CONTROL BANK REACTIVITY WORTH DETERMINATION

USING THE ROD SWAP TECHNIQUE

Nuclear Fuel Group
Licensing & Fuels Department
Union Electric Company
St. Louis, MO

June, 1991

UNION ELECTRIC

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ABSTRACT

This report describes Union Electric Company's methodology and techniques for determining control and shutdown bank reactivity worths using the rod swap method. The methods presented are applicable to the Callaway Nuclear Plant. As such, benchmark data collected at Callaway in support of the proposed methods are also presented.

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1.0 INTRODUCTION

1.1 Purpose of Bank Reactivity Worth Testing

Control and shutdown bank reactivity worth testing is part of the normal reload physics testing sequence at virtually all commercial nuclear power plants. The main purpose of bank worth testing is to validate the cycle specific core models used to design the reload and document its acceptability from a safety perspective, particularly in terms of shutdown margin. Bank worth testing is accomplished by measuring selected bank worths and comparing the values obtained against corresponding predictions generated with design models. Historically, the two primary methods used to perform bank worth testing are boron dilution and rod swap.

1.2 Dilution Method[1]

Currently, the boron dilution method of measuring bank worths is used at Callaway. Starting with an all-rods-out (ARO) configuration, a constant rate of boron dilution is

initiated. Control banks are periodically inserted to maintain the core near criticality (or within the specified physics testing range). First, Control Bank D (CBD) is incrementally inserted, then CBC, CBB, and finally, CBA. When CBA approaches full insertion, the dilution is terminated, and the core is allowed to stabilize with CBA at or near full insertion.

Bank worths are determined by analyzing reactivity traces recorded on strip charts. The periodic negative reactivity insertions of each bank are measured and then summed. The result is a tabulation of differential and integral bank worths which are then compared to corresponding predicted values. Note that only the control banks are measured, and each worth measurement is made in the presence of the previously inserted bank(s).

1.3 Rod Swap Method[2]

Rod swap is an alternative method of measuring bank worths which offers a number of advantages over boron dilution. The first step in rod swap is to measure the worth of the single highest worth bank (based on predictions) using the boron dilution technique, beginning from an ARO core configuration. This bank is designated the Reference Bank (RB).

The dilution test produces a curve or tabulation of Reference Bank worth versus position (steps withdrawn). After the Reference Bank measurement, the core is allowed to stabilize with the Reference Bank inserted, all other rods out (ORO), and boron dilution terminated. While maintaining the core within the specified physics testing range, each other bank is then individually "swapped" with the Reference Bank. Since the Reference Bank is the highest worth bank, the swapped bank will end fully inserted, while the Reference Bank will be withdrawn to some partially inserted, critical position. Initial and final positions of the Reference Bank are recorded, and then the swap process reversed to return to the original configuration (RB-in, ORO). This process is repeated for all remaining banks.

Bank worths (other than the Reference Bank) are determined by combining the Reference Bank worth tabulation with the recorded critical position data. As described in more detail later in this report, each swapped bank worth is equivalent to the incremental worth of the Reference Bank from its starting point (usually near full insertion) to the respective critical position. This worth value is based on the Reference Bank worth tabulation, and includes the presence of the Reference Bank at the critical position. As is done for the boron dilution method, the determined worths are compared against corresponding design predictions.

The advantages of the rod swap technique are significant. First, rod swap testing requires approximately half the time of conventional boron dilution testing. This directly translates into reduced replacement power costs by increasing overall plant availability. Second, rod swap involves less water processing, which also reduces costs. Finally, and most important, since both control and shutdown banks are measured, rod swap represents a net increase in the number and diversity of reactor physics measurements taken during startup physics testing. Thus, rod swap results in a more encompassing description of core behavior than boron dilution, ultimately enhancing plant safety.

1.4 Similarity to Previously-Licensed Methods

It should be noted that Union Electric's proposed rod swap methodology, as described in this report, is equivalent to methods previously-licensed for such companies as Virginia Electric Power Co. (VEPCO)[3] and Public Service Electric and Gas Co. (PSE&G)[4]. Although certain calculation sequences and data manipulations may differ, the methods are fundamentally the same, particularly in terms of the number of measurements taken, the conservatism of the acceptance/review criteria, and the fact that calculations represent what is actually being measured in the core.

2.0 ROD SWAP TEST DESCRIPTION

2.1 Rod Swap Fundamentals

Rod swap is based on the premise that if the worth of one bank is explicitly known (or measured), then the worths of the remaining banks can be inferred by individually exchanging or "swapping" them with the known bank. Although this seems reasonable intuitively, it is useful to visualize the exchange as two independent steps.

First, assume that Reference Bank worth versus position is known, as well as its critical position for a particular bank. The exchange begins with a stable, critical core with the Reference Bank inserted alone. The first step is to withdraw the Reference Bank to the known critical position for the swap configuration. As a result, the positive core reactivity will equal the known reactivity worth of the Reference Bank from zero steps to the new position. The second step is to fully insert the unknown bank. Since the position of the Reference Bank was known to represent the critical position with the unknown bank fully inserted, the core is now theoretically critical, assuming test conditions have not changed. Also, since the negative reactivity of the unknown bank must exactly offset the positive reactivity produced by the withdrawal of the Reference Bank, the worth of the unknown bank, in the presence of the Reference Bank, is now known. In equation form, this identity is:

$$W(RB) = [W(x)_{RB@CP}] + [W(RB)_{CP-ARO}]$$

or;

$$W(x)_{RB@CP} = W(RB) - [W(RB)_{CP-ARO}]$$

where;

$W(x)_{RB@CP}$ = Worth of Bank(x) with the Reference Bank at the critical position

$W(RB)$ = Total Reference Bank worth with no other banks present

$W(RB)_{CP-ARO}$ = Reference Bank worth from the critical position to fully withdrawn

In reality, both steps proceed at the same time. However, if the core is truly critical at both the starting and ending configurations, the above identity holds true regardless of the path followed.

2.2 Test Objectives

As previously stated, the objective of rod swap testing is to measure the reactivity worth of control and shutdown banks in the core. Measurement results are compared against corresponding design predictions through the use of acceptance criteria.

2.3 Test Sequence

Rod swap begins with a critical and stable core, and all banks withdrawn. The worth of the most reactive bank, as determined by design predictions, is measured using the standard boron dilution technique. To do this, a stable boron dilution is initiated, equivalent to a reactivity

insertion rate of approximately 300 to 500 pcm per hour. To compensate for the positive reactivity addition, the Reference Bank is periodically inserted to maintain approximate criticality and flux level.

When the Reference Bank nears full insertion, the dilution is terminated and the core allowed to stabilize. If the Reference Bank is not fully inserted after stabilization, the remaining worth segment is measured by temporarily inserting the Reference Bank, recording the resulting negative core reactivity, and then returning the bank to its original position. The Reference Bank worth is subsequently determined by analyzing the reactivity traces, as previously described. This results in a tabulation of Reference Bank worth versus position.

Thereafter, the Reference Bank is individually exchanged with each other bank. Before each exchange, the initial position of the Reference Bank is recorded. The Reference Bank is then gradually exchanged with the other bank until the other bank is fully inserted and the Reference Bank is at some critical position. If the Reference Bank finishes fully withdrawn and the core is still sub-critical (called the "swap-out" condition), the core's negative reactivity is recorded. After recording the Reference Bank position (and swap-out reactivity if fully withdrawn), the exchange is reversed, thus returning to the original state. The final

position of the Reference Bank is recorded. This process is repeated for all remaining banks, with initial, critical, and final Reference Bank positions recorded for each exchange. After all swap measurements are completed, the core is returned to a stable condition with shutdown banks withdrawn and control banks in normal overlap mode. During system restoration, rod swap bank worths are determined from the measurement data as described below.

2.4 Data Interpretation

Reference Bank worth is determined using the standard data analysis techniques associated with the boron dilution method. All other bank worths are determined through a combination of the Reference Bank worth data and the Reference Bank's initial, critical, and final positions recorded during each bank exchange. Thus, the test data consists of the following information:

1) RB worth table (pcm versus bank position)
2) RB position before swap
3) RB critical position after swap
4) RB position after swap is reversed

(Items 2-4 are collected for each bank exchanged with the Reference Bank)

In addition, the following predicted data are supplied:

1) Predicted Reference Bank integral worth
2) Predicted Reference Bank critical positions

3) Predicted Bank X worth versus Reference Bank position

4) Test Acceptance/Review Criteria

(Predicted Reference Bank critical positions are provided as plant information only, and are not used in the measurement procedure.)

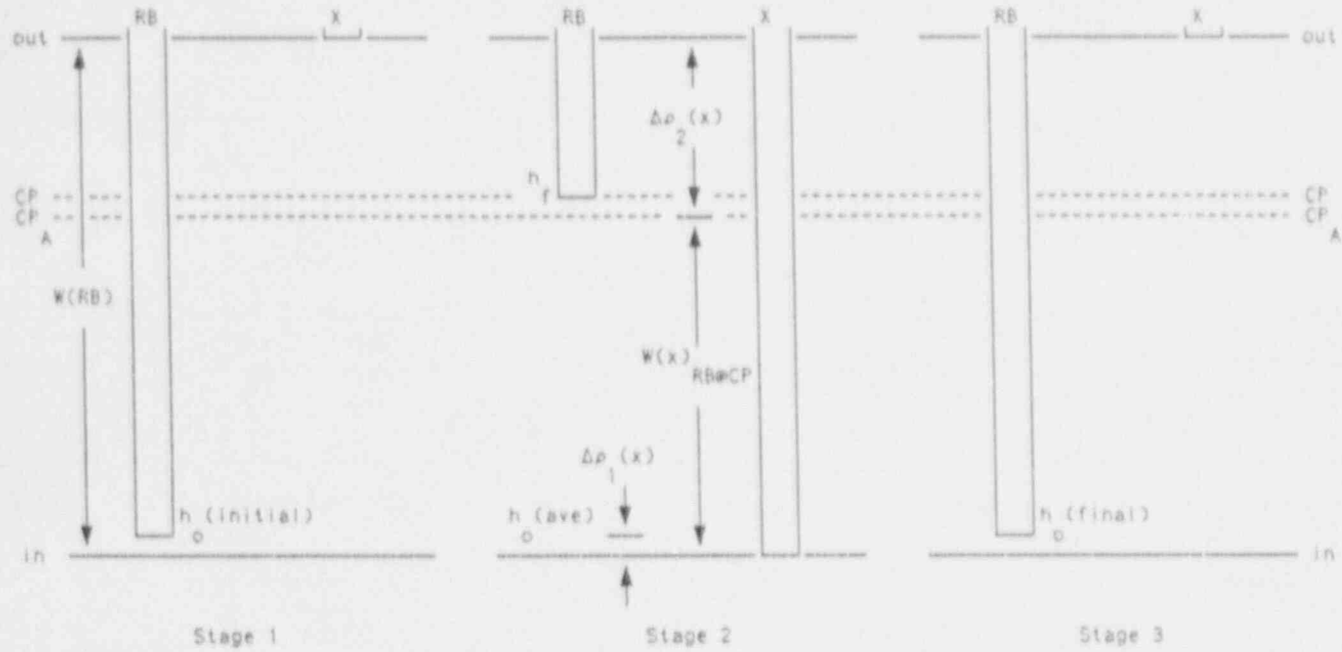
Bank worths are obtained by retrieving from the Reference Bank worth measurement the Reference Bank's worth from fully inserted to its adjusted measured critical position, CP_A. The measured critical position is adjusted to account for any test condition drift as well as a non-fully inserted initial Reference Bank position. Thus, the adjusted critical position represents the critical position that would have been measured had the Reference Bank started fully inserted and test conditions remained completely stable. It should be noted that such adjustments are usually very small.

If the Reference Bank was required to be fully withdrawn during the swap and the reactor was still sub-critical (a "swap-out" condition), then the bank worth is simply the Reference Bank worth from the average of its starting positions to fully withdrawn, plus the swap-out reactivity.

The predicted bank worths, with the Reference Bank at the adjusted measured critical position, are obtained from curves (or tabulations) of calculated Bank X worth versus Reference Bank position. Thus, the predicted values are placed directly on the same basis as the measurements.

The rod swap sequence is illustrated in Figure 1.

ROD SWAP ILLUSTRATION AND EQUATIONS



$$W(x)_{RB@CP} = W(RB) - \text{Delta-Rho}_2(x)$$

where: $W(x)_{RB@CP}$ = Worth of Bank X with the Reference Bank at the adjusted measured critical position, CP_A.

W(RB) = Total integral worth of the Reference Bank, based on dilution measurment.

$\Delta\rho_1(x)$ = Integral worth of the Reference Bank from fully inserted to the average test starting point, h_o (ave) (RB may not start fully inserted). Worth is based on RB dilution measurement. $\Delta\rho_1(x)$ is used in determining the adjusted measured critical position, CP_A.

$\Delta\rho_2(x)$ = Integral worth of the Reference Bank from fully withdrawn to the adjusted measured critical position. As with $\Delta\rho_1(x)$, $\Delta\rho_2(x)$ is based on the initial RB dilution measurement.

CP_A = Adjusted measured critical position. The nominal critical position is adjusted to account for test condition drift as well as a non-fully inserted initial RB position.

Figure 1

3.0 CALCULATION METHODOLOGY

3.1 Overview of Codes and Methods

The primary reload design codes used by Union Electric are CASMO-3[5] and SIMULATE-3P[6]. In addition, the code GRPDQ (an advanced version of PDQ-7 with 2D thermal feedback capabilites) is also used for certain model development applications, but not specifically for rod swap analysis.

The state-of-the-art codes CASMO-3 and SIMULATE-3P are products of Studsvik of America, Inc. These codes are used extensively throughout the industry, both in the United States and abroad.

CASMO-3 is a multigroup, two-dimensional transport theory code for performing fuel burnup calculations. Nuclear data is based on ENDF-B versions IV and V, and is assembled in both 40 and 70 group libraries ranging from 0 to 10 MeV. CASMO is used for generating cross-section and discontinuity factor data for each nuclear fuel type loaded in the core. This data is subsequently transferred to SIMULATE-3P though the processing program TABLES-3.

SIMULATE-3P is an advanced two-group, two and three-dimensional nodal code for performing PWR and BWR core analysis. SIMULATE-3P is based on the QPANDA neutronics

model which represents both fast and thermal intranodal flux distributions by fourth order polynomials. SIMULATE-3P also features pin power reconstruction, which makes use of discontinuity factors and heterogeneous intra-assembly flux distributions generated in CASMO. Due to SIMULATE's advanced features, the code requires no normalization. As such, SIMULATE is relatively easy to use, and produces consistently accurate results. SIMULATE is the main tool used for performing rod swap calculations.

Union Electric controls the use of the codes described above through firm adherence to procedures governed by Union Electric's Quality Assurance program. These procedures address such subjects as preparation of calculations; software validation, verification, installation, and documentation; software development; and control of nuclear analysis activities.

3.2 Required Data

The necessary rod swap calculations include the following:

1) Reference Bank Identity
2) Reference Bank Integral Worth
3) Predicted Reference Bank Critical Positions
4) Bank X Worths vs. Reference Bank Position
5) Test Acceptance/Review Criteria

3.3 Calculation Sequence

The rod swap calculation sequence is as follows:

1. Reference Bank Identity

   The Reference Bank is the highest-worth bank, assuming all other banks withdrawn. The Reference Bank is determined by individually inserting each bank into a critical, ARO core model and calculating corresponding eigenvalues. The bank which produces the largest reduction in k-effective is selected as the Reference Bank.

2. Reference Bank Integral Worth, W(RB)

   Reference Bank integral worth is obtained by essentially modelling the dilution test. Beginning with a critical, ARO core, the Reference Bank is inserted into each successive node of the 3-D core model. After each insertion (boron is held constant), the core eigenvalue is calculated. Reference Bank integral worth at each position is the sum of all reactivity changes up to that point. A table of Reference Bank integral worth vs. position (steps withdrawn) is generated from the data. After the bank is fully inserted, a

critical boron calculation is perfomed. All subsequent SIMULATE calculations for rod swap modelling are performed at this boron concentration.

3. Reference Bank Critical Positions, CP

SIMULATE-3P features the capability of searching on critical bank positions. Beginning from a critical core with the Reference Bank inserted, the predicted critical positions are generated by individually inserting each remaining bank, and then instructing SIMULATE to re-establish criticality by iteratively adjusting Reference Bank position.

4. Bank X Worths vs. Reference Bank Position

Bank X worths versus Reference Bank position, $W(x)_{RB@CP}$, are generated by explicitly calculating the worth of a fully inserted Bank X with the Reference Bank placed at a range of positions. All other banks remain fully withdrawn, and the boron level is set at the Reference Bank - in, ORO critical boron concentration.

5. Test Acceptance/Review Criteria

Test acceptance/review criteria percentages are obtained by tightening the base percentages (i.e., ±15% on swapped bank worths and ±10% on the sum of all bank worths) based on comparisons of Union Electric and vendor bank worth predictions. The determination of allowed percentages is addressed in detail in Section 4.0.

Table 1 presents a summary of the initial bank worth calculations used in selecting the Reference Banks in Callaway Cycles 4 and 5, as well as predicted Reference Bank critical positions for each Bank X.

Predictions of Reference Bank worths and Bank X worths versus Reference Bank position for each cycle are presented in Figures 2-7 and 8-16, respectively.

Comparisons of predictions against measurements are provided in Section 5.0, "Test Results and Method Validation."

ROD SWAP CALCULATION RESULTS

CALLAWAY CYCLE 4

Bank	Worth (PCM)	Predicted RB CP (Steps)
CBD	701.0	204
CBC	721.6	202
CBB	700.1	193
CBA	304.8	117
SBE	371.5	110
SBB*	780.1	NA

CALLAWAY CYCLE 5

Bank	Worth (PCM)	Predicted RB CP (Steps)
CBD	519.5	137
CBC*	882.8	NA
CBB	788.4	192
CBA	308.4	80
SBE	431.4	104
SBD	476.4	129
SBC	477.8	129
SBB	881.1	218
SBA	313.0	105

