CEN-319

CONTROL ROD GROUP EXCHANGE TECHNIQUE

Prepared for the C-E OWNERS GROUP

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COMBUSTION ENGINEERING

LEGAL NOTICE

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1.0 INTRODUCTION

The measurement of the reactivity worths of selected control rod groups is routinely performed as part of the initial startup of an NSSS and prior to resuming power operation following each refueling. This testing is performed to confirm that the measured control rod group worths conform to those predicted for the design and assumed in the safety analysis. This confirmation is derived from a comparison of the measured to the predicted reactivity worths at the conditions of the measurements. The control rod group worths have traditionally been measured on C-E NSSS using the dilution/boration method.

The Control Rod Group Exchange Technique is an alternate measurement technique to the dilution/boration method for obtaining essentially equivalent information. The Exchange technique offers several advantages:

a. Both the regulating and the shutdown group reactivity worths are measured and evaluated.

b. The amount of dilution and boration required to perform the measurement is significantly reduced . This results in less radiological waste water generation and its associated expense.

c. The critical path test times are significantly reduced.

Therefore, for both technical and economic reasons, the Exchange technique is an attractive alternative for routine use.

The implementation of the Exchange technique was initiated with a program designed to demonstrate the general applicability of this approach for the various C-E NSSS designs. The demonstration program included side-by-side measurements using both the dilution/boration and the Exchange methods for SCE SONGS 2 Cycle 2 and for APS PVNGS Unit 1 Cycle 1. On SONGS 2, the six regulating groups and one shutdown group were measured using the dilution/boration method.

On PVNGS Unit 1, a N-1 (All Rods in with the worst rod kept out) measurement was made at cold shutdown conditions (320°F) and the five regulating groups were measured at hot zero power conditions (565°F) using the dilution/boration method. On both units, all control rod groups (Regulating and Shutdown) were measured using the Exchange technique. These two NSSS units utilize the basic control rod designs employed in all the C-E NSSS designs (except the Palisades NSSS). The demonstration included both a first cycle with all fresh fuel and a later cycle with both burned and fresh fuel.

The following sections describe the Exchange measurement and calculative methodologies, provide results from the demonstration program and evaluate these results. It is concluded from this demonstration program that the control rod Exchange technique is a technically equivalent approach to the dilution/boration method of evaluation control rod reactivity worths and is significantly superior in its efficiency.

2.0 TEST METHODOLOGY

As with the boration/dilution technique, the Exchange technique involves a comparison between a measurement based on the integrated response of a reactivity calculator and a design code prediction for the test configuration. However, unlike the boration/dilution technique, the Exchange technique utilizes the reactivity worth measured as a function of the Reference Group position as a repeatable measure of the worth of less worthy control rod groups.

Based on the predicted worth of each control rod group inserted individually, the group worths are ordered and the most worthy group selected to be a Reference Group. The incremental and integral worths of this Reference Group are measured (by the dilution/boration method) as the group traverses the core.

After dilution of the Reference Group to the fully inserted position, the integrated rod worth curve for the Reference Group is determined and core reactivity is stabilized at approximately zero. Relevant system parameters are recorded and any residual reactivity of the Reference Group, if not fully inserted, is measured with the reactivity calculator. At this point, the exchange maneuver is initiated by withdrawing the Reference Group in small increments and inserting the Test Group to compensate reactivity. The maneuver is complete when the Test group is fully inserted and the Reference Group is at a position such that the reactor is essentially critical as measured by the reactivity calculator. Any small deviation from criticality is recorded together with the relevant system parameters. The position of the Reference Group at this point is termed the Measured Critical Position (MCP). The differential worth of the Reference group about the MCP is measured to permit adjusting the MCP for any reactivity drifts during the measurement.

After correcting for reactivity drifts induced by minor state parameter changes, it is possible to conclude that the reactivity worth of the Test Group in that configuration is exactly equal to the withdrawn worth of the Reference Group to the MCP. Since the withdrawn worth of the Reference group was determined during the dilution, the Test Group reactivity worth is known for that configuration.

The exchange may be repeated in reverse order such that the Test Group is fully withdrawn and the Reference Group is returned to its original position. A change in reactivity from that recorded at the start of the exchange is indicative of slight changes in system conditions, e.g., boron concentration. System parameters are recorded and this information is used to adjust the MCP, if required.

The re-exchange of the Reference Group with the Test Group is not necessary when system conditions are maintained very steady. As an alternate approach, the Reference Group is held at the MCP and the present Test Group is exchanged directly with the next Test Group. The exchange is completed by moving the Reference Group to a new MCP. The differential reactivity worth about the new MCP is measured and system parameters are recorded. The alternate approach may be repeated one or more times before the Reference Group is finally returned to the fully inserted position with all other control rods fully withdrawn, i.e., the initial condition.

The alternate approach substantially reduces the time to perform the exchanges and, consequently, reduces the time system changes can occur. This can result in more accurate measurements as well as reduced test time.

In the C-E NSSS designs, individual control rod group worths may vary by factors of 7 to 10 from each other. To increase the accuracy of the measurements for the demonstration of the Exchange Technique, two separate Reference Groups, one for the higher and one for the lower group worth categories, were used. The Exchange methodology, however, remains the same.

In summary, the reactivity worth of a Reference Group is measured using the conventional dilution/boration technique. The individual worths of the remaining Test Groups are measured by withdrawal of the applicable Reference Group.

3.0 ANALYSIS METHODOLOGY OF MEASUREMENT DATA

The incremental and integral reactivity worths of the Reference Group(s) are determined from the reactivity calculator traces obtained while applying the dilution/boration method. The reactivity worth of each Test Group fully inserted with the Reference Group partially inserted is determined from the MCP of the Reference Group and its measured reactivity worth as a function of its position.

The data recorded during the test includes:

1. the incremental and integral reactivity worth of the Reference Group(s) with all other control rod groups fully withdrawn from the reactor (temperature corrected to a reference temperature as necessary).
2. the initial and final core reactivites (measured before and after the exchange) with the Reference Group(s) fully inserted in the reactor with all other control rod groups fully withdrawn.
3. the isothermal temperature coefficients measured with the Reference Group (most worthy) fully withdrawn and fully inserted.
4. the critical positions of the Reference Group with each Test Group individually fully inserted in the reactor.
5. the deviation from criticality and the primary coolant temperature measured at the MCP's associated with the exchange with each of the Test Groups.
6. the differential reactivity worth of the Reference Group about the MCP's while each of the Test Groups is fully inserted.

Several different measurement sequences may be employed to obtain the data described above.

Minor adjustments to the measured critical positions (MCPs) are required to account for small changes in primary system conditions and for deviations from criticality at the statepoints. Adjustments are minimized by maintaining very stable conditions during the testing. Small deviations from criticality are unavoidable since the control rod groups are moved in small discrete steps.

The MCP is adjusted using the following relationship:

$$MCP_A = MCP_M + [(\alpha_{ITC} \times \Delta T) + (\alpha_{BW} \times \Delta C) + \rho_I - \rho_F + \rho_{EQUI}] / \frac{\Delta\rho}{\Delta h} \quad 3\text{-}1$$

where:

MCP_A is the adjusted MCP expressed in terms of inches of withdrawal from the fully inserted position.

MCP_M is the measured MCP in the same units.

α_{ITC} is the isothermal temperature coefficient appropriate for the conditions of the measurement.

ΔT is the difference in temperature between the start and completion of an exchange with a Test Group, i.e., $T_F - T_I$.

α_{BW} is the boron worth coefficient.

ΔC is the change in boron concentration between the start and completion of the exchange, i.e., $C_F - C_I$.

ρ_I is the deviation from criticality with the Reference Group at its initial position at the start of an exchange with a Test Group.

ρ_F is the deviation from criticality with the Reference Group at the MCP and the Test Group fully inserted.

ρ_{EQUI} is the reactivity worth of the Reference Group from its initial position (typically essentially fully inserted) to the fully inserted position. The term is negative if the Reference Group is initially slightly withdrawn.

$\Delta\rho/\Delta h$ is the differential reactivity worth of the Reference Group about the MCP. This value is calculated from the measured data such that it is a positive value to be consistent with the sign convention in the equation.

4.0 TEST RESULTS

The Reference Group reactivity worths for PVNGS Unit 1 Cycle 1 and SONGS Unit 2 Cycle 2 measured with the boration/dilution technique are summarized in Table 4-1. The relevant measurement data associated with the performance of the control rod exchange of the Test Groups for PVNGS and SONGS are summarized in Tables 4-2 and 4-3, respectively. Adjustments to the MCP were applied using Equation 3.1. The adjusted MCPs for the PVNGS and SONGS measurements are shown graphically superimposed on the Reference Group worth curves as a function of position in Figures 4-1/4-2 and 4-3/4-4, respectively.

The worth of each Test Group with the applicable Reference Group at the MCP_A is determined from the following reactivity balance equation:

$$T^M_{i,MCP_A} = R^M_i - \Delta R^M_{i,MCP_A} \qquad 4\text{-}1$$

where:

R^M_i is the reactivity worth of the Reference Group (measured by boron dilution method) to which Test Group i is assigned.

$\Delta R^M_{i,MCP_A}$ is the worth of the Reference Group from the fully withdrawn position to the MCP_A.

T^M_{i,MCP_A} is the measured worth of Test Group i with its Reference Group at the MCP_A.

The results of applying Eq. 4-1 to the data contained in Figures 4-1 through 4-4 are summarized in Tables 4-4 and 4-5 for PVNGS and SONGS, respectively.

TABLE 4-1

MEASURED REFERENCE GROUP WORTHS

PVNGS Unit 1 Cycle 1

Group	Worth (%$\Delta\rho$)
B	2.745
3	0.733

SONGS Unit 2 Cycle 2

Group	Worth (%$\Delta\rho$)
B	2.223
3	0.695

TABLE 4-2

PVNGS Unit 1 Cycle 1

Test Group	Ref. Group	RCS Temp. °F Final	Init	ΔT	Reactivity ρ_I(¢)	ρ_F(¢)	RCS Boron C_F	C_I	ΔC	Reference GP Init Pos	ρ_{EQUI}(¢)	MCP_M inches withdrawn	Δρ/Δh (¢)/inch	ΔMCP	MCP_A inches withdrawn
A	B	565.11	565.00	0.11	+0.25	+0.10	799	799	0	10.33	-3.84	108.92	1.053	-3.46	105.5
1 [1]	3	565.20	565.20	0.00	-0.85	-1.80	954	954	0	LEL [2]	0.00	UEL	N/A	N/A	UEL [3]
2	3	565.21	565.06	0.15	+1.70	-0.10	954	954	0	LEL	0.00	89.05	1.26	+1.27	90.3
4	3	565.20	565.18	0.02	+1.74	-0.14	954	954	0	LEL	0.00	72.85	1.27	+1.48	74.3
5	3	565.20	565.18	0.02	+1.88	-0.40	954	954	0	LEL	0.00	47.57	1.07	+2.13	49.7

[1] Group 1 was worth slightly more than Group 3 so the difference in worth was measured with the reactivity calculator after the exchange between Group 1 and Group 3 was completed. Group 3 was chosen as the Reference Group rather than Group 1 because the control rods of Group 3 are better distributed over the core.

[2] Lower Electrical Limit - Fully Inserted

[3] Upper Electrical Limit - Fully Withdrawn

TABLE 4-3

SONGS Unit 2 Cycle 2

Test Group	Ref. Group	RCS Temp. °F Final	RCS Temp. °F Init	RCS Temp. °F ΔT	Reactivity ρ_I(¢)	Reactivity ρ_F(¢)	RCS Boron C_F	RCS Boron C_I	RCS Boron ΔC	Reference GP Init Pos	Reference GP ρ_{EQUI}(¢)	MCP_M inches withdrawn	Δρ/Δh (¢)/inch	ΔMCP	MCP_A inches withdrawn
A	B	544.28	544.39	-.11	0.00	+0.05	988	988	0	LEL[1]	0.00	48.70	3.54	0.04	48.7
6	3	544.75	544.85	-.11	-0.60	-0.20	1133	1133	0	LEL	0.00	87.30	1.14	-.26	87.0
5	3	544.50	544.85	-.35	-0.60	+0.25	1133	1133	0	LEL	0.00	74.50	1.13	-.45	74.0
4	3	544.90	544.90	0.00	-0.90	0.00	1133	1133	0	LEL	0.00	123.28	1.09	-.83	122.4
2	3	545.80	544.90	-.10	-0.90	-0.30	1133	1133	0	LEL	0.00	100.03	1.00	-.50	99.5
1	3	545.30	544.90	+.40	-0.90	-0.40	1133	1133	0	LEL	0.00	113.53	1.24	-.72	112.8

[1] Lower Electrical Limit - Fully Inserted

TABLE 4-4

MEASURED TEST GROUP WORTHS
CEA EXCHANGE

PVNGS Unit 1 Cycle 1

Test Group	Reference Group	Adjusted Meas. Crit Position MCP_A inches w/d	Test Group Worth (%Δρ) (In the presence of the Reference Group at the MCP)
A	B	105.5	2.532
1	3	Note [1]	0.752
2	3	90.3	0.568
4	3	74.3	0.463
5	3	49.7	0.238

[1] Group 1 was worth more than the Reference Group 3. With Group 3 fully withdrawn and Group 1 fully inserted, the difference in reactivity worth was measured with the reactivity calculator and amounted to 0.02%Δρ.

