| 7 x 7 + 8 elements | 8.907 | 2.265 | 0.764 |
| 7 x 7 + 8 elements | 8.902 | 2.309 | 0.759 |

From Fig. 3.8, $-S_z$ is -5.75 in. and the slope,

$$\left(\frac{2\pi^2 M^2}{k_\infty}\right)^{1/3}$$

is 19.4, from which $\frac{M^2}{k_\infty}$ is equal to 2.673 in.$^2$

### 3.7 SUMMARY

The five rod cold clean critical bank position with skirt for the PM-2A Core II containing a total of 19490.88 gm of U-235 was 7.303 in. or an approximate dial reading of 6.75 in. at the PM-2A site. The minimum number of fuel elements to attain criticality was 17 with a corresponding total U-235 mass of 8644.08 gm and a five rod critical position of 19.798 in. corresponding to a dial reading of 18.5 in. at the PM-2A site. Due to the increased B-10 loading of Core II fuel elements over that of Core I, 17 elements were required for minimum critical mass, as compared to 15 fuel elements for Core I.

Stuck rod measurements showed that at criticality could not be achieved with a single control rod but required at least the partial withdrawal of a second control rod.

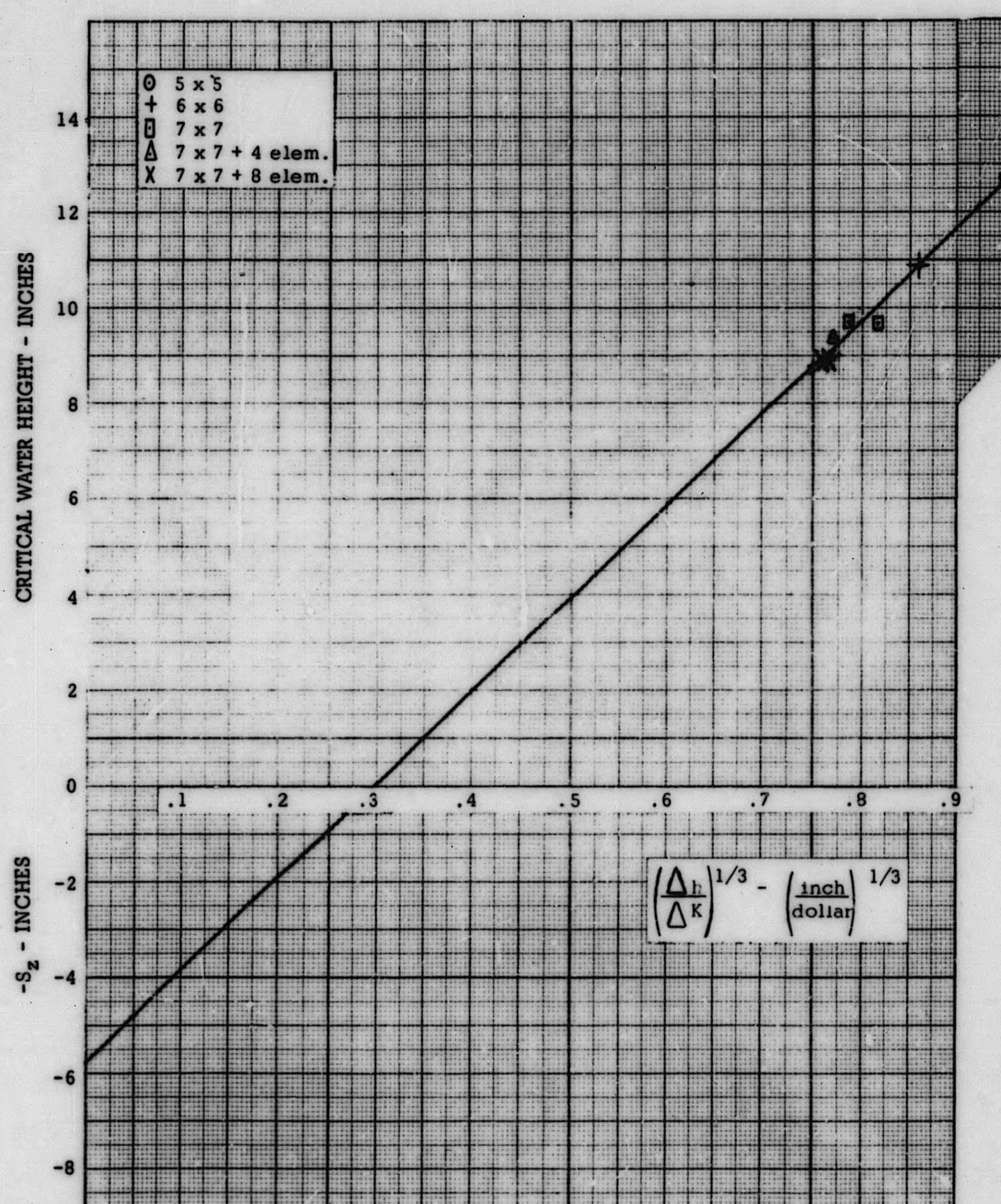



Figure 3.9. Critical Water Height - Axial Reflector Savings Intercept
PM-2A Core II ZPE VI

# 4.0 ON-SITE LOADING PROCEDURE

## 4.1 INTRODUCTION

Because of the time involved in recording the inverse multiplication, it is necessary to develop a procedure that can be followed at the PM-2A site for fueling without the necessity of an inverse multiplication approach to criticality. The experiment described below, provides the minimum core loading that permits detection of startup neutrons, count rates for all fuel loading steps, the critical bank positions for all fuel loadings, and the worth of each fuel addition.

## 4.2 PROCEDURE

A mockup of the PM-2A shielding was arranged in the experimental assembly. A diagram of the mockup shield, core assembly, and associated instrumentation is shown in Fig. 4.1. The shielding mockup used is not an exact duplicate of the PM-2A; however, for the purposes of this experiment, the two closely resemble each other. In order to duplicate the PM-2A site situation, the source was moved from its normal position at the Criticality Facility to lattice position 61.

Count rates were taken with the control rods fully inserted. The core was fully loaded at the start of the experiment and unloaded in steps that reversed the original loading sequence shown in Fig. 3.1. The Criticality Facility count rates were multiplied by the ratio of PM-2A to Alco's Criticality Facility source strengths to provide an estimate of startup count rate during initial loading. Because PM-2A shielding could not be mocked up exactly at the Facility, there will be a difference between expected and actual count rates; however, ratios of count rates from one loading to another should be the same for site and Facility measurements.

## 4.3 DATA

The count rates observed during the unloading sequence are given in Table 4.1. These count rates were taken with the counting chamber located 21 in. from the core boundary. In addition, Fig.4.2 shows the count rate as a function of the total number of fuel elements.

## 4.4 COUNT RATE CORRECTION

Table 4.2 is a tabulation of the PM-2A and Facility mockup shields. From this, it is determined that the PM-2A shielding has approximately 2.721 in. more steel and 0.375 in. more boral than the mockup, while the mockup contains 3.125 in. more water. For the purpose of calculating the ratio of the PM-2A to the Facility

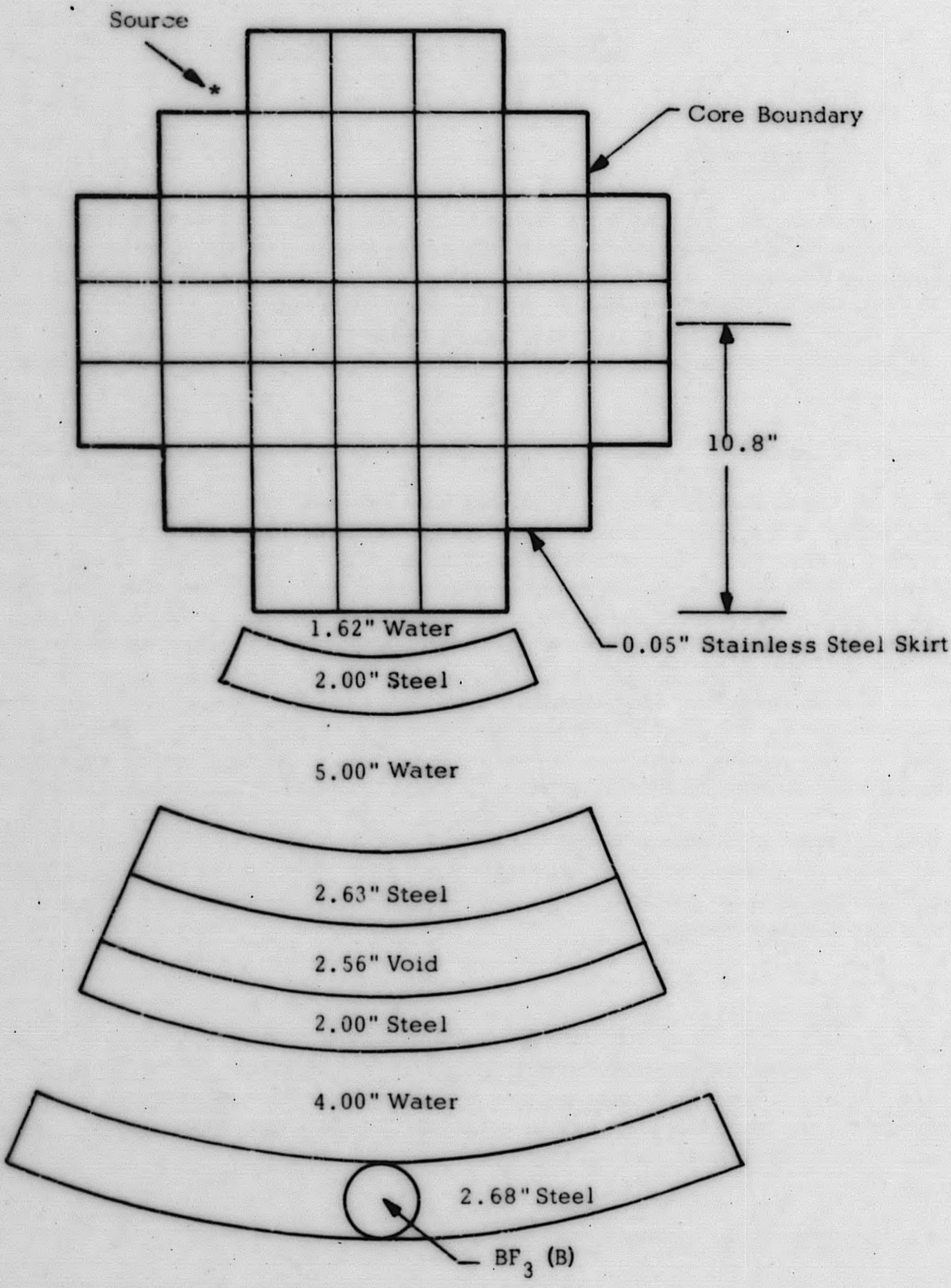



Figure 4.1. PM-2A Mockup Shield
PM-2A Core II ZPE VI

TABLE 4.1
CORE UNLOADING COUNT RATE
PM-2A CORE II ZPE VI

| U-235 Mass, gm | No. of Fuel Elements | Count Rate, cps - $BF_3$ (B) |
|---|---|---|
| 19490.88 | 37 | 0.847 |
| 17321.52 | 33 | 0.540 |
| 15152.16 | 29 | 0.233 |
| 12982.80 | 25 | 0.157 |
| 10812.44 | 21 | 0.100 |
| 8644.08 | 17 | 0.0533 |
| 8101.74 | 16 | 0.0433 |
| 7559.40 | 15 | 0.0367 |
| 7017.60 | 14 | 0.0433 |
| 5390.04 | 11 | 0.0467 |
| 2136.00 | 5 | 0.0467 |
| 0 | 0 | 0.0367 |
| 0 | No Source | 0.0167 |