* Designated as the Reference Bank

Table 1

CYCLE 4 ROD SWAP CALCULATIONS
RB INTEGRAL WORTH

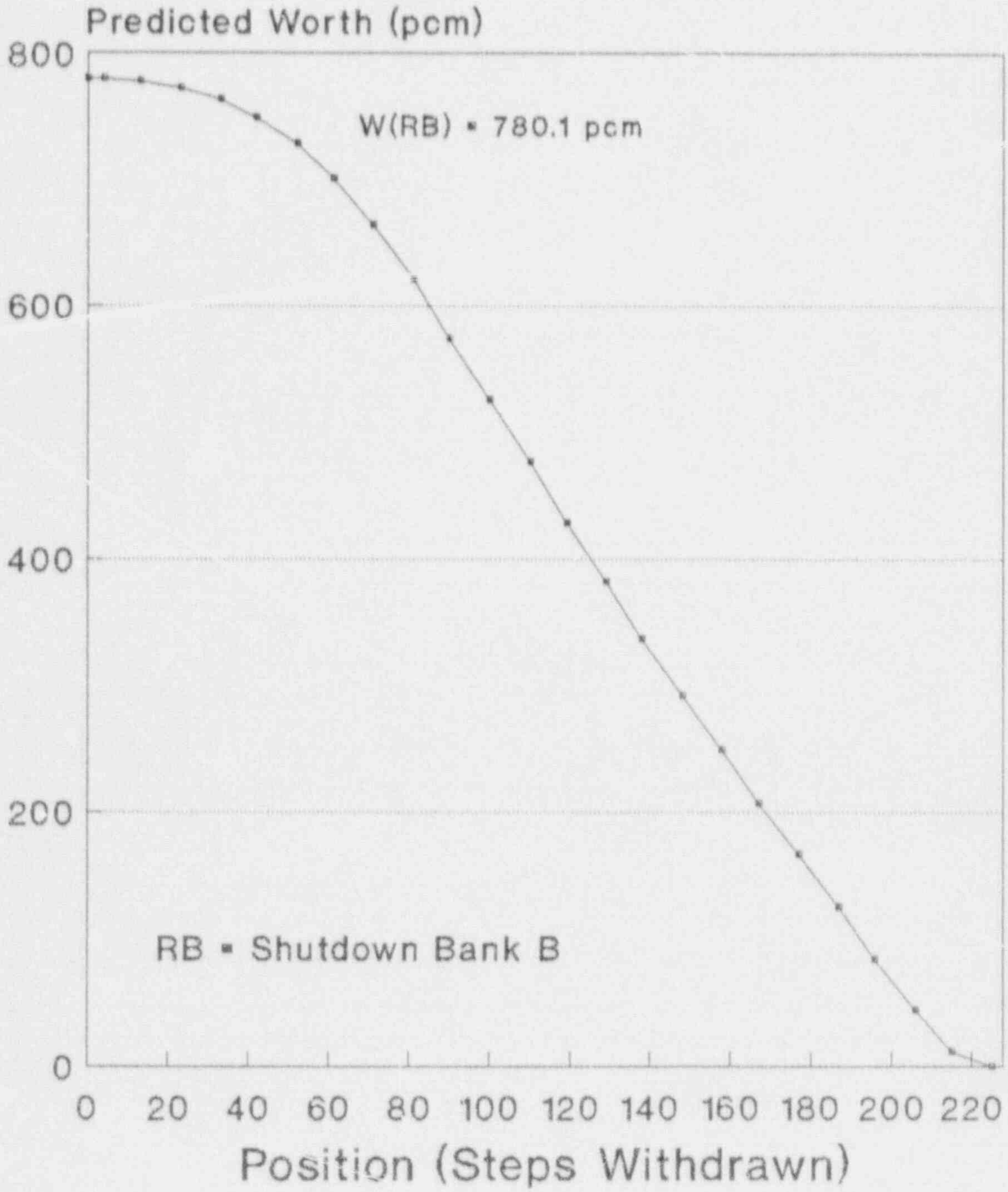


Figure 2

CYCLE 4 ROD SWAP CALCULATIONS
CBD WORTH VS. RB POSITION

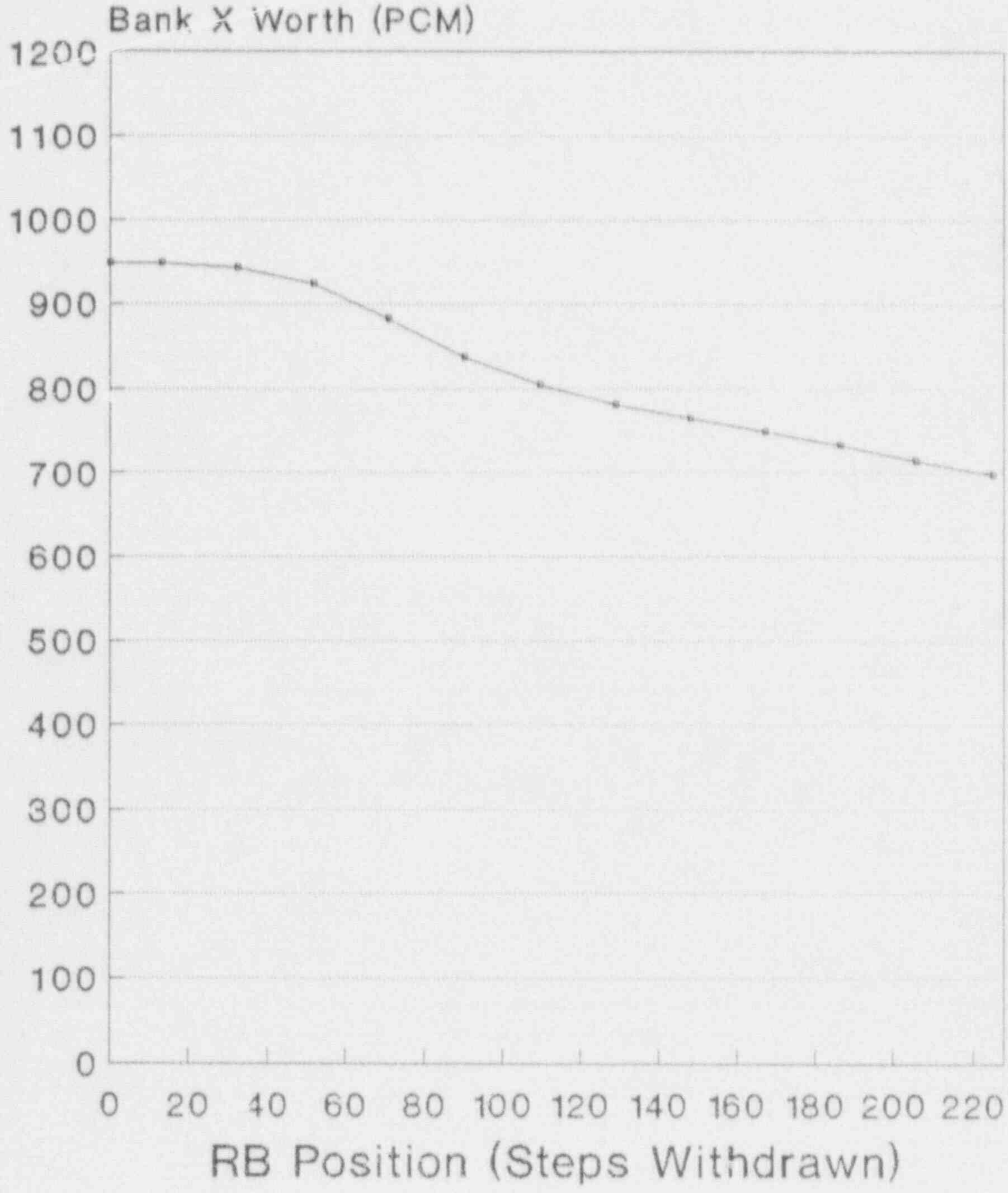


Figure 3

CYCLE 4 ROD SWAP CALCULATIONS
CBC WORTH VS. RB POSITION

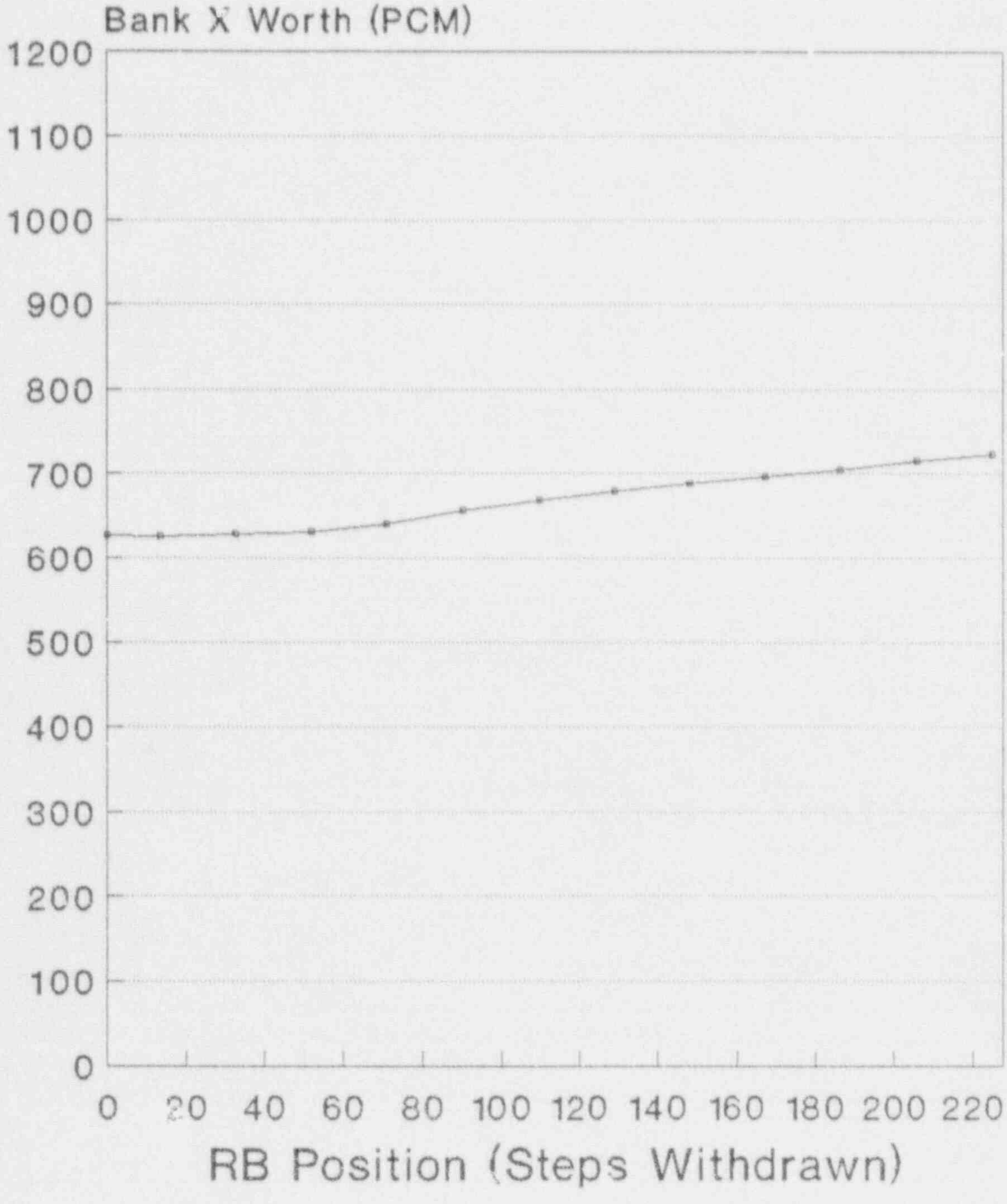


Figure 4

CYCLE 4 ROD SWAP CALCULATIONS
CBB WORTH VS. RB POSITION

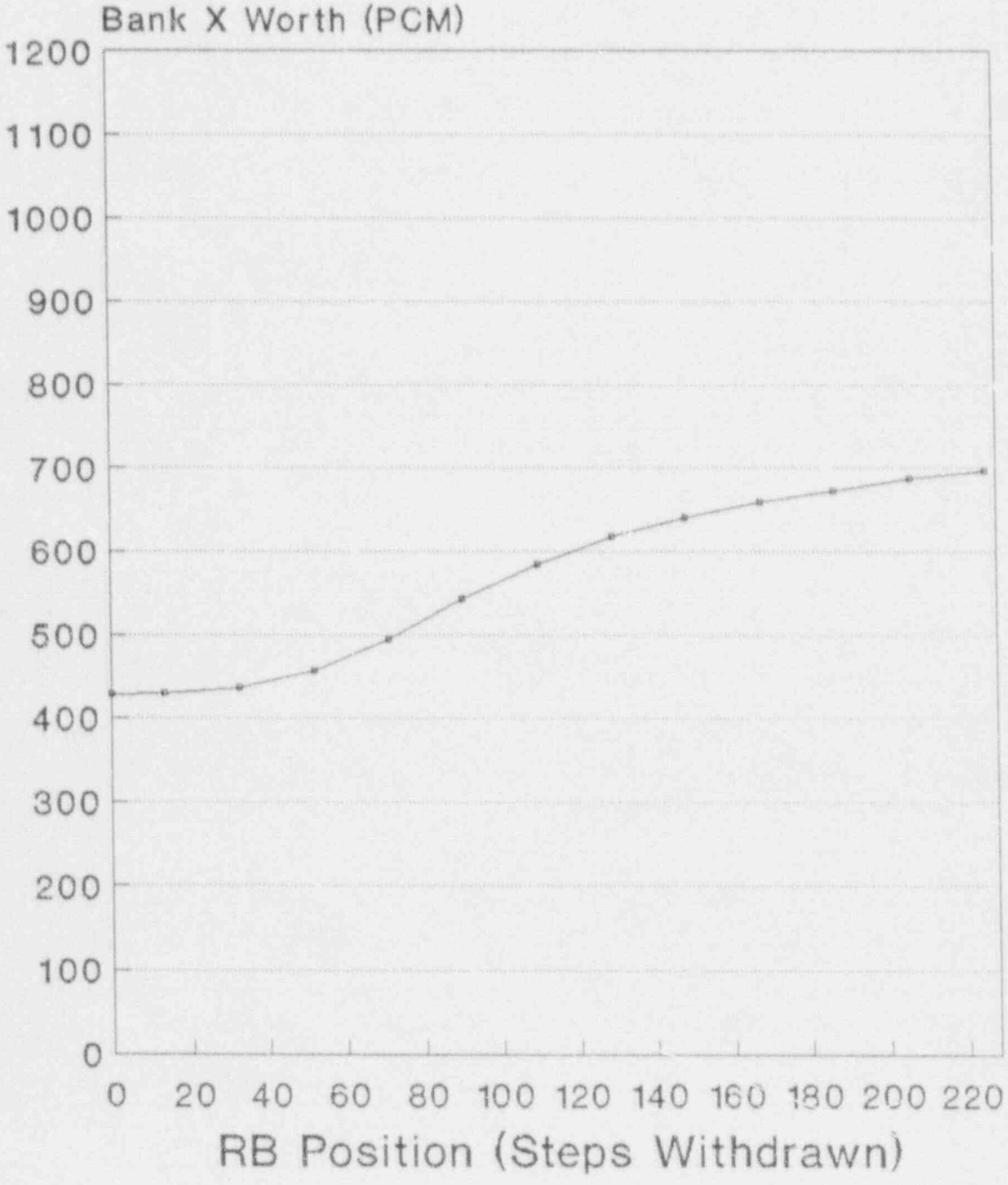


Figure 5

CYCLE 4 ROD SWAP CALCULATIONS
CBA WORTH VS. RB POSITION

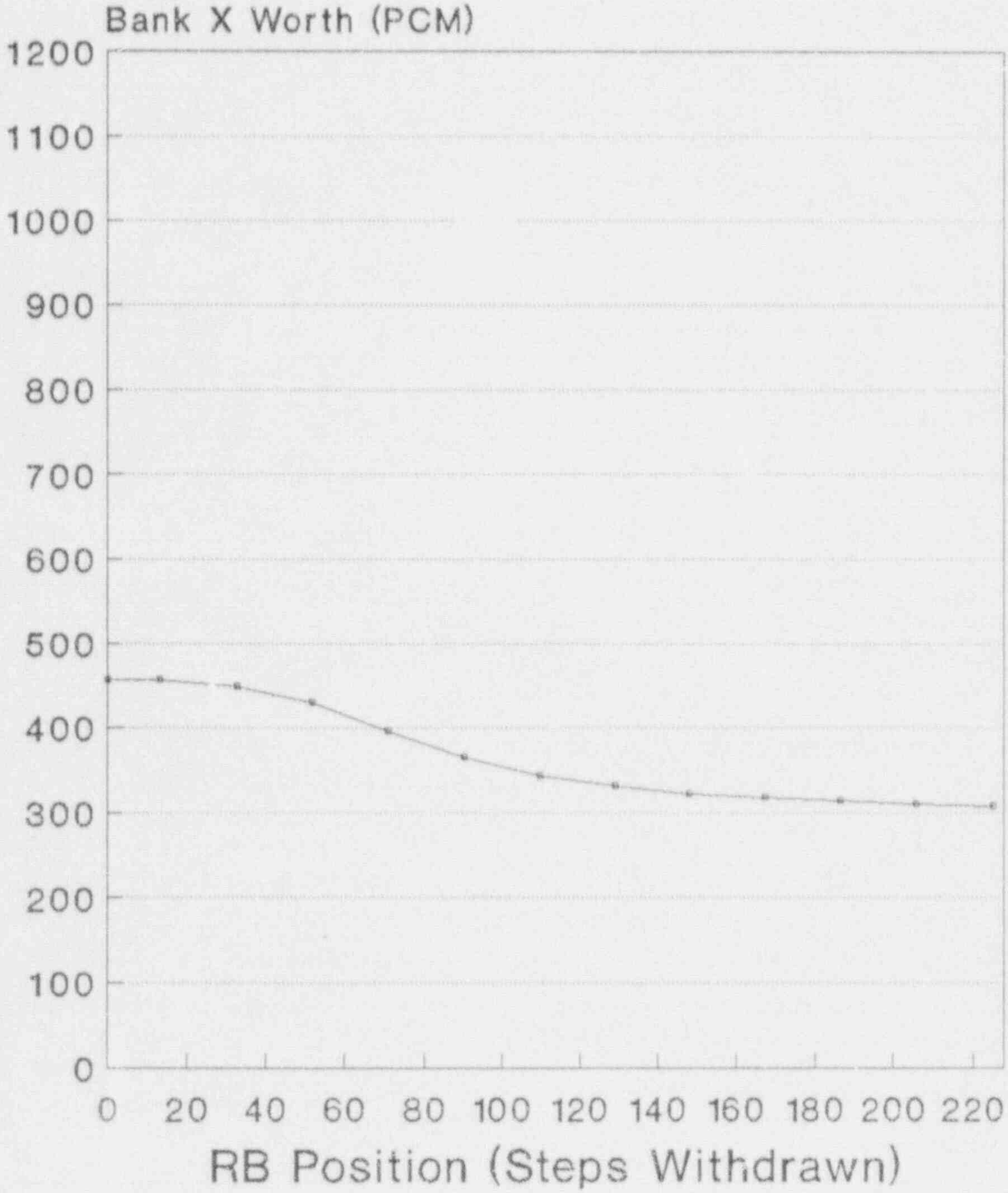


Figure 6

CYCLE 4 ROD SWAP CALCULATIONS
SBE WORTH VS. RB POSITION

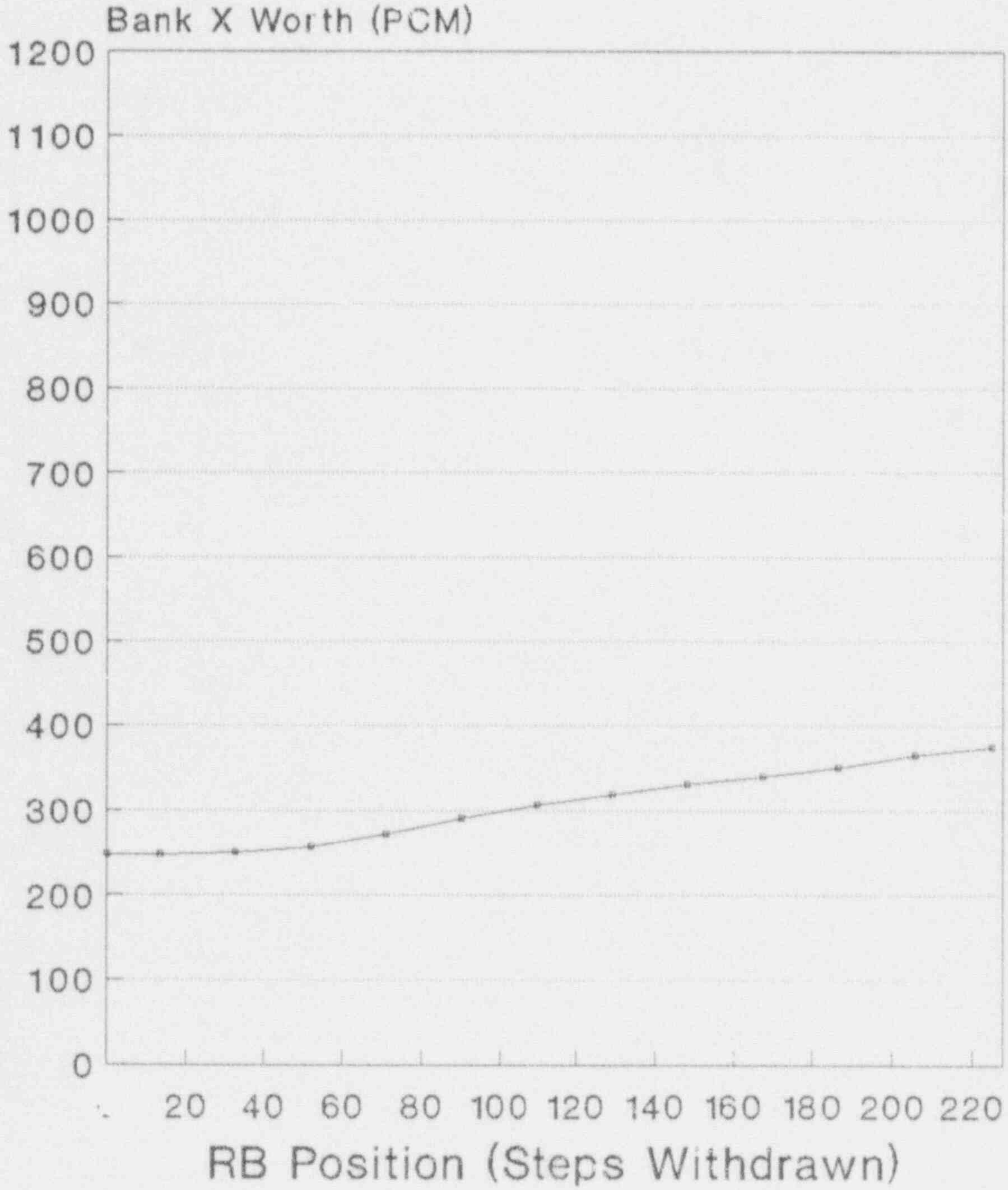


Figure 7

CYCLE 5 ROD SWAP CALCULATIONS
RB INTEGRAL WORTH

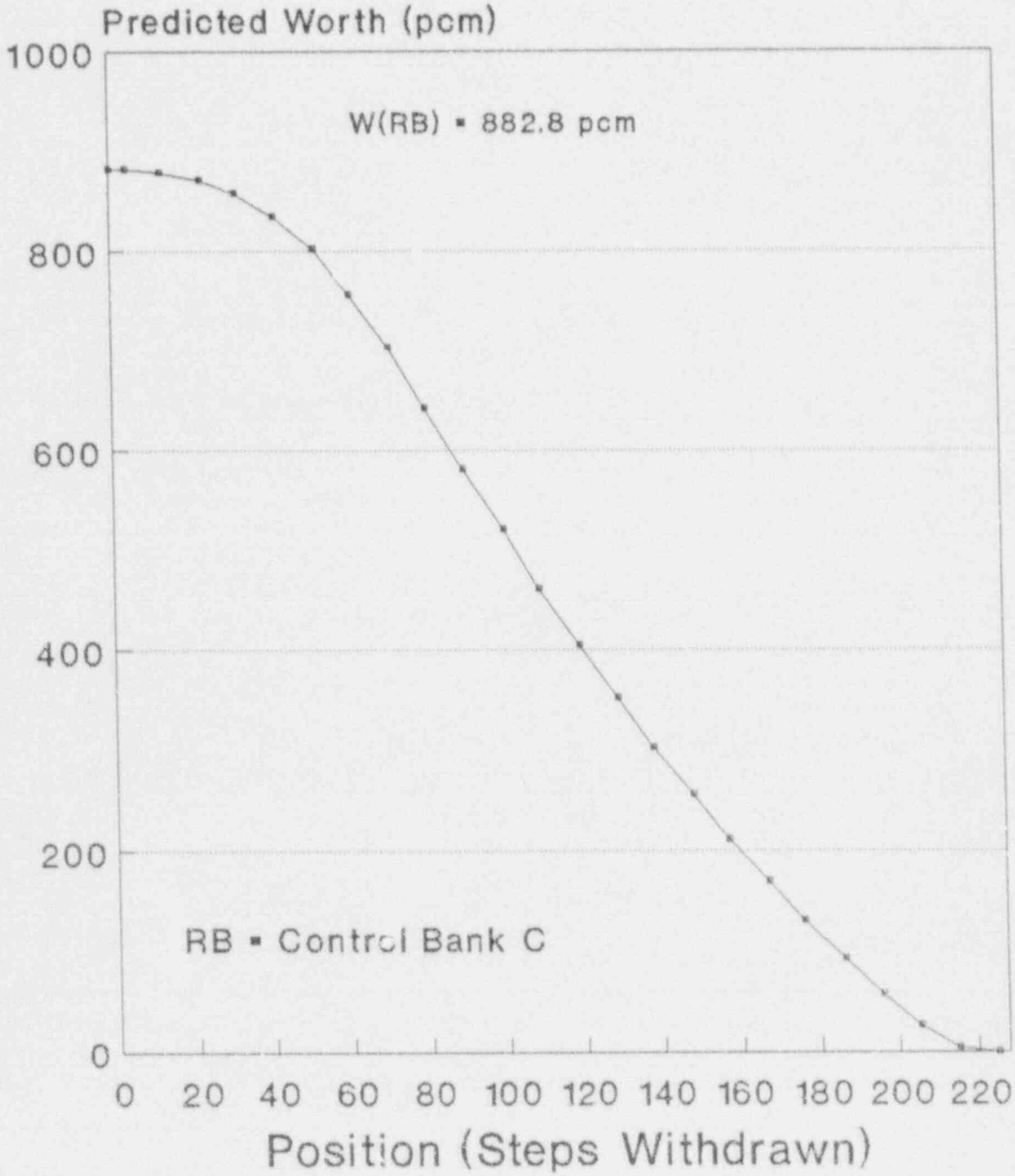


Figure 8

CYCLE 5 ROD SWAP CALCULATIONS
CBD WORTH VS. RB POSITION

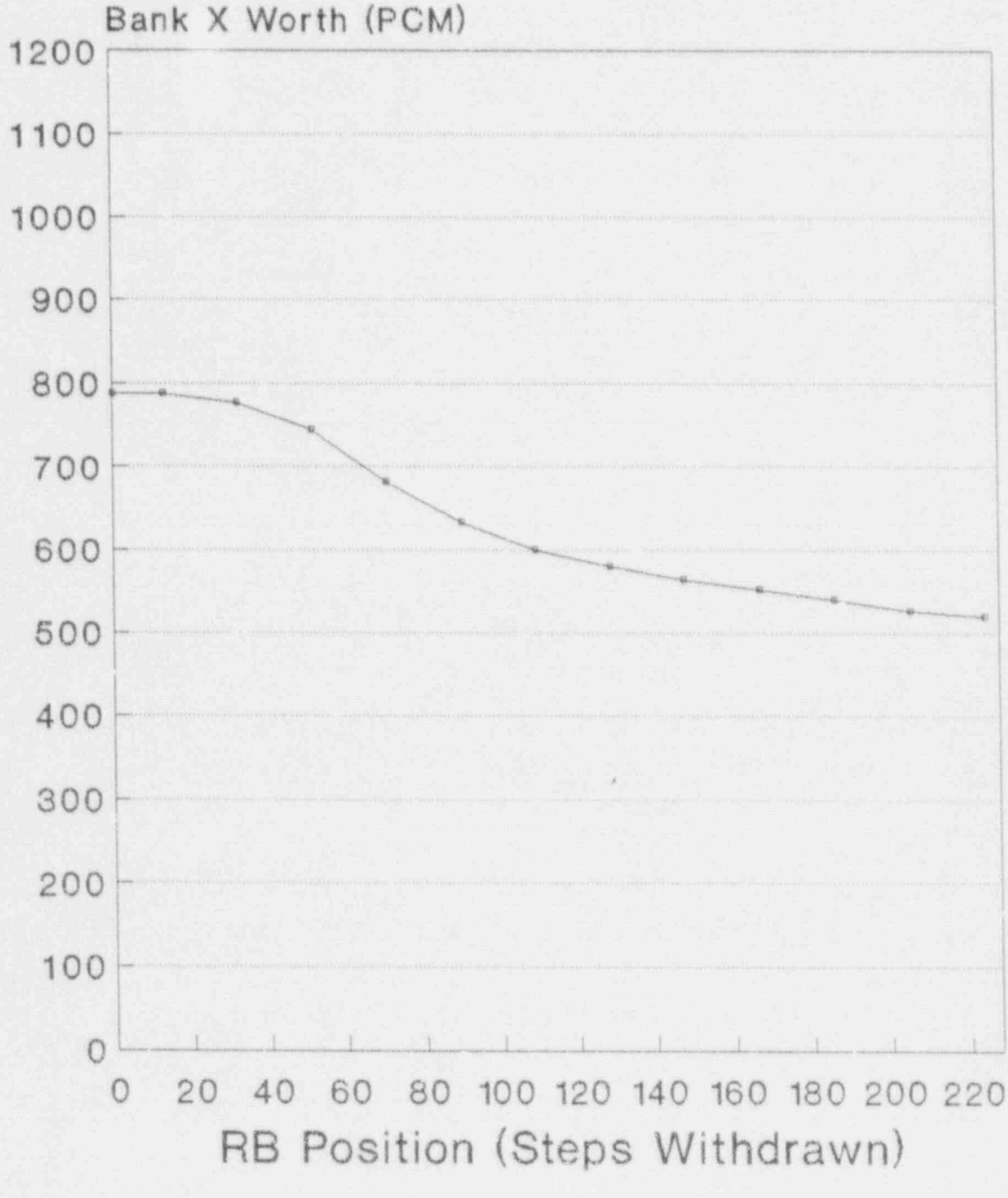


Figure 9

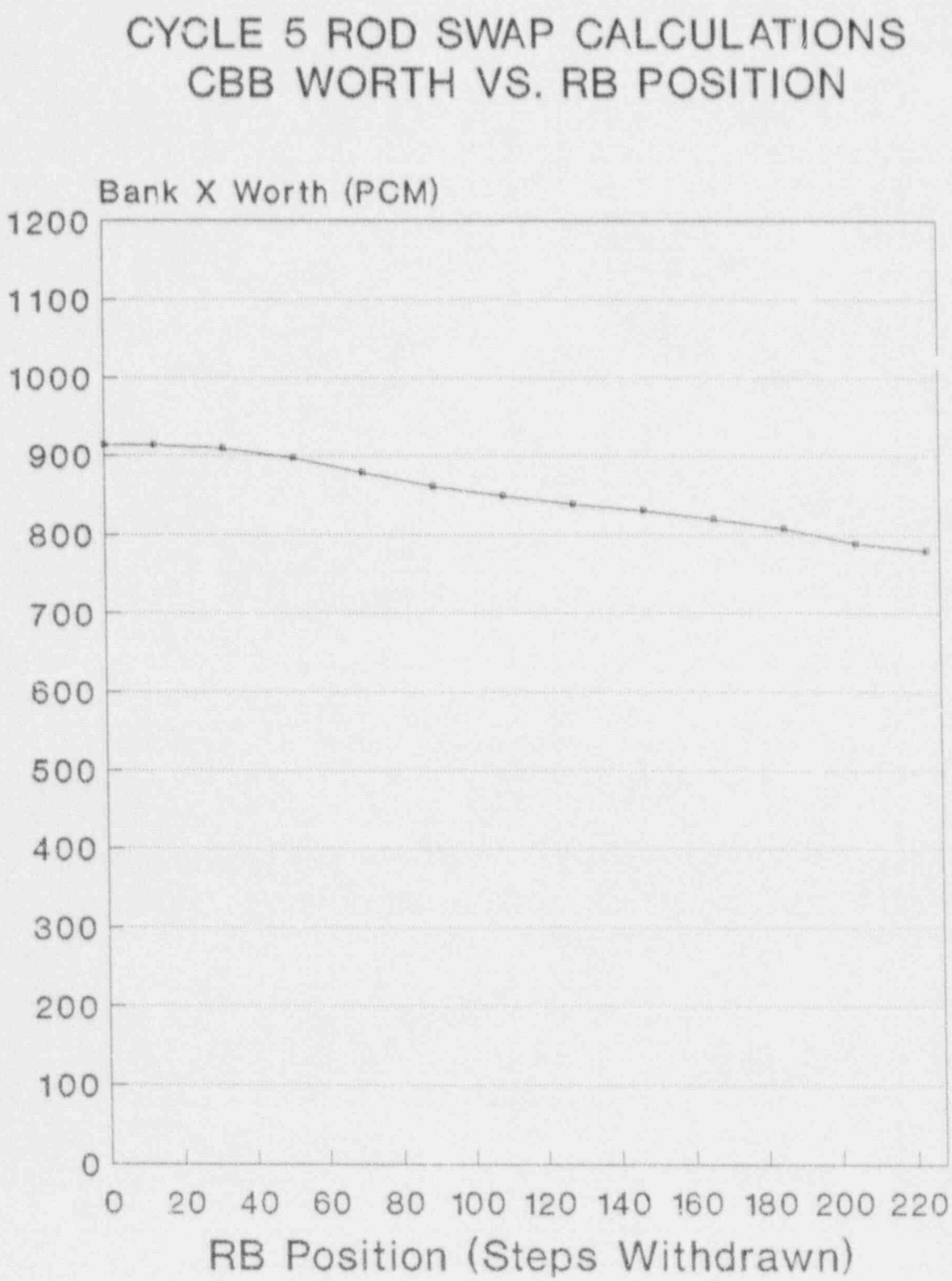

CYCLE 5 ROD SWAP CALCULATIONS
CBB WORTH VS. RB POSITION
Bank X Worth (PCM)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0 20 40 60 80 100 120 140 160 180 200 220
RB Position (Steps Withdrawn)