TABLE 4-5

MEASURED TEST GROUP WORTHS
CEA EXCHANGE

SONGS Unit 2 Cycle 2

Test Group	Reference Group	Adjusted Meas. Crit Position MCP_A inches w/d	Test Group Worth (%Δρ) (In the presence of the Reference Group at the MCP)
A	B	48.7	1.087
6	3	87.0	0.360
5	3	74.0	0.268
4	3	122.4	0.590
2	3	99.5	0.435
1	3	112.8	0.526

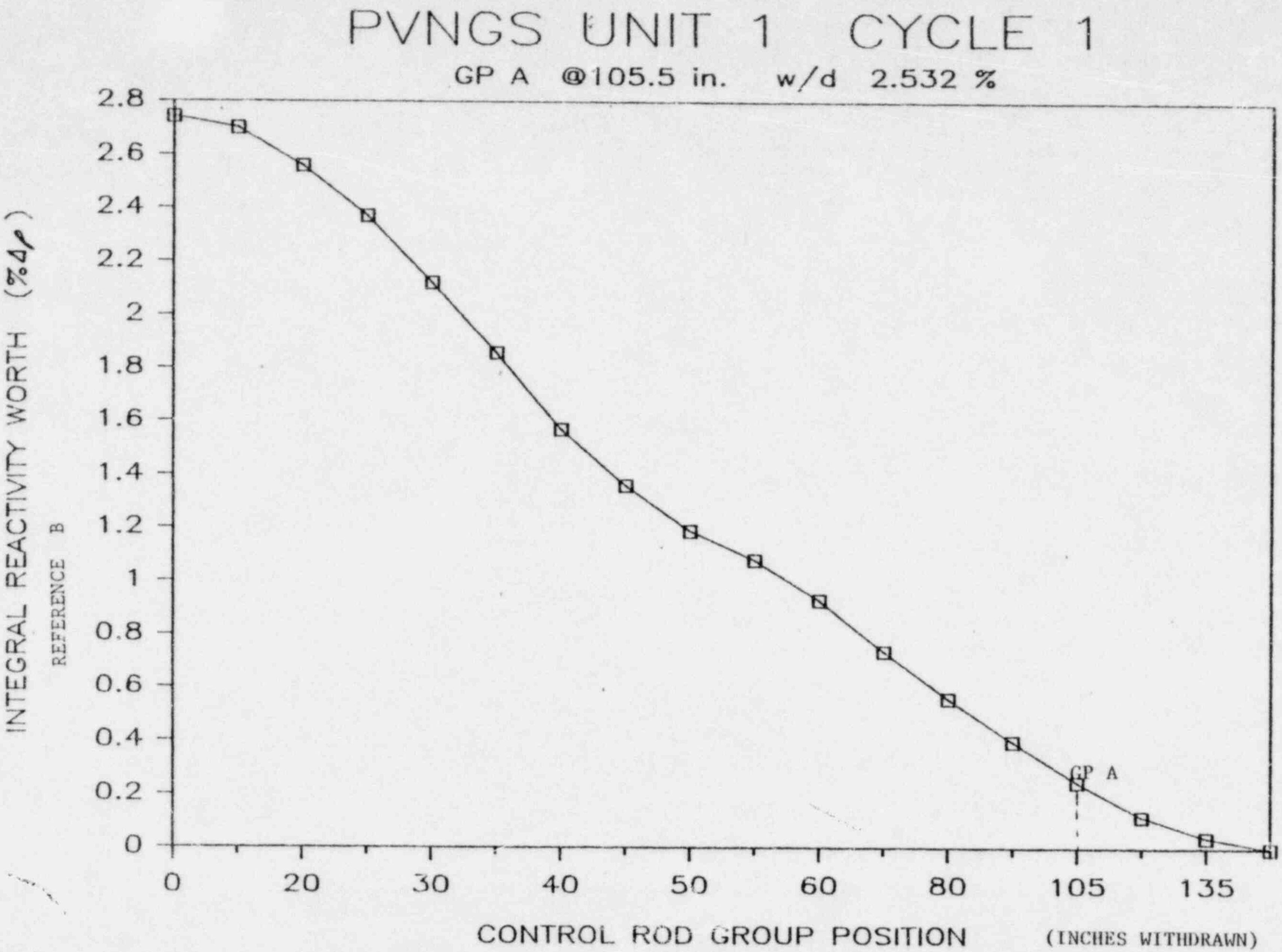

PVNGS UNIT 1 CYCLE 1
GP A @105.5 in. w/d 2.532 %
INTEGRAL REACTIVITY WORTH (%Δρ)
REFERENCE B
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
GP A
0
20
30
40
50
60
80
105
135
CONTROL ROD GROUP POSITION
(INCHES WITHDRAWN)

FIGURE 4-1

PVNGS UNIT 1 CYCLE 1

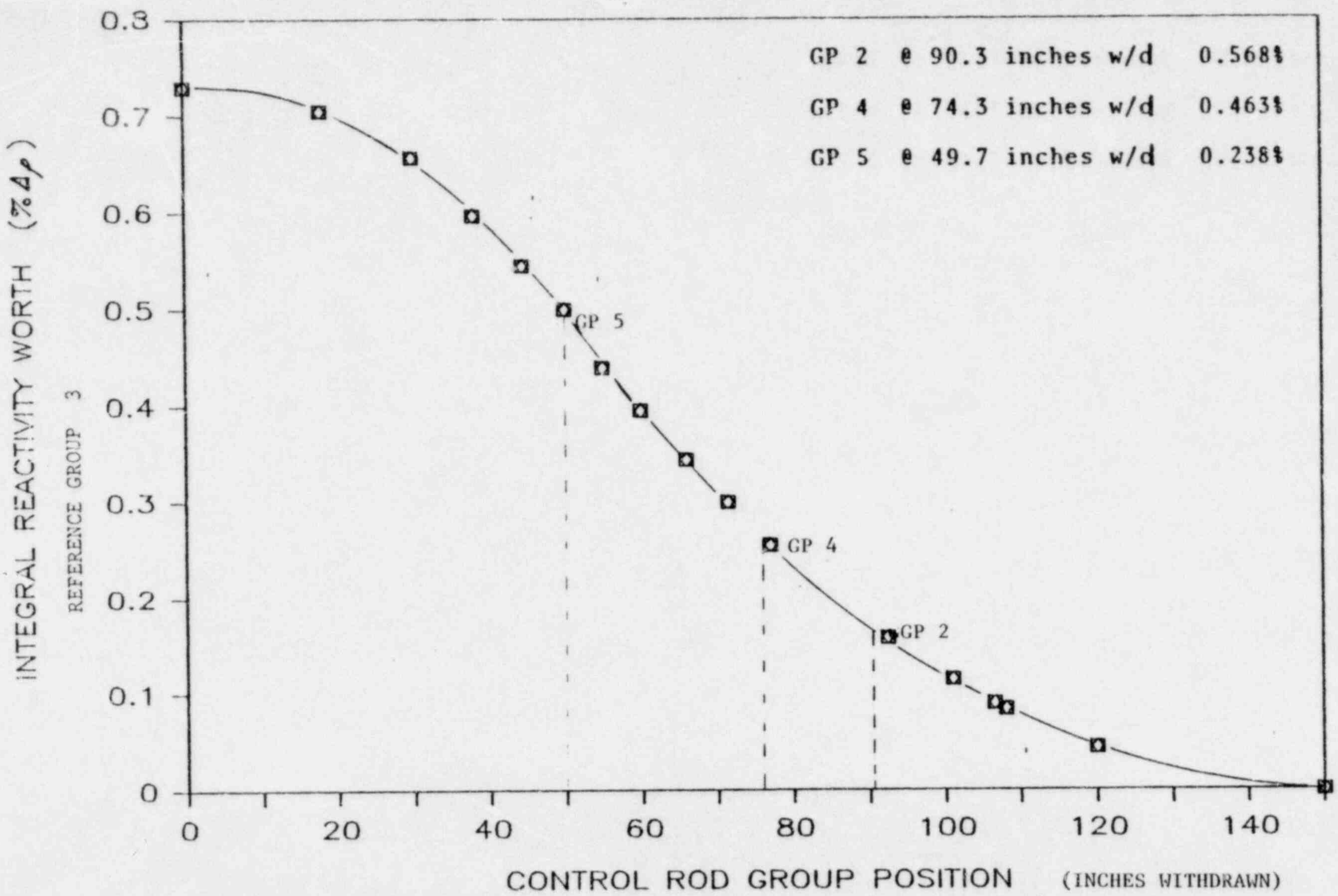


FIGURE 4-2

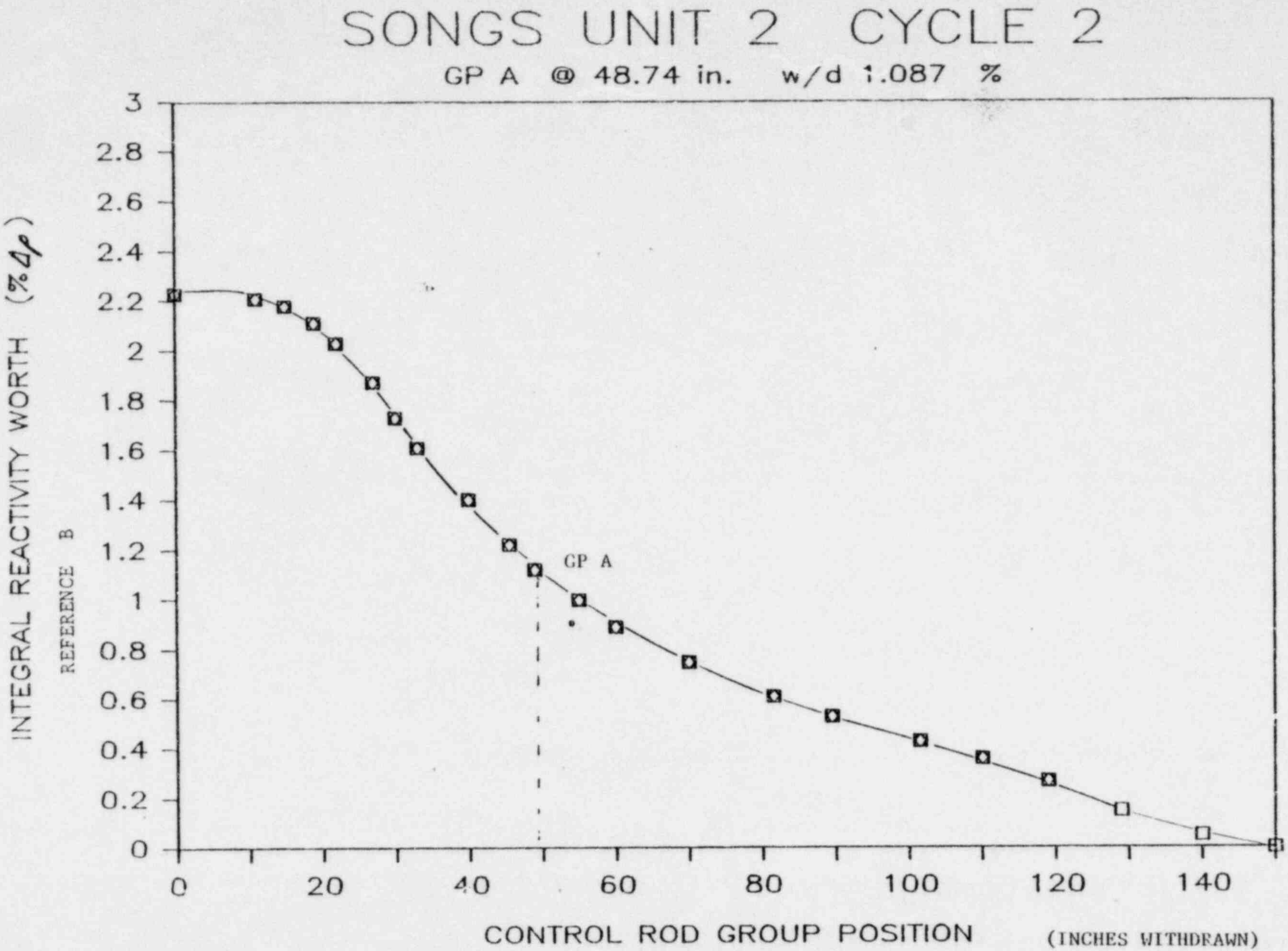

SONGS UNIT 2 CYCLE 2
GP A @ 48.74 in. w/d 1.087 %
INTEGRAL REACTIVITY WORTH (%Δρ)
REFERENCE B
GP A
CONTROL ROD GROUP POSITION (INCHES WITHDRAWN)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
20
40
60
80
100
120
140

FIGURE 4-3

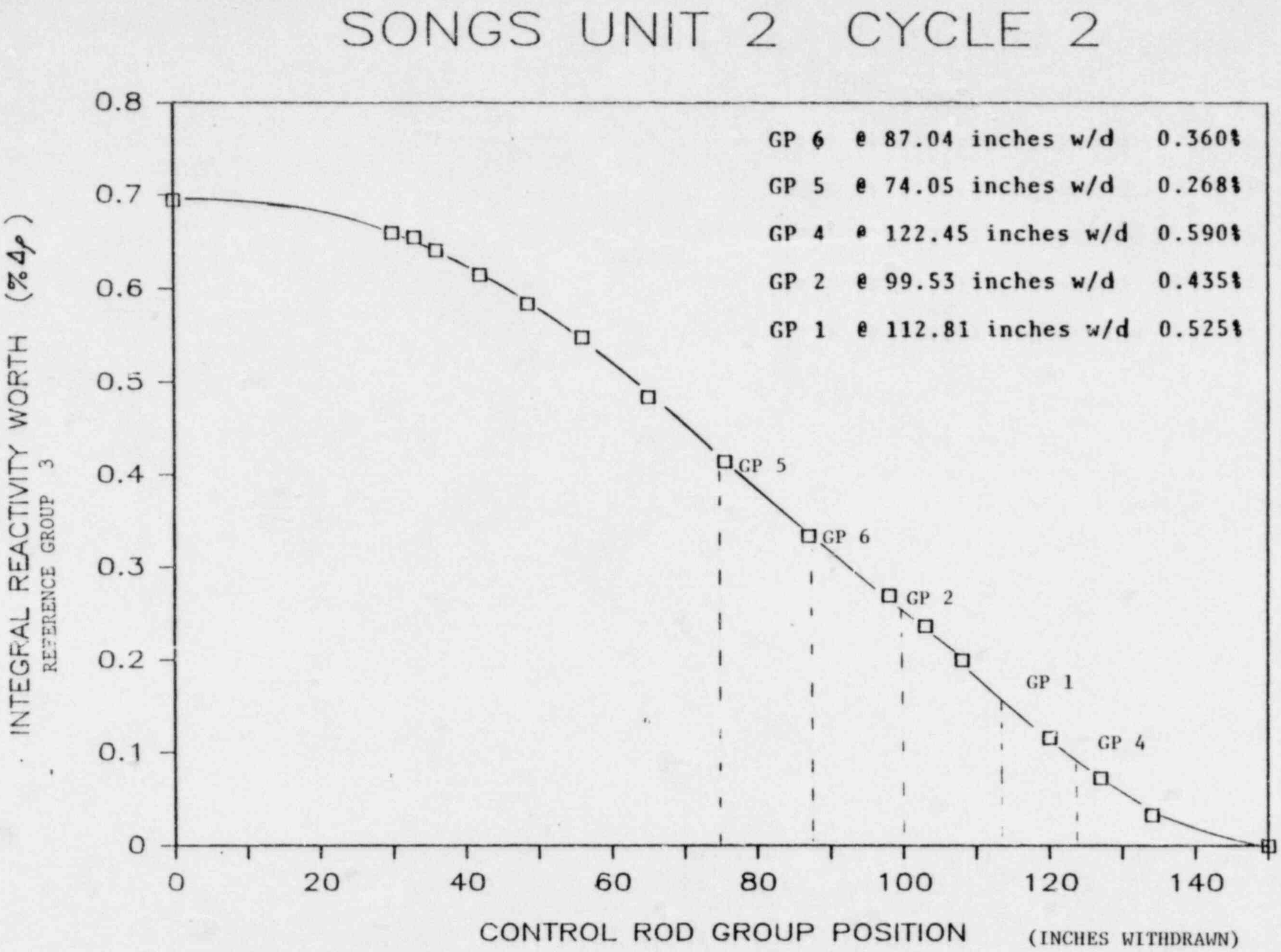

SONGS UNIT 2 CYCLE 2
GP 6 @ 87.04 inches w/d 0.360%
GP 5 @ 74.05 inches w/d 0.268%
GP 4 @ 122.45 inches w/d 0.590%
GP 2 @ 99.53 inches w/d 0.435%
GP 1 @ 112.81 inches w/d 0.525%
GP 5
GP 6
GP 2
GP 1
GP 4
INTEGRAL REACTIVITY WORTH (% Δρ)
REFERENCE GROUP 3
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
CONTROL ROD GROUP POSITION (INCHES WITHDRAWN)

FIGURE 4-4

5.0 CALCULATIVE METHODOLOGY

The calculated information required to support the Control Rod Group Exchange technique is summarized as follows:

a. The integral reactivity worth of each control rod group inserted individually in the reactor is calculated. The calculations are performed at the planned conditions of the measurements and at the critical boron concentration with all control rods withdrawn. These reactivity worths are used to select the Reference Group(s).

b. The incremental and integral reactivity worths of the Reference Group(s) from the fully withdrawn to the fully inserted position are calculated. From this information, the reactivity worth of the Reference Group(s) as a function of its inserted position is determined. The calculations are performed at the boron concentration associated with the Reference Group fully inserted.

c. The reactivity worth of each Test Group in the fully inserted position as a function of the position of its Reference Group is calculated. A graph of this relationship becomes the prediction of the worth of a Test Group and is used with the measurement data as described later in this section. The value of the Predicted Critical Position (PCP) of the applicable Reference Group for each Test Group is also derived from this information. The calculations are performed for the planned conditions of the measurements and at the critical boron concentration corresponding to the Reference Group fully inserted.

d. The critical boron concentrations and the isothermal temperature coefficients with the most worthy Reference Group fully withdrawn and fully inserted is calculated. This information is normally calculated as part of the low power test physics test predictions to apply to other tests.