TABLE 4.2
PM-2A SHIELDING SPECIFICATIONS AND COMPARABLE
FACILITY MOCKUP

| | PM-2A, In. | Mockup, In. |
|---|---|---|
| Equivalent Core Radius | 10.08 | 10.08 |
| Stainless Steel Skirt | 0.05 | 0.05 |
| Water | 1.62 | 1.62 |
| Stainless Steel | 2.00 | 2.00 |
| Water | 5.00 | 5.00 |
| Stainless Steel | 0.250 | 2.625 |
| Steel | 2.375 | |
| Void Insulation | 2.00 | |
| Stainless Steel | 0.125 | |
| Air Gap | 0.4375 | 2.56 |
| Steel | 1.000 | 2.00 |
| Boral | 0.125 | |
| Water | 1.125 | 4.00 |
| Boral | 0.125 | |
| Steel | 3.250 | |
| Boral | 0.125 | |
| Water | 0.5625 | |
| Stainless Steel | 0.346 | |
| Void | 1.5 | 1.345 |

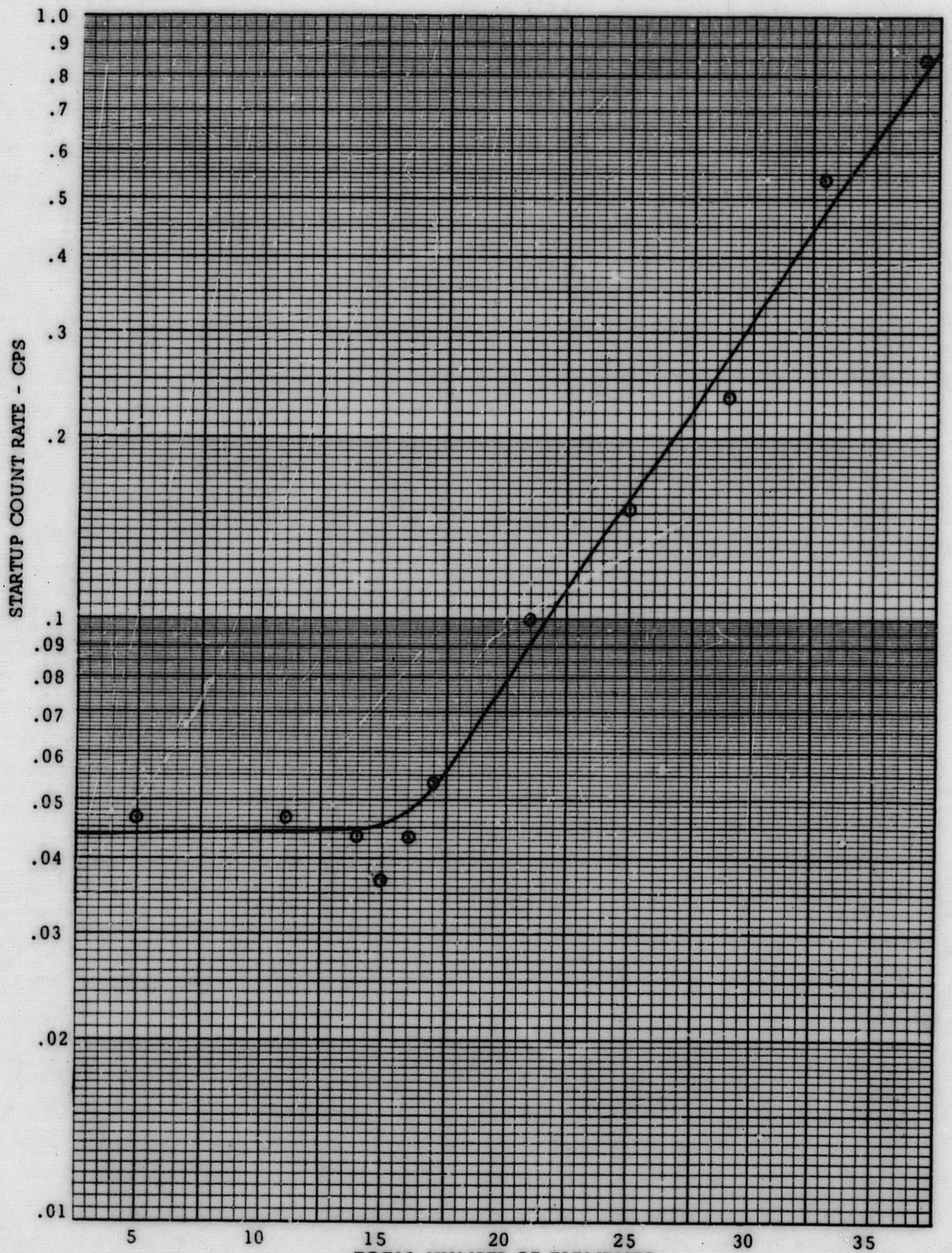



Figure 4.2. Startup Channel Count Rate Vs Core Loading - PM-2A Core II ZPE VI

neutron response rates, it will be assumed that the respective neutron fluxes will only have to pass through the difference in shielding. Since the orientation and separation distances of the two systems are essentially identical, they will not affect the ratio. It is assumed that a fresh polonium-beryllium source with a neutron yield of $8 \times 10^7$ n/sec will be installed with Core II, and therefore count rate calculations are based on this source strength.

The equation $\frac{\phi}{\phi_o} = e^{-\Sigma_r X}$

gives an estimate of the fraction of incident fast neutrons of a fission spectrum that will succeed in penetrating the thickness X of material with a removal cross section $\Sigma_r$ without undergoing a reaction.

$\phi$ = Final neutron flux in neutrons per $cm^2$/sec.

$\phi_o$ = Initial neutron flux in neutrons per $cm^2$/sec.

$\Sigma_r$ = Removal cross section in $cm^{-1}$.

X = Thickness of material in cm.

For the PM-2A and the mockup, assume chamber response and thermal neutron fluxes at the chamber to be proportional to the neutron source strength by a factor A, which is taken as being identical for both systems. Therefore the corrected fluxes are:

PM-2A (Assuming a fresh polonium-beryllium source with a neutron yield of $8 \times 10^7$ n/sec will be installed with Core II)

$\phi_o$ source $= \frac{8 \times 10^7}{A}$ n/$cm^2$ sec

$\Sigma_r$ (steel) = 0.167 $cm^{-1}$ (9)

$\Sigma_r$ (boral) = 0.08 $cm^{-1}$ (9)

X (steel) = 2.721 in. = 6.91 cm

X (boral) = 0.375 in. = 0.95 cm

$$\phi_{PM\text{-}2A} = \frac{8 \times 10^7}{A} e^{-(0.167 \times 6.91 + 0.08 \times 0.95)}$$

$$= \frac{2.3 \times 10^7}{A}$$

Mockup

$$\phi_o \text{ (source)} = \frac{8.18 \times 10^6}{A} \text{ n/sec cm}^2$$

$$\Sigma_r \text{ (water)} = 0.100 \text{ cm}^{-1} \text{ (9)}$$

$$X \text{ (water)} = 3.125 \text{ in.} - 7.94 \text{ cm}$$

$$\phi \text{ Mockup} = \frac{8.18 \times 10^6}{A} e^{-(0.100 \times 7.94)} = \frac{3.7 \times 10^6 \text{ n/cm}^2 \text{ sec}}{A}$$

$$\frac{\phi \text{ PM-2A}}{\phi \text{ Mockup}} = \text{ratio of PM-2A to Facility neutron response rates}$$

$$= \frac{2.336 \times 10^7}{3.7 \times 10^6} \frac{A}{A} = 6.3$$

The expected count rate on site is 6.3 times the Facility count rate. The chamber sensitivity for the mockup and the PM-2A are essentially identical; however, because of the presence of a considerable amount of steel and boral in the vicinity of the PM-2A startup channel, A is probably smaller than for the mockup assembly.

## 4.5 SUMMARY

With the information derived from this experiment, a safe loading procedure was developed and it can be used at the PM-2A site. This procedure does not require the inverse multiplication approach to criticality. Neutrons can be effectively detected with the loading of the 17th element, the minimum critical mass, at which time the control rods may be withdrawn and critical bank positions determined.

The ratio of the count rates expected at the site to that measured at the Alco Criticality Facility was calculated to be about 6.3. During the initial stages of loading, from zero to 16 fuel elements including the five control rods (fully down position), the count rate was approximately 0.04 cps. This rate is equivalent to 0.25 cps at the PM-2A site. With 17 elements loaded, the count rate was 0.053 cps, equivalent to 0.34 cps at the site. The increase in count rate with further stages of loading is shown in Table 4.1 and Appendix B.

## 5.0 ANALYSIS OF ZERO-POWER EXPERIMENT

### 5.1 INTRODUCTION

The intent of this analysis is to evaluate the data obtained from the zero-power experiment. The analysis interprets the uniformity measurements, makes a comparison of important measurements of Core I to Core II, and determines core life and thermal effects.

The uniformity measurements provided an estimate of the U-235 and B-10 distribution based on chemical analysis, as well as relative reactivity measurements.

Important measurements of Core I and Core II used for comparison include rod bank positions, stuck rod positions, core reactivities, rod reactivities, and shutdown reactivities.

Based on the estimated B-10 content of Core II, a uniform burnout calculation was performed of the bare equivalent core.

### 5.2 ANALYSIS OF UNIFORMITY MEASUREMENTS AND B-10 CONTENT

#### 5.2.1 Chemical Analysis

At the beginning of manufacturing the PM-2A Core II fuel plates, a chemical analysis was made of the vendors qualification plates to determine the natural boron losses during fabrication. Natural boron in the form of $B_4C$ was used and contained 18.3 percent wt B-10. The chemical analysis indicated the boron losses would be about 28.5 percent. The desired B-10 loadings were 23.7 mg B-10 in the control rod fuel plates and 26.7 mg B-10 in the stationary fuel plates. Therefore, the stationary fuel plates were loaded with 202.78 mg of natural boron and the control rod fuel plates were loaded with 182.50 mg of natural boron.