Figure 10

CYCLE 5 ROD SWAP CALCULATIONS
CBA WORTH VS. RB POSITION

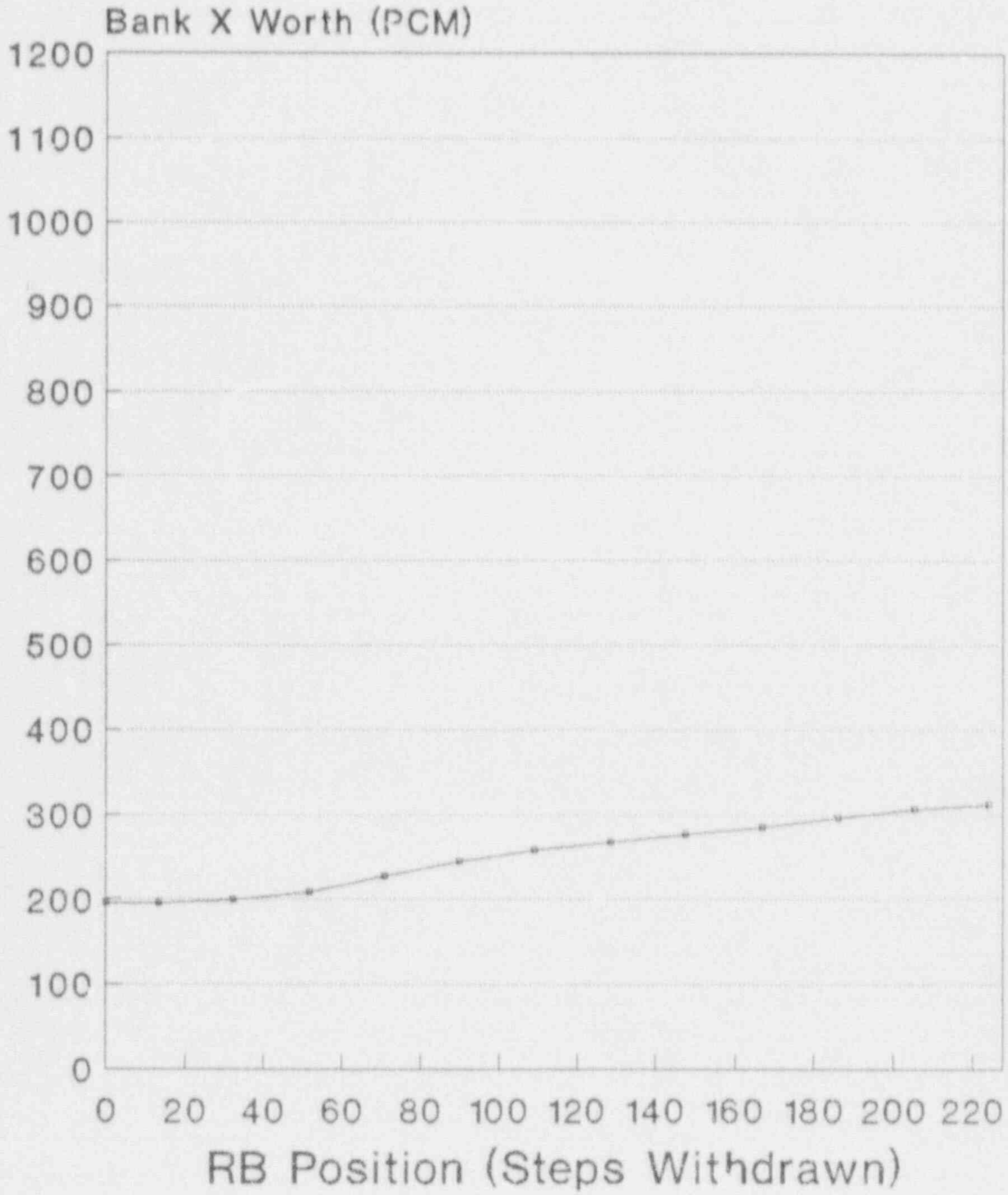


Figure 11

CYCLE 5 ROD SWAP CALCULATIONS
SBE WORTH VS. RB POSITION

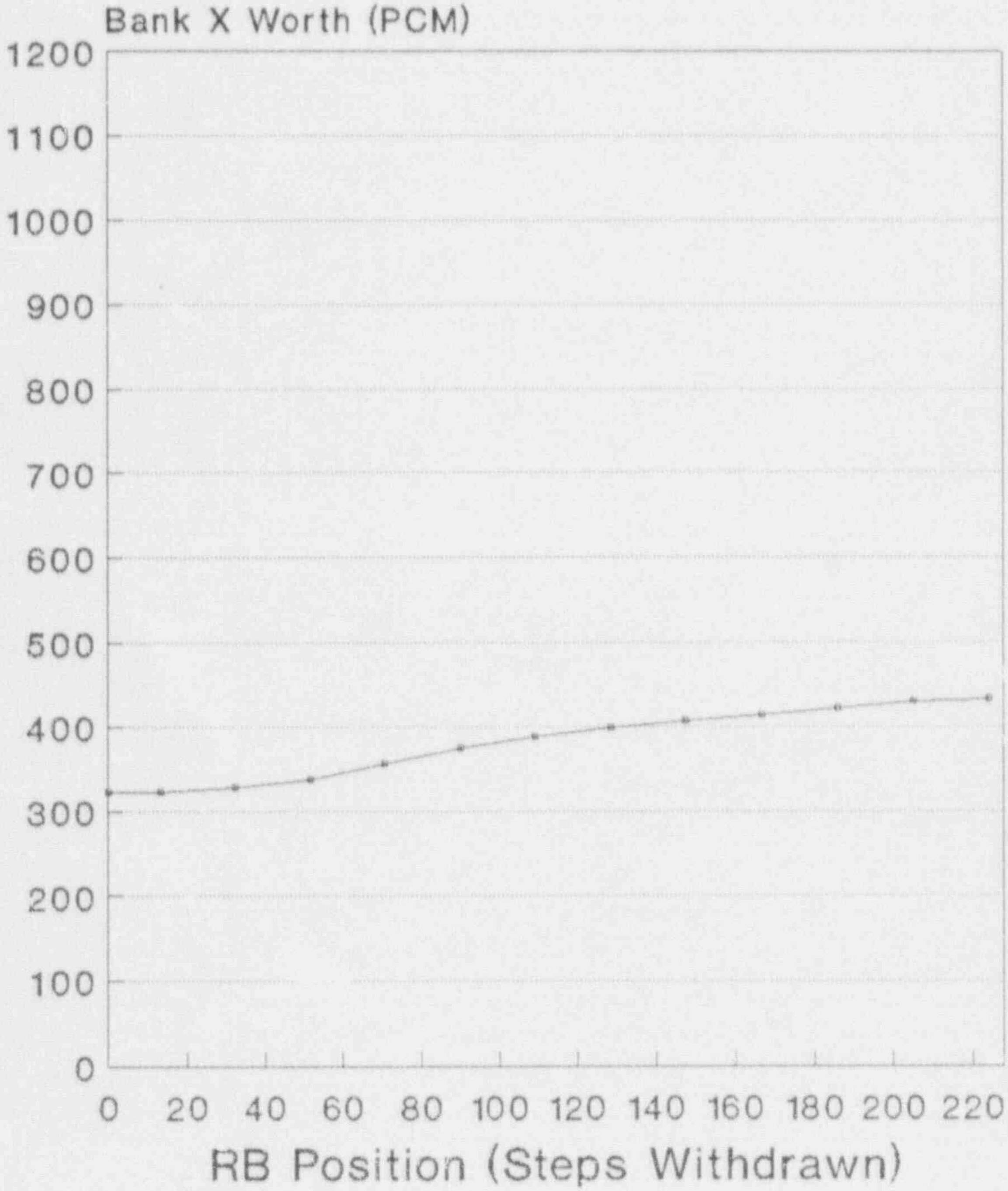


Figure 12

CYCLE 5 ROD SWAP CALCULATIONS
SBD WORTH VS. RB POSITION

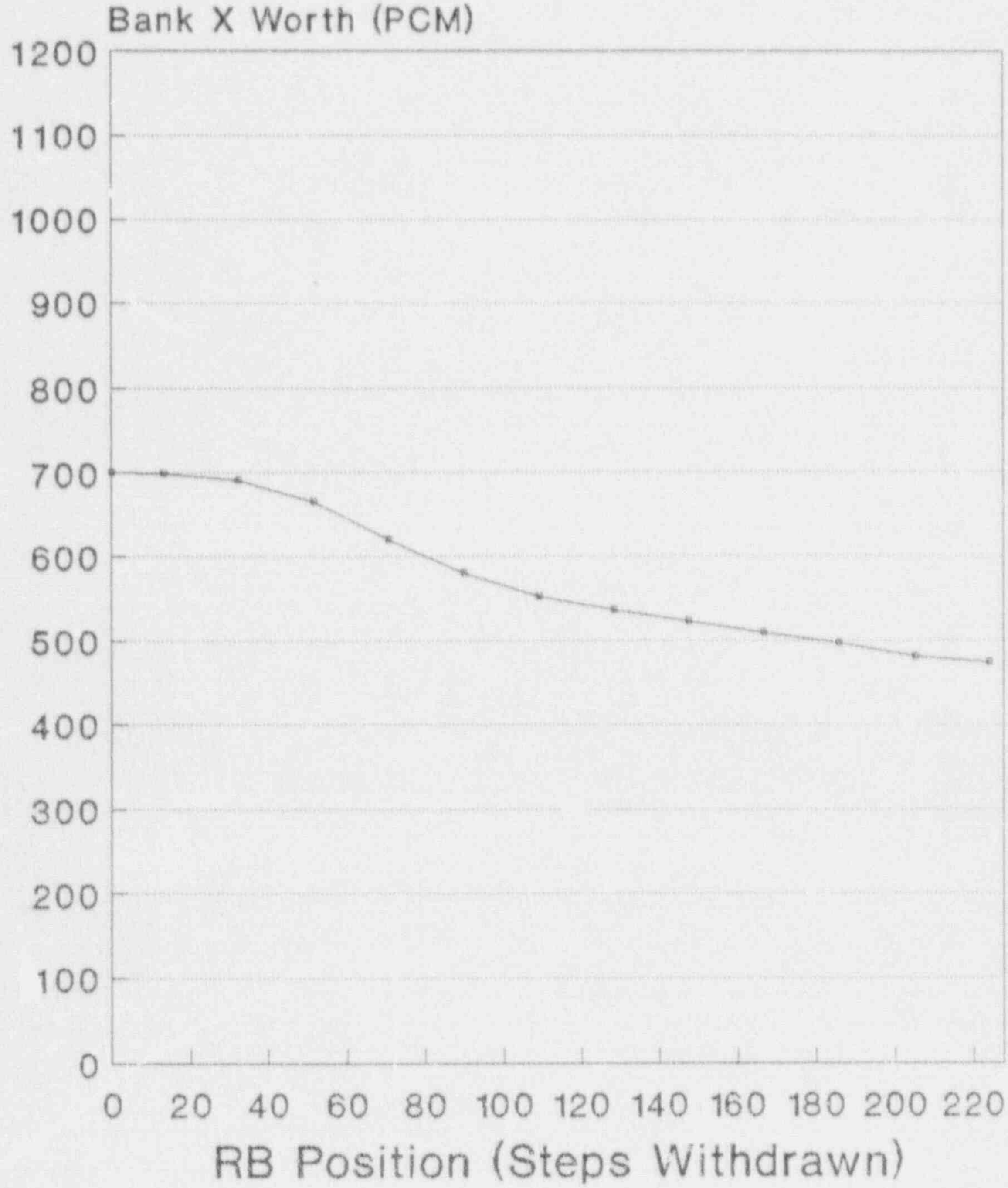


Figure 13

CYCLE 5 ROD SWAP CALCULATIONS
SBC WORTH VS. RB POSITION

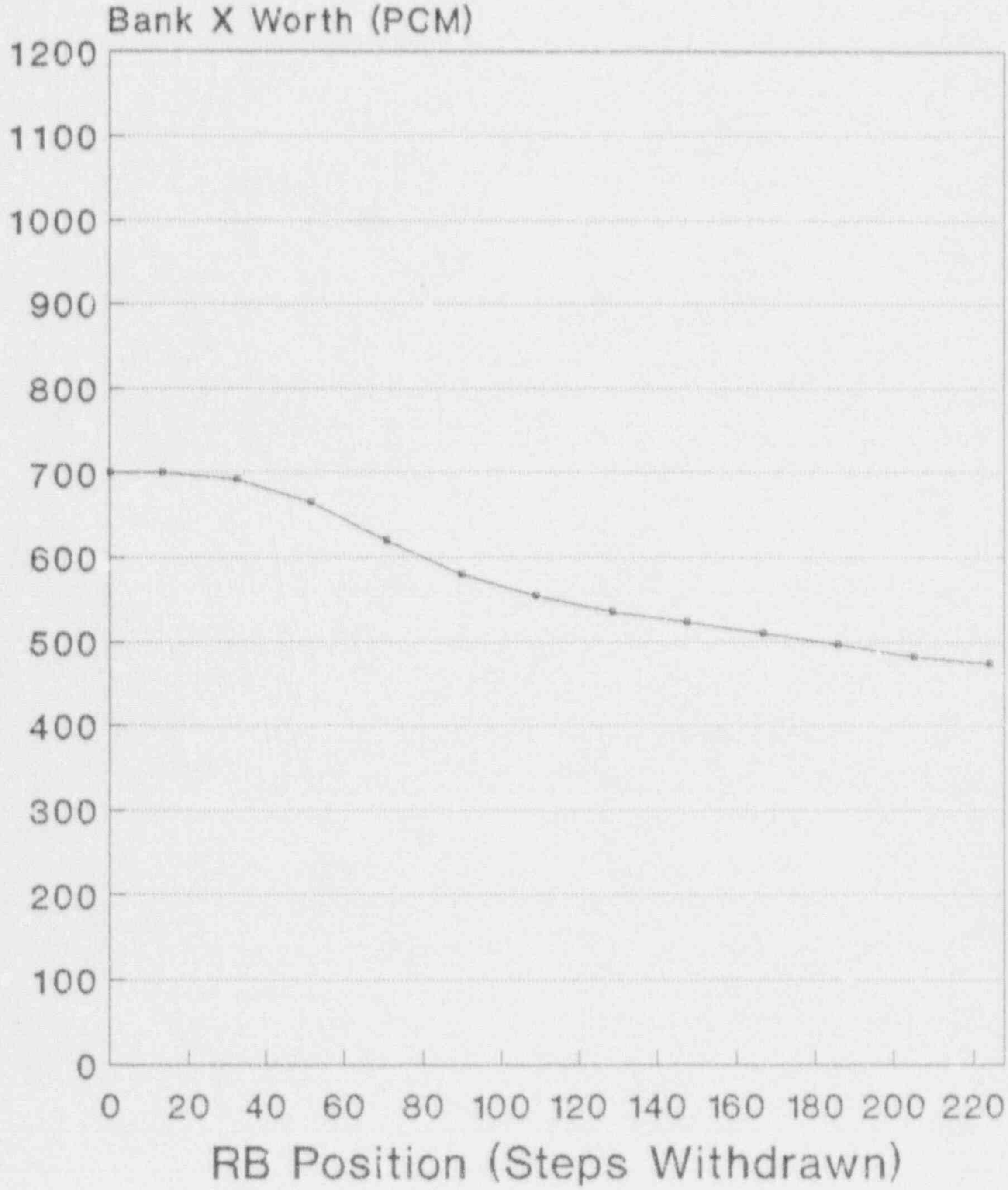


Figure 14

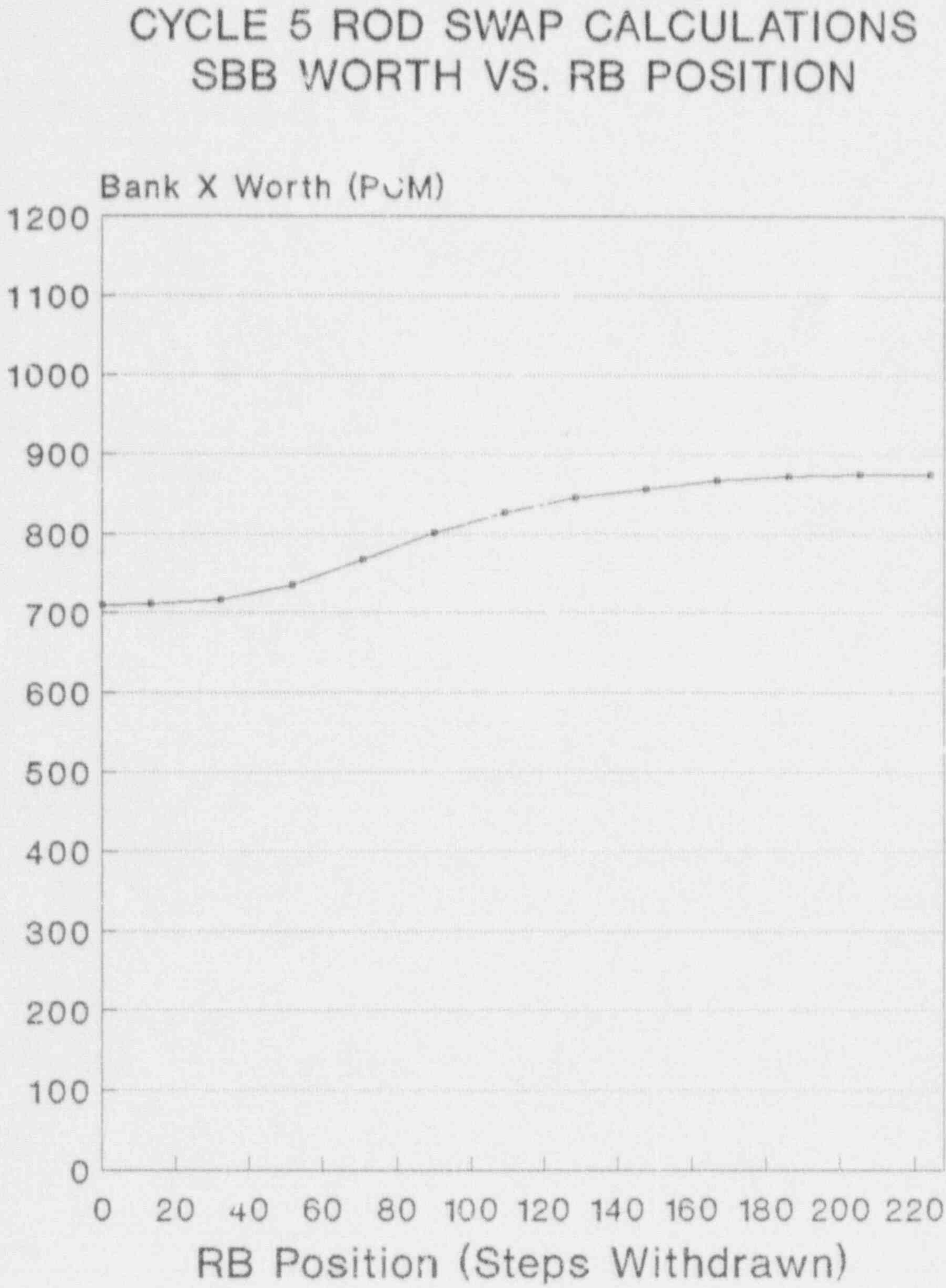

CYCLE 5 ROD SWAP CALCULATIONS
SBB WORTH VS. RB POSITION
Bank X Worth (PCM)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0 20 40 60 80 100 120 140 160 180 200 220
RB Position (Steps Withdrawn)

Figure 15

CYCLE 5 ROD SWAP CALCULATIONS
SBA WORTH VS. RB POSITION

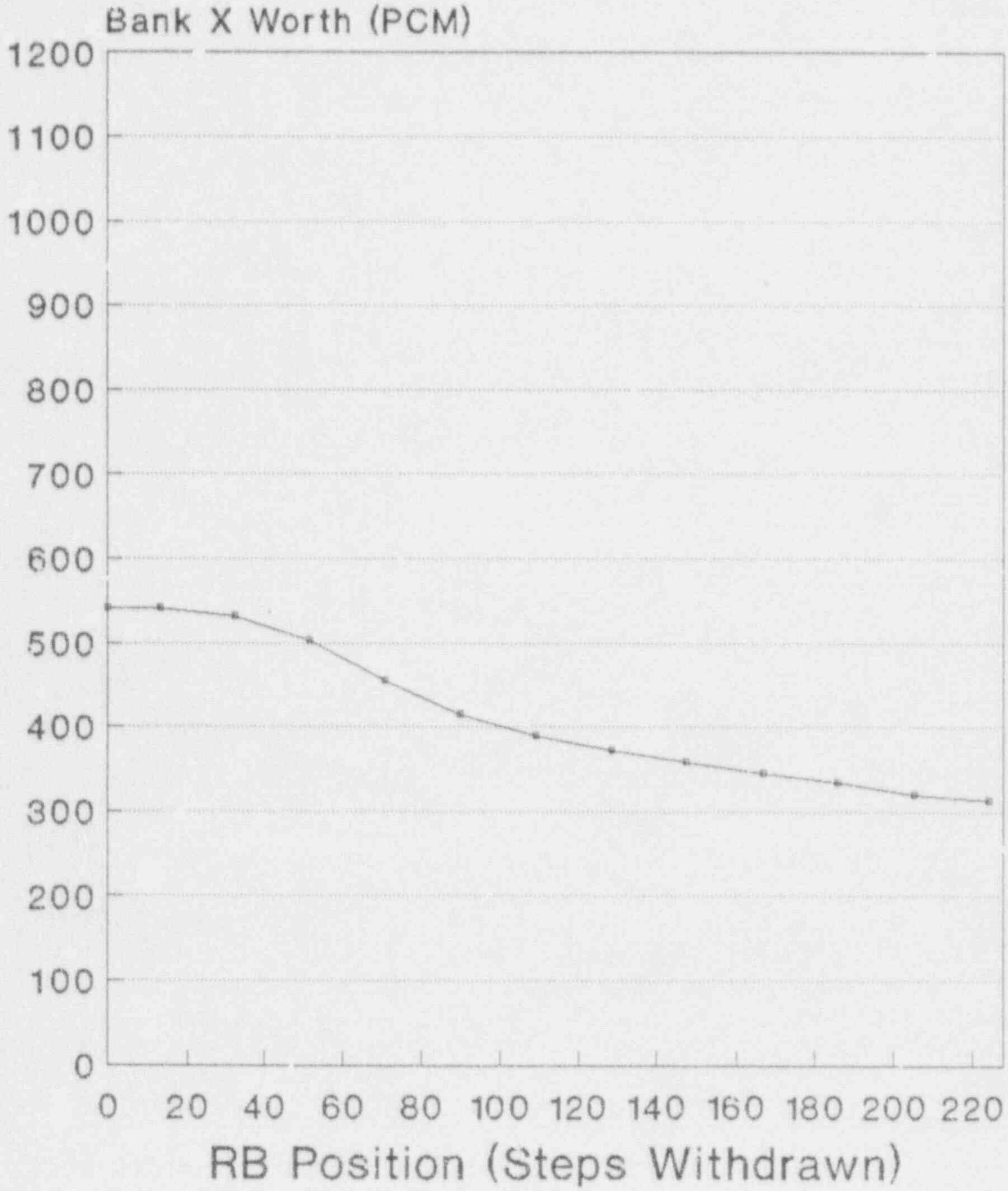


Figure 16

4.0 ACCEPTANCE AND REVIEW CRITERIA

4.1 Typical Criteria Structure

Acceptance/review criteria, as used in previously-licensed methods, involve three basic comparisons[3,4]. First, the Reference Bank worth must be within 10% of the predicted value. Since other bank worths are inferred from the Reference Bank worth, the test results shall meet this acceptance criterion.

Second, individual bank worths must be within 15% of predicted values. This criterion constitutes a review requirement. In other words, if an individual bank exceeds the criterion, then a review must be performed by the appropriate personnel to determine test acceptability. Such reviews, including corrective actions as necessary, must be completed prior to power escalation.

Third, the total worth of all banks, including the Reference Bank, must be within 10% of the predicted sum. As with the Reference Bank worth, this comparison is an acceptance criterion, and shall be met.

4.0 ACCEPTANCE AND REVIEW CRITERIA

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Third, the total worth of all banks, including the Reference Bank, must be within 10% of the predicted sum. As with the Reference Bank worth, this comparison is an acceptance criterion, and shall be met.

4.2 Union Electric Criteria Approach

Union Electric's proposed criteria structure is fundamentally the same as described above. However, to ensure meaningful validation of vendor models as well as consistency with previously-approved rod swap methods, the percentages are tightened, as discussed below.

Since Westinghouse Electric Corporation will continue to perform the licensed reload design and safety evaluations for Callaway, it is important to relate the measured bank worths to the vendor models. This could be done by performing two sets of comparisons: i) measurements vs. UE calculations, and ii) measurements vs. vendor calculations. However, this approach would be cumbersome for plant personnel. An alternative approach is to directly incorporate vendor calculations into the acceptance/review criteria. In other words, acceptance/review criteria percentages for each bank (excluding the Reference Bank) and the sum of all banks will implicitly include a comparison of Union Electric and vendor design predictions. This ensures that individual bank worths will be within +/- 15%, and the total worth of all banks will be within +/-10%, of both Union Electric <u>and</u> vendor design calculations. Reference Bank percentages are not tightened since they are set at a more stringent criteria of +/-10%.

Deviation percents between Union Electric and vendor predictions are calculated using the equation:

$$\text{Deviation}\ (\%) = [W(UE)-W(vendor)]/W(vendor) * 100$$

Where W(UE) is the bank worth value predicted by Union Electric, and W(vendor) is the worth value predicted by Westinghouse.

For example, assume the following bank worths:

CBD (UE predicted) = 700 pcm
CBD (vendor predicted) = 715 pcm
SUM (UE predicted) = 3500 pcm
SUM (vendor predicted) = 3600 pcm

(CBD = Control Bank D, and SUM = Sum of all banks)

The percent differences between the UE and vendor values are:

CBD = (700-715)/715 * 100 = - 2.1%
SUM = (3500-3600)/3600 * 100 = - 2.8%

The resulting criteria percentages, based upon both Union Electric and vendor predictions, are then:

CBD = +15%/-12.9% SUM = +10%/-7.2%

(Note that the percentages are never greater than the nominal acceptance values.)

In summary, the proposed acceptance/review criteria are fundamentally the same as in previously-licensed methods. However, to ensure consistency with vendor design models, criteria percentages will be tightened, as appropriate, based on comparisons of Union Electric and vendor design predictions. A summary of criteria range calculations for Callaway Cycles 4 and 5 is presented in Table 2.[7]

4.3 Remedial Actions

If any acceptance criterion is not met (i.e., Reference Bank worth or sum of all bank worths), then dilution measurements of the control banks will be required. This requirement is explicity incorporated into Callaway rod swap procedures.

If any review criterion is not met, the situation shall be reviewed prior to power escalation by the responsible Reactor Engineering and Nuclear Fuel engineers in conjunction with the appropriate supervisory personnel. Based on the review, testing may be repeated, other confirmatory tests performed, or based on acceptance criteria results, the test may be considered acceptable. Final resolution shall be based on analyses of plant data, any confirmatory tests, and evaluations of the impact of the discrepancy on plant safety. Again, these requirements are explicitly incorporated into Callaway rod swap procedures.