Several calculative methodologies can be utilized to provide the information outlined above. For this program, a straightforward approach involving the use of a three dimensional (3-D) core simulator code (ROCS) was chosen to provide the formal test predictions for the Exchange testing. This approach allowed essentially a direct simulation of the measurement using routine design methodology. It is anticipated that an alternate approach utilizing 1D/2D synthesis methods would yield comparable results when appropriately normalized to 3-D results.

Calculative Sequence

The calculative sequence involves a set of statepoint calculations for various combinations of control rod configurations. The core reactivity values (eigenvalues) derived from these calculations are used as described below to obtain the information described in the previous section.

a. The individual control rod group worths are determined from the reactivity relationship between two statepoints:

$$\text{Group Worth } (\%\Delta\rho) = \frac{\left(k_i - k_o\right) \times 100}{k_i \times k_o} \qquad 5\text{-}1$$

where:

k_o is the calculated eigenvalue with all control rods withdrawn.

k_i is the calculated eigenvalue with the individual control rod group i fully inserted with all other groups fully withdrawn.

b. The incremental reactivity worth of the Reference Group(s) as a function of its position in traversing from the full out to the full in position is derived from:

$$\Delta R_j^p = \frac{\left(k_o - k_j\right) \times 100}{k_o \times k_j} \qquad 5\text{-}2$$

where:

k_o is the eigenvalue with all control rod groups withdrawn.

k_j is the eigenvalue for Reference Group at inserted position j.

ΔR_j^p is the incremental reactivity worth (%Δρ) of the Reference Group from the fully withdrawn position to position j.

c. The reactivity worth of a Test Group in the presence of its Reference Group is determined from the following statepoint calculations:

$$T_{i,j}^{p} = \frac{\left(k_{OUT}^{j} - k_{in}^{j}\right) \times 100}{k_{OUT}^{j} \times k_{in}^{j}} \qquad 5\text{-}3$$

where:

k_{OUT}^j is the eigenvalue with the Reference Group inserted to position j with all other groups fully withdrawn.

k_{IN}^j is the eigenvalue with the Reference Group inserted to position j and Test Group i fully inserted.

$T_{i,j}^p$ is the reactivity worth (%Δρ) of Test Group i with its Reference Group inserted to position j.

The magnitude of the variation of the Test Group worth as a function of the Reference Group position is dependent on the degree of interaction between the two groups. By proper selection of Reference Group(s) and assignment of Test Groups to a Reference Group, this variation can be minimized to a large extent. The reactivity worth of a Test Group as a function of the position of its Reference Group is the prediction to which the measured Test Group worth is compared.

The Predicted Critical Position (PCP) of a Reference Group with a Test Group fully inserted is derived from the calculated information. The PCP is used primarily as a guide to performing the measurements and a direct comparison between the PCP and the MCP is not evaluated against a test criterion.

The PCP is derived from a reactivity balance such that:

$$R_i^P = T_{i,j}^P + \Delta R_{i,j}^P \qquad 5\text{-}4$$

where:

R_i^P is the integral worth of the Reference Group i.

$T_{i,j}^P$ is the reactivity worth (%Δρ) of Test Group i with its Reference Group inserted to position j.

$\Delta R_{i,j}^P$ is the incremental reactivity worth of the Reference Group from the fully withdrawn position to position j.

A plot of the sum of $T_{i,j}^P$ and $\Delta R_{i,j}^P$ versus position of the Reference Group yields the PCP at the intersection of the curve with the value R_i^P.

d. The calculations of critical boron concentrations and temperature coefficients of interest are done in accordance with routine design methods.

The predicted group worths for each test bank inserted individually are summarized in Tables 5-1 and 5-2 for PVNGS and SONGS, respectively. From this data, Groups B and 3 were chosen to be the Reference Groups for both plants. Group A was assigned as a Test Group to Reference Group B and the numbered regulating groups were assigned as Test Groups to Reference Group 3 for both plants.

The determination of these PCPs is shown graphically in Figures 5-1 and 5-2 for PVNGS and SONGS, respectively. The PCPs of the applicable Reference Groups for the assigned Test Groups are tabulated in Tables 5-3 and 5-4 for PVNGS and SONGS, respectively. The MCP_As for each Test Group as determined from the measurements are also tabulated in Tables 5-3 and 5-4.

The worths of the Test Groups as a function of the position of their Reference Groups are shown graphically in Figures 5-3 through 5-6 for PVNGS and in Figures 5-7 through 5-12 for SONGS. This data constitutes the predictions for the Exchange Test. Using this data, the worth of each Test Group at the adjusted Measured Critical Position (MCP_A) of its Reference Group is determined. These worths are the predicted Test Group worths that are compared to the measured worths and are tabulated in Tables 5-3 and 5-4 for PVNGS and SONGS, respectively. The comparison of the predictions to the measurements is summarized in the next section.

TABLE 5-1

PREDICTED CONTROL ROD GROUP WORTHS

GROUP INSERTED INDIVIDUALLY

PVNGS Unit 1 Cycle 1

Group	Worth %Δρ
A	2.413
B (Ref.)	2.476
5	0.260
4	0.405
3 (Ref.)	0.757
2	0.479
1	0.773

TABLE 5-2

PREDICTED CONTROL ROD GROUP WORTHS

GROUP INSERTED INDIVIDUALLY

SONGS Unit 2 Cycle 2

Group	Worth $\%\Delta\rho$
A	1.287
B (Ref.)	2.282
6	0.301
5	0.254
4	0.537
3 (Ref.)	0.670
2	0.493
1	0.479

TABLE 5-3

PREDICTED CRITICAL POSITIONS (PCP)

AND TEST GROUP WORTHS

PVNGS Unit 1 Cycle 1

Test Group	Ref Group	PCP Inches Withdrawn	Pred Worth at PCP (%Δρ)	MCP_A Inches Withdrawn	Pred Worth at MCP_A (%Δρ)
A	B	132.0	2.430	105.5	2.450
5	3	48.0	0.215	49.7	0.213
4	3	72.0	0.444	74.3	0.438
2	3	85.5	0.540	90.3	0.530
1	3	Note [1]	0.773	N/A	0.773

[1] Group 1 was worth more than the Reference Group 3. With Group 3 fully withdrawn and Group 1 fully inserted, the small difference in reactivity worth was measured with the reactivity calculator.

TABLE 5-4

PREDICTED CRITICAL POSITIONS (PCP)

AND TEST GROUP WORTHS

SONGS Unit 2 Cycle 2

Test Group	Ref Group	PCP Inches Withdrawn	Pred Worth at PCP (%Δρ)	MCP_A Inches Withdrawn	Pred Worth at MCP_A (%Δρ)
A	B	52.0	1.300	48.7	1.301
6	3	87.0	0.340	87.0	0.340
5	3	72.0	0.251	74.0	0.250
4	3	127.5	0.575	122.5	0.575
2	3	97.5	0.405	99.5	0.405
1	3	117.0	0.515	112.8	0.518

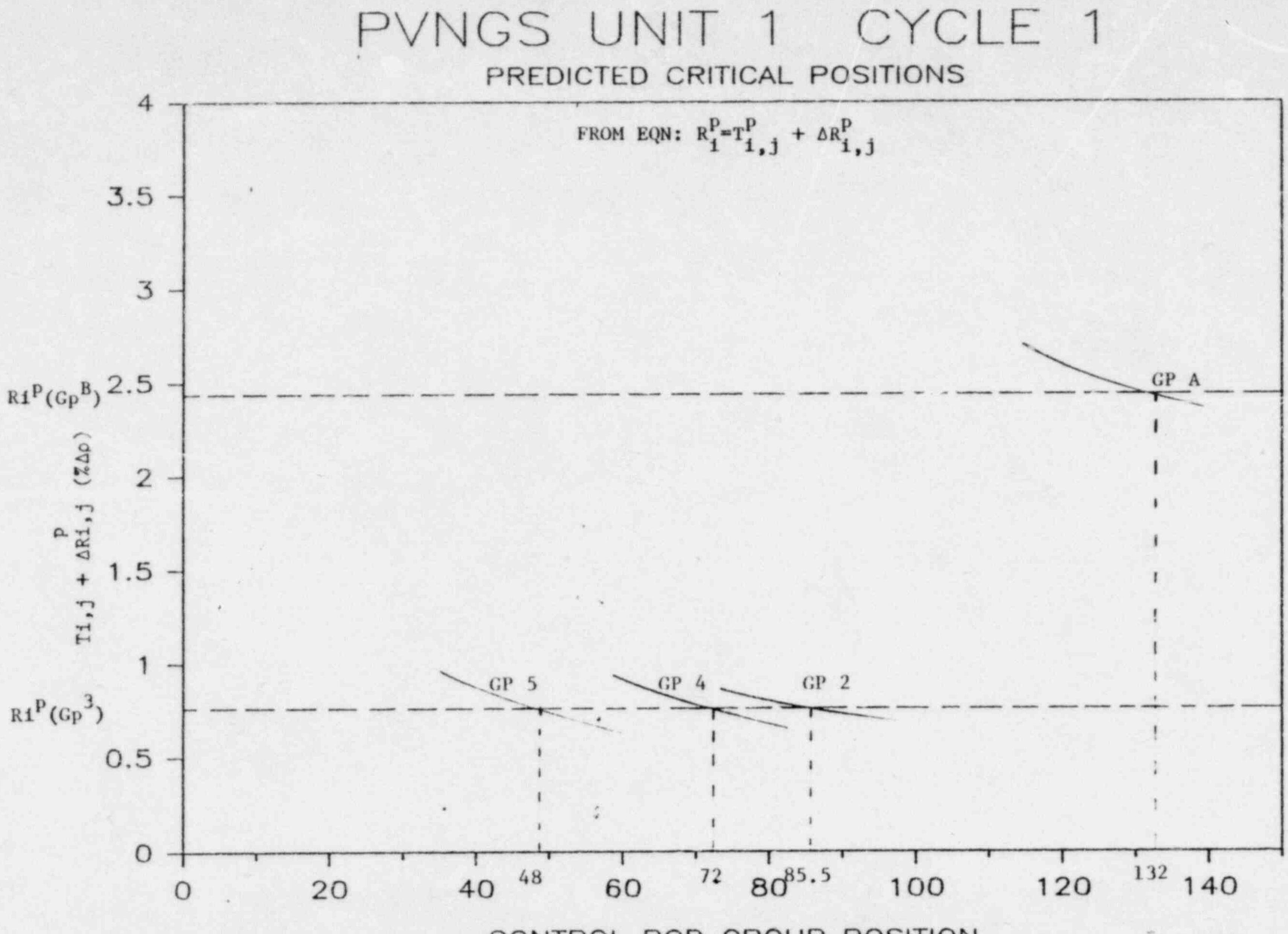
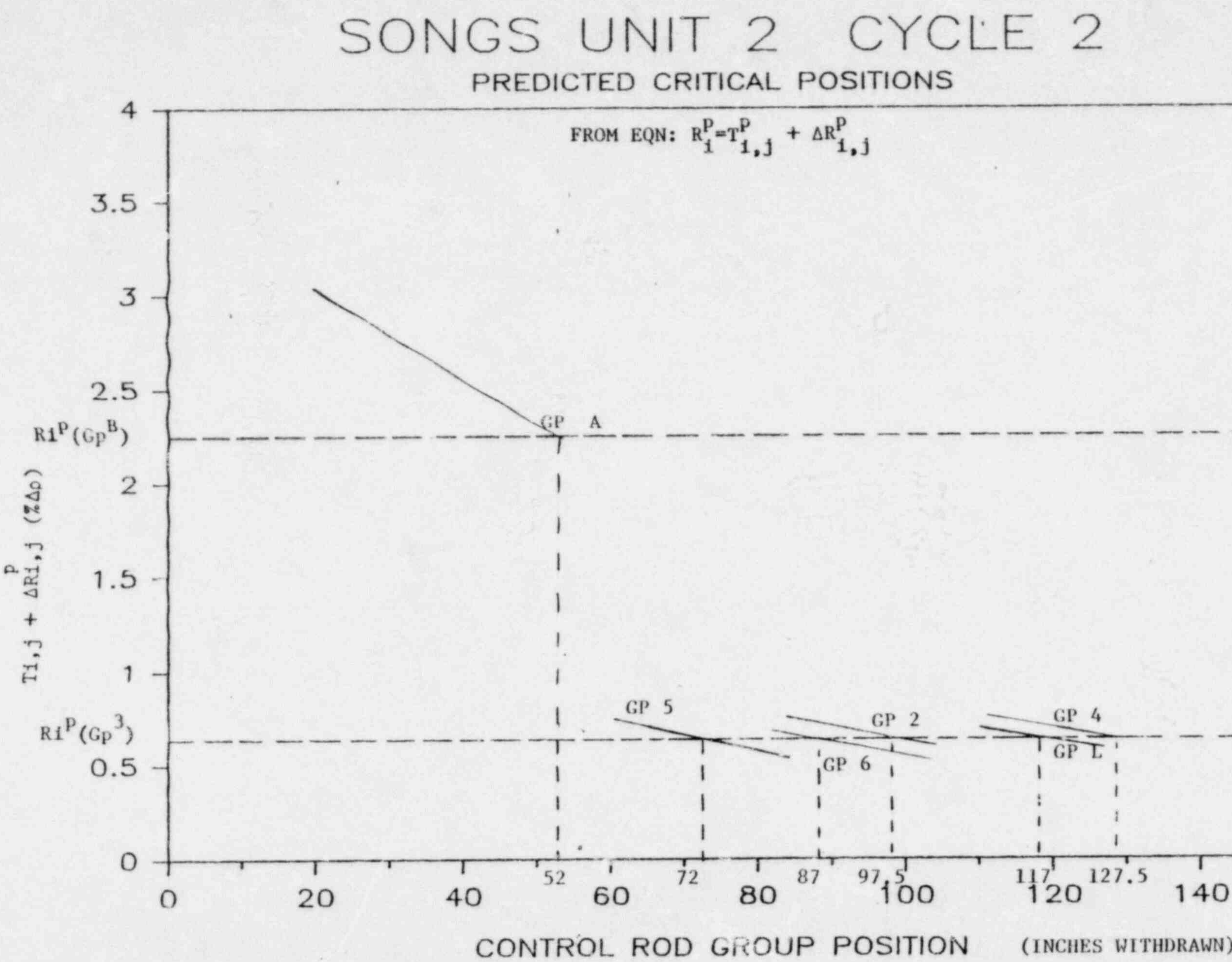