#### 5.2.2 Reactivity Measurements

##### 5.2.2.1 Reactivity Differences of Individual Elements

From the data of Table 2.1, it was estimated that the PM-2A Core II stationary fuel elements contain 0.492 gm of B-10. From this figure, it was estimated that B-10 manufacturing losses were about 26 percent. Assuming that approximately the same percent of losses were experienced in the manufacture of the control rod fuel elements, these elements would contain 0.390 gm of B-10. This yields a total core loading of 17.70 gm of B-10. These are in good agreement with chemical analysis.[18]

It was estimated from reactivity comparisons that PM-2A Core I contained 0.425 gm of B-10 per stationary element and 0.335 gm of B-10 per control rod fuel element.[6] Chemical analysis for Core I indicated a B-10 content of 0.473 gm per stationary element and 0.373 gm per control rod element.[18] Core II, in comparison, has a relatively higher B-10 content, and this is reflected in its higher critical bank position. The total estimated B-10 loading of Core I was 15.235 gm.

The uniformity of the stationary fuel elements is revealed in their relatively even reactivity differences, Table 2.1, from the standard element. The uniformity of the control rod fuel elements can only be shown in their reactivity variations from their own average, which from Table 2.2, are very small.

While this uniformity test is adequate to establish the losses of either fuel or poison, certain combinations of losses are not revealed by this single and simple reactivity test. Those would be the cases in which the reactivity effects of fuel and poison are essentially compensating. However, using these tests are a criteria, it can be stated that PM-2A Core II fuel elements are essentially uniform and that B-10 losses fall within acceptable limits and specified limits and specified tolerances.[4]

#### 5.2.2.2 Intercomparison with Other Cores

A general approximation of the total B-10 loading of PM-2A Core II can be made through the cold clean bank differences between Core I and Core II by making a few general assumptions. The method assumes that the B-10 loading of PM-2A Core I is known to be 15.2 gm, critical rod bank differences are due to differences in B-10 loading, and B-10 worth in PM-2A cores can be estimated by a ratio of B-10 worth in SM-1 cores.

No measurements were made of the average B-10 worth in PM-2A cores with PM-2A fuel elements; however, a ratio can be set up of SM-1 core mockups in which the average B-10 worths were measured. These B-10 worth measurements were made in the SM-1 mockups with SM-1 fuel elements, the SM-1 mockup with SM-2 fuel elements, and the PM-2A mockup with SM-2 fuel elements. A PM-2A mockup with SM-1 fuel elements is very much the same as the PM-2A cores. Therefore, the following ratio can be set up:

$$\frac{\text{B-10 worth SM-1 (SM-1 elements)}}{\text{B-10 worth SM-1 (SM-2 elements)}} = \frac{\text{B-10 worth PM-2A (SM-1 elements)}}{\text{B-10 worth PM-2A (SM-2 elements)}}$$

B-10 worth SM-1 (SM-1 elements) = 60.3 ¢/gm

B-10 worth SM-1 (SM-2 elements) = 23.8 ¢/gm

B-10 worth PM-2A (SM-2 elements) = 30.2 ¢/gm

$$\text{B-10 worth PM-2A (SM-1 elements)} = \frac{(30.2)\ (60.3)}{23.8} = 76.4\ \text{¢/gm}$$

This yields an approximate B-10 worth for the PM-2A cores if the ratios are approximately the same.

The critical bank position for Core II with the stainless steel skirt is 7.303 inches. The critical bank position for Core I without the stainless steel skirt is 6.4 inches. The stainless steel skirt has a negative reactivity effect of about 50 cents (Section 3.5). The critical bank position of Core I with the skirt is, therefore, about 6.6 inches. From Fig. 5.3, this yields approximately two dollars for the average integral bank worth difference between Core I and Core II.

From the B-10 worth, 76.4 ¢/gm, and the integral bank worth difference, 200 cents, the B-10 difference between Core I and Core II is determined to be 2.62 gm. On the basis of 15.235 gm of B-10 in Core I, the total B-10 loading in Core II would be 17.86 gm. This compares very favorably with the 17.70 gm of B-10 determined by reactivity differences between individual elements.

## 5.3 ANALYSIS OF CRITICAL ASSEMBLY MEASUREMENTS

### 5.3.1 Integral Bank Worth From Bank Calibration

The five rod bank calibration curves for Core I and Core II are shown in Fig. 5.1. Although Cores I and II have different B-10 loadings, it is expected that PM-2A cores with the same U-235 loading should have essentially one bank calibration curve. The calibration curves for Core I and Core II do not coincide, probably because they were developed with slightly different effective core diameters and also because of statistical variations in data.

For the foregoing reasons, an average curve was developed between the calibration curves of Core I and Core II. It is shown in Fig. 5.2. This new calibration curve was extrapolated to the zero bank position based on the shape of the SM-1 bank calibration curve. A large amount of uncertainty is apparent about the extrapolated portion of the calibration curve, because the SM-1 calibration curve was developed by boron variation and PM-2A calibration curve was developed by changing the effective core diameter. In view of the available data, however, it is the best approximation that can be made.

Integration of Fig. 5.2 yields estimates of core reactivity, excess reactivity, and shutdown reactivity depending on the limits of integration. Fig. 5.3 is a plot of the integral bank worth versus bank position. The integral bank worth is taken here to mean the amount of reactivity added to the core when the bank is withdrawn to a bank position. The limits of integration are zero to the bank position. The integrated bank worth of the PM-2A Cores I and II is 31 dollars. The excess reáctivity at the cold clean critical bank positions for Core I and Core II are 20.40 and 18.40 dollars, respectively. These were determined by subtracting the integral bank worth at the cold clean bank position from the total core reactivity. The Core I critical bank position was adjusted from 6.4 in. to 6.6 in. to include the stainless steel skirt.