ACCEPTANCE/REVIEW CRITERIA

RANGE CALCULATIONS

CALLAWAY CYCLE 4

Bank	UE Worth	Vendor Worth	% Diff	Criteria Range (%)
CBD	701.0	719	-2.5	+15/-12.5
CBC	721.6	703	2.6	+12.4/-15
CBB	700.1	675	3.7	+11.3/-15
CBA	304.8	303	0.6	+14.4/-15
SBE	371.5	355	4.6	+10.4/-15
SBB	780.1	755	3.3	+10/-10 *
Total	3579.1	3510	2.0	+8/-10

CALLAWAY CYCLE 5

Bank	UE Worth	Vendor Worth	% Diff	Criteria Range (%)
CBD	519.5	519	0.1	+14.9/-15
CBC	882.8	885	-0.2	+10/-10 *
CBB	788.4	723	9.0	+6/-15
CBA	308.4	335	-7.9	+15/-7.1
SBE	431.4	430	0.3	+14.7/-15
SBD	476.4	452	5.4	+9.6/-15
SBC	477.8	452	5.7	+9.3/-15
SBB	881.1	830	6.2	+8.8/-15
SBA	313.0	291	7.6	+7.4/-15
Total	5078.8	4917	3.3	+6.7/-10

* Not adjusted (Reference Bank)

Table 2

5.0 TEST RESULTS AND METHODS VALIDATION

5.1 Callaway Cycles 4 & 5 Test Results

Rod swap testing was perfomed at Callaway during startup physics testing for cycles 4 and 5, in addition to conventional bank worth testing by boron dilution. Due to outage constraints in Cycle 4, only six banks were measured (including the Reference Bank). However, all nine banks were measured in Cycle 5. Thus, a total of fifteen control and shutdown banks in a wide range of core locations have been measured using rod swap over the course of two cycles. The results of these measurements are presented in Table 3 and Figures 17-31.

5.2 Other Benchmarking

Although direct comparison of rod swap measurements against design calculations is the primary validation technique, other types of comparisons are very valuable. All physics measurements are generally impacted by the same set of core parameters (i.e., power distribution, boron concentration, cross-sections, etc.). Therefore, the ability of design models to accurately predict a wide range of core behavior adds further validation of the codes and methods used.

Tables 5-9 and Figures 32-47 present additional benchmarking comparisons. These comparisons include HZP boron endpoints, HZP reactivity coefficients, HZP bank worths (boron dilution method), HFP boron letdown, and in-core detector reaction rates for BOC, MOC, and EOC burnup points. Table 4 contains a summary of the design characteristics of each cycle.

5.3 Method Equivalency (Rod Swap vs. Boron Dilution)

By comparing the percent deviations of rod swap to those of boron dilution (see Tables 3, 8, and 9), it is seen that rod swap is equivalent to boron dilution in terms of verification of design models. The standard deviation of the rod swap measurements versus predictions is 2.44%, while the standard deviation of the dilution measurements is 3.96%.

In Callaway Cycle 4, the boron dilution worth deviations for individual banks ranged from 3.4% to 5.6%, while the sum of all control banks was 4.2%. Corresponding rod swap values are -3.8% to +6.1% for individual banks, and +0.2% for the sum of banks measured.

In Cycle 5, the boron dilution worth ranges were -1.3% to 5.4%, and 2.2% respectively. Rod swap ranges were +0.1% to +4.2%, and +1.8%.

In addition, it should be noted that rod swap involves significantly less interpretation of raw test data. After the Reference Bank is measured and analyzed, all other worths are based on objective quantities. However, for boron dilution, all banks involve the tedious (and subjective) interpretation of reactivity traces. Thus, rod swap should produce greater consistency of results. To an extent, this tendency is seen in the rod swap vs. boron dilution comparisons - there is less overall scatter in the rod swap deviations.

5.4 Benchmarking Conclusions

The benchmark data contained in this report demonstrates that Union Electric's codes and methods are highly accurate in peforming reactor physics calculations. In particular, comparisons of rod swap measurements to design predictions validate Union Electric's rod swap methodology and confirm that rod swap is equivalent to boron dilution in terms of validation of design models.

ROD SWAP TEST RESULTS

Callaway Cycle 4

Bank	RB CP (Raw)	RB CP (Adj)	Meas. Worth	Pred. Worth	Error(%)	Accept Range(%)	OK ?
SBB (RB)	NA	NA	808.6	780.1	+3.3	+10/-10	Yes
CBD	197.5	194.0	697.6	725.3	-3.8	+15/-12.5	Yes
CBC	200.5	197.2	712.9	710.2	+0.4	+12.4/-15	Yes
CBB	189.0	186.0	658.2	672.3	-2.1	+11.3/-15	Yes
CBA	122.0	119.5	337.8	337.5	+0.1	+14.4/-15	Yes
SBE	118.5	118.0	330.5	311.6	+6.1	+10.4/-15	Yes
Total			3545.6	3537.0	+0.2	+8.0/-10	Yes

Callaway Cycle 5

Bank	RB CP (Raw)	RB CP (Adj)	Meas. Worth	Pred. Worth	Error(%)	Accept Range(%)	OK ?
CBC (RB)	NA	NA	889.1	882.8	+0.7	+10/-10	Yes
CBD	143.0	138.0	583.8	572.0	+2.1	+14.9/-15	Yes
CBB	200.0	192.0	808.0	801.6	+0.8	+6.0/-15	Yes
CBA	82.5	79.0	235.1	234.8	+0.1	+15/-7.1	Yes
SBE	108.0	104.0	399.4	385.2	+3.7	+14.7/-15	Yes
SBD	136.5	132.0	554.9	532.6	+4.2	+9.6/-15	Yes
SBC	136.5	132.0	552.8	533.6	+3.6	+9.3/-15	Yes
SBB*	228.0	(NA)	876.0	875.1	+0.1	+8.8/-15	Yes
SBA	109.0	105.0	407.9	394.8	+3.3	+7.4/-15	Yes
Total			5307.0	5212.5	+1.8	+6.7/-10	Yes

* "Swap-out" condition occured: W(SBB) = W(RB) - Delta-Rho 1 + excess reactivity
= 889pcm - 29.5pcm + 16.5pcm = 876 pcm

Table 3

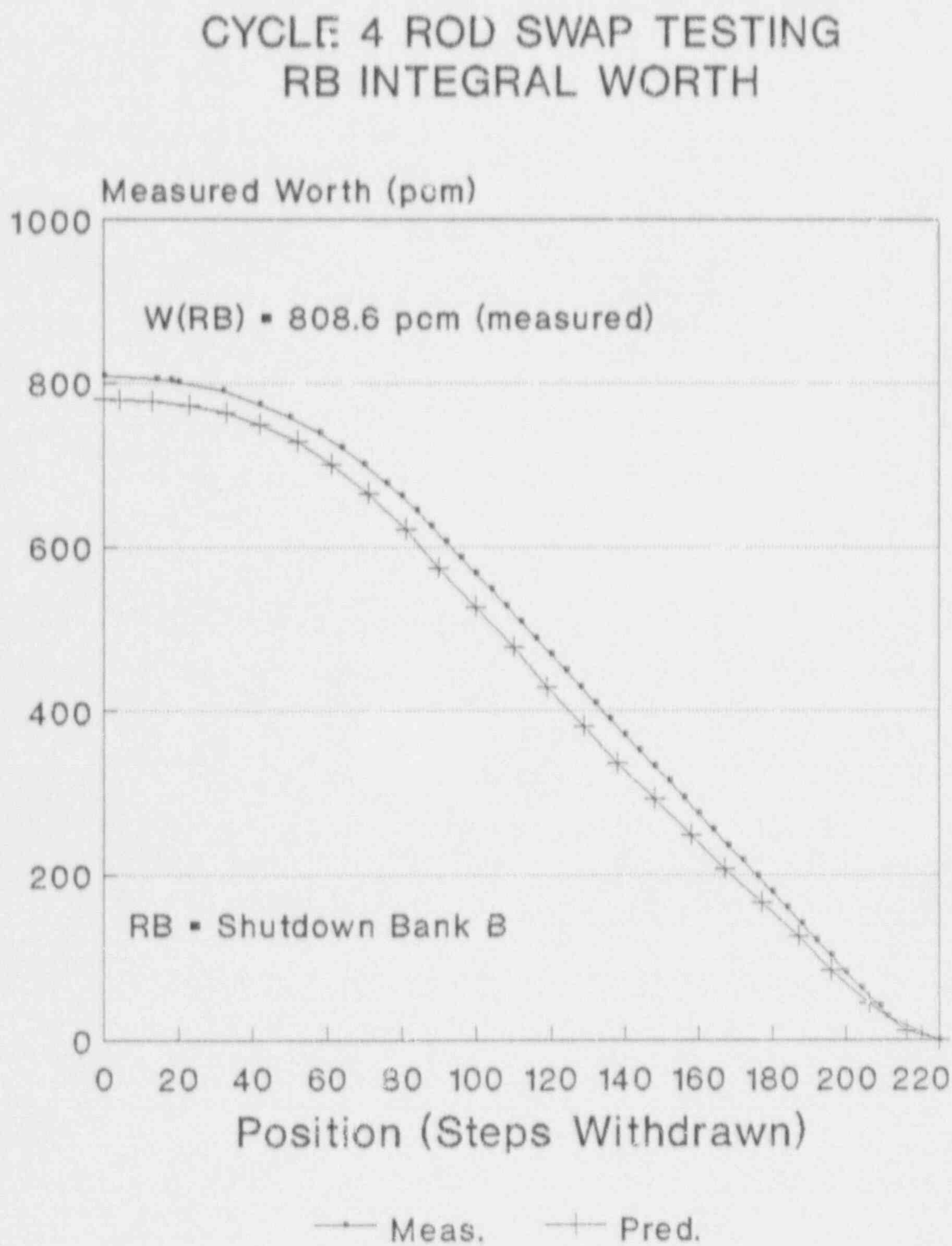

CYCLE 4 ROD SWAP TESTING
RB INTEGRAL WORTH
Measured Worth (pcm)
1000
800
600
400
200
0
W(RB) = 808.6 pcm (measured)
RB = Shutdown Bank B
0 20 40 60 80 100 120 140 160 180 200 220
Position (Steps Withdrawn)
Meas.
Pred.