PVNGS UNIT 1 CYCLE 1
PREDICTED CRITICAL POSITIONS
FROM EQN: $R_i^P = T_{i,j}^P + \Delta R_{i,j}^P$
$Ti,j + \Delta Ri,j^P$ (%Δρ)
$Ri^P(Gp^B)$
$Ri^P(Gp^3)$
GP A
GP 5
GP 4
GP 2
0
0.5
1
1.5
2
2.5
3
3.5
4
0
20
40
48
60
72
80
85.5
100
120
132
140
CONTROL ROD GROUP POSITION (INCHES WITHDRAWN)

FIGURE 5-1



SONGS UNIT 2 CYCLE 2
PREDICTED CRITICAL POSITIONS
FROM EQN: $R_i^P = T_{i,j}^P + \Delta R_{i,j}^P$
$Ri^P(Gp^B)$
$Ri^P(Gp^3)$
$T_{i,j} + \Delta R_{i,j}^P$ (%Δρ)
GP A
GP 5
GP 2
GP 6
GP 4
GP L
52
72
87
97.5
117
127.5
CONTROL ROD GROUP POSITION (INCHES WITHDRAWN)

FIGURE 5-2

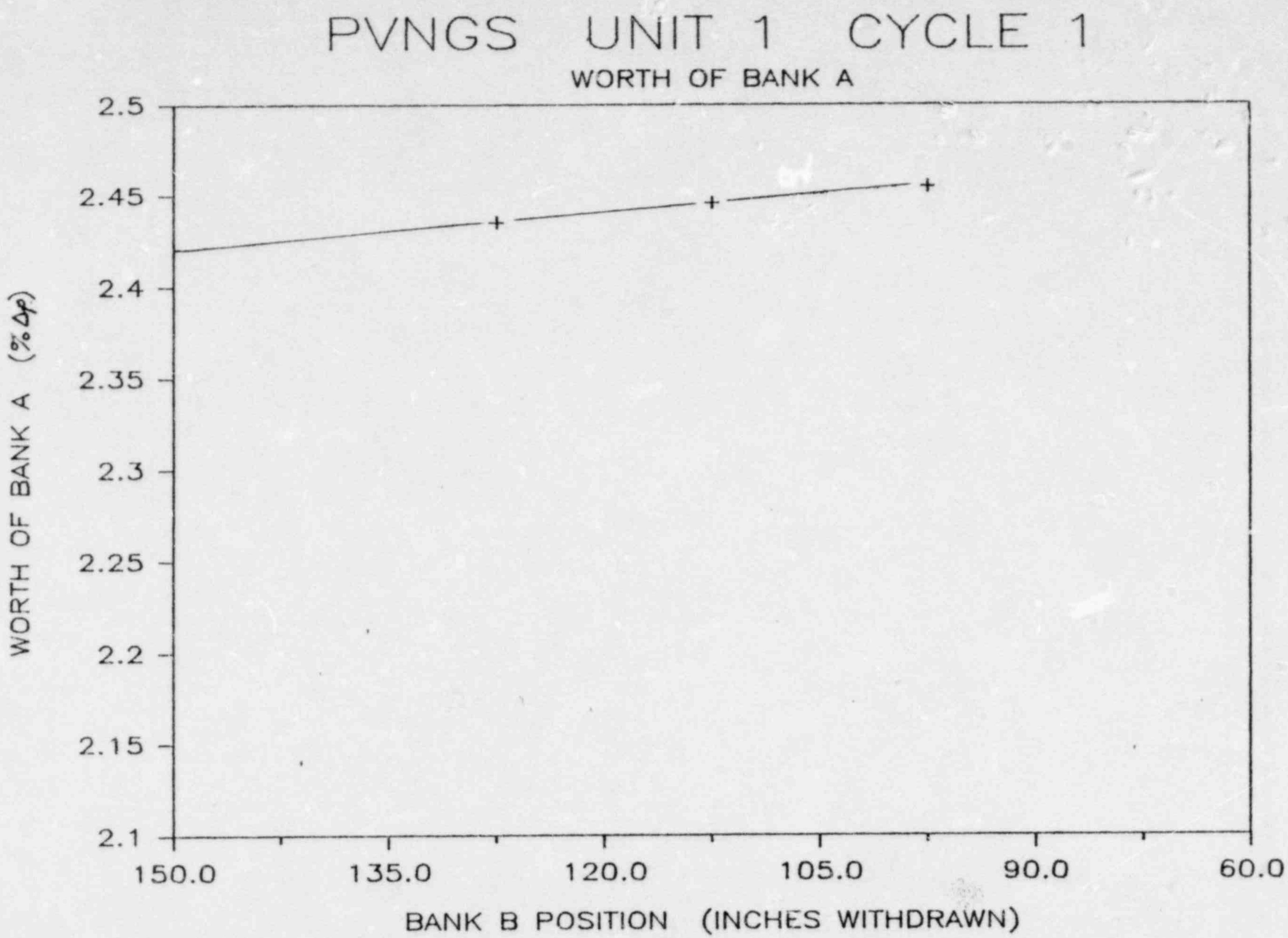

PVNGS UNIT 1 CYCLE 1
WORTH OF BANK A
WORTH OF BANK A (%Δρ)
2.5
2.45
2.4
2.35
2.3
2.25
2.2
2.15
2.1
150.0
135.0
120.0
105.0
90.0
60.0
BANK B POSITION (INCHES WITHDRAWN)

FIGURE 5-3

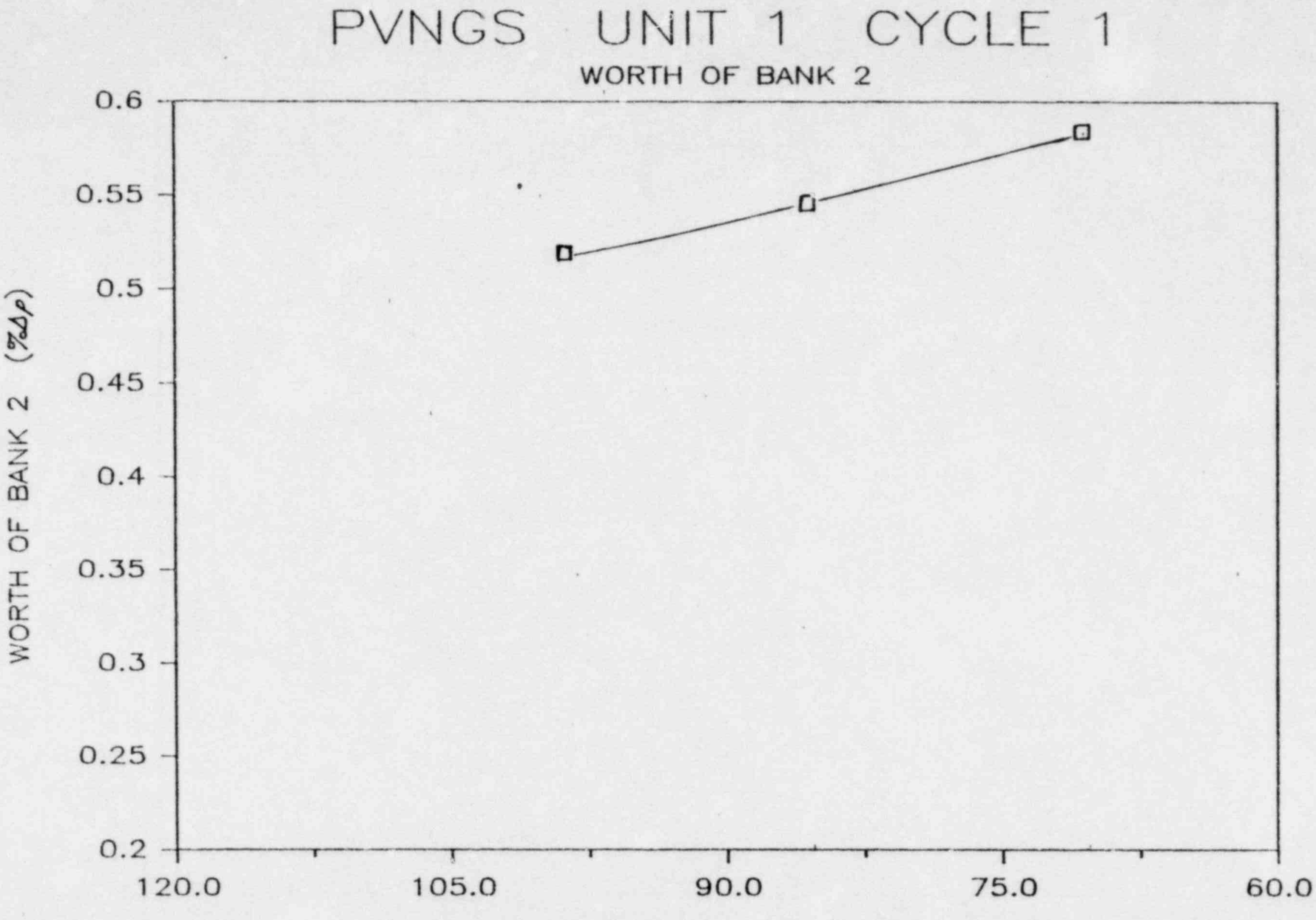

PVNGS UNIT 1 CYCLE 1
WORTH OF BANK 2
WORTH OF BANK 2 (%Δρ)
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
120.0
105.0
90.0
75.0
60.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-4

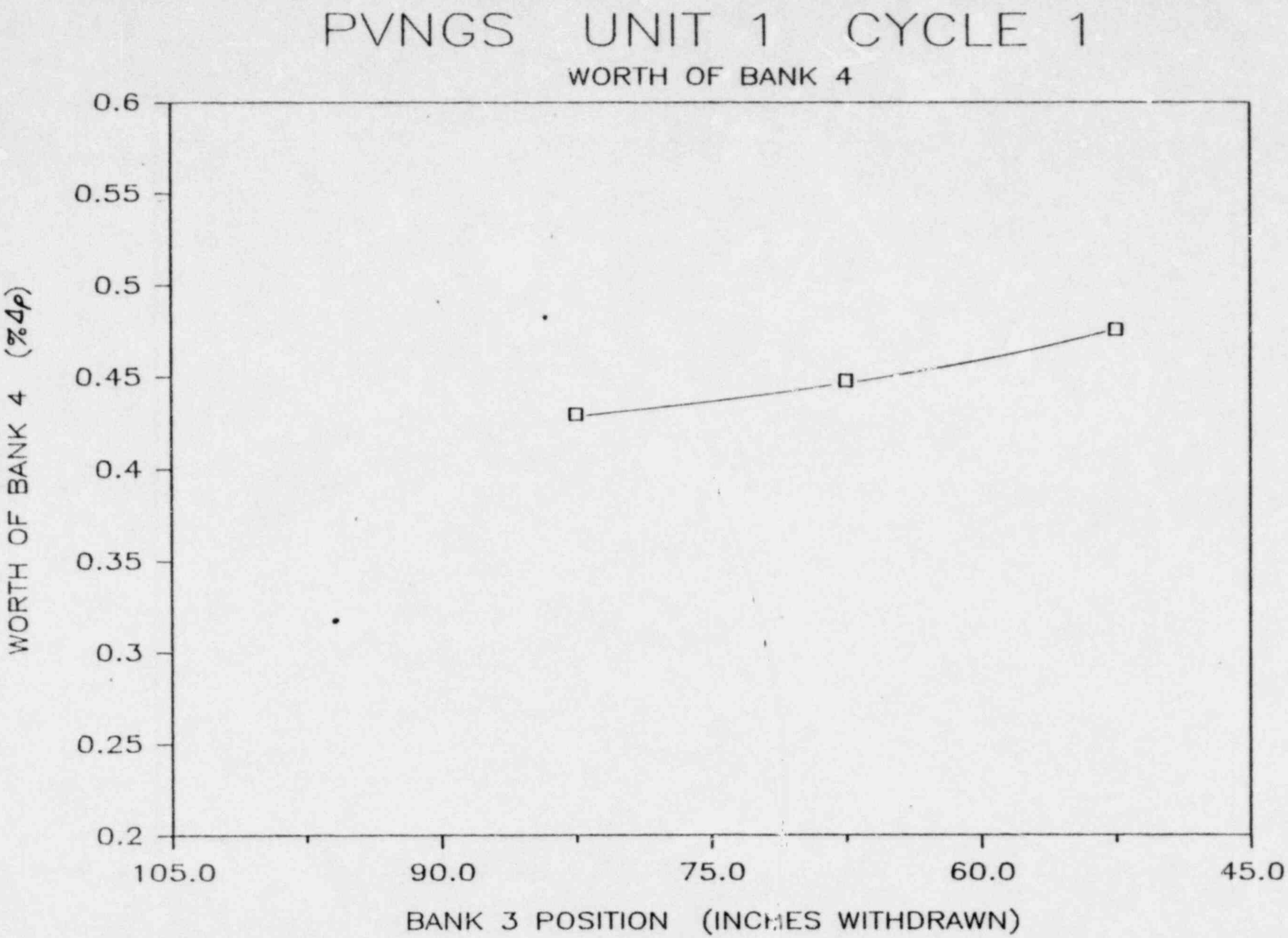

PVNGS UNIT 1 CYCLE 1
WORTH OF BANK 4
WORTH OF BANK 4 (%Δρ)
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
105.0
90.0
75.0
60.0
45.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-5