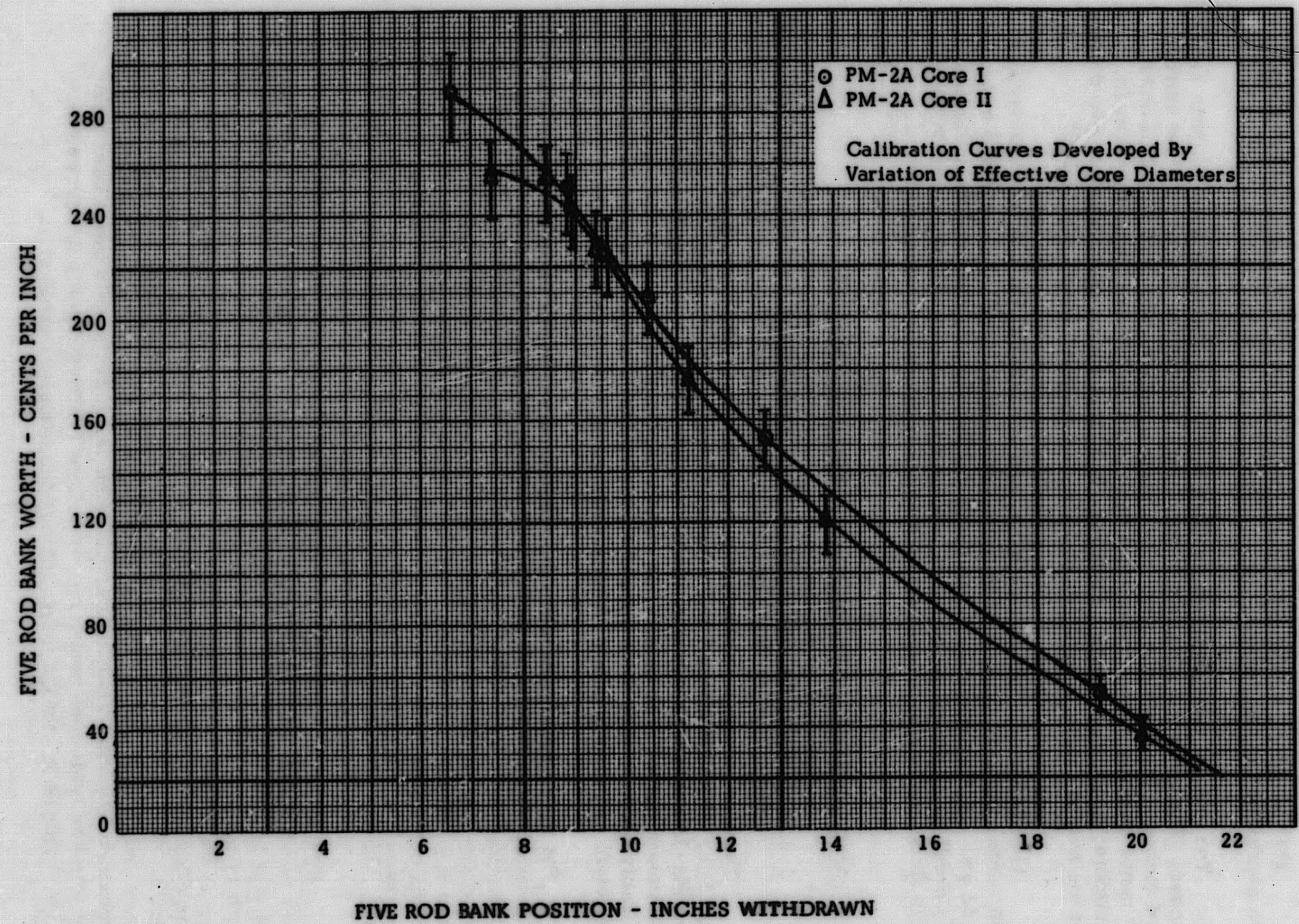



Figure 5.1. Bank Worth Vs Bank Position - PM-2A Core I and Core II ZPE VI

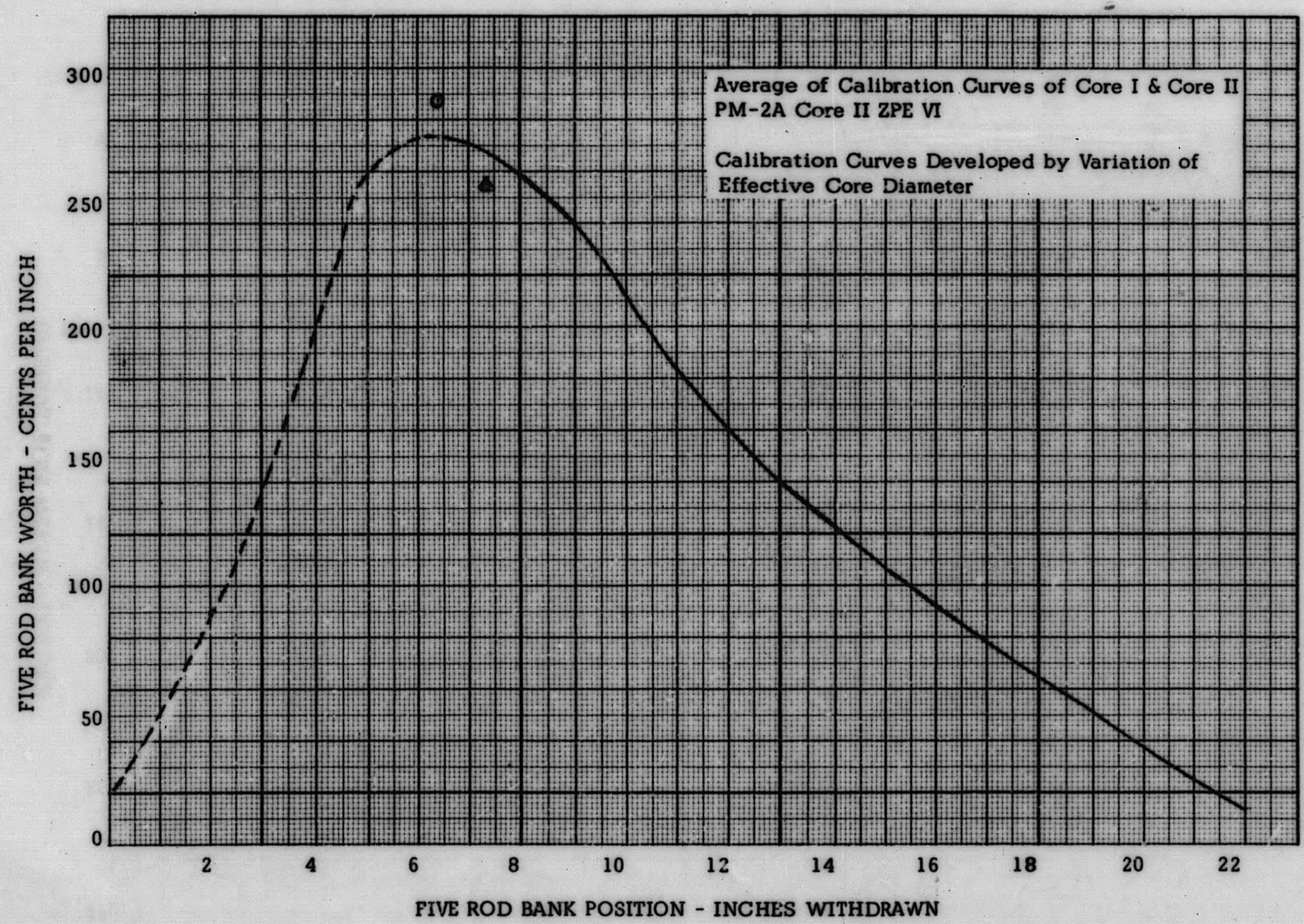



Figure 5.2. PM-2A Five Rod Bank Calibration Curve - PM-2A Core II ZPE VI

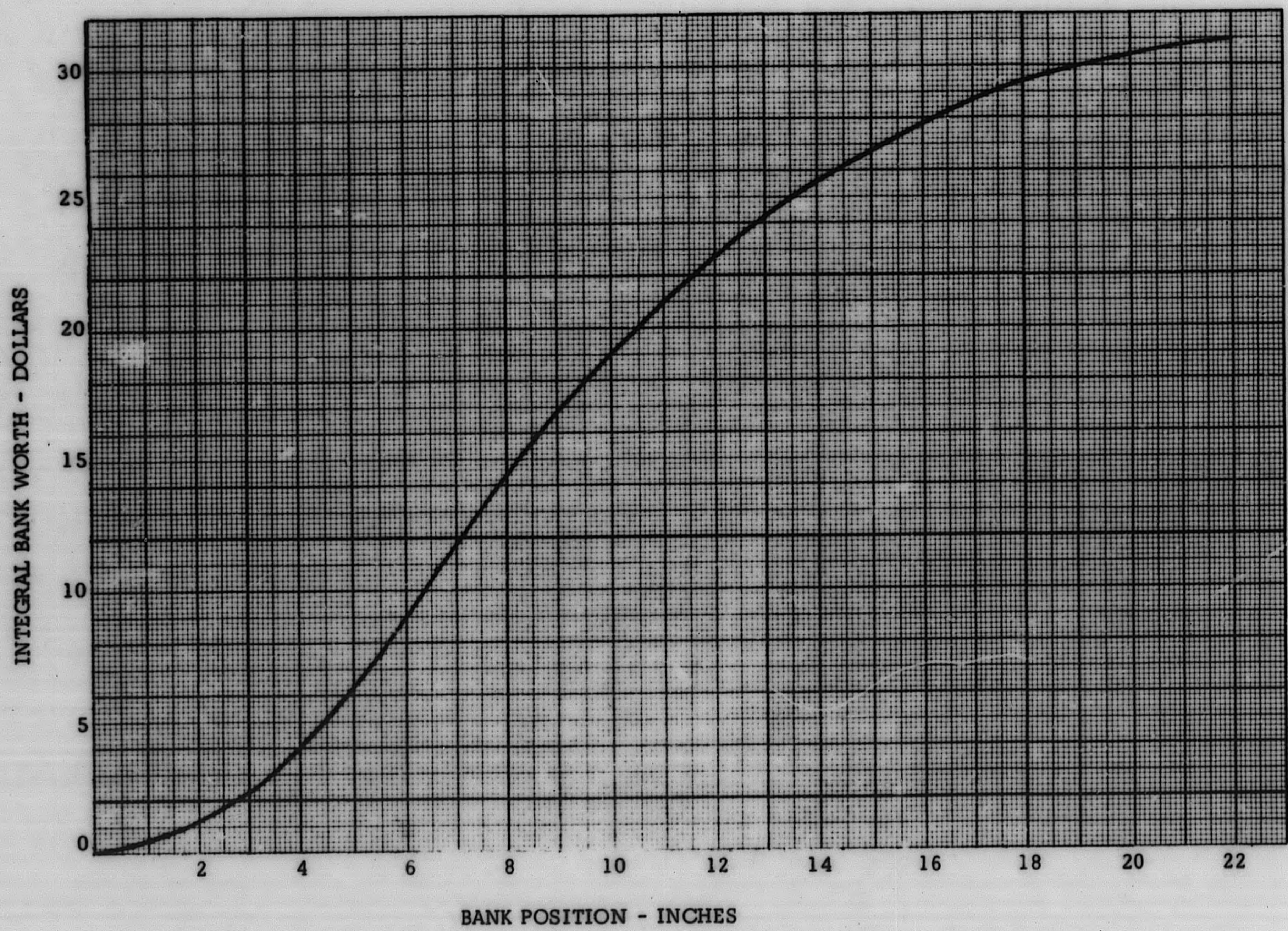



Figure 5.3. Integral Bank Worth Vs Core Reactivity For PM-2A Cores - PM-2A Core II ZPE VI

### 5.3.2 Excess Reactivity From Critical Water Height Measurements

From paragraph 3.6.1, it is seen that the excess reactivity can be determined from

$$\int_{h_{water}}^{h_{core}} d\rho = 1/2 \left( \frac{2\pi^2 M^2}{k_\infty} \right) \left[ \frac{1}{(h_{water} + S_z)^2} - \frac{1}{(h_{core} + S_z)^2} \right]$$

if it assumed that radial flux distributions are independent of axial position and that axial reflector savings are independent of the core height.

Using reactivity worth measurements of the critical water height, a value of 19.4 was determined for

$$\left( \frac{2\pi^2 M^2}{k_\infty} \right)^{1/3}$$

and 5.75 in. for $S_z$. Inserting these values into the above equation and integrating from the cold clean critical bank position (7.303 in.) to the top of the core (22 in.), the excess reactivity is computed to be 16.50 dollars. This value is lower than the value determined from the bank calibration curve, which was 18.40 dollars.

### 5.3.3 Bank Position at PM-2A Site

Because the Alco Criticality Facility mockups do not completely represent the PM-2A site conditions, certain adjustments must be made to bank positions determined at the Facility to predict PM-2A site bank positions. These adjustments consist of the use of: $Eu_2O_3$ absorbers, effect of PM-2A thermal shield, cold-to-hot temperature change, and effect of equilibrium xenon. The following tabulation predicts the bank change due to these factors.

1. Use of $Eu_2O_3$ Absorbers, 68°F, Clean

| | |
|---|---|
| Excess core reactivity | 1840 cents |
| $Eu_2O_3$ absorber | 46 cents* |
| Net excess reactivity | 1886 cents |

Critical bank position from Fig. 5.3 is 7.15 in., equivalent to a dial reading of 6.95 in. at the PM-2A site.

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* NOTE: Correction for B-10 in iron absorbers to $Eu_2O_3$ absorbers is 21 cents per absorber in the control rod.[6] For eccentric rods, the estimated correction is 14 cents per absorber, or 77 cents for the five rod bank. It is assumed that the integral worth curve for the absorbers is the same shape as the bank worth curve, and therefore a ratio of the total integral worth of the bank to the worth at the bank position is the same for the absorbers. This ratio is used to determine the proportional worth of partially inserted absorbers.

2. Effect of PM-2A Thermal Shield

| | |
|---|---|
| Excess core reactivity with $Eu_2O_3$ absorbers, 68°F | 1886 cents |
| Thermal Shield | 46 cents |
| Net excess reactivity | 1932 cents |

Critical bank position from Fig. 5.3 is 6.9 in., equivalent to a dial reading of 6.75 in. at the PM-2A site.

3. Temperature Change to 510°F, Equilibrium Xenon at 4.8 Mw

| | |
|---|---|
| Excess core reactivity | 1932 cents |
| Cold to hot change, equilibrium xenon | -1200 cents *(11) |
| Net excess reactivity | 732 cents |

Critical bank position from Fig. 5.3 is 12.5 in., equivalent to a dial reading of 12.3 inches at the PM-2A site.

## 5.4 LIFETIME EVALUATION OF PM-2A CORES I AND II

In evaluating the lifetime of PM-2A Core II, it is of interest to make a comparison with a similar evaluation of PM-2A Core I.(11) The results of the zero power experiments on the two cores however indicate that Core I does not contain so much boron as was originally believed.(11) In addition, improvements have been made on the slowing down model used in the calculation. For these reasons, and in order to make a valid comparison between the cores, the Core I lifetime analysis has been repeated in conjunction with the Core II evaluation.

The techniques employed in evaluating the lifetimes of PM-2A Cores I and II are basically the same as the method used on the original evaluation of Core I.(11) The description of the method is included here for completeness.