Figure 17

CYCLE 4 ROD SWAP TESTING
CBD MEASUREMENT

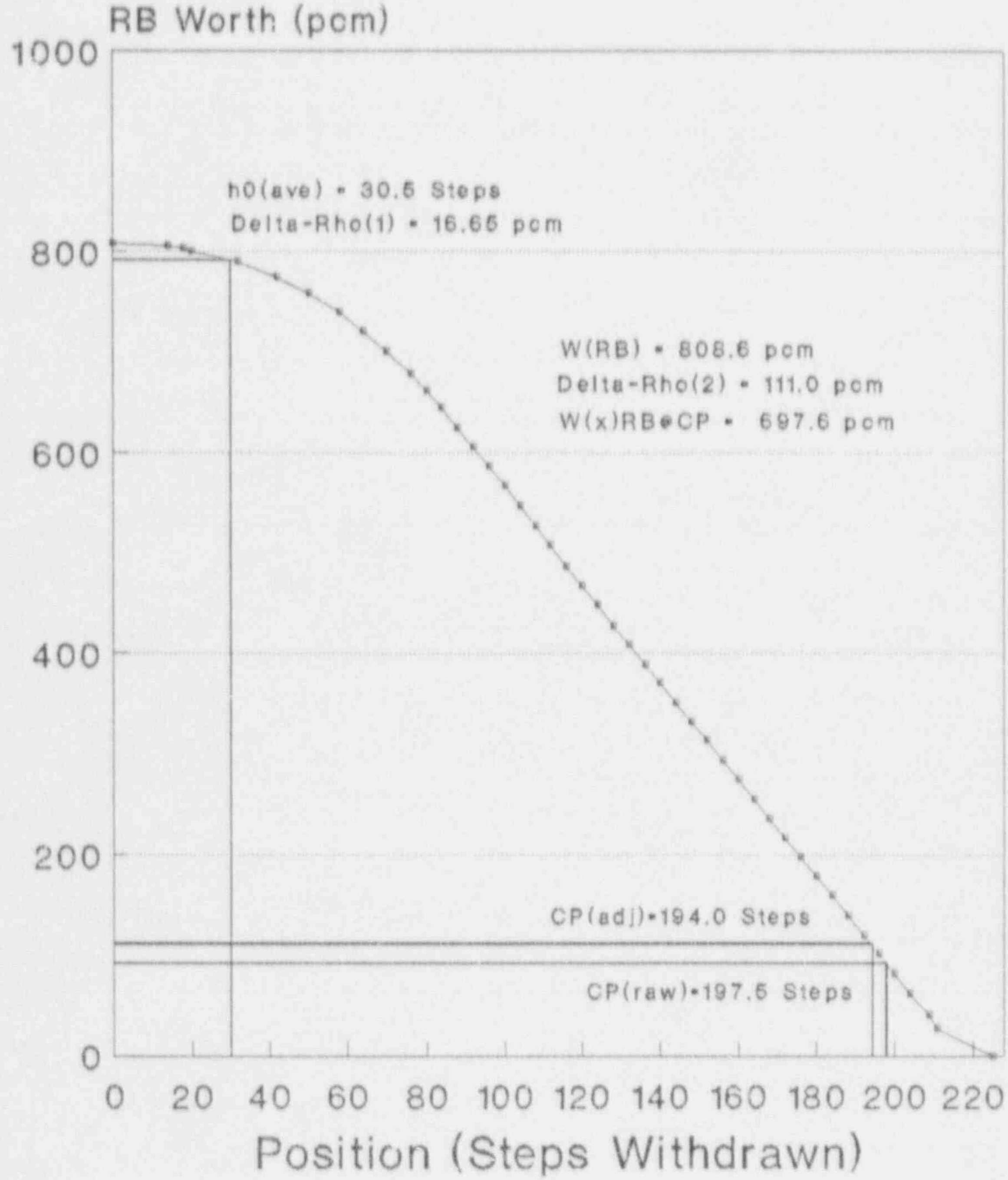


Figure 18

CYCLE 4 ROD SWAP TESTING
CBC MEASUREMENT

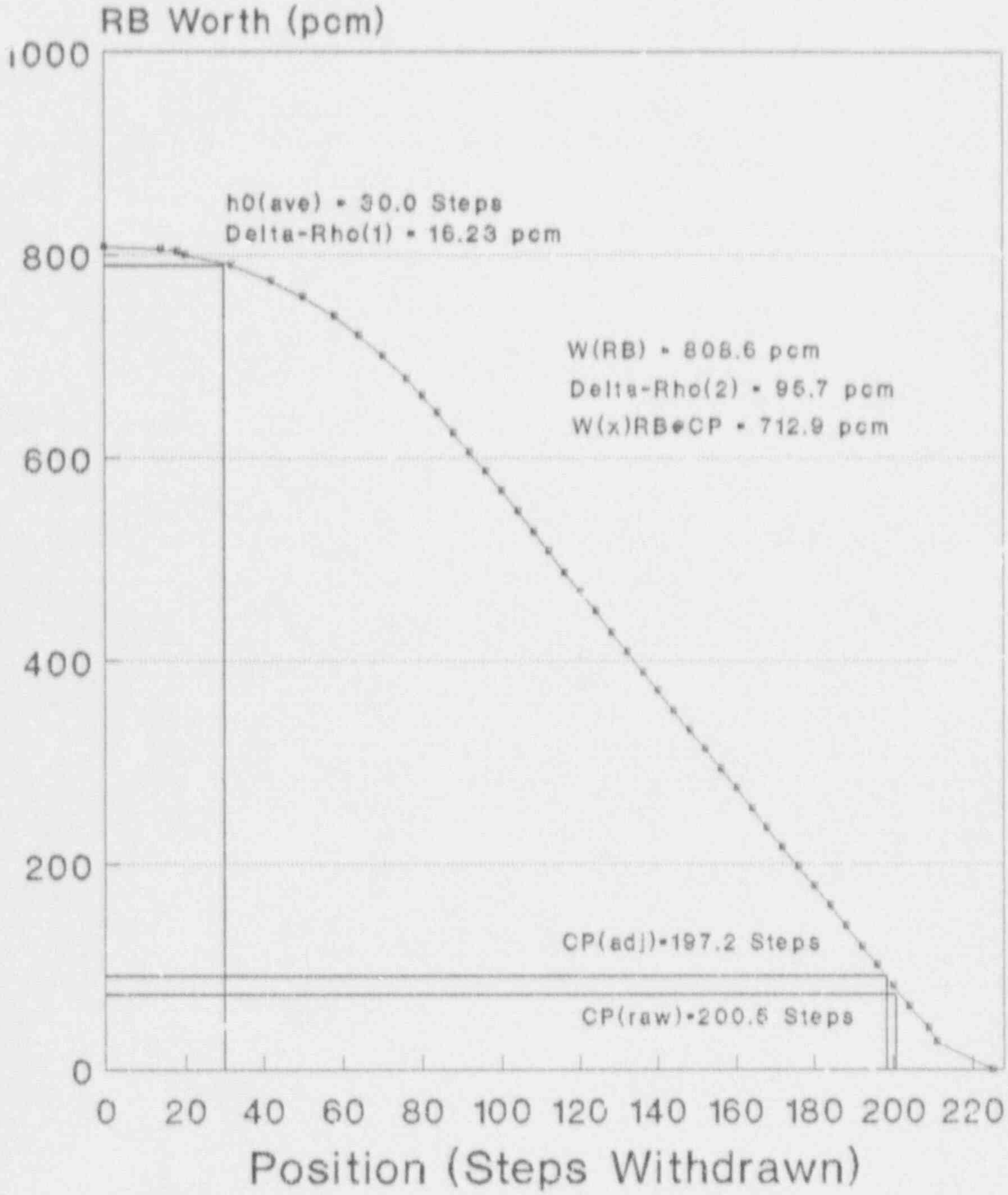


Figure 19

CYCLE 4 ROD SWAP TESTING
CBB MEASUREMENT

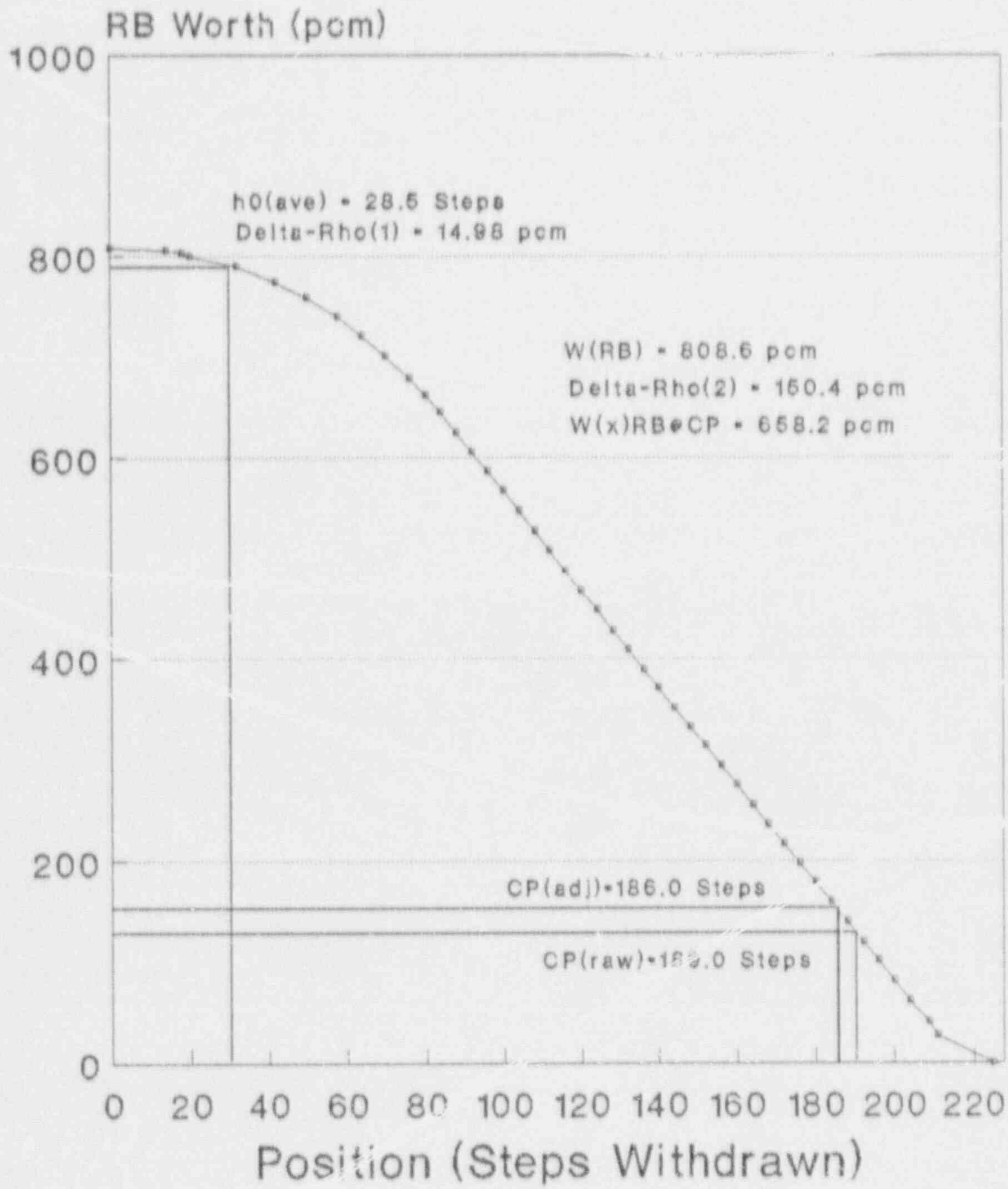


Figure 20

CYCLE 4 ROD SWAP TESTING
CBA MEASUREMENT

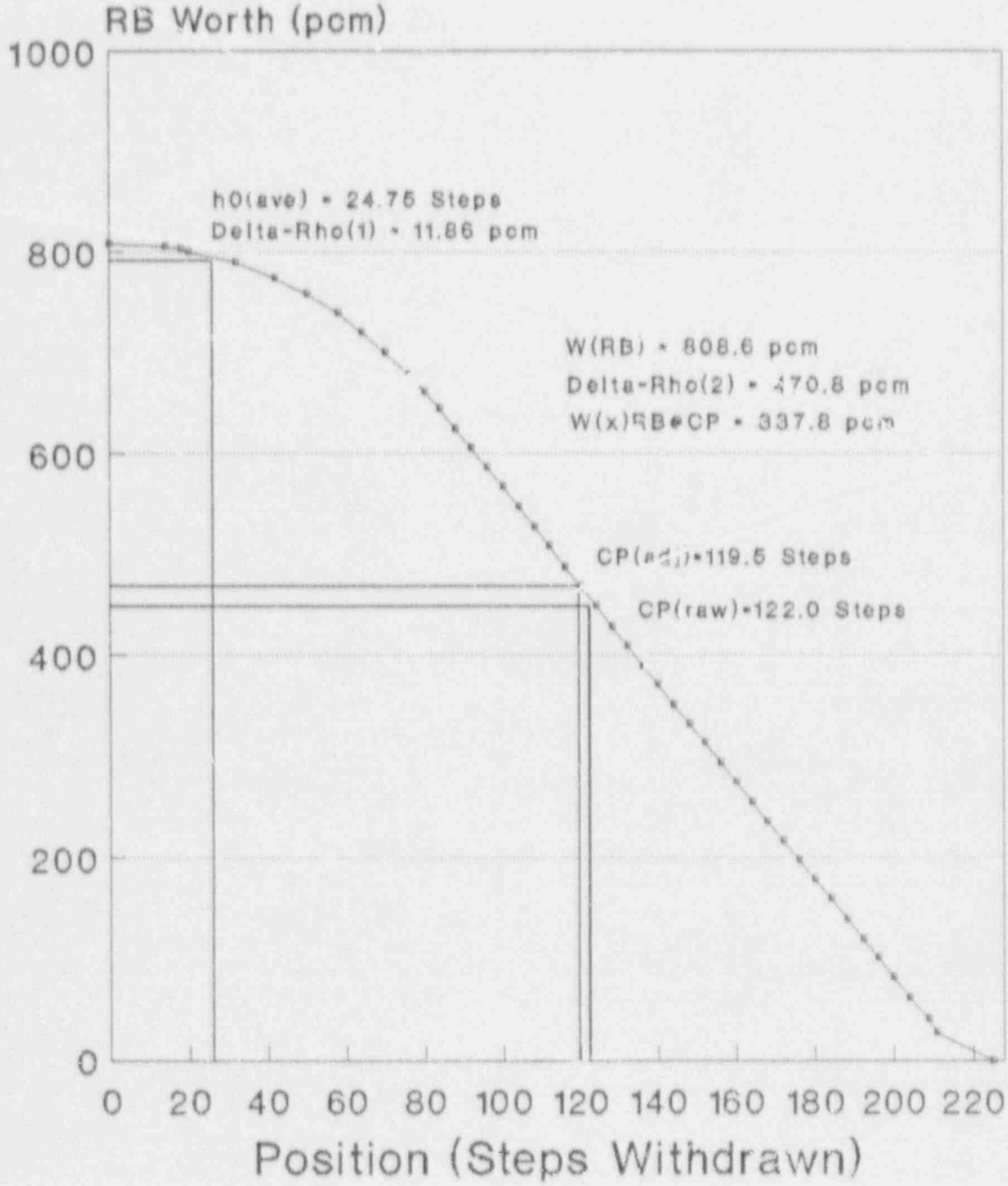


Figure 21

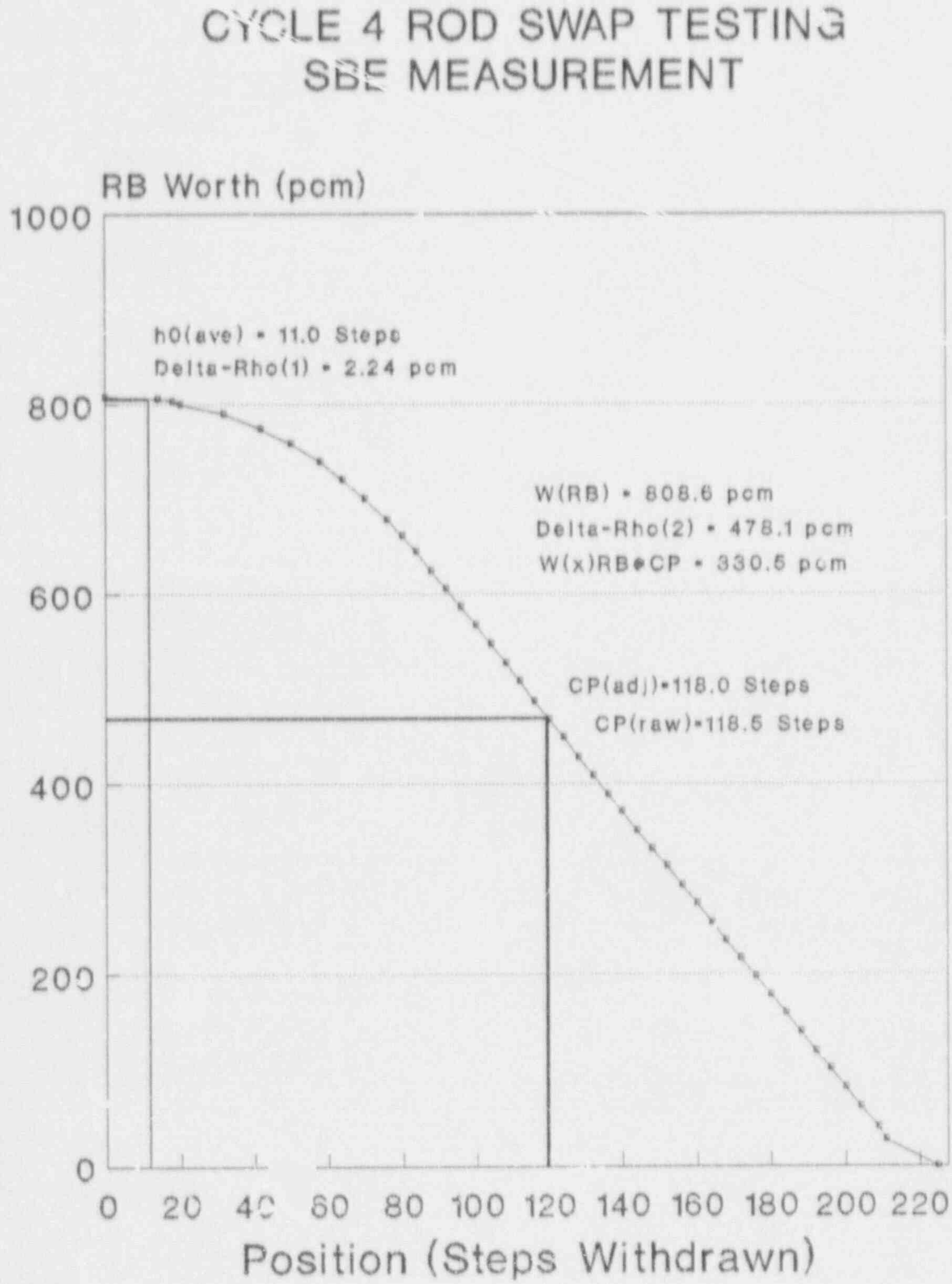

CYCLE 4 ROD SWAP TESTING
SBE MEASUREMENT
RB Worth (pcm)
1000
800
600
400
200
0
h0(ave) = 11.0 Steps
Delta-Rho(1) = 2.24 pcm
W(RB) = 808.6 pcm
Delta-Rho(2) = 478.1 pcm
W(x)RB@CP = 330.5 pcm
CP(adj)=118.0 Steps
CP(raw)=118.5 Steps
0 20 40 60 80 100 120 140 160 180 200 220
Position (Steps Withdrawn)