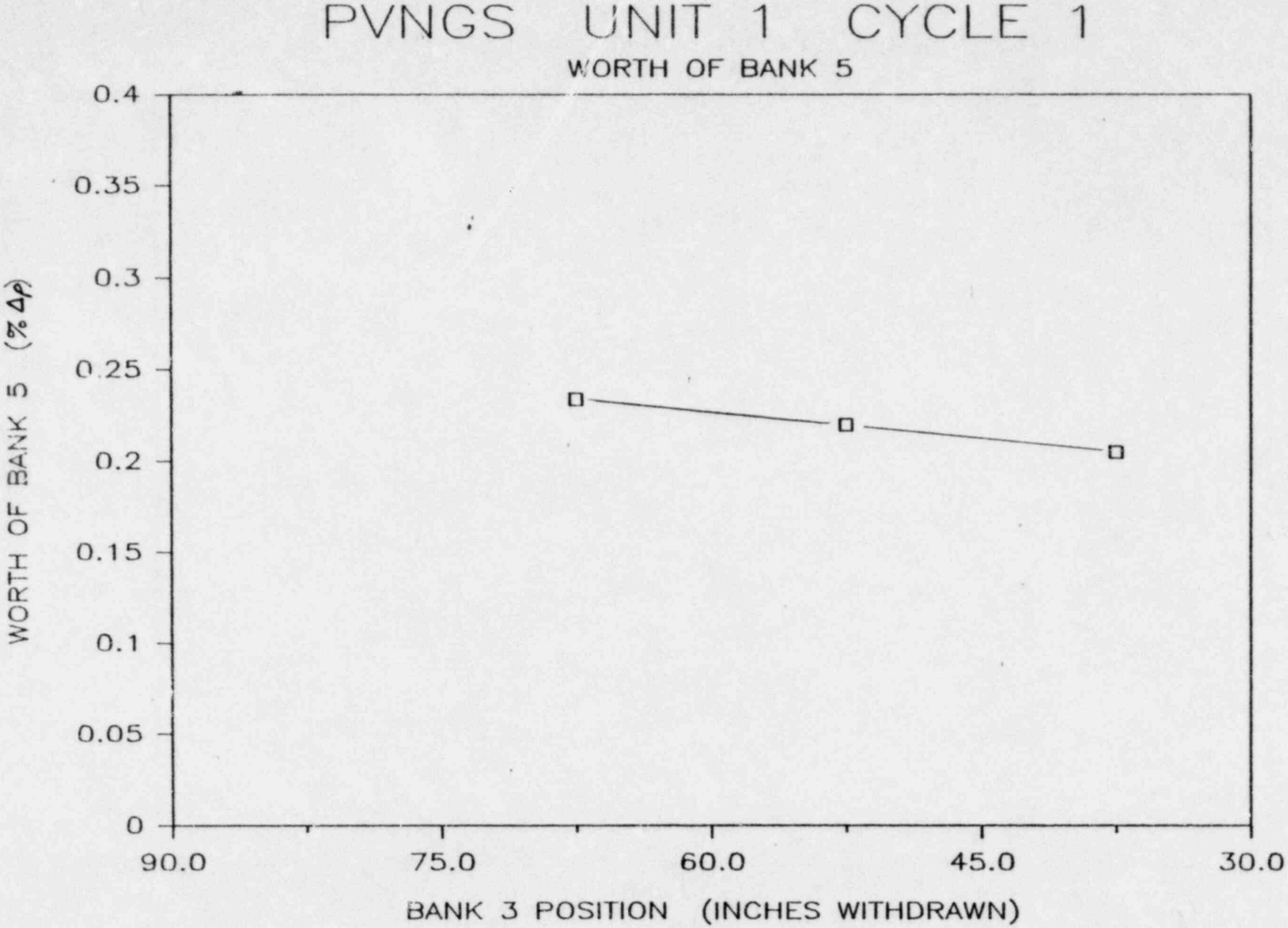

PVNGS UNIT 1 CYCLE 1
WORTH OF BANK 5
WORTH OF BANK 5 (% Δρ)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
90.0
75.0
60.0
45.0
30.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-6

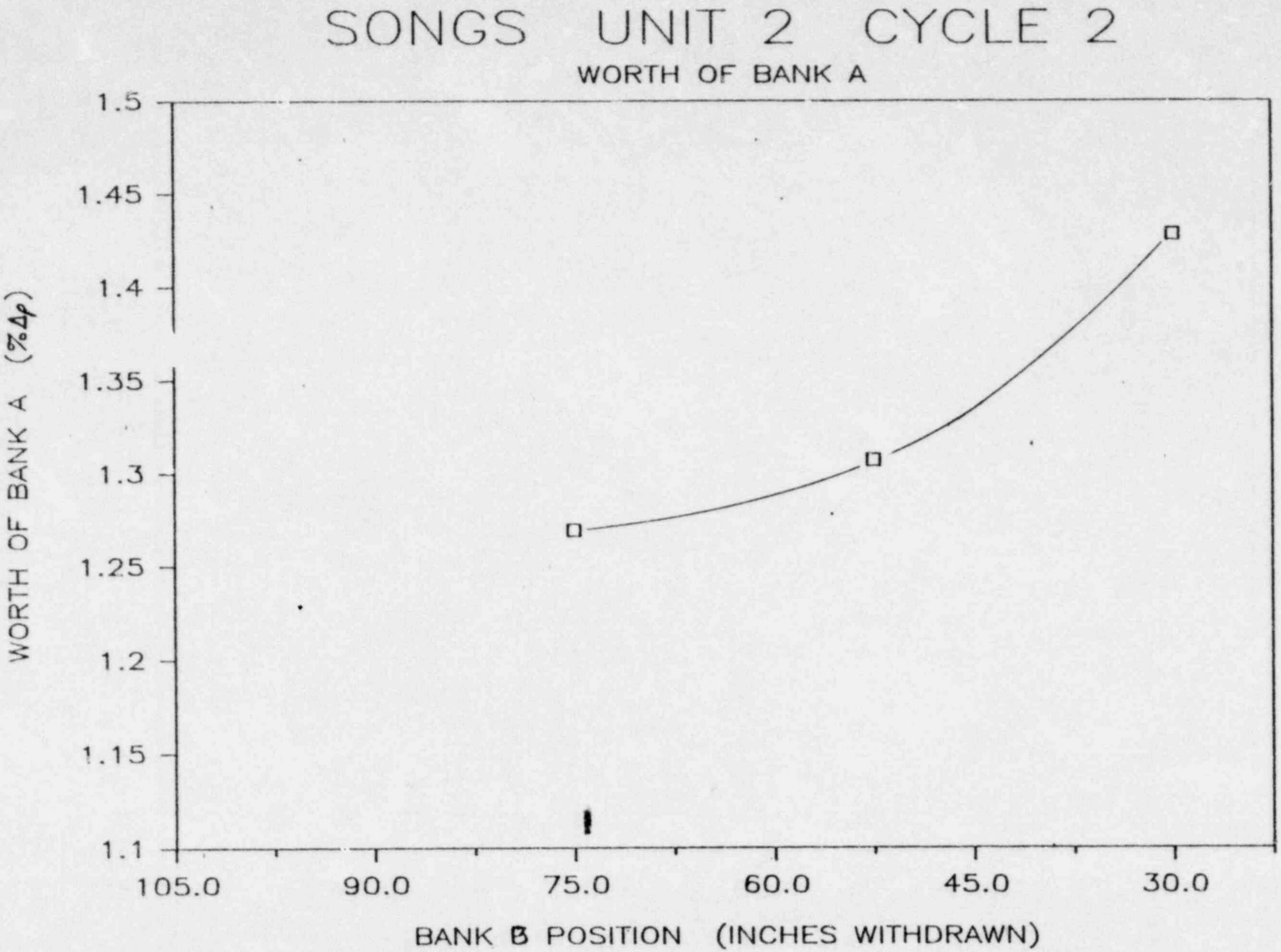
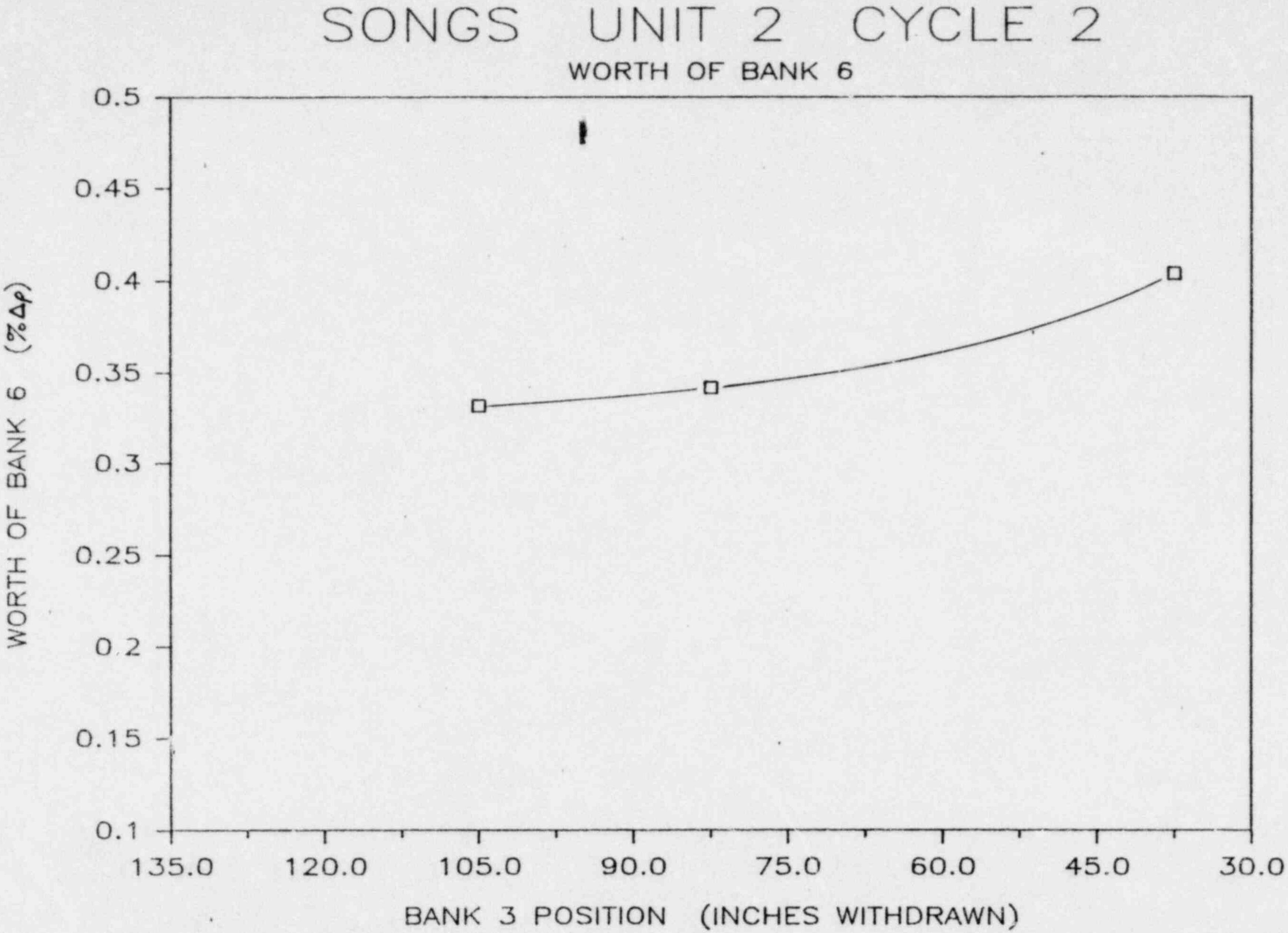

SONGS UNIT 2 CYCLE 2
WORTH OF BANK A
WORTH OF BANK A (%Δρ)
1.5
1.45
1.4
1.35
1.3
1.25
1.2
1.15
1.1
105.0
90.0
75.0
60.0
45.0
30.0
BANK B POSITION (INCHES WITHDRAWN)

FIGURE 5-7



SONGS UNIT 2 CYCLE 2
WORTH OF BANK 6
WORTH OF BANK 6 (%Δρ)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
135.0
120.0
105.0
90.0
75.0
60.0
45.0
30.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-8

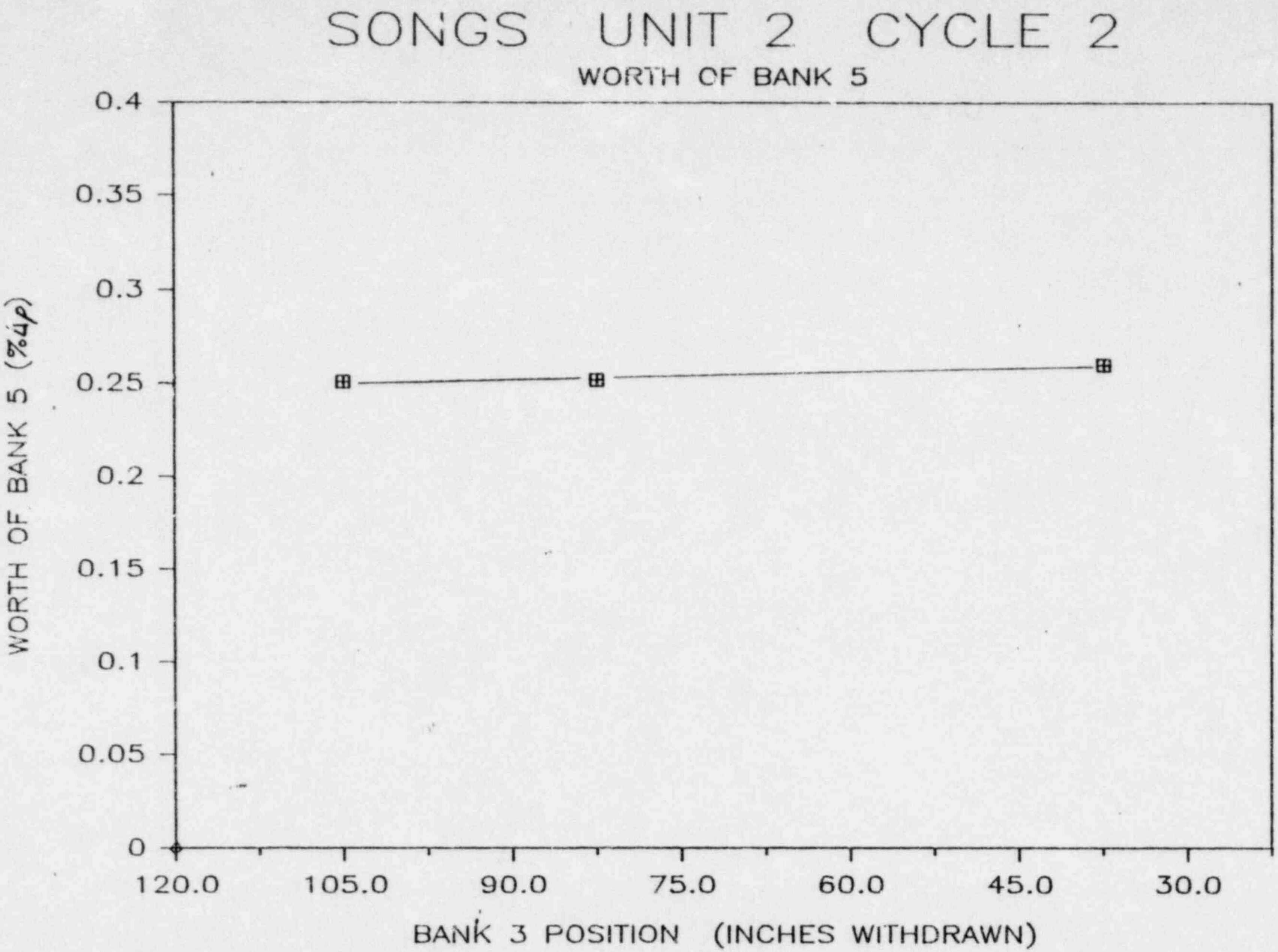

SONGS UNIT 2 CYCLE 2
WORTH OF BANK 5
WORTH OF BANK 5 (%Δρ)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
120.0
105.0
90.0
75.0
60.0
45.0
30.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-9