The first step in the method involves obtaining a uniform burnup of the core. Correction factors obtained by using data from SM-1 calculations are then incorporated to convert the uniform burnup calculation to an equivalent non-uniform calculation. A more complete description of these techniques is included in the following sections.

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* NOTE: The effective reactivity change of Core I from 68°F, clean to 510°F, equilibrium xenon was 12.10 dollars. It is assumed that the same change will be true for Core II.

5.4.1 Uniform Burnup

To calculate the uniform burnup of the first two PM-2A cores, the standard two-group, bare equivalent, critical equation was used at a temperature of 510°F with equilibrium xenon (at 10 Mw).

$$K_{eff} = \frac{K_{th}''}{(1 + \tau B^2)\ (1 + L^2B^2)} + \frac{K_f\ (1 - P)}{(1 + \tau B^2)} \qquad (5.1)$$

where the symbols are defined in Table 5.1. The nuclear parameters in equation (5.1) were evaluated by the use of BOBCAT,[13] MUFT III[14], and Plate Type $P_3$[15] IBM-650 codes as a function of burnup. All the parameters except $K_{th}''$ were based on stationary element nuclear characteristics. Because, however, the core has five control rod elements in addition to 32 stationary elements, it is necessary to make a correction to these parameters. This is done by defining $K_{th}''$ as:

$$K_{th}'' = \frac{\nu \Sigma_f}{\Sigma_a + \Sigma_a^{sub} + \Sigma_a^{Xe}} \qquad (5.2)$$

where $\Sigma_a^{sub}$ is a macroscopic cross section which has been position and volume weighted to reflect the differences in the control rod element properties from the properties of the stationary elements. The variation of $\Sigma_a^{sub}$ with burnup was assumed to conform to the relation:

$$\Sigma_a^{sub}\ (B) = (1 - B)\ \Sigma_a^{sub}\ (B = 0).$$

A more detailed description of $\Sigma_a^{sub}$ may be found in reference (11).

The variation of $\Sigma_a^{Xe}$ as a function of burnup was calculated with the aid of equation 5.3.

$$\Sigma_a^{Xe} = \frac{\alpha \Psi\ \sigma_a^{Xe}\ (\gamma_I + \gamma_{Xe})\ \frac{\delta \bar{P}}{V}}{\lambda_{Xe} + \sigma_a^{Xe}\ \frac{\delta \bar{P} \beta}{V \Sigma_2^f}} \qquad (5.3)$$

The burnup independent variables are defined and the values assigned are given in Table 5.2. The burnup dependent variables used to calculate $\Sigma_a^{Xe}$ are given in Table 5.3.

5.4.2 Variation of Nuclear Constants with Burnup

Having evaluated $\Sigma_a^{sub}$ and $\Sigma_a^{Xe}$ it is now possible to determine all the parameters used in equation (5.1). The variation of the nuclear constants with burnup, as obtained with the aid of the BOBCAT, MUFT III, and Plate Type $P_3$ codes are given in Tables 5.4 and 5.5 for PM-2A Cores I and II respectively.

The total buckling and its components used in this analysis are given in Table 5.6.

## TABLE 5.1
## NON-UNIFORM BURNUP CALCULATIONS

The non-uniform burnup calculations of the PM-2A Core I were performed at an average core temperature of 510°F, an average pressure of 1750 psia, with equilibrium xenon. The core was assumed to operate at a thermal power of 10 MW.

**NUMENCLATURE**

| Symbol | Description | Units |
|---|---|---|
| $\tau$ | Neutron age | $cm^2$ |
| $D_1$ | Fast diffusion coefficient | cm |
| $\Sigma_{a_1}$ | Fast macroscopic absorption cross-section | |
| $\Sigma_{f_1}$ | Fast macroscopic fission cross-section | $cm^{-1}$ |
| $\nu$ | Number of neutrons per fission | |
| P | Resonance escape probability | |
| $K_f$ | Total neutrons produced by epithermal fission per epithermal neutron absorbed | |
| $L^2$ | Thermal diffusion length squared | $cm^2$ |
| $\Sigma_{f_2}$ | Thermal macroscopic fission cross-section | $cm^{-1}$ |
| $\bar{B}$ | Average fuel burnup fraction | |
| $\bar{P}$ | Thermal power level | watts |
| $K_{th}$ | Total neutrons produced by thermal fissions per thermal neutron absorbed | |
| $K_{eff}$ | Effective multiplication factor | |
| $\Sigma_a^{sub}$ | Substitution cross-section | $cm^{-1}$ |
| $\Sigma_a^{Xe}$ | Effective xenon cross-section | $cm^{-1}$ |
| $\Sigma_{a_2}$ | Thermal macroscopic absorption cross-section | $cm^{-1}$ |
| $B^2$ | Total buckling | $cm^2$ |
| $B_z^2$ | Axial buckling | $cm^2$ |
| $B_r^2$ | Radial buckling | $cm^2$ |
| $S_r$ | Radial reflector savings | cm |
| $S_z$ | Axial reflector savings | cm |
| $\alpha$ | Xenon non-uniform factor | |
| $\gamma_I + \gamma_{Xe}$ | Fission yield of iodine and xenon | |
| $\bar{\sigma}_a^{Xe}$ | Hardened xenon thermal microscopic absorption cross-section | $cm^2$ |
| $\delta$ | Number of fissions per watt-second | $(watt\text{-}sec)^{-1}$ |
| V | Volume of core | $cm^3$ |
| $\lambda_{Xe}$ | Decay constant of xenon | $sec^{-1}$ |
| $\Psi$ | Self-shielding factor for xenon | |
| $\beta$ | Fraction of total fissions which are thermal | |
| g' | Average flux in fuel plate relative to average flux in entire fuel element | |
| $\rho$ | Excess reactivity, $= \frac{K_{eff}-1}{K_{eff}}$ | % |

## TABLE 5.2
## $\Sigma_a^{Xe}$ PARAMETERS INDEPENDENT OF FUEL BURNUP

| Symbol | Definition | Value for PM-2A |
|---|---|---|
| $\alpha$ | Xenon non-uniform factor | 1.13 |
| $\gamma_I + \gamma_{Xe}$ | Fission yield of iodine and xenon | 0.0629 |
| $\sigma_a^{Xe}$ | Hardened xenon thermal microscopic absorption cross-section (510°F) | $2.9 \times 10^{-18}$ |
| $\sigma$ | Fissions per watt-second | $3.2175 \times 10^{10}$ |
| V | Volume of core in $cm^3$ | $1.1379 \times 10^5$ |
| $\lambda_{Xe}$ | Decay constant of xenon | $2.092 \times 10^{-5}$ |
| $\overline{P}$ | Thermal power level in watts | $10^7$ |

## TABLE 5.3
## VARIATION OF BURNUP DEPENDENT $\Sigma_a^{Xe}$ PARAMETERS AT 510°F

| Average Fuel Burnup, B | $\Psi$ | $\beta$ |
|---|---|---|
| 0.000 | 0.9421 | 0.7312 |
| 0.018 | 0.9432 | 0.7328 |
| 0.033 | 0.9444 | 0.7385 |
| 0.069 | 0.9474 | 0.7457 |
| 0.135 | 0.9525 | 0.7614 |
| 0.200 | 0.9570 | 0.7758 |
| 0.305 | 0.9634 | 0.7977 |

## TABLE 5.4
## VARIATION OF NUCLEAR CONSTANTS WITH AVERAGE FUEL BURNUP AT 510°F

| Average Fuel Burnup | $\tau$ | $D_f$ | $\Sigma_a^f$ | $\nu\Sigma_f^f$ | P |
|---|---|---|---|---|---|
| 0 | 48.8676 | 1.49955 | 0.009240 | 0.011887 | 0.698895 |
| 0.018 | 48.9252 | 1.49984 | 0.009136 | 0.011693 | 0.7019703 |
| 0.033 | 48.9744 | 1.50001 | 0.009031 | 0.011537 | 0.705142 |
| 0.069 | 49.1025 | 1.50047 | 0.008765 | 0.011159 | 0.713178 |
| 0.135 | 49.3204 | 1.501136 | 0.008288 | 0.010456 | 0.727687 |
| 0.200 | 49.5415 | 1.501969 | 0.007838 | 0.009746 | 0.741451 |
| 0.305 | 49.8916 | 1.50334 | 0.007143 | 0.008571 | 0.762928 |

| Burnup | $K_f$ | $\Sigma_a^{th}$ | $\nu\Sigma_f$ | $K_{th}$ |
|---|---|---|---|---|
| 0 | 1.28650 | 0.2053995 | 0.3223029 | 1.5691515 |
| 0.018 | 1.27988 | 0.2027843 | 0.31683461 | 1.5624217 |
| 0.033 | 1.27741 | 0.19991157 | 0.31233713 | 1.5623765 |
| 0.069 | 1.27312 | 0.19263286 | 0.30161922 | 1.5657724 |
| 0.135 | 1.26153 | 0.17967587 | 0.28153406 | 1.5668997 |
| 0.200 | 1.24342 | 0.16792932 | 0.26172845 | 1.5585632 |
| 0.305 | 1.19979 | 0.15010647 | 0.22884872 | 1.5245760 |

| Burnup | $L^2$ | $\Sigma_a^{Xe}$ | $\Sigma_a^{sub}$ | $K''_{th}$ |
|---|---|---|---|---|
| 0 | 1.2937687 | 0.008364 | 0.004031 | 1.47986 |
| 0.018 | 1.3132789 | 0.008316 | 0.003958 | 1.47322 |
| 0.033 | 1.3352925 | 0.008275 | 0.003898 | 1.47262 |
| 0.069 | 1.3940831 | 0.008144 | 0.003753 | 1.47477 |
| 0.135 | 1.5107564 | 0.007780 | 0.003487 | 1.47437 |
| 0.200 | 1.6325106 | 0.007391 | 0.003225 | 1.46595 |
| 0.305 | 1.8542618 | 0.006698 | 0.002802 | 1.43380 |