Figure 22

CYCLE 5 ROD SWAP TESTING
RB INTEGRAL WORTH

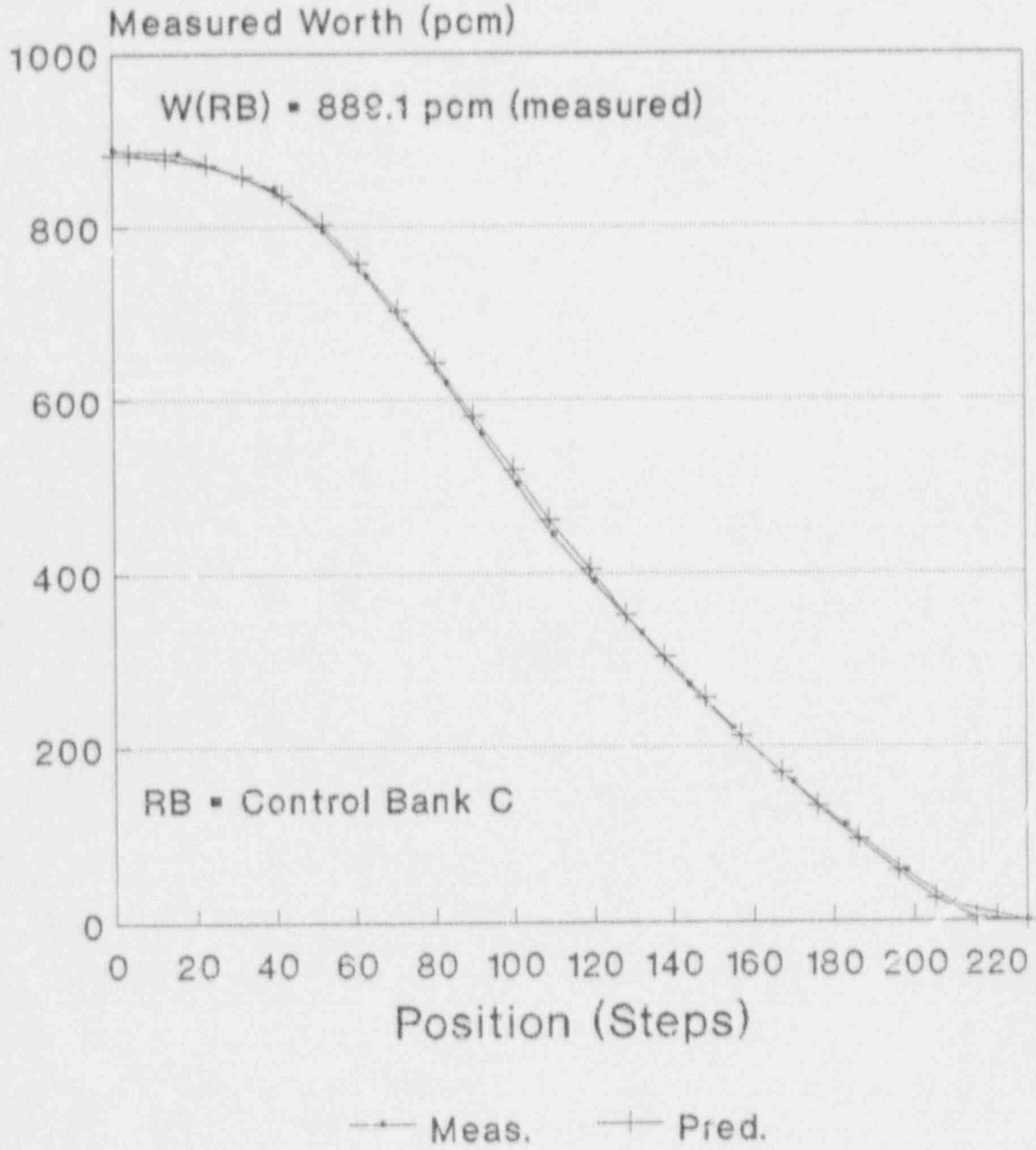


Figure 23

CYCLE 5 ROD SWAP TESTING
CBD MEASUREMENT

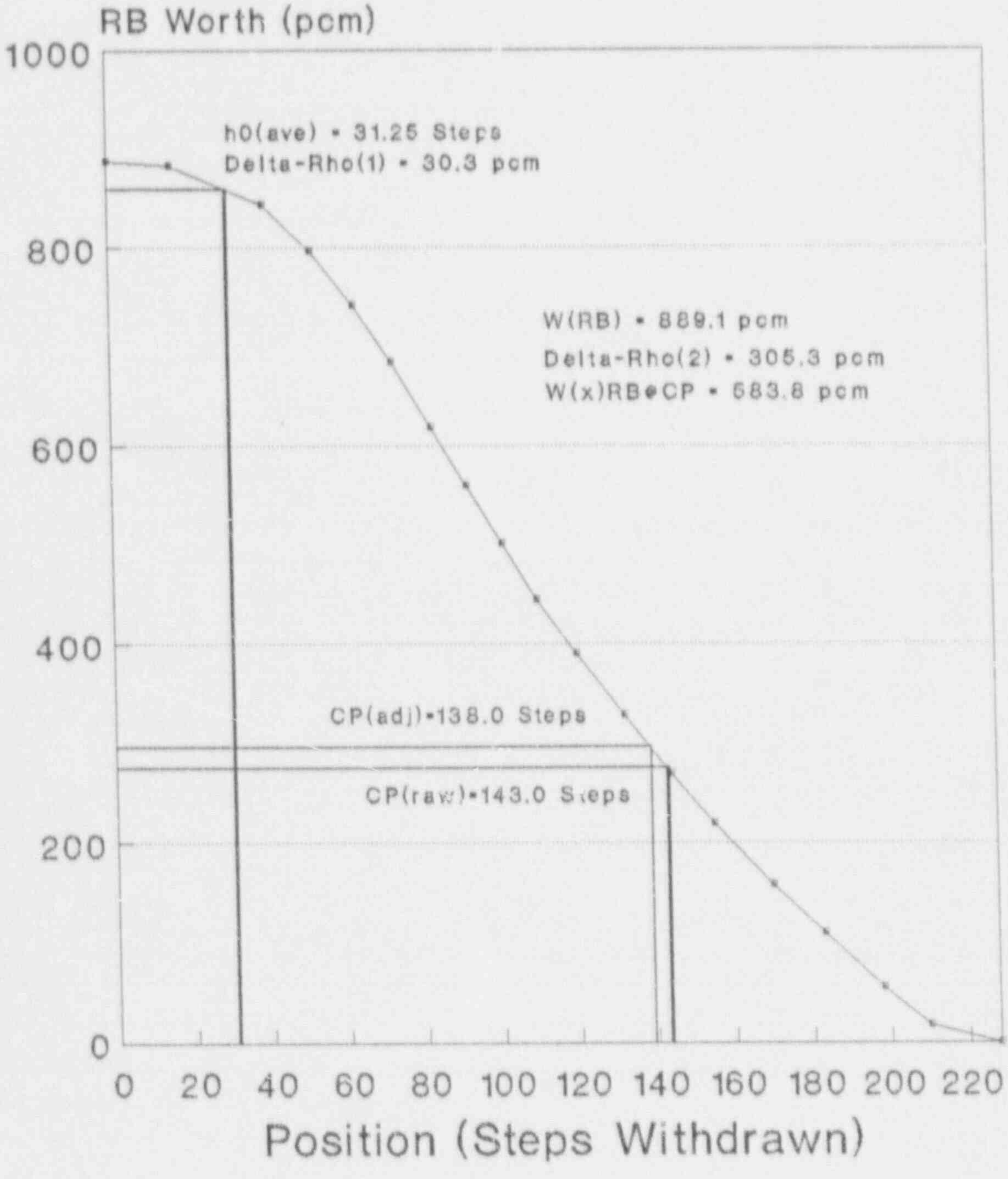


Figure 24

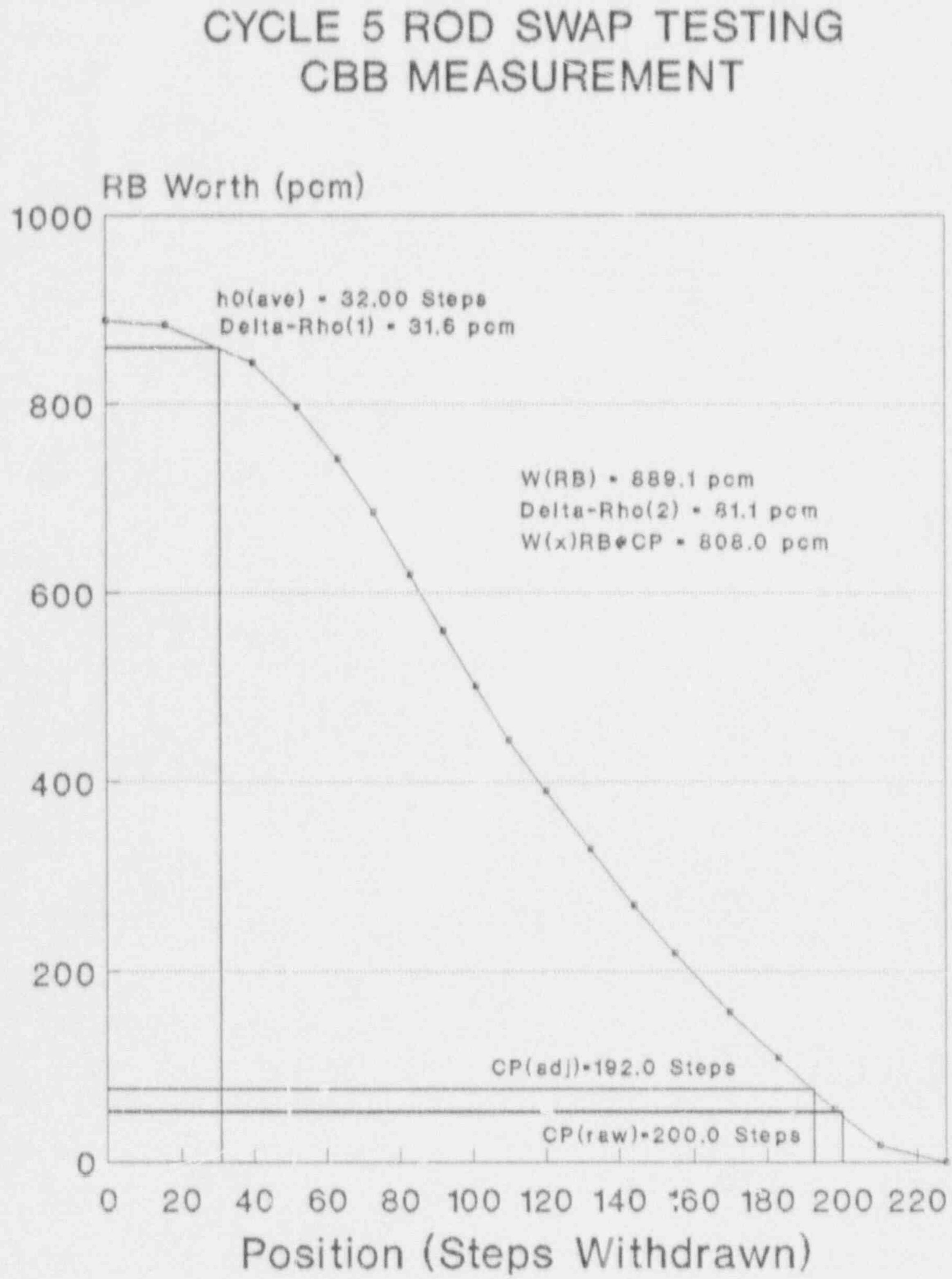

CYCLE 5 ROD SWAP TESTING
CBB MEASUREMENT
RB Worth (pcm)
1000
800
600
400
200
0
h0(ave) = 32.00 Steps
Delta-Rho(1) = 31.6 pcm
W(RB) = 889.1 pcm
Delta-Rho(2) = 81.1 pcm
W(x)RB*CP = 808.0 pcm
CP(adj)=192.0 Steps
CP(raw)=200.0 Steps
0 20 40 60 80 100 120 140 160 180 200 220
Position (Steps Withdrawn)

Figure 25

CYCLE 5 ROD SWAP TESTING
CBA MEASUREMENT

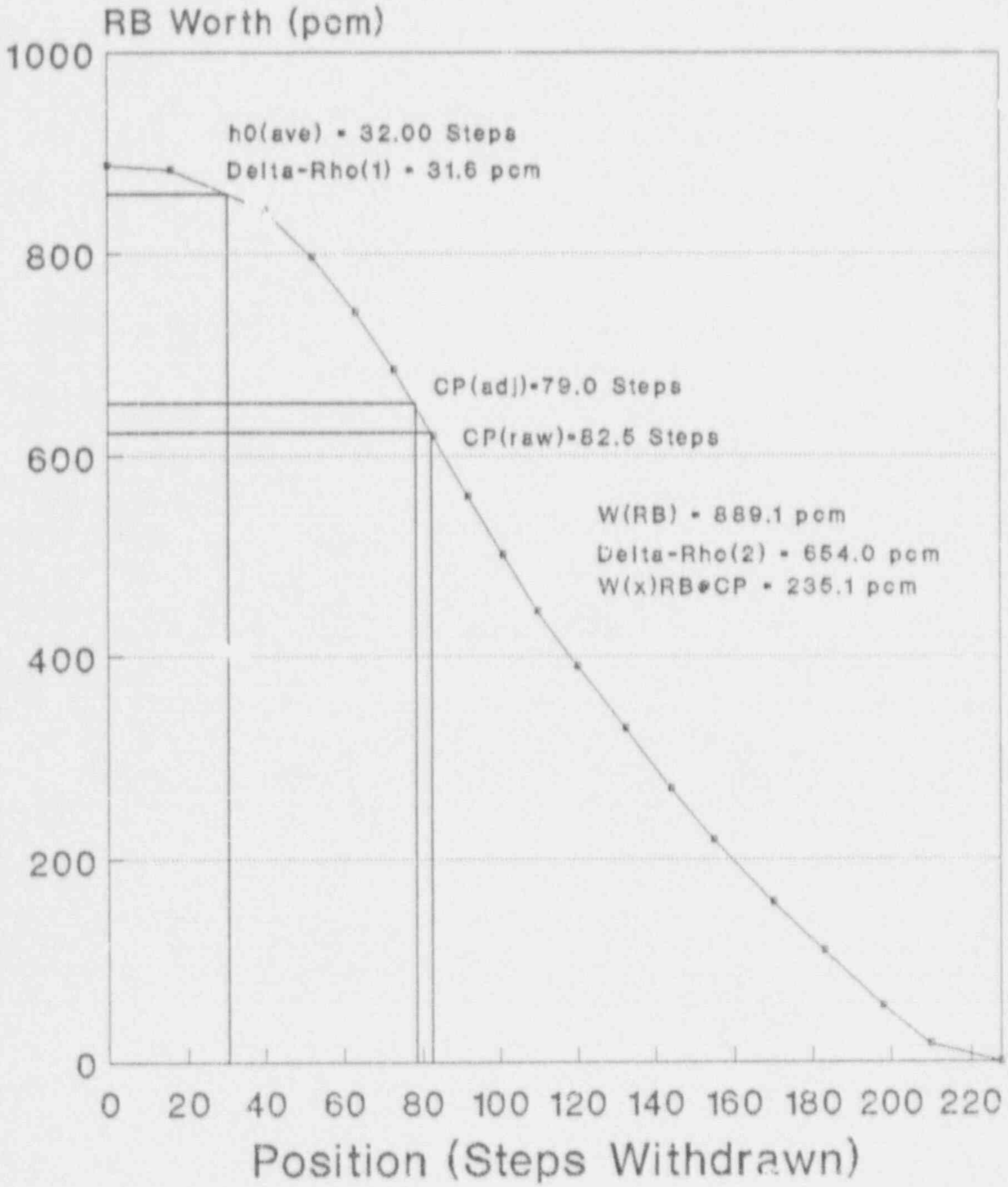


Figure 26

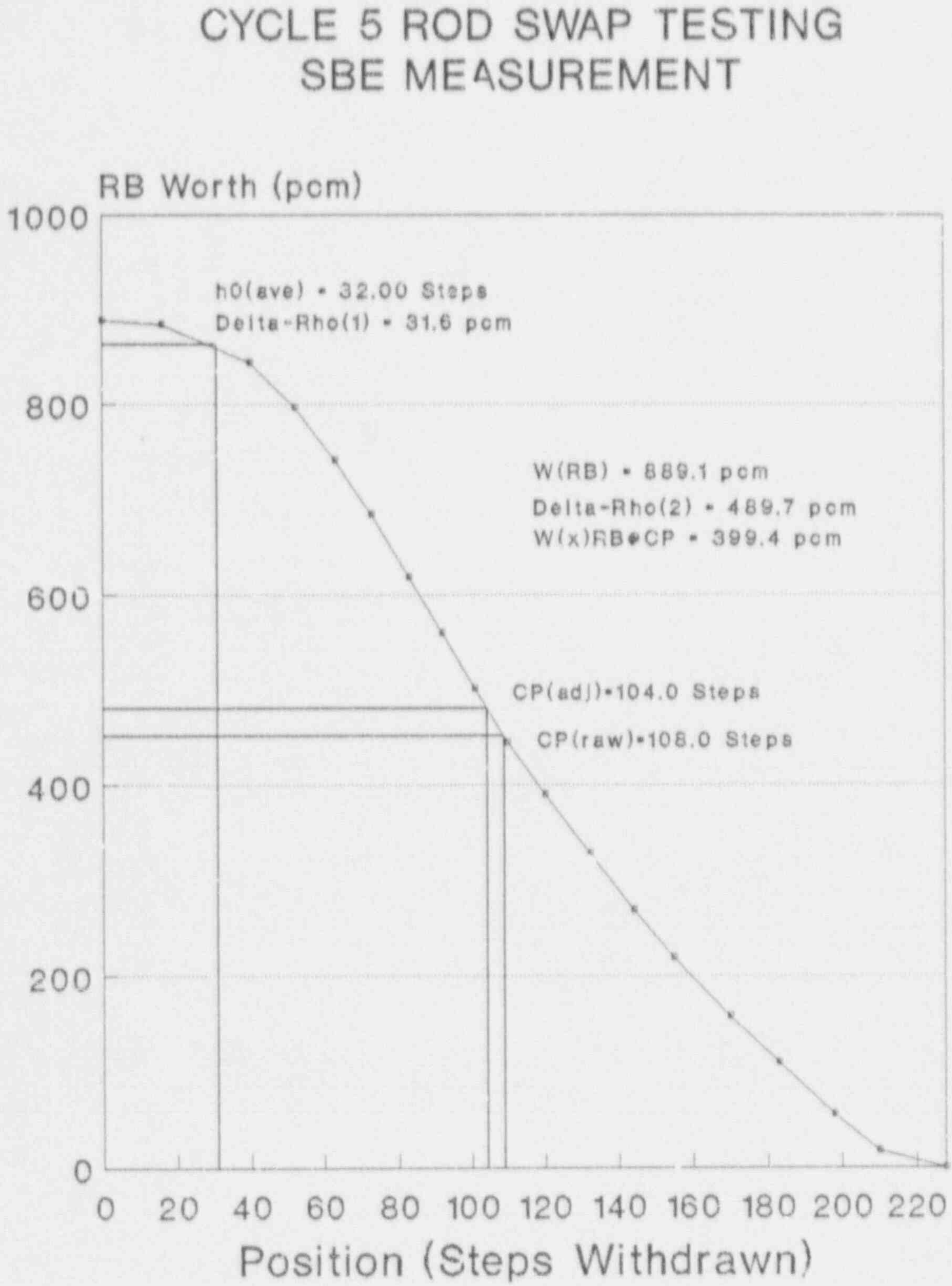

CYCLE 5 ROD SWAP TESTING
SBE MEASUREMENT
RB Worth (pcm)
1000
800
600
400
200
0
h0(ave) • 32.00 Steps
Delta-Rho(1) • 31.6 pcm
W(RB) • 889.1 pcm
Delta-Rho(2) • 489.7 pcm
W(x)RB•CP • 399.4 pcm
CP(adj)•104.0 Steps
CP(raw)•108.0 Steps
0 20 40 60 80 100 120 140 160 180 200 220
Position (Steps Withdrawn)

Figure 27

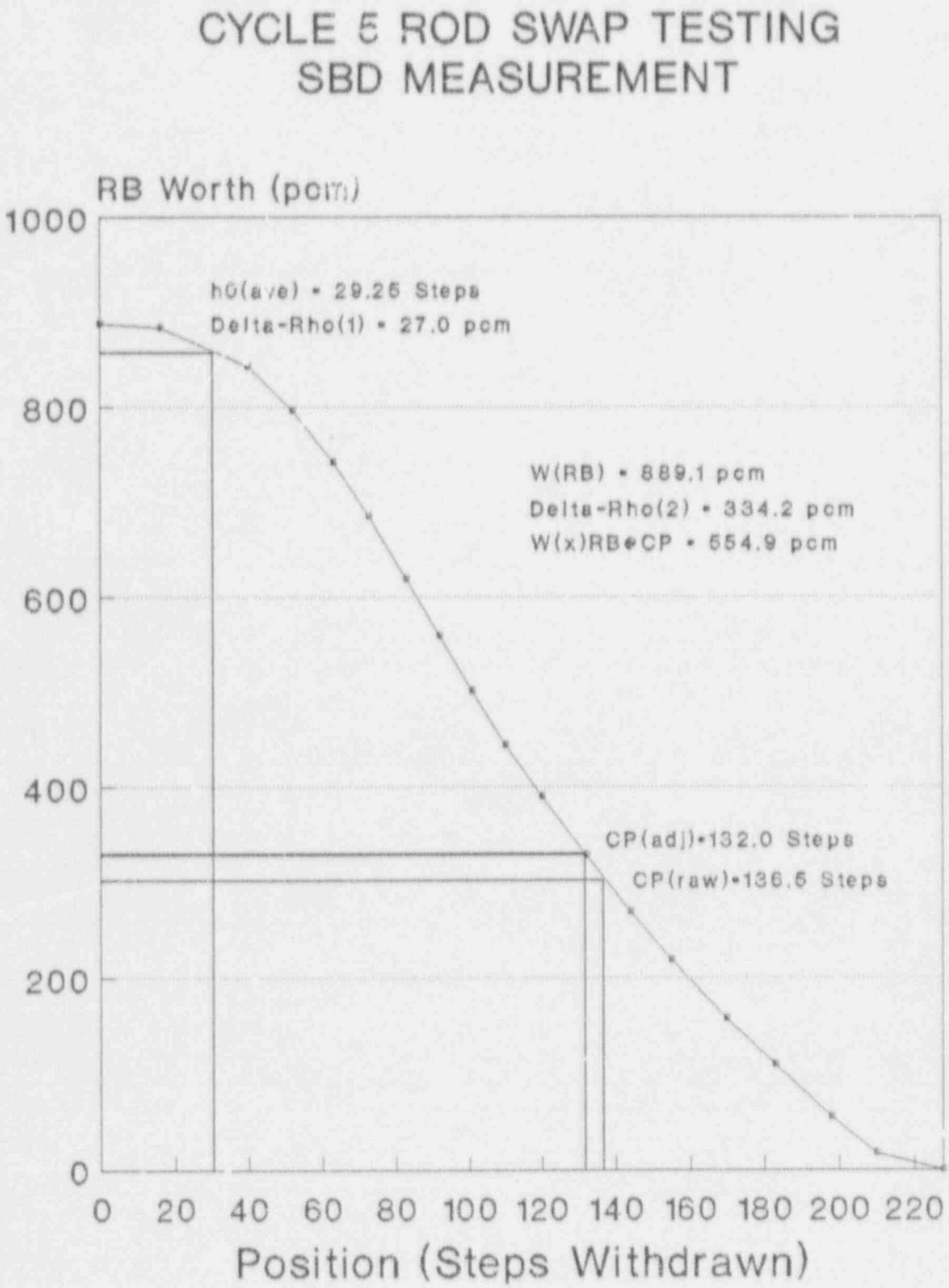

CYCLE 5 ROD SWAP TESTING
SBD MEASUREMENT
RB Worth (pcm)
1000
800
600
400
200
0
h0(ave) • 29.25 Steps
Delta-Rho(1) • 27.0 pcm
W(RB) • 889.1 pcm
Delta-Rho(2) • 334.2 pcm
W(x)RB*CP • 554.9 pcm
CP(adj)•132.0 Steps
CP(raw)•136.5 Steps
0 20 40 60 80 100 120 140 160 180 200 220
Position (Steps Withdrawn)