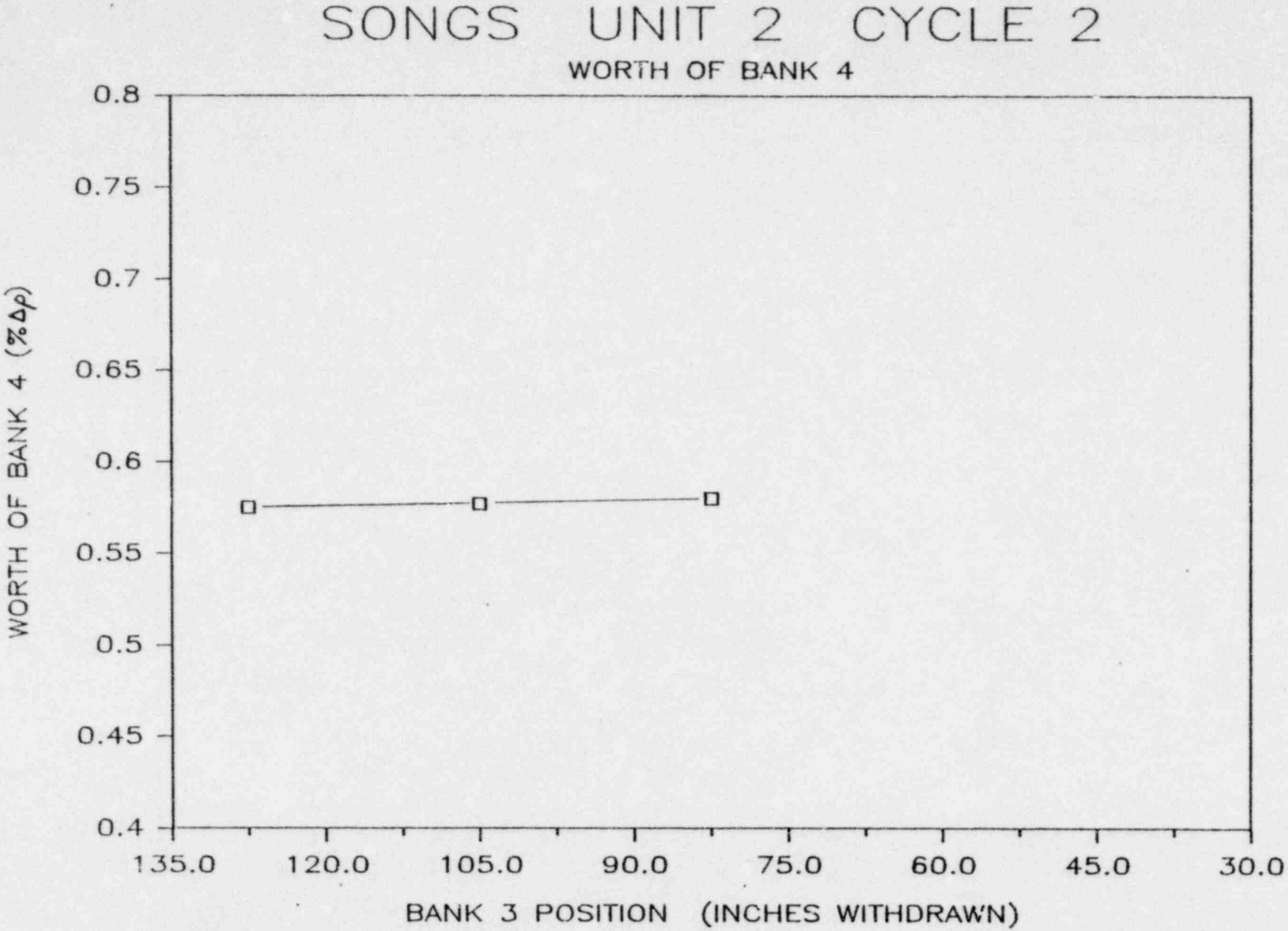

SONGS UNIT 2 CYCLE 2
WORTH OF BANK 4
WORTH OF BANK 4 (%Δρ)
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
135.0
120.0
105.0
90.0
75.0
60.0
45.0
30.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-10

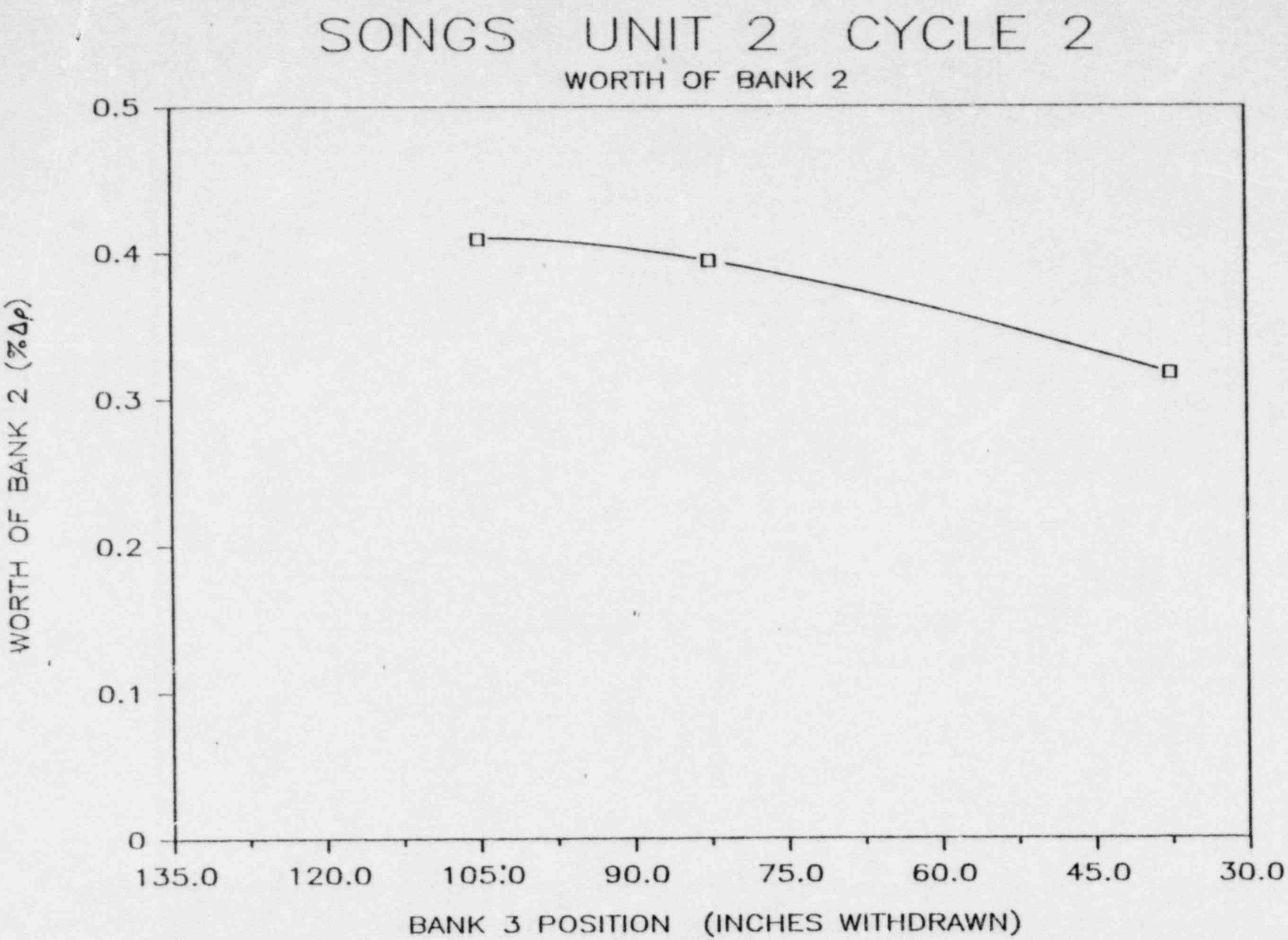
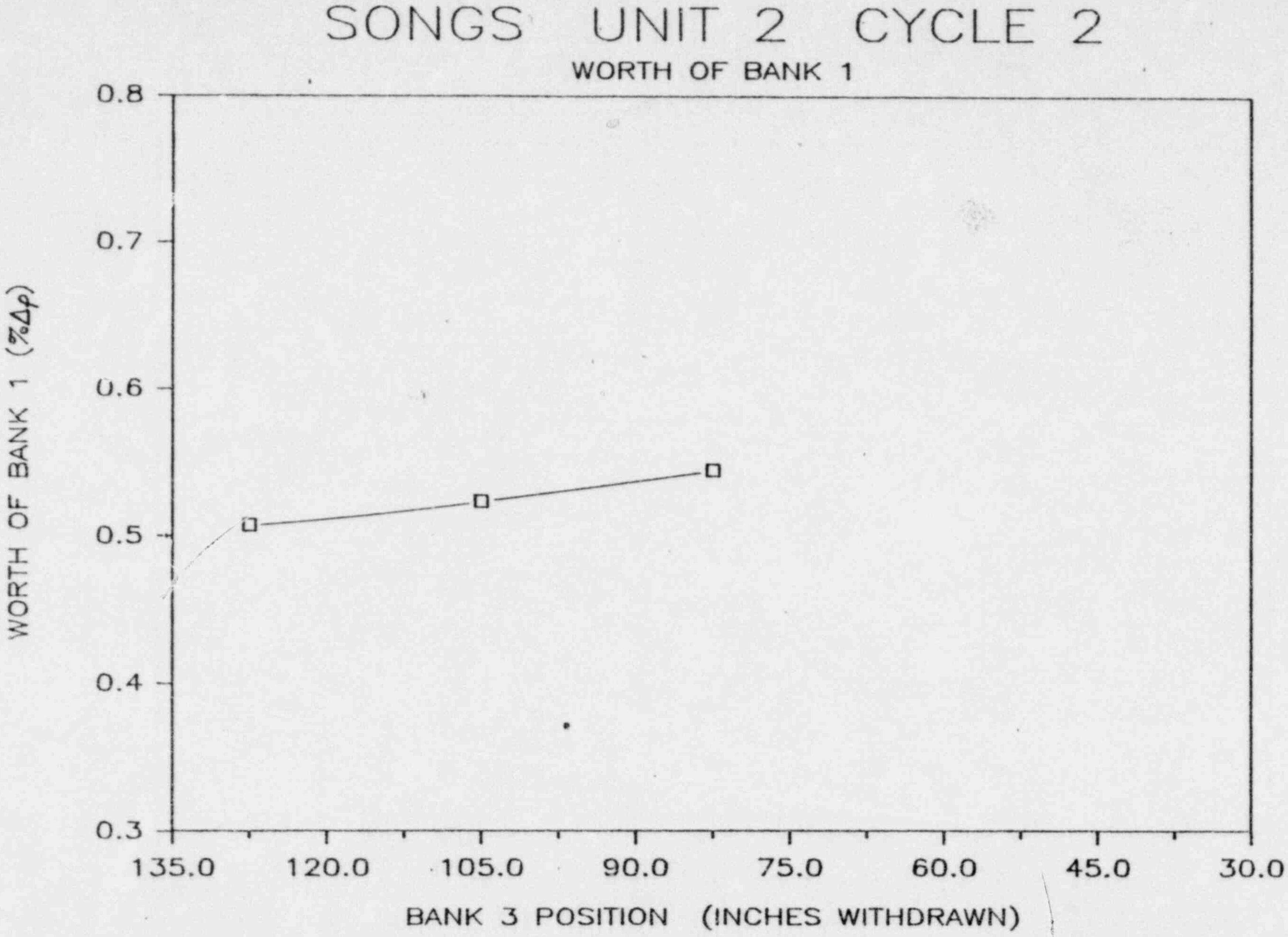

SONGS UNIT 2 CYCLE 2
WORTH OF BANK 2
WORTH OF BANK 2 (%Δρ)
0.5
0.4
0.3
0.2
0.1
0
135.0
120.0
105.0
90.0
75.0
60.0
45.0
30.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-11



SONGS UNIT 2 CYCLE 2
WORTH OF BANK 1
WORTH OF BANK 1 (%Δρ)
0.8
0.7
0.6
0.5
0.4
0.3
135.0
120.0
105.0
90.0
75.0
60.0
45.0
30.0
BANK 3 POSITION (INCHES WITHDRAWN)

FIGURE 5-12

6.0 TEST RESULTS EVALUATION

The acceptability of the results from the control rod group worth measurements demonstrates that this aspect of the reactor response is in accordance with the design. In addition, the results provide additional confirmation that the design methodology is adequate to insure sufficient shutdown capability is available. Acceptability of the test results is evaluated by comparing measurements to predictions against established criteria. This comparison has normally been based on the percentage difference between prediction and measurement as expressed below:

$$\Delta\% = \frac{\rho_{PRED} - \rho_{MEAS}}{\rho_{MEAS}} \times 100$$

The established criterion for individual control rod groups is:

$$|\Delta\%| \leq 15\%$$

A secondary criterion is based on an absolute difference between prediction and measurement:

$$|\rho_{PRED} - \rho_{MEAS}| \leq 0.1\% \; \Delta\rho$$

The greater of the two criteria is applied to the individual group worths.

An additional criterion is applied to the sum of the worths of the control rod groups measured in order to evaluate net shutdown worth:

$$\Delta\%_{SUM} = \left| \frac{\sum_{GPS} \rho_{PRED} - \sum_{GPS} \rho_{MEAS}}{\sum_{GPS} \rho_{MEAS}} \times 100 \right| \leq 10\%$$

The acceptance criteria discussed above have traditionally been applied in the evaluation of control rod group worths using the boration/dilution test methodology. The predictions for the evaluation of these results are developed using approved design methodology. The calculative approach employed in the Control Rod Group Exchange technique also uses the same design methodology in essentially a direct simulation of the exchange endpoints. As a consequence, the same criteria are used in the evaluation of the test results. However, since the worths of the Reference Group or Groups, as applicable, are used as the basis for determining the worth of remaining groups, a tighter criterion is applied:

$$\left| \Delta\%_{\text{Reference}} \right| \leq 10\%$$

For the Exchange Technique, the sum of the individual group worths measured are compared against the sum of the predicted worths. The acceptability of these results demonstrates the adequacy of the net shutdown worth for this core configuration.