TABLE 5.5

PM-2A CORE II

VARIATION OF NUCLEAR CONSTANTS WITH FUEL BURNUP AT 510°F

| Average Fuel Burnup (B) | $\tau$ | $D_f$ | $\Sigma_{af}$ | $\nu\Sigma_f^f$ |
|---|---|---|---|---|
| 0 | 48.8808 | 1.50014 | 0.009317 | 0.011868 |
| 0.018 | 48.9392 | 1.50045 | 0.009207 | 0.011678 |
| 0.033 | 48.9891 | 1.50056 | 0.0090962 | 0.011522 |
| 0.069 | 49.1193 | 1.50096 | 0.008818 | 0.011148 |
| 0.135 | 49.3410 | 1.500163 | 0.008324 | 0.010449 |
| 0.200 | 49.5633 | 1.502419 | 0.007862 | 0.009742 |
| 0.305 | 49.9159 | 1.50375 | 0.007154 | 0.0085686 |

| $\overline{B}$ | P | $K_f$ | $L^2$ | $\nu\Sigma_{f2}$ |
|---|---|---|---|---|
| 0 | 0.696394 | 1.27380 | 1.27355 | 0.321947 |
| 0.018 | 0.699690 | 1.26838 | 1.29456 | 0.316502 |
| 0.033 | 0.703035 | 1.26668 | 1.31745 | 0.312065 |
| 0.069 | 0.711441 | 1.26423 | 1.37842 | 0.301411 |
| 0.135 | 0.726493 | 1.25529 | 1.49787 | 0.281568 |
| 0.200 | 0.740651 | 1.23912 | 1.62385 | 0.261615 |
| 0.305 | 0.762539 | 1.19774 | 1.84950 | 0.228801 |

| $\overline{B}$ | $\Sigma_a^{th}$ | $\Sigma_a^{sub}$ | $\Sigma_a^{Xe}$ | $K''_{th}$ |
|---|---|---|---|---|
| 0 | 0.208228 | 0.00403088 | 0.008364 | 1.4583 |
| 0.018 | 0.205335 | 0.00395832 | 0.008316 | 1.4538 |
| 0.033 | 0.202274 | 0.00389786 | 0.008275 | 1.4548 |
| 0.069 | 0.194557 | 0.00375275 | 0.008144 | 1.4600 |
| 0.135 | 0.181057 | 0.0034867 | 0.007780 | 1.4641 |
| 0.200 | 0.168744 | 0.0032247 | 0.007391 | 1.4586 |
| 0.305 | 0.150477 | 0.0028015 | 0.006698 | 1.4300 |

TABLE 5.6
BUCKLINGS FOR PM-2A CORES I AND II

| | 68°F | 510°F |
|---|---|---|
| Radial Reflector Savings, $S_r$ ($cm^{-1}$) | 6.11721 | 8.2488 |
| Axial Reflector Savings, $S_z$ ($cm^{-1}$) | 6.03080 | 7.97834 |
| Radial Buckling, $B_r^2$ ($cm^{-2}$) | 0.005747 | 0.005046 |
| Axial Buckling, $B_z^2$ ($cm^{-2}$) | 0.002176 | 0.001945 |
| Total Buckling, $B^2$ ($cm^2$) | 0.007923 | 0.006991 |

5.4.3 Core Lifetime

Using equation (5.1), $k_{eff}$ was determined as a function of fuel burnup. $K_{eff}$ was converted to core reactivity by the relation,

$$\rho = \frac{K_{eff} - 1}{K_{eff}} \qquad (5.4)$$

To convert fuel burnup to energy release, the following relation was used: (11)

$$MWYR = 2(19.49)\,\overline{B}$$

The variation of core reactivity with uniform burnup and energy release for the two cores is given in Table 5.7.

5.4.4 Non-Uniform Burnup

To convert from uniform to non-uniform burnup, recourse was made to calculations on the SM-1 Core I. Figure 5.4 shows the variation of reactivity with energy release for both uniform and non-uniform burnup. The difference between the two curves, $\Delta K$, at a particular average fuel burnup, B, was converted to a change in $\Delta \rho$ using equation (5.4). These values of $\Delta \rho$ were applied to the uniform burnup calculations for the PM-2A for the same values of average fuel burnup to obtain the non-uniform burnup.

The resulting reactivity variation with lifetime for the uniform and non-uniform calculations are shown in Fig. 5.5 and 5.6.

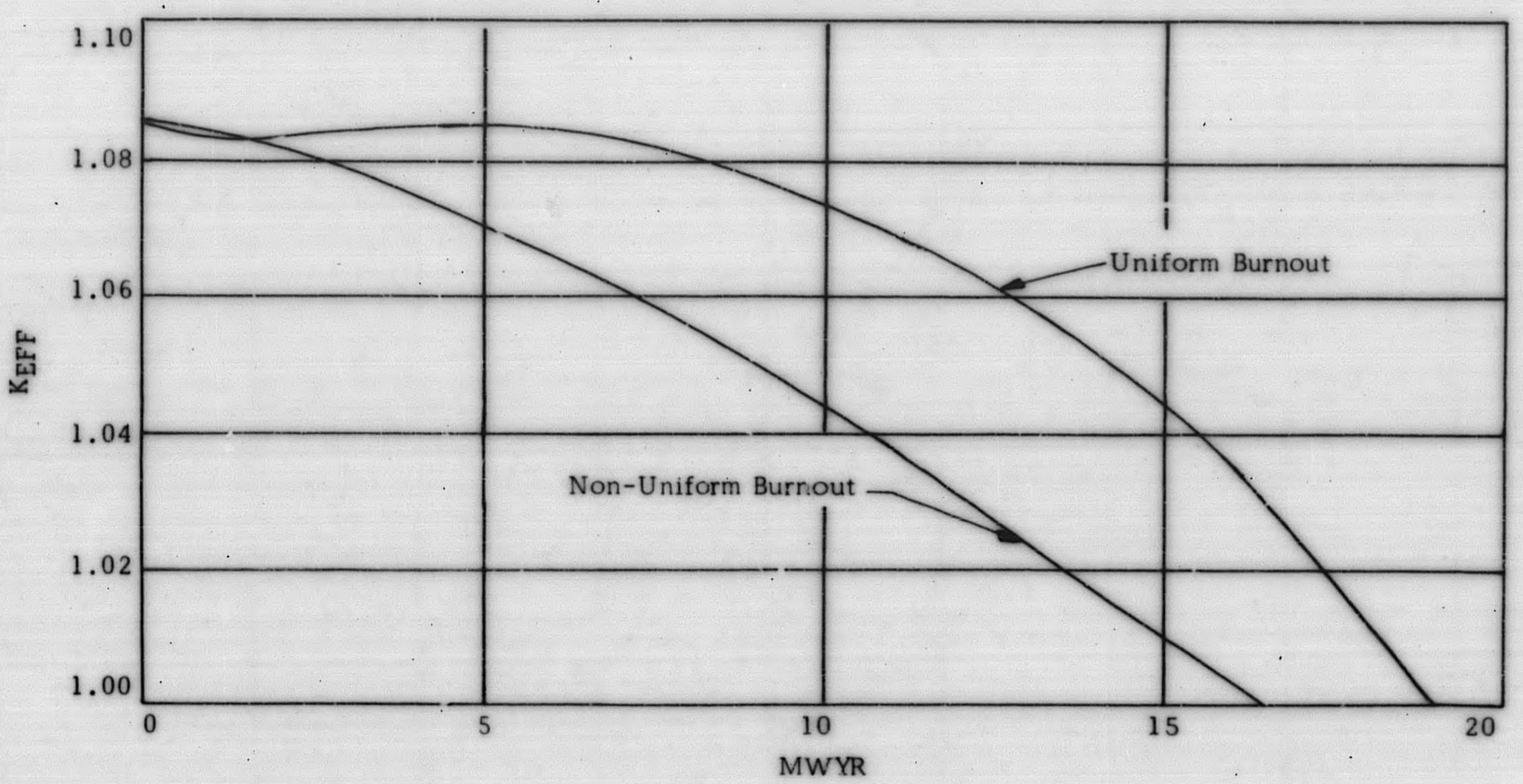


Figure 5.4. SM-1 Core I $K_{eff}$ Vs Core Energy, 440°F, Eq Xe - PM-2A Core II ZPE VI