Figure 28

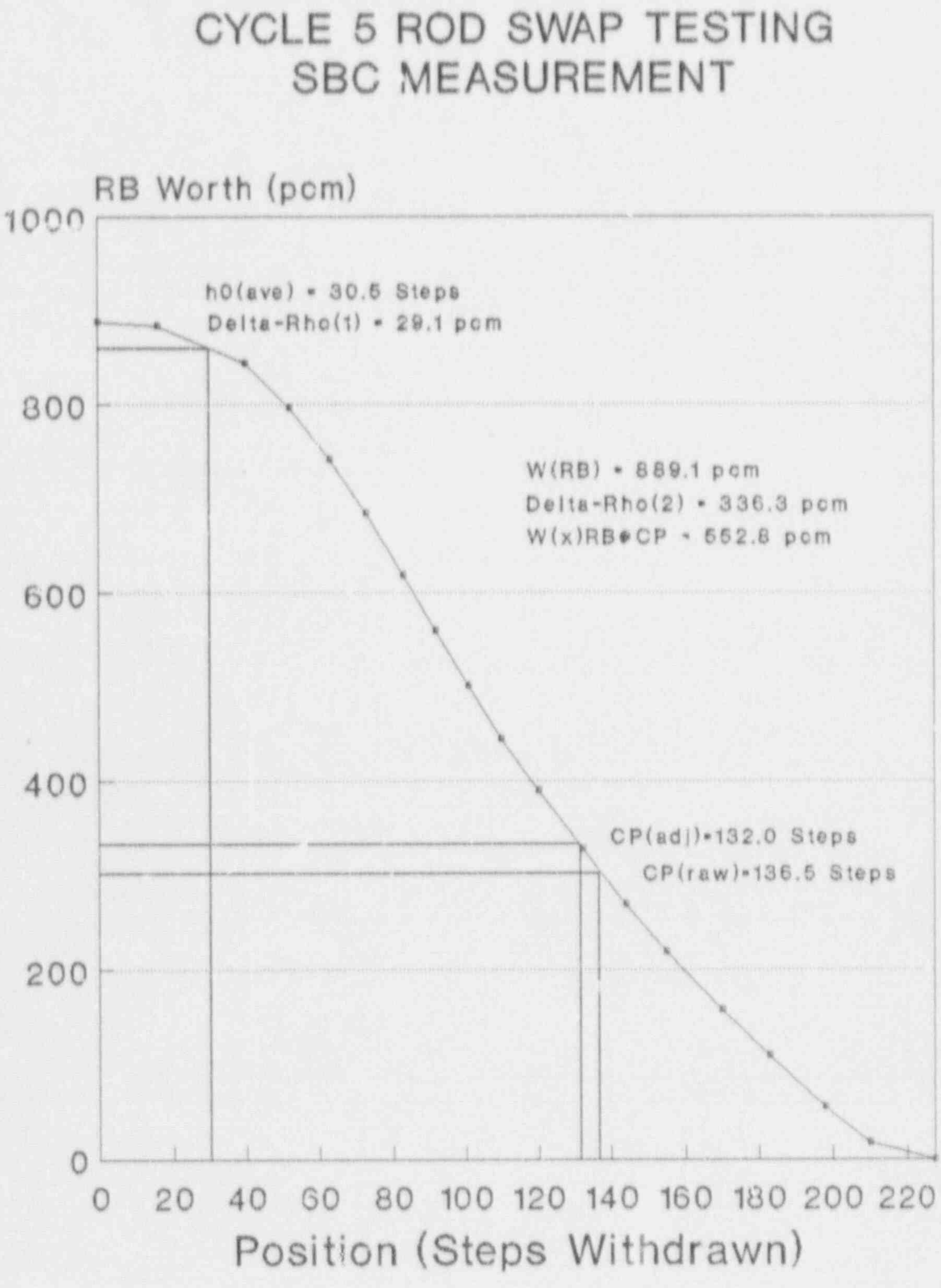

CYCLE 5 ROD SWAP TESTING
SBC MEASUREMENT
RB Worth (pcm)
1000
800
600
400
200
0
h0(ave) = 30.5 Steps
Delta-Rho(1) = 29.1 pcm
W(RB) = 889.1 pcm
Delta-Rho(2) = 336.3 pcm
W(x)RB*CP = 552.8 pcm
CP(adj)=132.0 Steps
CP(raw)=136.5 Steps
0 20 40 60 80 100 120 140 160 180 200 220
Position (Steps Withdrawn)

Figure 29

CYCLE 5 ROD SWAP TESTING
SBB MEASUREMENT

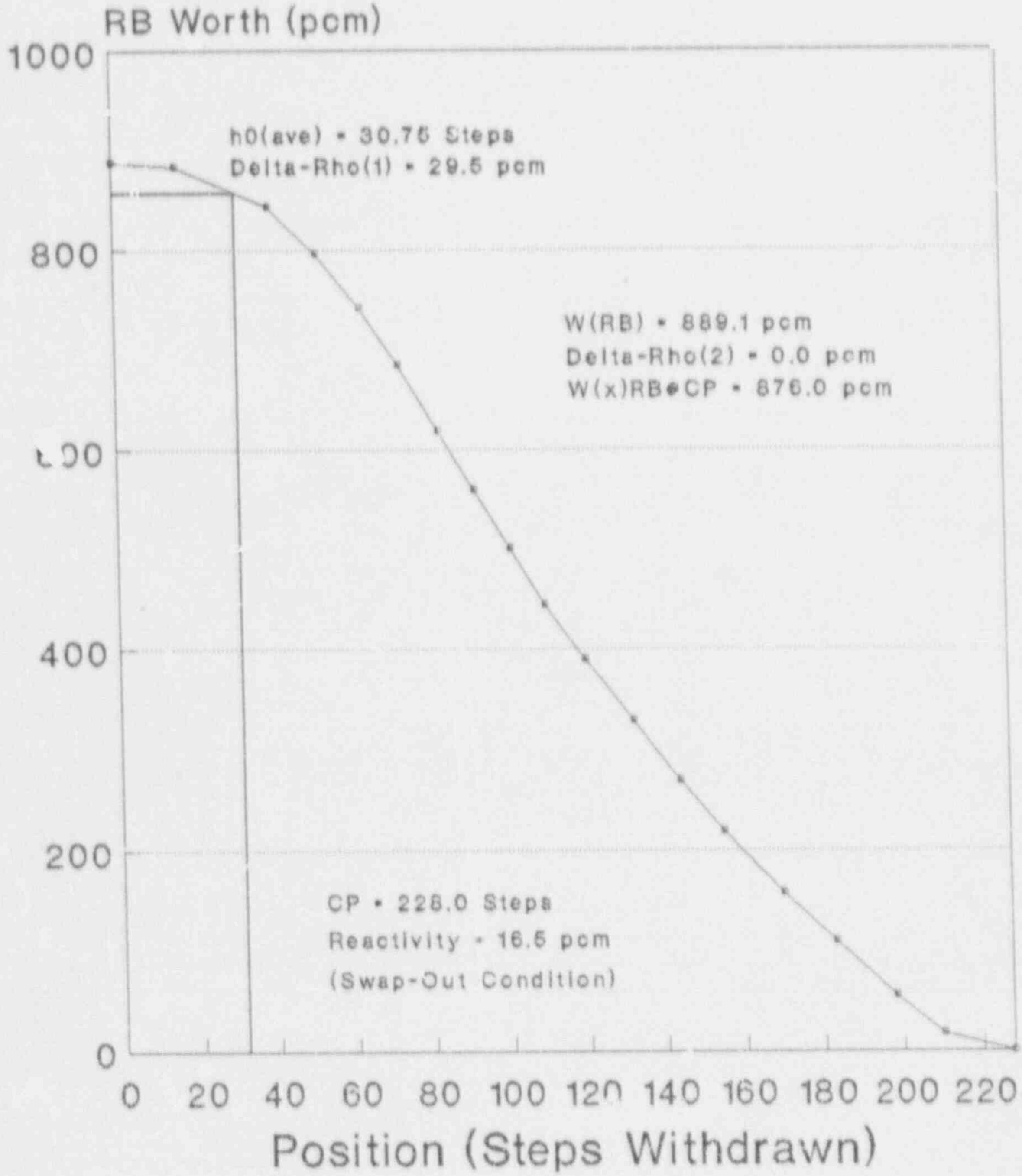


Figure 30

CYCLE 5 ROD SWAP TESTING
SBA MEASUREMENT

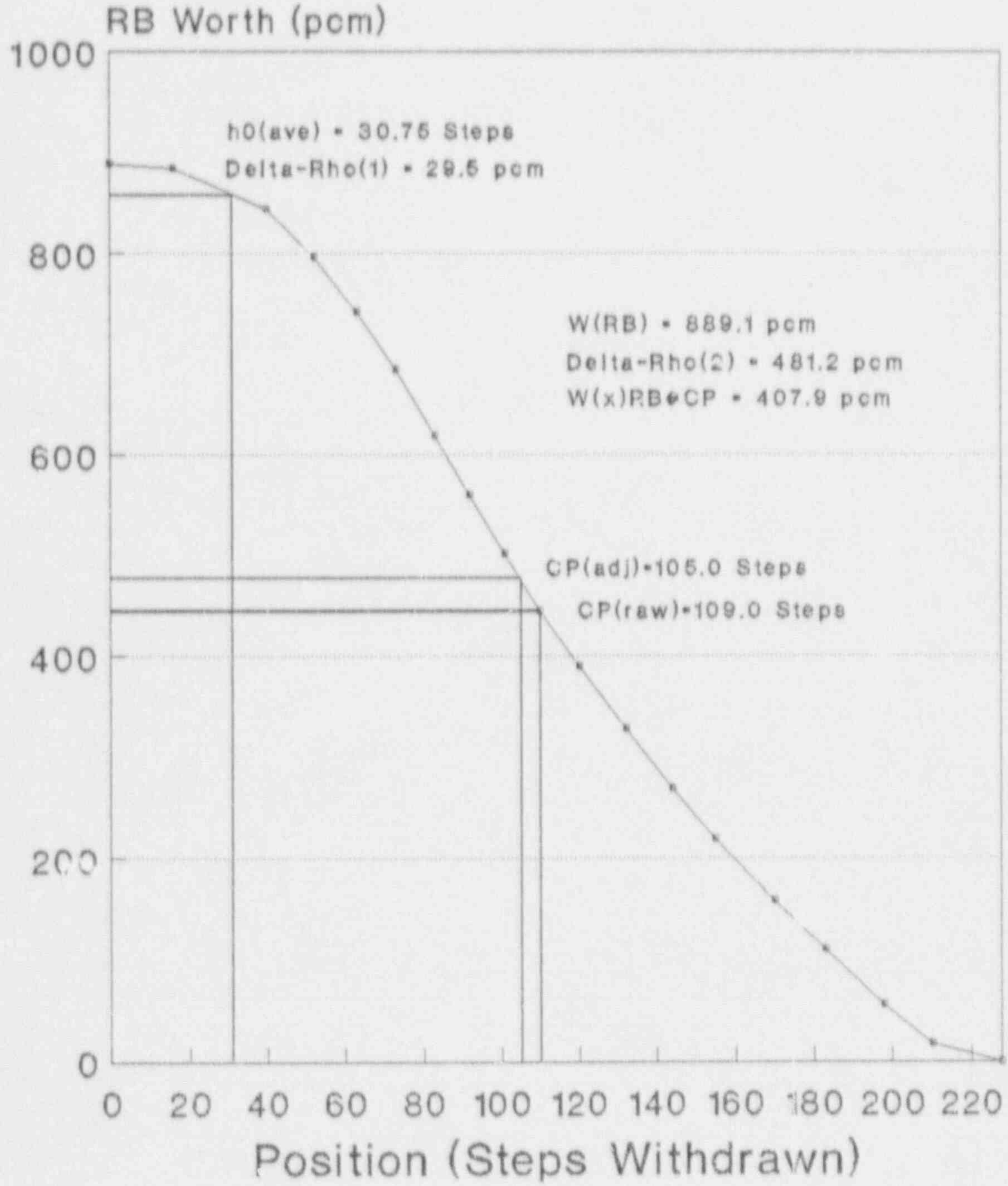


Figure 31

CALLAWAY NUCLEAR PLANT

REACTOR DESCRIPTION
and
CYCLE DESIGN SUMMARY

REACTOR DESCRIPTION (CURRENT)

Westinghouse 4 Loop
193 Assemblies, 17x17 Lattice
3565 MWt (Uprated from 3411 MWt)
Low Leakage Loading Patterns
Ag-In-Cd RCCAs

CYCLE DESIGN SUMMARY

Cycle No.	Feed Assm	Mech Type	Feed w/o	BA Types	RCCA Type	Cycle BU GWD/MTU)
1	193	STD	2.1, 2.6, 3.1	STD BPR	Hafnium	15.286
2	84	OFA	3.4, 3.8	WABA	Hafnium	16.675
3	96	V5	3.6, 3.8, 4.2	WABA/IFBA	Hafnium	19.308
4	92	V5	4.0, 4.4	WABA/IFBA	Ag-In-Cd	20.015
5	92	V5	4.0, 4.4	IFBA	Ag-In-Cd	20.186

Table 4

CALLAWAY CYCLE 1

STARTUP PHYSICS TESTS RESULTS

BORON ENDPOINTS (PPM)

Configuration	Measured	SIMULATE	Delta (S-M)
ARO	1334	1351	17
D-in	1276	1288	12
D+C-in	1148	1167	19
D+C+B-in	1042	1071	29
D+C+B+A-in	979	1006	27

REACTIVITY COEFFICIENTS (PCM/DEG F)

	Measured	SIMULATE	Delta (S-M)
ARO ITC	-0.66	-0.24	0.42
D-in ITC	-2.20	-1.52	0.68
D+C-in ITC	-5.58	-5.20	0.38

INTEGRAL CONTROL BANK WORTHS (PCM)

Bank	Measured	SIMULATE	Error (%)
D	663	641	-3.3
C (D-in)	1177	1232	4.7
B (D+C-in)	1010	997	-1.3
A (D+C+B-in)	685	673	-1.8
SE (D+C+B+A-in)	882	852	-3.4
SD (D+C+B+A+SE-in)	738	737	-0.1
SC (D+C+B+A+SE+SD	978	961	-1.7
Total	6133	6093	-0.7

Table 5

CALLAWAY CYCLE 2

STARTUP PHYSICS TESTS RESULTS

BORON ENDPOINTS (PPM)

Configuration	Measured	SIMULATE	Delta (S-M)
ARO	1529	1497	-32
D-in	1457	1425	-32
D+C-in	1328	1296	-32

REACTIVITY COEFFICIENTS (PCM/DEG F)

	Measured	SIMULATE	Delta (S-M)
ARO ITC	-2.17	-1.47	0.70
D-in ITC	-3.16	-3.01	0.15
D+C-in ITC	-5.79	-5.88	-0.09

INTEGRAL CONTROL BANK WORTHS (PCM)

Bank	Measured	SIMULATE	Error (%)
D	621	618	-0.5
C (D-in)	1043	1115	6.9
B (D+C-in)	905	921	1.8
A (D+C+B-in)	470	522	11.1 *
Total	3039	3176	4.5

* Test acceptance based on measurement vs. vendor, which passed.

Table 6

CALLAWAY CYCLE 3

STARTUP PHYSICS TESTS RESULTS

BORON ENDPOINTS (PPM)

Configuration	Measured	SIMULATE	Delta (S-M)
ARO	1550	1532	-18
D-in	1486	1467	-19
D+C-in	1379	1363	-16

REACTIVITY COEFFICIENTS (PCM/DEG F)

	Measured	SIMULATE	Delta (S-M)
ARO ITC	-1.97	-1.52	0.45
D-in ITC	-2.92	-2.67	0.25
D+C-in ITC	-6.06	-5.95	0.11

INTEGRAL CONTROL BANK WORTHS (PCM)

Bank	Measured	SIMULATE	Error (%)
D	551	538	-2.4
C (D-in)	896	872	-2.7
B (D+C-in)	1327	1242	-6.4
A (D+C+B-in)	394	389	-1.3
Total	3168	3041	-4.0

Table 7

CALLAWAY CYCLE 4

STARTUP PHYSICS TESTS RESULTS

BORON ENDPOINTS (PPM)

Configuration	Measured	SIMULATE	Delta (S-M)
ARO	1708	1657	-51
Control Banks-In	1327	1353	26

REACTIVITY COEFFICIENTS (PCM/DEG F)

	Measured	SIMULATE	Delta (S-M)
ARO ITC	1.79	2.71	0.93

INTEGRAL CONTROL BANK WORTHS (PCM)

Bank	Measured	SIMULATE	Er[illegible] (%)
D	678	701	3.4
C (D-in)	928	961	3.6
B (D+C-in)	857	905	5.6
A (D+C+B-in)	656	684	4.3
Total	3119	3251	4.2

Table 8

CALLAWAY CYCLE 5

STARTUP PHYSICS TESTS RESULTS

BORON ENDPOINTS (PPM)

Configuration	Measured	SIMULATE	Delta (S-M)
ARO	1720	1697	-23
Control Banks-in	1311	1282	-29

REACTIVITY COEFFICIENTS (PCM/DEG F)

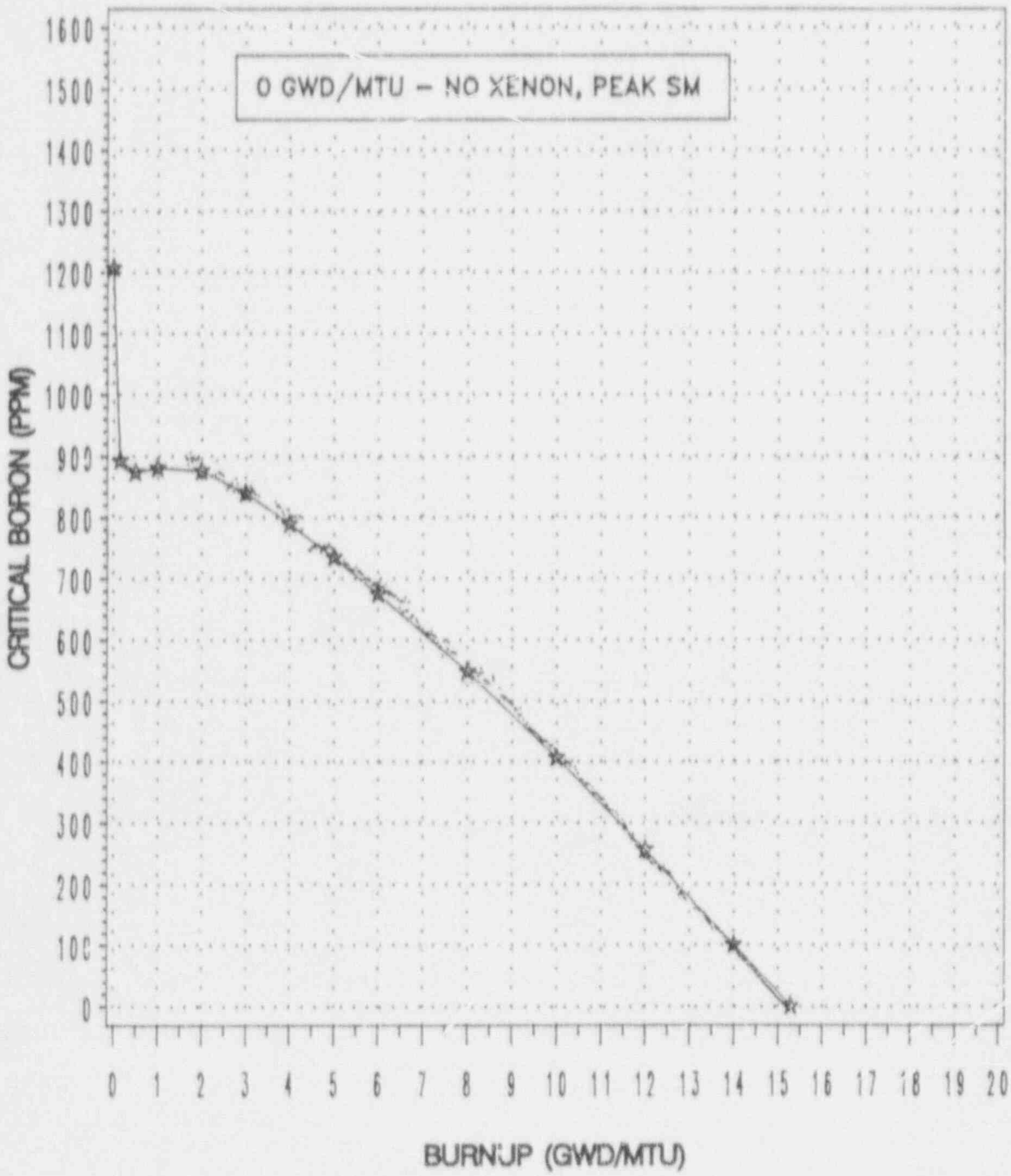
	Measured	SIMULATE	Delta (S-M)
ARO ITC	0.92	3.38	2.47

INTEGRAL CONTROL BANK WORTHS (PCM)

Bank	Measured	SIMULATE	Error (%)
D	527	520	-1.3
C (D-in)	1114	1150	3.2
B (D+C-in)	1009	1019	1.0
A (D+C+B-in)	609	642	5.4
Total	3259	3331	2.2

Table 9

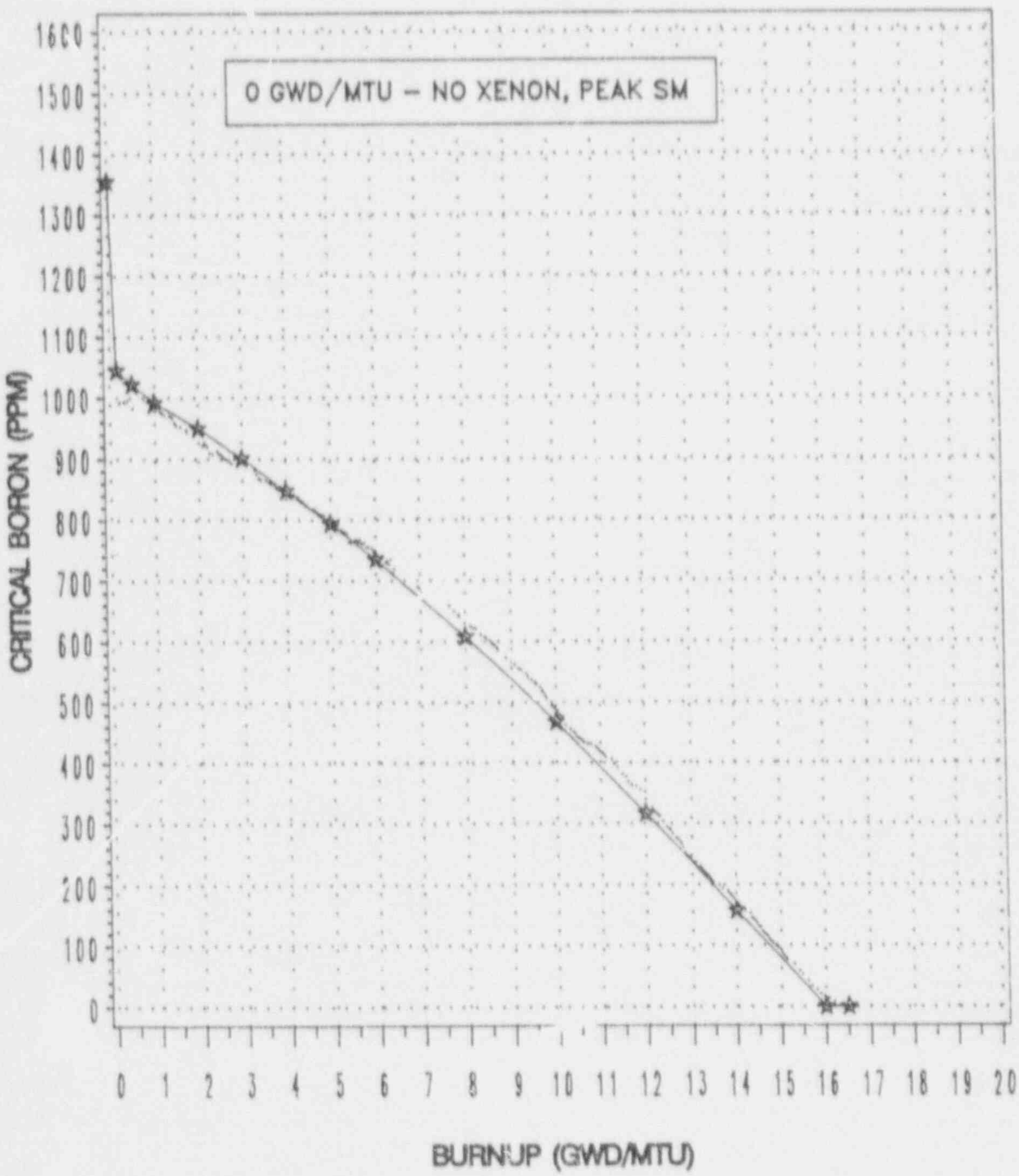
CALLAWAY CYCLE 1
BORON LETDOWN
HFP, ARO, EQ. XENON



•= MEASURED
⋆= UNION ELECTRIC (SIMULATE-3P)