The overall evaluation of the test results is performed in a manner comparable to that used with the results of the boration/dilution method. Failure to meet an acceptance criterion is addressed first by a re-evaluation of the test data. This is typically performed concurrently with a review of the prediction to insure that the conditions at which the test is performed are consistent to those at which the prediction was made. If still unresolved, the significance of the difference is evaluated. Based on this evaluation and the possible impact on plant safety, additional testing may be performed. The extent of this additional testing would be dependent on the nature of the missed criterion.

7.0 EVALUATION/VALIDATION OF CONTROL ROD EXCHANGE TECHNIQUE

The results from the Control Rod Exchange tests performed on PVNGS Unit 1 Cycle 1 and SONGS Unit 2 Cycle 2 are summarized in Tables 7-1 and 7-2, respectively. Also summarized are the results from the side-by-side group worth measurements made on the two plants using the boration/dilution technique. The acceptance criteria applied to the test results are listed in the tables.

Comparisons of the measured and predicted incremental and integral worths of the Reference Groups are shown graphically in Figures 7-1 and 7-2 for PVNGS and Figures 7-3 and 7-4 for SONGS. The overall agreement is considered very good.

For both techniques, all acceptance criteria were met with the exception of SONGS Group A in the Exchange test. The criterion of ≤15% was exceeded by about 4%. An evaluation of the measurements and the predictions for Group A indicated the following:

1) During the exchange of Group A and Group B, the plant computer was not accurately counting the movement pulses of four of the Group B control rods during the first twenty inches of Group B movement. In addition, the plant computer was not available for a short period of time during the exchange. This required that the rod positions be reloaded into the computer. The rod positions at the time of the loss of the computer were determined from the reed switch position indicators for each rod. When the exchange was completed, the reed switch indicators showed the Group B average position to be about 2 inches more withdrawn than indicated by the Plant Computer. If Group B was actually 2 inches more withdrawn, the measured Group A worth would have increased to 1.15% $\Delta\rho$.

2) The calculative model used for the predictions did not precisely model the actual configuration of Group A in the SONGS unit. Four Group A rods on the core periphery straddle two fuel assemblies each when they are inserted. This restricts their full insertion to about 10 inches withdrawn. The model assumed full insertion. In addition, near the center of the core, Group A has control rods only in two quadrants, i.e., the pattern is not quadrant symmetric in this region. These control rods are modelled in the design analysis to allow the designer to assume a quadrant symmetric pattern. These two modelling assumptions lead to negligible reactivity effects when Group A is inserted in the normal manner, i.e., in its shutdown role. The effect is also negligible in the measurement of Group A's worth using the boration/dilution method. However, in the exchange between Group A and Group B, the endpoint configuration with Group A fully inserted and Group B at about 50 inches withdrawn causes the neutron flux to be highly peaked below Group B. This causes the four Group A rods that are not fully inserted to be worth slightly less than if fully inserted. Both these effects would reduce the predicted value to about 1.28% $\Delta\rho$.

With both these items considered, the difference between the predicted and measured worth of Group A would be approximately 11%; within the acceptance criteron. In addition, the agreement between the measured and predicted worth of Group A using the boration/dilution indicates that Group A's shutdown worth is in accordance with the design.

For the PVNGS test, the agreement between measurement and prediction for each group and the summed worths using the Exchange Technique is very consistent with that obtained with the Boration/Dilution method. PVNGS Unit 1 is a first-of-a-kind plant and, consequently, low temperature testing was performed. At 320°F, a measurement to the N-1 configuration was performed using the boration/dilution method. At Hot Zero Power (HZP), the five regulating groups were measured using the boration/dilution method.

All groups were measured using the Exchange Technique at HZP. As shown in Table 7-1, the difference between measured and predicted summed worth from the Exchange measurements is in excellent agreement with the difference between measurement and prediction of the N-1 worth.

For the SONGS test, the differences shown in Table 7-2 between measurement and prediction of the individual group worths and the summed worth are in very good agreement with the comparable differences using the boration/dilution technique.

In summary, the Exchange Technique has been demonstrated to provide data comparable to that using the boration/dilution method to verify the adequacy of control rod worths as predicted for the core design. The demonstration testing has included an initial core and a second cycle. In addition, it has been applied to control rod designs which bracket those used by C-E in its NSSS designs (except the Palisades NSSS). It is concluded that the Exchange Technique may be generally applied for any cycle in all C-E NSSS designs as an alternate to the boration/dilution method. A discussion of the applicability of the Exchange Technique to the various classes of C-E plants is provided in Appendix A.

TABLE 7.1

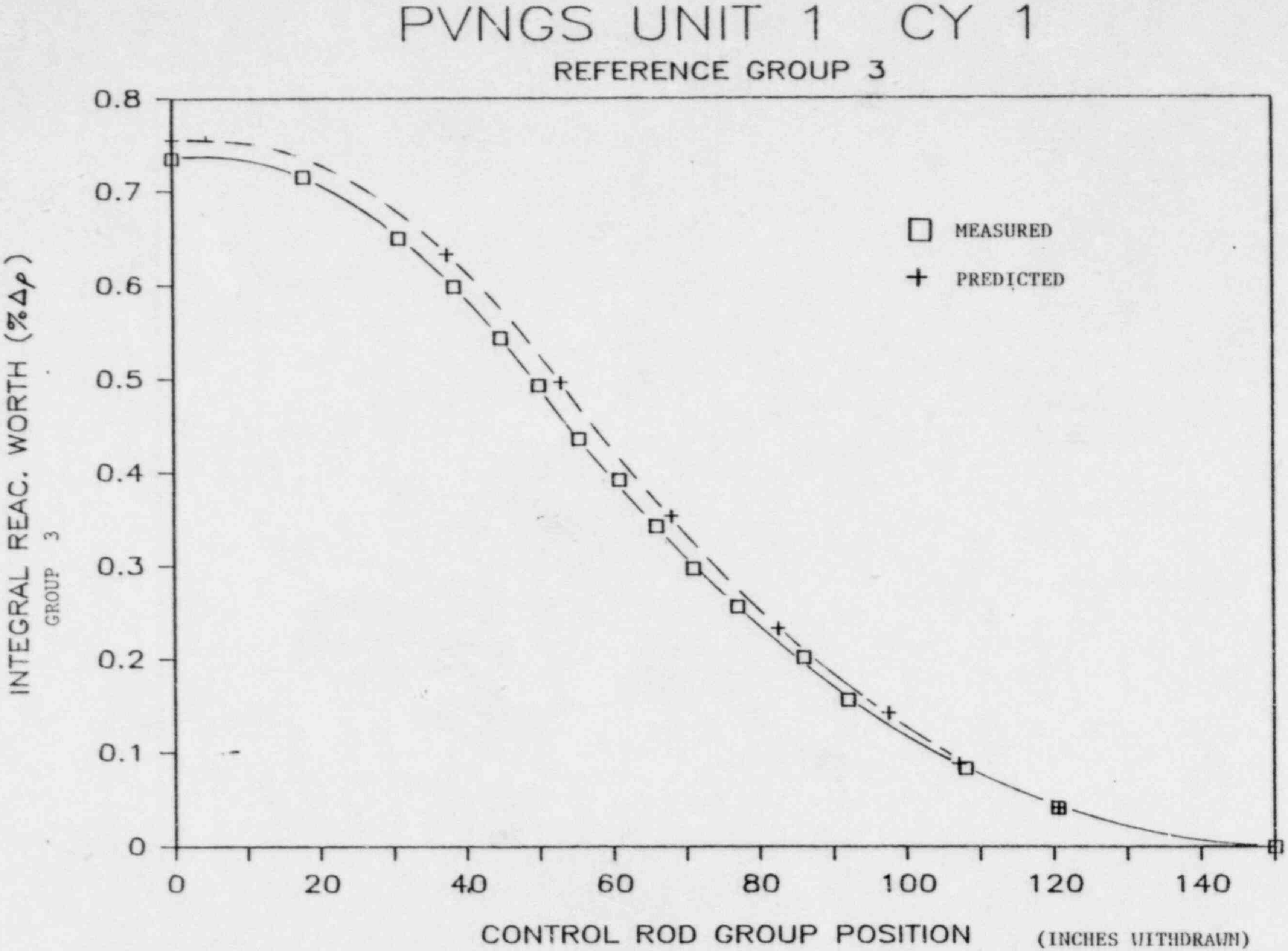
PVNGS Unit 1 Cycle 1

CEA Exchange Control Rod Group	Group Worth (%Δρ) Measured	Predicted	%Δρ (P-M)	% Difference $\frac{(P-M)}{M} \times 100$	Acc. Crit.
B (Ref.)	2.745	2.476	-0.269	-9.80	±10%
A	2.532	2.450	-0.082	-3.24	±15%
5	0.238	0.213	-0.025	-10.50	±15%
4	0.463	0.438	-0.025	-5.40	±15%
3 (Ref.)	0.733	0.757	+0.024	+3.27	±10%
2	0.568	0.530	-0.038	-6.69	±15%
1	0.752	0.773	+0.021	+2.79	±15%
SUM	8.031	7.637	-0.394	-4.91	±10%
Boration/Dilution					
At 320°F B	3.615	3.353	-0.262	-7.25	±15%
5	0.101	0.093	-0.008	-7.92	±15%
4	0.241	0.223	-0.018	-7.47	±15%
3	0.722	0.795	+0.073	+10.11	±15%
2	0.750	0.730	-0.020	-2.67	±15%
1	1.418	1.518	+0.100	+7.05	±15%
N-1	7.397	7.083	-0.314	-4.24	±10%
At 565°F (Hot Zero Power) 5	0.277	0.260	-0.017	-6.14	±15%
4	0.445	0.421	-0.024	-5.39	±15%
3	0.790	0.848	+0.058	+7.34	±15%
2	1.037	0.994	-0.043	-4.15	±15%
1	1.231	1.276	+0.045	+3.66	±15%
SUM	3.790	3.799	+0.009	+0.24	+10%

TABLE 7.2

SONGS Unit 2 Cycle 2

CEA Exchange Control Rod Group	Group Worth (%Δρ) Measured	Predicted	%Δρ (P-M)	% Difference $\frac{(P-M)}{M} \times 100$	Acc. Crit. ±%
B (Ref.)	2.223	2.282	+0.059	+2.65	±10%
A	1.087	1.301	+0.214	+19.69	±15%
6	0.360	0.340	-0.020	-5.56	±15%
5	0.268	0.250	-0.018	-6.72	±15%
4	0.590	0.575	-0.015	-2.54	±15%
3 (Ref.)	0.695	0.670	-0.025	-3.60	±10%
2	0.435	0.405	-0.030	-6.90	±15%
1	0.526	0.518	-0.007	-1.33	±15%
SUM	6.183	6.341	+0.158	+2.56	+10%
Boration/Dilution					
A	1.359	1.402	+0.043	+3.16	±15%
6	0.315	0.320	+0.005	+1.58	±15%
5	0.275	0.280	+0.005	+1.82	±15%
4	0.542	0.540	-0.002	-0.37	±15%
3	0.950	1.000	+0.050	+5.26	±15%
2	0.450	0.420	-0.030	-6.67	±15%
1	0.819	0.880	+0.061	+7.45	±15%
SUM	4.710	4.842	+0.132	+2.80	+10%



PVNGS UNIT 1 CY 1
REFERENCE GROUP 3
INTEGRAL REAC. WORTH (%Δρ)
GROUP 3
CONTROL ROD GROUP POSITION (INCHES WITHDRAWN)
MEASURED
PREDICTED
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140

FIGURE 7-1

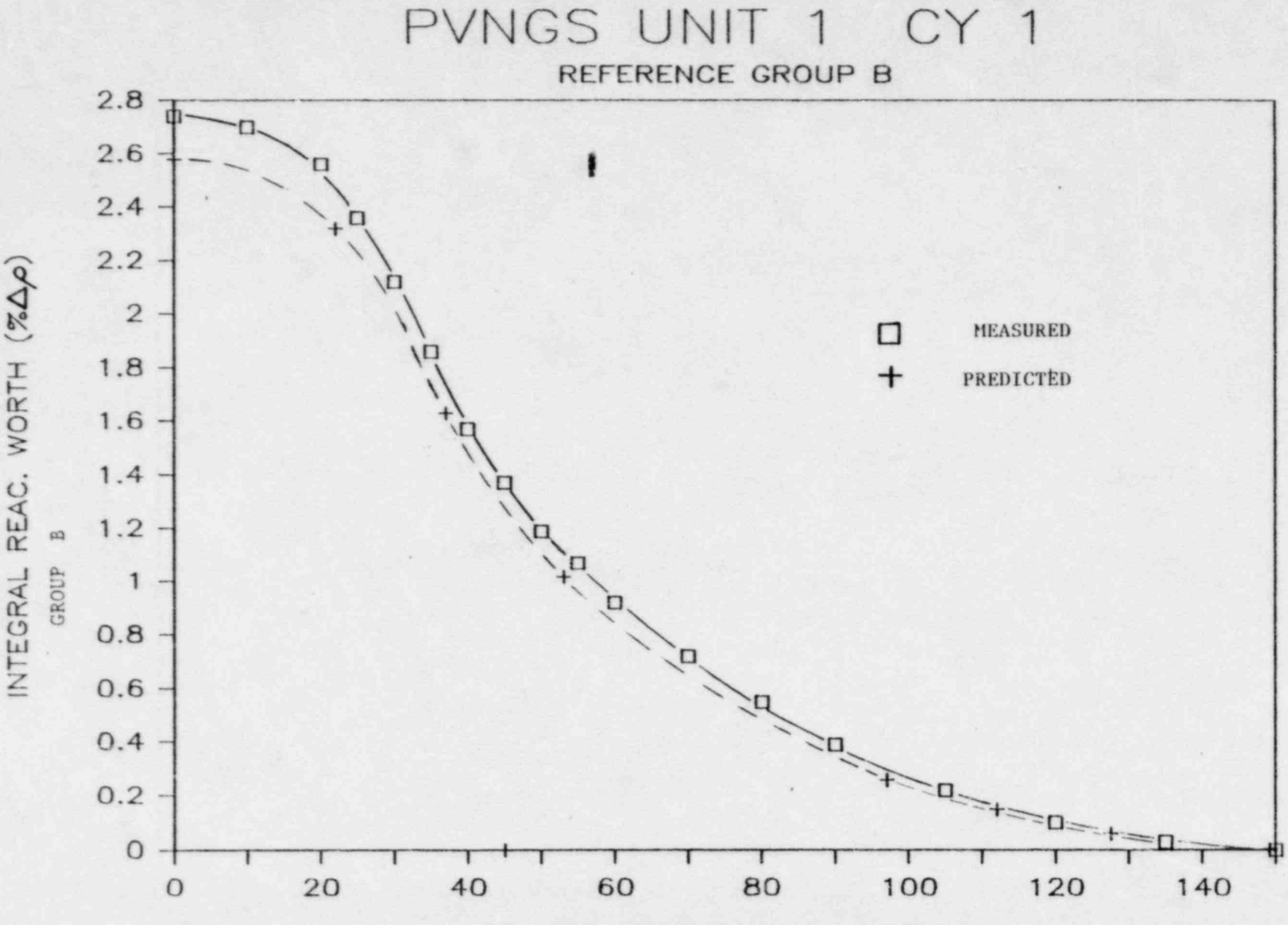

PVNGS UNIT 1 CY 1
REFERENCE GROUP B
INTEGRAL REAC. WORTH (%Δρ)
GROUP B
MEASURED
PREDICTED
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
100
120
140
CONTROL ROD GROUP POSITION
(INCHES WITHDRAWN)