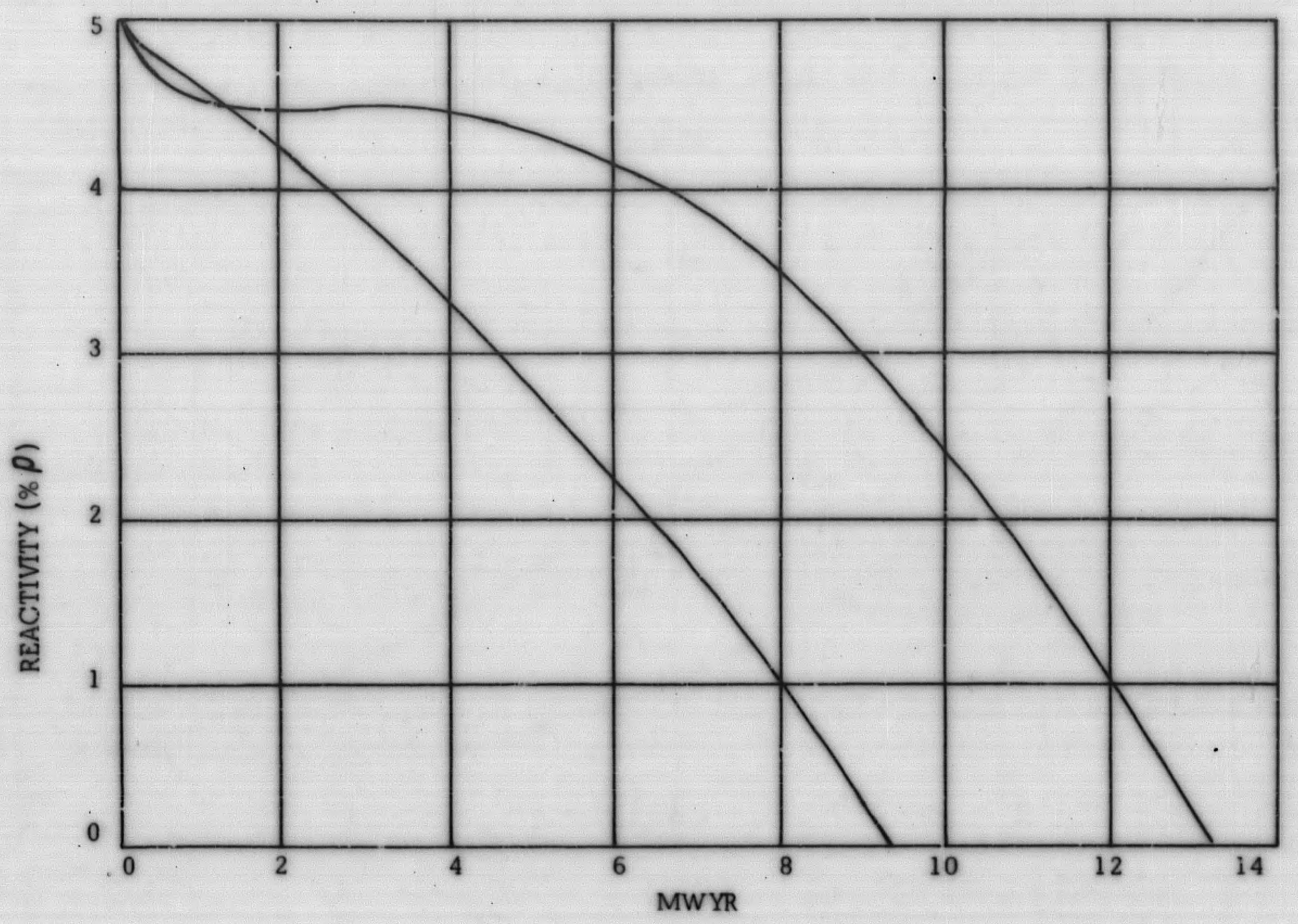


Figure 5.5. PM-2A Core I Uniform and Non-Uniform Burnup
PM-2A Core II ZPE VI

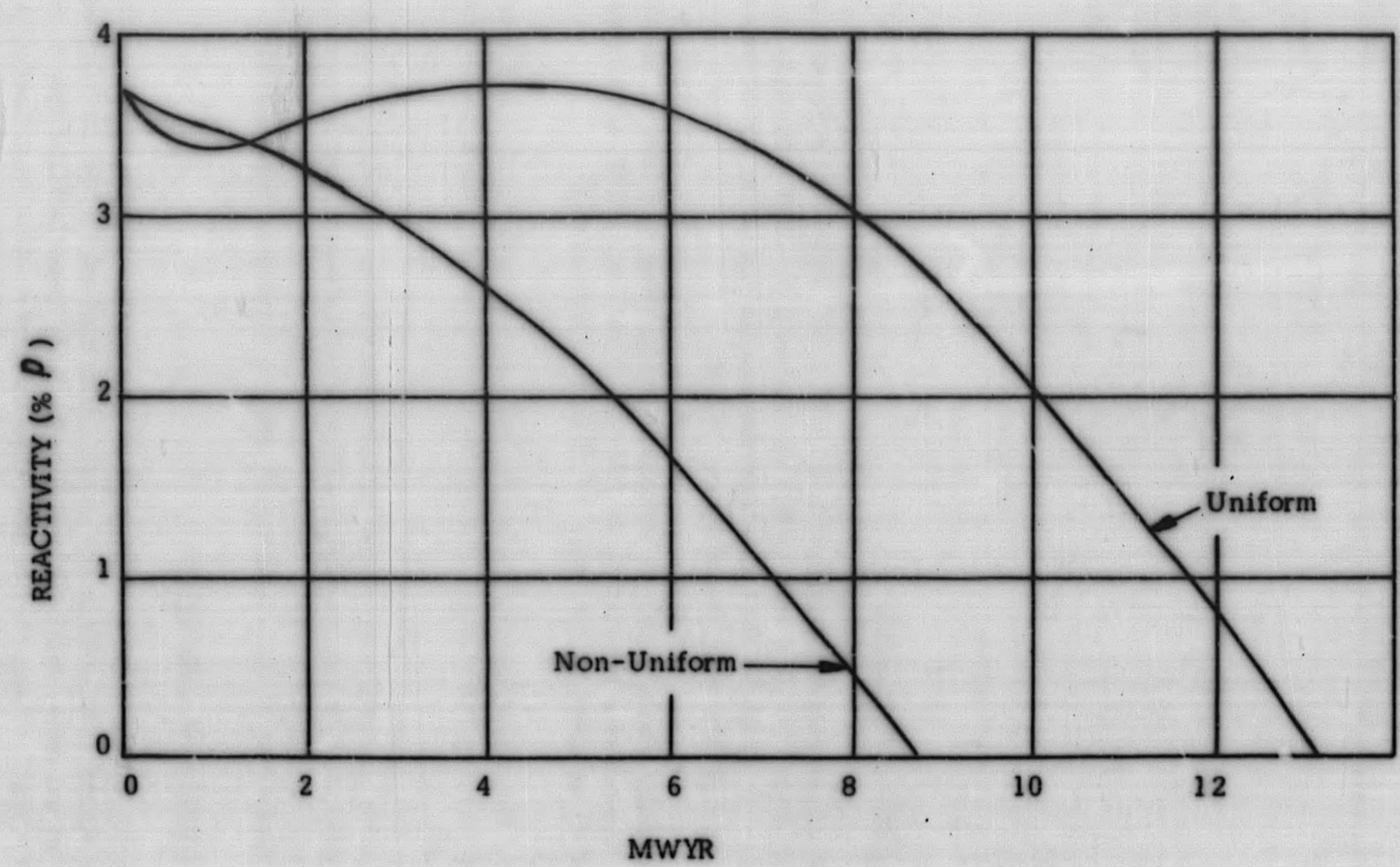


Figure 5.6. PM-2A Core II Uniform and Non-Uniform Burnup
PM-2A ZPE VI

TABLE 5.7
VARIATION OF REACTIVITY AND BURNUP
WITH LIFETIME FOR PM-2A CORES I AND II

| Burnup $\bar{B}$ | Reactivity (%$\rho$) Core I | Core II | Energy Release (MWYR) |
|---|---|---|---|
| 0.0 | 5.0 | 3.7 | 0.0 |
| 0.018 | 4.6 | 3.5 | 0.70 |
| 0.033 | 4.5 | 3.4 | 1.25 |
| 0.069 | 4.5 | 3.1 | 2.70 |
| 0.135 | 4.3 | 2.0 | 5.25 |
| 0.200 | 1.1 | 0.6 | 7.80 |
| 0.305 | -2.2 | -2.5 | 11.90 |

5.4.5 Model Correction

The cold clean excess reactivities of PM-2A Cores I and II were found to be (see Section 5.3.1) \$20.4 and \$18.4 respectively. The integral rod worth curves (see Fig. 5.3) show that the temperature defect plus the xenon worth at a power level of 4.8 Mw was found to be \$12.0.

The reactivity change due to xenon in going from 4.8 Mw to 10 Mw is \$0.9. Hence the excess reactivity of PM-2A Core I at 510°F, equilibrium xenon (at 10 Mw) at start of life was \$7.5 or 5.7 percent $\rho$.

Assuming the same hot-to-cold change plus xenon worth for Core II as for Core I, the excess reactivity of PM-2A Core II under these conditions will be \$5.5 or 4.2% $\rho$.

Normalizing the reactivity versus lifetime curves for PM-2A Cores I and II to the above start of life values gives the best estimate of the lifetime of the two cores. This is shown in Fig. 5.7. Core I is seen to have an estimated life of 9.7 MWYR and Core II is estimated to have a lifetime of 9.6 MWYR.

5.4.6 Stuck Rod Conditions

In the zero power experiments and in the initial startup and testing of PM-2A Core I, it was found that criticality could be achieved by the withdrawal of any one of three control rods, with all other rods fully inserted and the core in the cold clean condition. The critical position for rod 4, the most reactive rod, was 16.28 in. The integral worth of rod 4 from 16.28 in. to full out (22 in.) is \$1.10. Hence core reactivity must decrease by \$1.10 before the core will meet the condition of one rod being fully withdrawn without having achieved criticality. Figure 5.7 shows that Core I will meet the one stuck rod criteria after 2.2 MWYR.

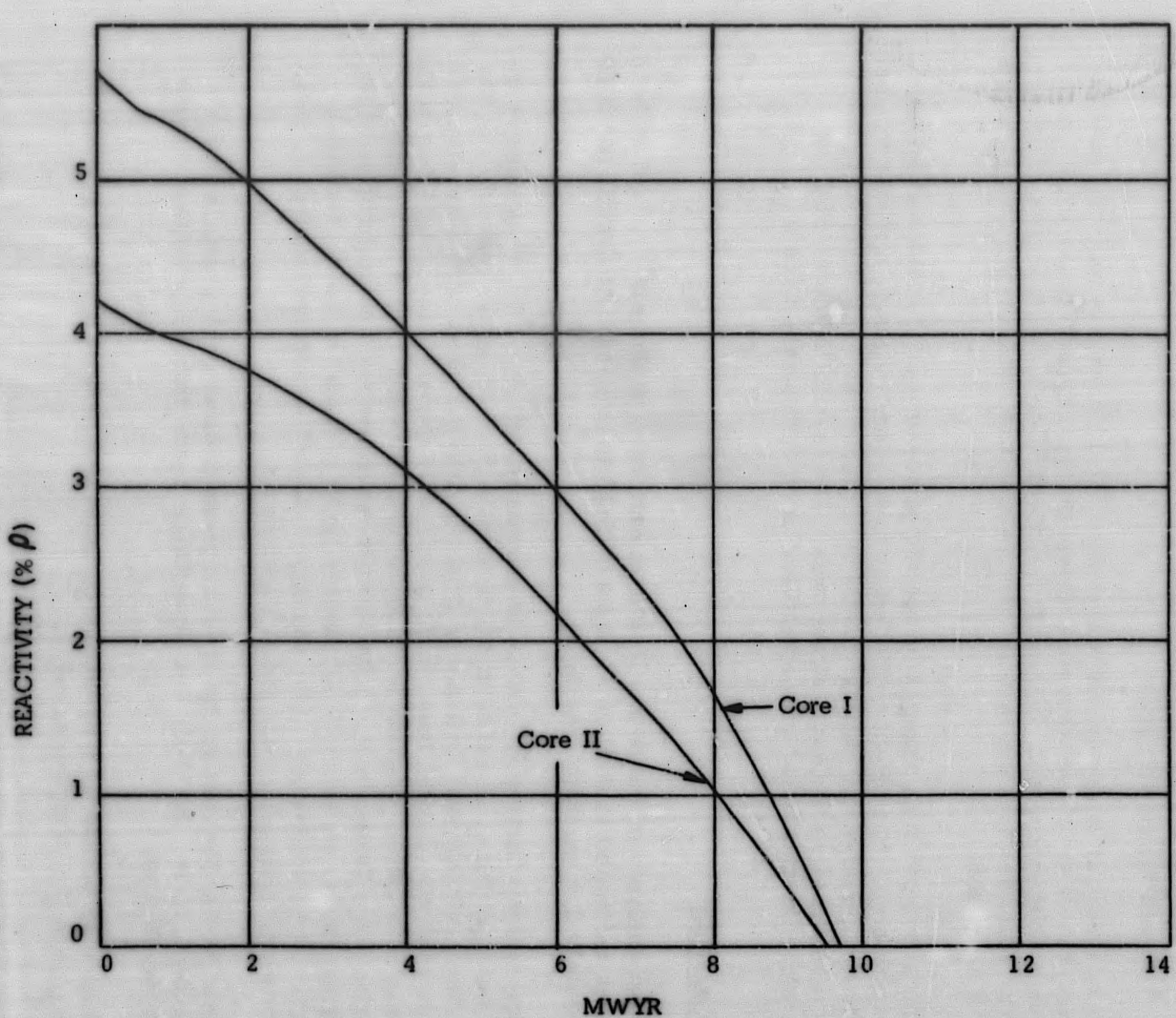


Figure 5.7. Estimate of Variation of Reactivity with Energy Release
PM-2A Cores I and II, 510°F, Eq. Xenon (10 Mw)
PM-2A Core II ZPE VI

The zero power experiments on Core II (see Section 3.5) show that at start of life, Core II cannot be made critical by the complete withdrawal of any single control rod at 68°F. The shutdown margin with rod 4 fully withdrawn is estimated to be about $0.9. From Fig. 5.7 it is seen that maximum core reactivity occurs at start of life. Hence it is concluded that PM-2A Core II will meet the "one stuck rod" criteria throughout life.