FIGURE 7-2

SONGS UNIT 2 CY 2

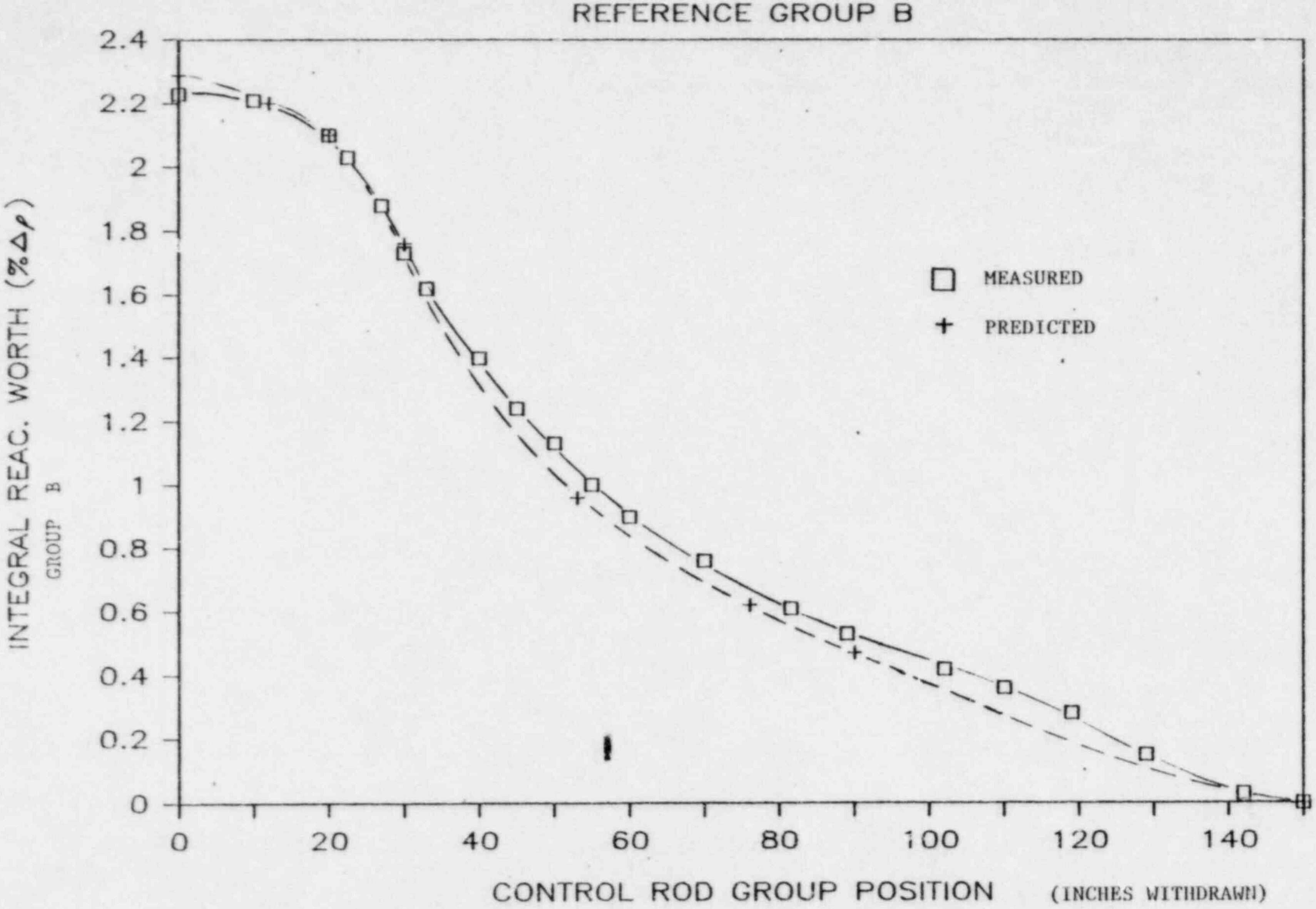


FIGURE 7-3

SONGS UNIT 2 CY 2

REFERENCE GROUP 3

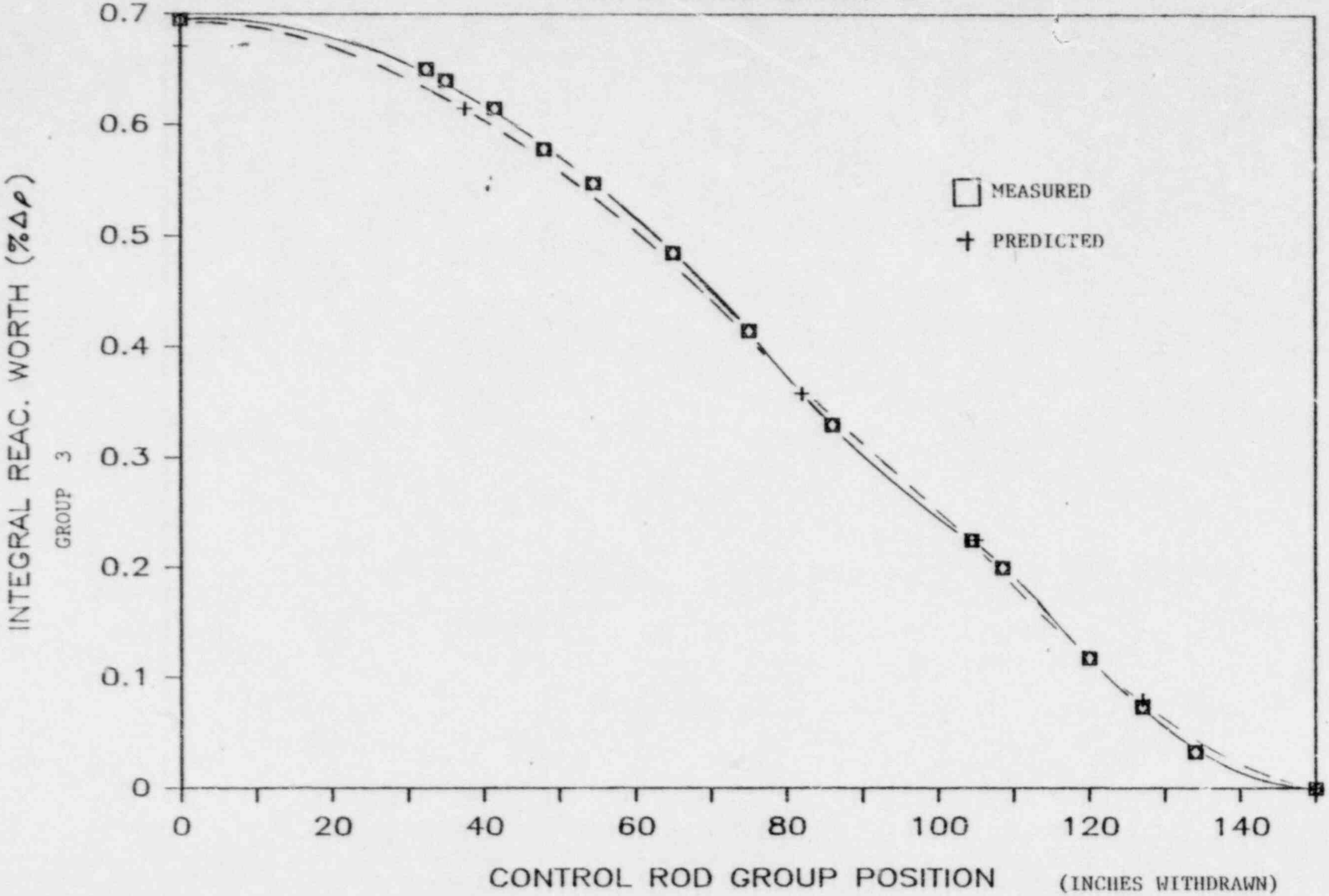


FIGURE 7-4

APPENDIX A

Applicability of Control Rod Exchange Technique to Other C-E Plants

The testing performed at SONGS 2 and Palo Verde 1 directly supports the use of the Control Rod Exchange Technique for these plants and their sister units (SONGS 3, Palo Verde 2,3). The applicability of this technique to other C-E plants depends on the similarity of their nuclear core and control rod designs. Differences in non-nuclear areas need not be considered.

When comparing nuclear designs, it is important to remember that neutrons have a relatively large mean free path in most materials (except, of course, in control rods). Design details on the scale of fractions of an inch will usually not have a first order effect on the neutronic behavior. Rather, neutrons tend to respond to the nuclear properties averaged over a few inches.

The two basic C-E fuel assembly designs (14 x 14 and 16 x 16 fuel rods) are very similar from a nuclear perspective. Parameters of importance such as $k\infty$, M^2, and few group macroscopic cross-sections are virtually indistinguishable between these lattice designs. In fact, the variation in these parameters among assemblies in any single reload core is much larger than between a 14 x 14 and a 16 x 16 assembly with the same fuel enrichment. Thus, the local fuel environment around the control rods is essentially the same in all C-E plants as in the tests performed at SONGS 2 and Palo Verde 1.

Associated with each lattice design is a control rod finger design. Both the PVNGS and the SONGS control rod designs use B_4C as the control material. Both designs insert into large waterholes with up to five control rod fingers per assembly. The 16 x 16 control rod design is about 14% smaller, as required by the reduction in fuel pin pitch, to allow 16 pins in the same distance formerly occupied by 14. Although this minor difference in size is explicitly considered in the generation of control rod cross-sections, it is not an important difference in the determination of nuclear similarity for applicability of the control rod Exchange Technique. That this variation in control rod size is a design detail rather than a fundamental concept is more obvious after examination of the C-E methods used to model core neutronic behavior.

The following is condensed from CENPD-266-P-A, The ROCS and DIT Computer Codes for Nuclear Design:

> Fine-group cross-sections used in design applications at C-E come from ENDF-IV with a single set of proprietary adjustments. Broad-group cross-sections are calculated with the DIT assembly transport code for both fine mesh (PDQ, MC) and coarse-mesh (ROCS, HERMITE) applications. Details of the fuel pin, burnable poison, and water-hole designs are maintained through the assembly calculation in DIT. Design depletions are performed without a control rod which are then inserted at multiple burnup points. Changes in assembly averaged cross-sections, due to the control rod, are then calculated for use in the ROCS code. ROCS solves the three dimensional, two-group diffusion equation via a higher-order Taylor series approximation to the neutron flux. In design applications, each assembly is represented by four equal nodes in the x-y plane.

Axially 20 to 24 planes are used. All control rod exchange predictions done by C-E follow this procedure. The only adjustment performed to the raw ROCS calculated control rod exchange prediction is the application of the same bias as for boron dilution measurements. That bias is documented in CENPD-266-P-A.

Having examined the similarity of the assembly designs, control rod designs, and calculative methods among C-E plants, these are not significant differences with respect to the applicability of the control rod exchange technique. This leaves core geometry, fuel management, and control rod patterns to be considered.

The smallest commercial C-E reactor is Fort Calhoun (133 assemblies, 128 inch active height) and the largest is Palo Verde (241 assemblies, 150 inch active height). Both of these are sufficiently large such that leakage is a small fraction of the total neutron balance. The difference in core leakage between these plants is of the same order as between an out-in-in-fuel management and an in-in-out fuel management for the same plant.

C-E plants are currently operated with both out-in and low leakage fuel managements with cycle lengths from 12 to 18 months and batch discharge burnups ranging up to the low 40 thousands MWd/T. Maximum Beginning of Cycle (BOC) fuel burnups tend to range up to the high 20 thousands MWd/T (exclusive of some very low power assemblies on the core periphery). Fuel enrichments range up to about 4 wt%. Integral burnable poison rods are used in low leakage reload cycles and all first cycles.

SONGS 2 is typical of out-in type reload cycles. Palo Verde 1 is typical of first cycles. Palo Verde is also similar to many low leakage reload cycles, in that considerable fresh fuel assemblies containing poison rods are loaded at the core interior. The range and distribution of nuclear properties in the fuel of SONGS 2 and Palo Verde 1 span those of most first and reload cores.

In all C-E plants (except the System 80), approximately one-third of the fuel assemblies are rodded. Adjacent assemblies are not both rodded. Diagonally adjacent fuel assemblies are frequently rodded. On the periphery of the core, fuel assemblies are only sparsely rodded. The C-E plants before ANO-2 contain "dual" control rods, that is, two five-finger control rods mechanically joined and operated by a single drive mechanism. SONGS 2/3, Waterford 3, and St. Lucie 2 have "mini-dual" control rods in peripheral locations. These four-finger control rods span two fuel assemblies. Palo Verde 1/2/3 and other System 80 plants contain 12-finger control rods which span five fuel assemblies, as well as 4-finger control rods which insert into single assemblies. From a neutronic calculative perspective, there is little difference between the pre-ANO-2 dual control rods and the System 80 12-finger control rods.

The location of control rods is very similar among the C-E 217 assembly plants: Calvert Cliffs 1/2, Millstone 2, Maine Yankee, SONGS 2/3, Waterford 3, and St. Lucie 1/2. Individual bank designations vary among plants and are occasionally changed from cycle-to-cycle as part of the reload design process. The control rod locations in ANO-2 are similar to SONGS 2 with one row of fuel removed. Those in Fort Calhoun are similar to SONGS 2 with two rows of fuel removed.

Thus, core geometry, fuel management, and control rod patterns are not significantly different among C-E plants with respect to the applicability of the control rod exchange technique. Variations in fuel management and control rod bank designation between cycles of the same plant may be more significant to the control rod exchange technique than variations among C-E plants.

In conclusion, based on the basic nuclear similarity of the fuel and the control rods, and after consideration of the pertinent geometric factors, the control rod exchange tests performed at SONGS 2 and Palo Verde 1 are adequate to justify the use of this technique on all C-E plants. The Palisades plant is an exception in that the core design is completely different.

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