5.4.7 Power Distribution

An analysis of the power distribution in PM-2A Core I is reported in APAE Memo No. 195.[16] There were two design changes made between Core I and Core II that affect the power distribution. In addition to changing the composition of the stainless steel in the cladding, a small increase in the boron loading in Core II was made.

The effect of these changes on the radial power distribution is slight and may be neglected. The effect on the axial power distribution is more pronounced since the increased boron loading results in a higher bank position. This results in a decrease in the axial power peak. The thermal analysis of Core I may therefore be considered conservative if used to describe Core II.

## 5.5 SUMMARY

From analysis of the data, Core II is estimated to contain 17.7 gm of B-10. Core I was estimated to contain 15.2 gm of B-10 indicating that Core II contains approximately 2.5 gm more than B-10.

The integral bank worth yields an excess reactivity of 18.40 dollars at the critical bank position. A value of 16.50 dollars for the excess reactivity at the critical bank position was determined from the critical water height experiment. The value from the integral bank worth is probably the more accurate value of the two. This is because equation (3.1) of the critical water height experiment is best applied to a large, low enriched U-235 reactor where $k_\infty$ is approximately one. Furthermore, equation (3.1) requires that the radial buckling remains a constant. Since there were slight changes in the effective core diameter, there would be slight changes in the radial buckling.

The PM-2A dial reading for the cold clean critical bank position is estimated to be 6.75 in. At 510°F and equilibrium xenon this dial reading is estimated to be 12.3 in.

Core II is estimated from burnup calculations to have a life of 9.6 MWYR as compared to 9.7 MWYR for Core I.

From the stuck rod measurements, it was found the Core II will meet the "one-stuck-rod" criteria throughout the core life. Core II will not attain criticality by withdrawal of a single rod. With rod #4 fully withdrawn the shutdown margin is estimated to be 0.9 dollars.

In comparison of Core I and Core II, there was only a slight change in the radial power distribution. However, the axial power distribution was affected in that the axial power peak of Core II is decreased compared to that of Core I.

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17. Gallagher, J.G. (Alco Products, Inc.) letter to McCool, W.J. (Alco Products) - based on telephone conversation with Captain Purple.

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## APPENDIX A
## SUMMARY DATA FOR PM-2A CORE II

| | |
|---|---|
| **Fuel Elements and Absorber Section (Qty.)** | |
| Number of Stationary Fuel Elements | 32 |
| Number of Control Rods with Fuel Elements | 5 |
| Total Number of Fuel Elements | 37 |
| Number of Europium Absorber Sections (From Core I) | 5 |
| **U-235 Mass (Grams)** | |
| Stationary Fuel Element | 542.34* |
| Control Rod Fuel Element | 427.20* |
| Total of Stationary Fuel Elements | 17354.88* |
| Total of Control Rod Fuel Elements | 2136.00* |
| Total U-235 Mass | 19490.88* |
| **B-10 Loading (Grams)** | |
| Estimated Average per Stationary Element | 0.492 |
| Estimated per Control Rod Element | 0.390** |
| Total of all Stationary Elements | 15.744 |
| Total of all Control Rod Elements | 1.950** |
| Total B-10 | 17.694 |
| **Cold Clean Critical Positions (Inches)** | |
| Five Rod Bank (Position at Alco Facility) | 7.303 |
| (Dial Reading at PM-2A Site) | 6.9 |

* Design Specifications, References (4,5) and corrections.

** Determine by assuming same percent loss in control rod fuel elements as in stationary fuel elements.

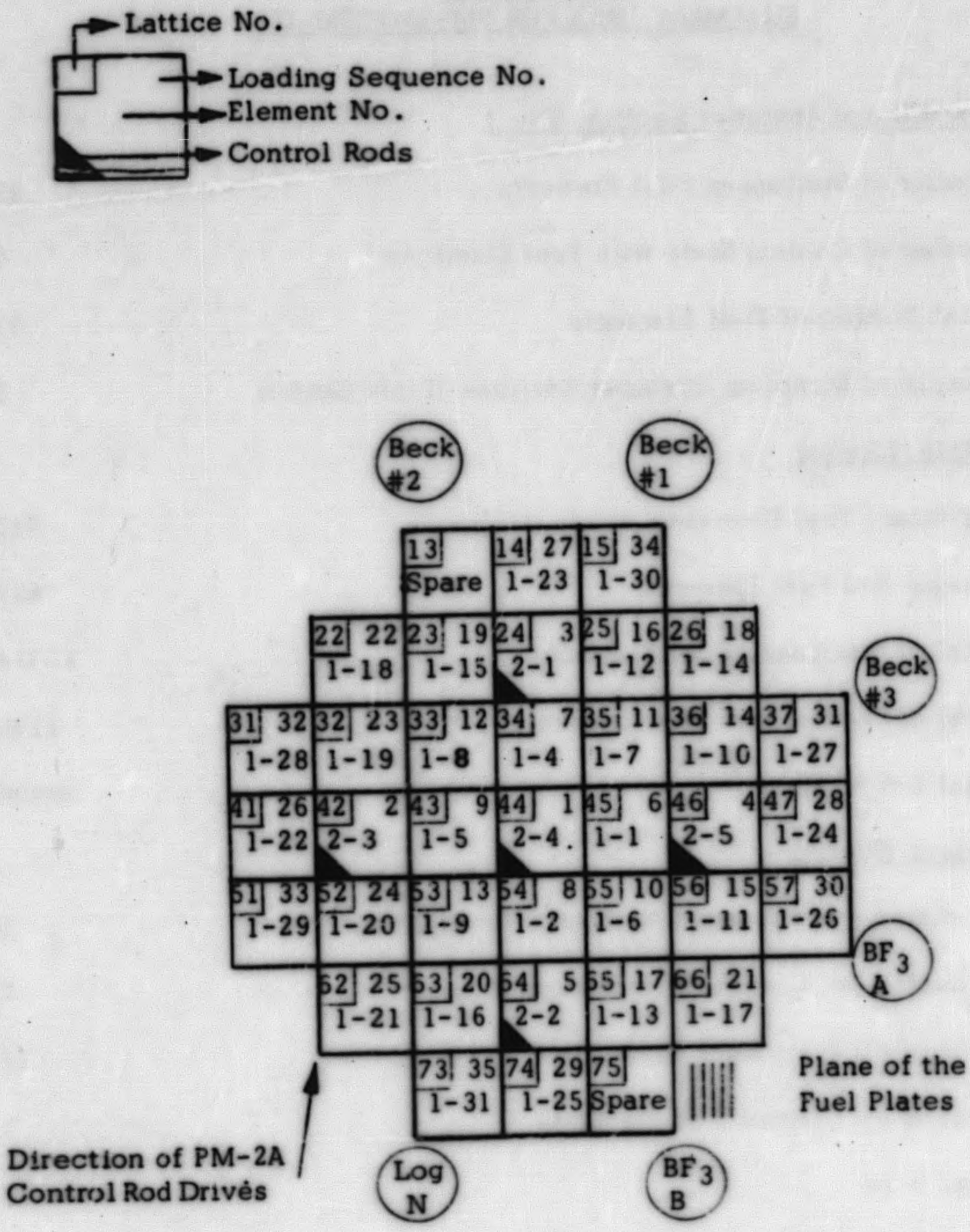


Figure A.1. Complete Loading Chart
PM-2A Core II ZPE VI

## APPENDIX B
## PM-2A CORE II LOADING TABLE

| Loading Sequence | Element Number | Lattice Position | Critical Bank Position, In. (Corrected for PM-2A Site) | Mass U-235, Kg | Count Rate Rod Bank Full In, cps | Count Rate Rod #4 Withdrawn 10 In., cps | Approx. Bank Worth, cents/In. | Approx. Worth of Fuel Added, Dollars |
|---|---|---|---|---|---|---|---|---|
| 1 | 2-4 | 44 | | | | | | |
| 2 | 2-3 | 42 | | | | | | |
| 3 | 2-1 | 24 | | | | | | |
| 4 | 2-5 | 46 | | | | | | |
| 5 | 2-2 | 64 | | 2.14 | | | | |
| 6 | 1-1 | 45 | | | | | | |
| 7 | 1-4 | 34 | | | | | | |
| 8 | 1-2 | 54 | | 3.76 | | | | |
| 9 | 1-5 | 43 | | | | | | |
| 10 | 1-6 | 55 | | | | | | |
| 11 | 1-7 | 35 | | 5.39 | | | | |
| 12 | 1-8 | 33 | | | | | | |
| 13 | 1-9 | 53 | | 6.47 | | | | |
| 14 | 1-10 | 36 | | 7.02 | | | | |
| 15 | 1-11 | 56 | | 7.56 | | | | |
| 16 | 1-12 | 25 | | 8.10 | | | | |
| 17 | 1-13 | 65 | 18.5 | 8.64 | 0.34 | 0.52 | 37 | |
| 18 | 1-14 | 26 | | | | | | |
| 19 | 1-15 | 23 | | | | | | |
| 20 | 1-16 | 63 | | | | | | |
| 21 | 1-17 | 66 | 13.1 | 10.81 | 0.63 | 0.77 | 120 | 4.95 |
| 22 | 1-18 | 22 | | | | | | |
| 23 | 1-19 | 32 | | | | | | |
| 24 | 1-20 | 52 | | | | | | |
| 25 | 1-21 | 62 | 10.5 | 12.98 | 0.99 | 1.6 | 175 | 4.13 |
| 26 | 1-22 | 41 | | | | | | |
| 27 | 1-23 | 14 | | | | | | |
| 28 | 1-24 | 47 | | | | | | |
| 29 | 1-25 | 74 | 9.0 | 15.15 | 1.47 | 2.7 | 224 | 3.28 |
| 30 | 1-26 | 57 | | | | | | |
| 31 | 1-27 | 37 | | | | | | |
| 32 | 1-28 | 31 | | | | | | |
| 33 | 1-29 | 51 | 7.7 | 17.32 | 3.41 | 7.6 | 253 | 2.53 |
| 34 | 1-30 | 15 | | | | | | |
| 35 | 1-31 | 73 | | | | | | |
| 36 | PM-2A Spare | 13 | | | | | | |
| 37 | PM-2A Spare | 75 | 6.7 | 19.49 | 5.35 | 10.5 | 255 | 2.54 |

END