Figure 32

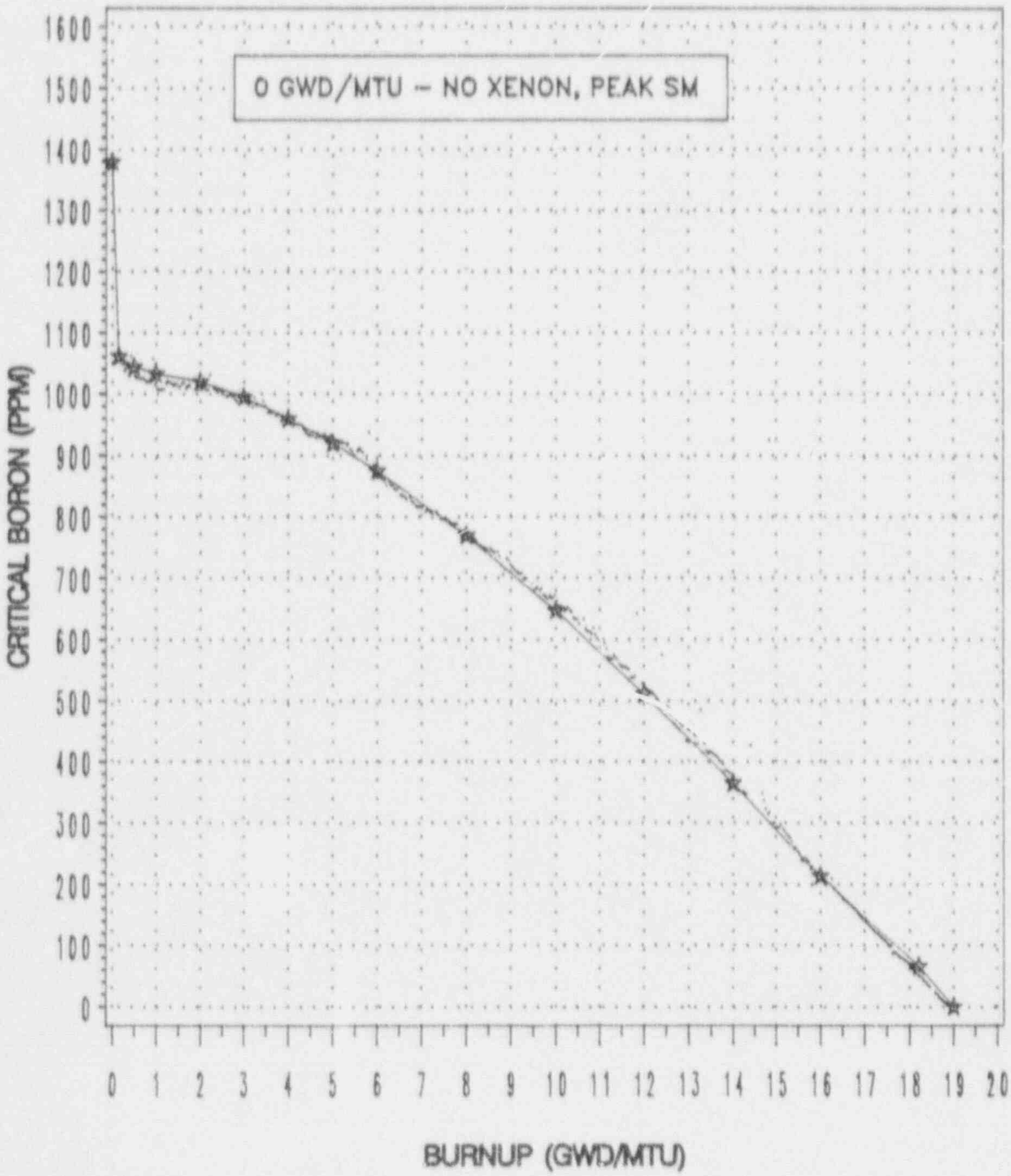
CALLAWAY CYCLE 2
BORON LETDOWN
HFP, ARO, EQ. XENON



•= MEASURED
⋆= UNION ELECTRIC (SIMULATE–3P)

Figure 33

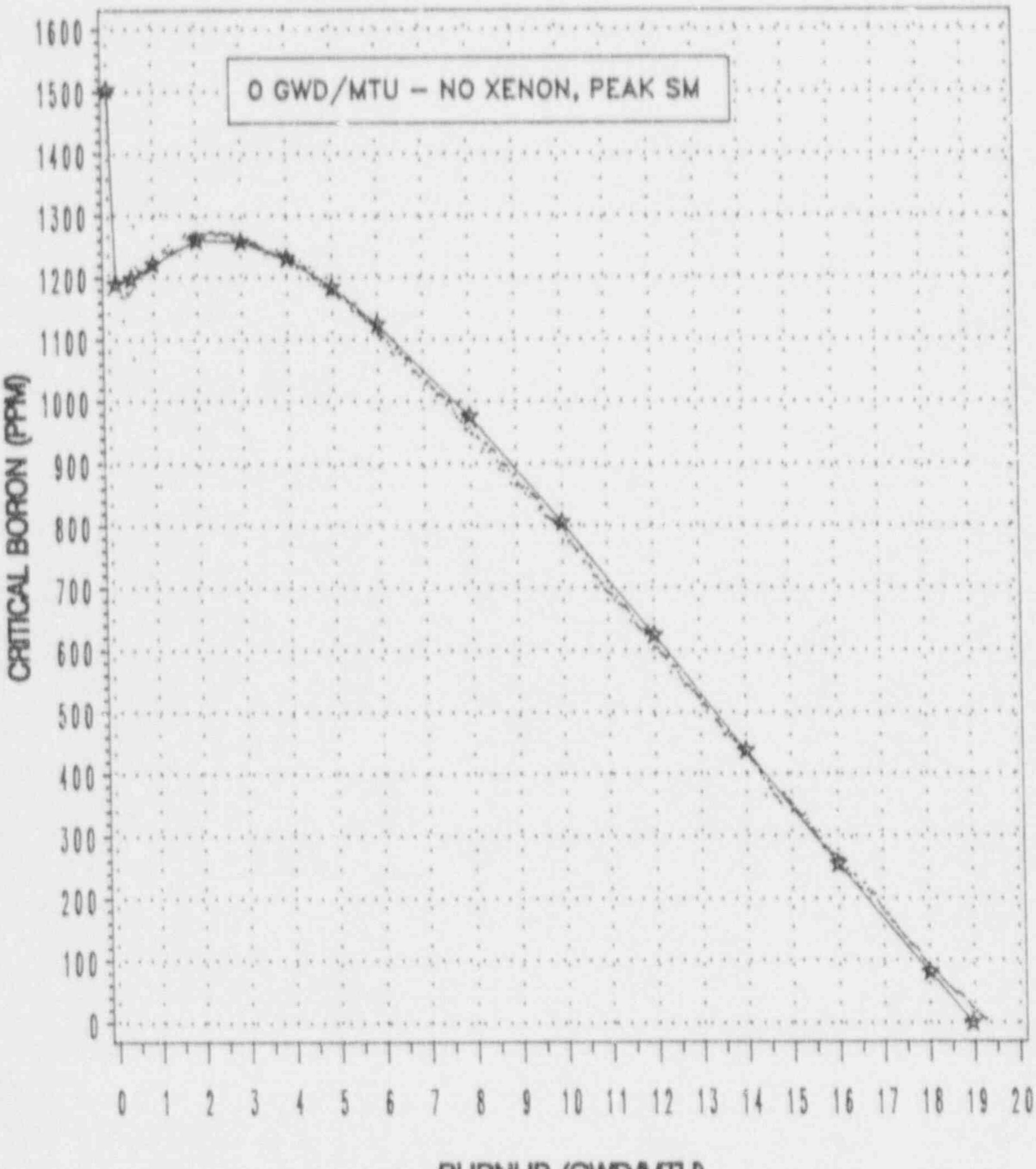
CALLAWAY CYCLE 3
BORON LETDOWN
HFP, ARO, EQ. XENON



•= MEASURED
☆= UNION ELECTRIC (SIMULATE–3P)

Figure 34

CALLAWAY CYCLE 4
BORON LETDOWN
HFP, ARO, EQ. XENON



•= Measured (corrected for HFP–ARO and SOL B10 Depletion)
☆= UNION ELECTRIC (SIMULATE–3P)

Figure 35

CALLAWAY CYCLE 1

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
8	--- --- ---	0.941 0.938 -0.33%	1.325 1.302 -1.77%	1.061 1.064 0.35%	*+*+* 1.430 1.399 -2.17%	1.036 1.044 0.83%	1.225 1.213 -0.93%	0.635 0.660 3.89%
9	0.941 0.938 -0.33%	1.283 1.260 -1.82%	0.989 0.986 -0.28%	1.400 1.374 -2.43%	*+*+* 1.054 1.076 2.13%	--- --- ---	0.841 0.864 2.68%	0.691 0.700 1.26%
10	1.325 1.302 -1.77%	0.982 0.986 0.34%	1.369 1.344 -1.80%	--- --- ---	1.396 1.366 -2.15%	1.006 1.019 1.25%	--- --- ---	0.583 0.611 4.80%
11	1.061 1.064 0.35%	--- --- ---	1.056 1.065 0.88%	1.389 1.365 -1.69%	--- --- ---	1.283 1.281 -0.17%	--- --- ---	0.499 0.505 1.32%
12	*+*+* 1.430 1.399 -2.17%	0.000 1.076	--- --- ---	--- --- ---	1.235 1.213 -1.75%	0.896 0.913 1.92%	0.726 0.743 2.38%	
13	*+*+* 1.036 1.044 0.83%	1.359 1.346 -0.91%	--- --- ---	1.305 1.281 -1.89%	--- --- ---	0.867 0.884 1.98%	0.433 0.454 4.89%	
14	1.225 1.213 -0.93%	0.847 0.864 1.94%	1.180 1.176 -0.34%	--- --- ---	0.742 0.743 0.12%	0.433 0.454 4.89%		
15	0.635 0.660 3.89%	0.000 0.700	--- --- ---	0.495 0.505 2.16%				

Burnup (GWD/MTU): 0.140
Power Level (MWt): 1706
Power Level (%): 50.0%
Bank D Position (Steps): 214

****
Peak Assm (Measured) : 1.430
****

+++++++++++++++++
Peak Assm (SIMULATE) : 1.399
+++++++++++++++++

Error Summary	
R.M.S. =	2.19%
Worst Assembly =	4.89%

KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 36

CALLAWAY CYCLE 1

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G		E	D	C	B	A
			++*					
	---	1.122	[illegible]	1.136	1.301	1.065	1.135	0.634
8	---	1.111	[illegible]	1.129	1.301	1.069	1.138	0.662
	---	-1.01%	-0.89%	-0.65%	-0.01%	0.31%	0.27%	4.45%
			++*					
	1.122	1.330	1.117	1.332	1.122	---	0.880	0.669
9	1.111	1.318	1.115	1.316	1.110	---	0.890	0.681
	-1.01%	-0.86%	-0.20%	-1.16%	-1.10%	---	1.16%	1.84%
	++*							
	1.333	1.116	.330	---	1.291	1.052	---	0.593
10	1.321	[illegible]	1.318	---	1.286	1.046	---	0.615
	-0.89%	-0.11%	[illegible]	---	-0.39%	-0.53%	---	3.64%
	++*							
	1.136	---	1.128	1.308	---	1.193	---	0.496
11	1.129	---	1.122	1.299	---	1.197	---	0.504
	-0.65%	---	-0.56%	-0.64%	---	0.34%	---	1.52%
	1.301	1.115	---	---	1.170	0.943	0.714	
12	1.301	[illegible]	---	---	1.136	0.946	0.717	
	-0.01%	[illegible]	---	---	-2.89%	0.38%	0.54%	
	1.065	1.259	---	1.205	---	0.835	0.449	
13	1.069	1.250	---	1.197	---	0.840	0.468	
	0.31%	-0.69%	---	-0.67%	---	0.55%	4.13%	
	1.135	0.890	1.092	---	0.716	0.444		
14	1.138	0.890	1.096	---	0.717	0.468		
	0.27%	0.01%	0.34%	---	0.25%	5.20%		
	0.634	0.000	---	0.487				
15	0.662	0.681	---	0.504				
	4.45%		---	3.31%				

Burnup (GWD/MTU):	7.757
Power Level (MWt):	3411
Power Level (%):	100.0%
Bank D Position (Steps):	208

****
Peak Assm (Measured) : 1.333
****

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Peak Assm (SIMULATE) : 1.321
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Error Summary

R.M.S. =	1.80%
Worst Assembly =	5.20%

KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 37

CALLAWAY CYCLE 1

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	K	G	F	E	D	C	B	A
8	--- --- ---	1.053 1.065 1.09%	1.229 1.235 0.47%	1.074 1.074 -0.03%	1.239 1.236 -0.23%	1.066 1.072 0.52%	1.178 1.169 -0.73%	0.701 0.718 2.39%
9	1.053 1.065 1.09%	1.238 1.234 -0.31%	1.054 1.067 1.18%	1.236 1.234 -0.15%	1.081 1.078 -0.27%	--- --- ---	0.932 0.941 0.95%	0.728 0.728 -0.10%
10	1.229 1.235 0.47%	1.049 1.067 1.67%	1.239 1.235 -0.23%	--- --- ---	1.243 1.241 -0.19%	1.066 1.066 -0.07%	--- --- ---	0.659 0.675 2.46%
11	1.074 1.074 -0.03%	--- --- ---	1.075 1.080 0.48%	*+*+* 1.252 1.247 -0.40% *+*+*	--- --- ---	1.222 1.212 -0.88%	--- --- ---	0.551 0.552 0.35%
12	1.239 1.236 -0.23%	1.074 1.078 0.39%	--- --- ---	--- --- ---	1.188 1.146 -3.49%	1.014 1.009 -0.46%	0.768 0.765 -0.42%	
13	1.066 1.072 0.52%	1.231 1.233 0.10%	--- --- ---	1.222 1.212 -0.88%	--- --- ---	0.892 0.893 0.04%	0.515 0.525 1.92%	
14	1.178 1.169 -0.73%	0.950 0.941 -0.99%	1.146 1.134 -1.06%	--- --- ---	0.773 0.765 -1.07%	0.511 0.525 2.73%		
15	0.701 0.718 2.39%	0.000 0.728	--- --- ---	0.551 0.552 0.26%				

Burnup (GWD/MTU):	14.806
Power Level (MWt):	3411
Power Level (%):	100.0%
Bank D Position (Steps):	213

****

Peak Assm (Measured) : 1.252

****

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Peak Assm (SIMULATE) : 1.247

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Error Summary

R.M.S. =	1.18%
Worst Assembly =	3.49%

KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 38

CALLAWAY CYCLE 2

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
	---	1.206	1.132	1.168	1.135	1.136	1.099	0.882
8	---	1.201	1.151	1.169	1.127	1.138	1.110	0.887
	---	-0.43%	1.64%	0.07%	-0.69%	0.25%	0.99%	0.61%
	1.206	1.137	1.205	1.117	1.166	---	1.073	0.733
9	1.201	1.161	1.183	1.124	1.175	---	1.073	0.735
	-0.43%	2.08%	-1.86%	0.66%	0.77%	---	-0.03%	0.27%
	1.132	1.217	1.113	---	1.153	1.113	---	0.781
10	1.151	1.183	1.136	---	1.154	1.105	---	0.787
	1.64%	-2.85%	2.12%	---	0.03%	-0.76%	---	0.79%
				+++++				
	1.168	---	1.181	1.220	---	1.091	---	0.528
11	1.169	---	1.160	1.202	---	1.120	---	0.529
	0.07%	---	-1.78%	-1.51%	---	2.67%	---	0.30%
				+++++	*****			
	1.135	1.187	---	---	1.241	1.059	0.717	
12	1.127	1.175	---	---	1.173	1.060	0.730	
	-0.69%	-1.04%	---	---	-5.45%	0.11%	1.83%	
					*****			
	1.136	1.147	---	1.105	---	0.799	0.392	
13	1.138	1.154	---	1.120	---	0.807	0.400	
	0.25%	0.60%	---	1.35%	---	0.97%	2.02%	
	1.099	1.079	1.024	---	0.753	0.385		
14	1.110	1.073	1.040	---	0.730	0.400		
	0.99%	-0.60%	1.58%	---	-2.97%	3.76%		
	0.882	0.000	---	0.525				
15	0.887	0.735	---	0.529				
	0.61%		---	0.69%				

Error Summary

R.M.S. =	1.75%
Worst Assembly =	5.45%

Burnup (GWD/MTU): 1.702
Power Level (MWt): 3373
Power Level (%): 98.9%
Bank D Position (Steps): 210

****
Peak Assm (Measured) : 1.241
****

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Peak Assm (SIMULATE) : 1.202
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KEY:

Measured Assembly Reaction Rate
SIMULATE-3P Predicted Assembly Reaction Rate
% Error (S-M)/M

Figure 39

CALLAWAY CYCLE 2

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
	---	1.230	1.165	1.234	1.131	1.057	1.004	0.756
8	---	1.203	1.184	1.218	1.133	1.067	1.023	0.770
	---	-2.16%	1.65%	-1.33%	0.20%	1.01%	1.86%	1.91%
	1.230	1.169	1.245	1.182	1.229	---	1.030	0.662
9	1.203	1.180	1.216	1.191	1.212	---	1.027	0.686
	-2.16%	1.00%	-2.29%	0.78%	-1.38%	---	-0.24%	3.62%
	1.165	1.243	1.202	---	1.200	1.158	---	0.703
10	1.184	1.216	1.207	---	1.212	1.132	---	0.710
	1.65%	-2.13%	0.36%	---	0.95%	-2.29%	---	1.06%
			++*					
	1.234	---	1.280	1.248	---	1.095	---	0.496
11	1.218	---	1.248	1.234	---	1.118	---	0.507
	-1.33%	---	-2.52%	-1.12%	---	2.04%	---	2.34%
			++*					
	1.131	1.228	---	---	1.199	1.073	0.703	
12	1.133	1.212	---	---	1.164	1.055	0.714	
	0.20%	-1.29%	---	---	2.95%	-1.63%	1.56%	
	1.057	1.128	---	1.101	---	0.805	0.397	
13	1.067	1.143	---	1.118	---	0.807	0.411	
	1.01%	1.33%	---	1.48%	---	0.19%	3.51%	
	1.004	1.037	1.002	---	0.713	0.398		
14	1.023	1.027	1.022	---	0.714	0.411		
	1.86%	-0.93%	1.98%	---	0.12%	3.25%		
	0.756	0.000	---	0.497				
15	0.770	0.686	---	0.507				
	1.91%		---	2.02%				

Error Summary

R.M.S. =	1.85%
Worst Assembly =	3.62%

Burnup (GWD/MTU):	9.274
Power Level (MWt):	3411
Power Level (%):	100.0%
Bank D Position (Steps):	212

****

Peak Assm (Measured) : 1.280

****

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Peak Assm (SIMULATE) : 1.248

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KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 40

CALLAWAY CYCLE 2

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
	---	1.191	1.130	1.218	1.108	1.049	1.023	0.779
8	---	1.162	1.149	1.198	1.116	1.063	1.041	0.785
	---	-2.40%	1.69%	-1.66%	0.70%	1.39%	1.77%	0.84%
	1.191	1.130	1.204	1.155	1.234	---	1.070	0.697
9	1.162	1.138	1.184	1.168	1.205	---	1.059	0.717
	-2.40%	0.79%	-1.65%	1.15%	-2.37%	---	-1.03%	2.87%
	1.130	1.201	1.174	---	1.186	1.177	---	0.728
10	1.149	1.184	1.174	---	1.197	1.146	---	0.732
	1.69%	-1.40%	0.02%	---	0.89%	-2.70%	---	0.62%
			++*					
	1.218	---	1.254	1.187	---	1.093	---	0.522
11	1.198	---	1.227	1.187	---	1.115	---	0.537
	-1.66%	---	-2.15%	-0.01%	---	2.00%	---	2.73%
			++*					
	1.108	1.214	---	---	1.160	1.094	0.726	
12	1.116	1.205	---	---	1.136	1.067	0.737	
	0.70%	-0.75%	---	---	-2.01%	-2.47%	1.46%	
	1.049	1.139	---	1.099	---	0.830	0.427	
13	1.063	1.151	---	1.115	---	0.832	0.443	
	1.39%	1.06%	---	1.44%	---	0.24%	3.96%	
	1.023	1.075	1.046	---	0.732	0.429		
14	1.041	1.059	1.054	---	0.737	0.443		
	1.77%	-1.49%	0.71%	---	0.63%	3.47%		
	0.779	0.000	---	0.520				
15	0.785	0.717	---	0.537				
	0.84%		---	3.13%				

Burnup (GWD/MTU):	15.365
Power Level (MWt):	3378
Power Level (%):	99.0%
Bank D Position (Steps):	213

****
Peak Assm (Measured) : 1.254
****

+++++++++++++++++
Peak Assm (SIMULATE) : 1.227
+++++++++++++++++

Error Summary

R.M.S. =	1.85%
Worst Assembly =	3.96%

KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 41

CALLAWAY CYCLE 3

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
8	--- --- ---	1.095 1.103 0.78%	1.118 1.113 -0.45%	0.983 1.026 4.34%	1.164 1.178 1.18%	+++++ 1.222 1.216 -0.46% +++++	1.173 1.159 -1.24%	0.858 0.858 -0.04%
9	1.095 1.103 0.78%	1.109 1.101 -0.68%	0.985 1.017 3.31%	1.116 1.124 0.77%	1.057 1.069 1.09%	--- --- ---	1.185 1.183 -0.20%	0.801 0.769 -3.89%
10	1.118 1.113 -0.45%	0.995 1.016 2.16%	1.139 1.141 0.23%	--- --- ---	1.169 1.177 0.66%	1.117 1.106 -0.99%	--- --- ---	0.830 0.823 -0.83%
11	0.983 1.026 4.34%	--- --- ---	1.143 1.160 1.46%	1.060 1.073 1.18%	--- --- ---	1.132 1.127 -0.40%	--- --- ---	0.525 0.514 -2.07%
12	1.164 1.178 1.18%	1.027 1.068 3.97%	--- --- ---	--- --- ---	1.133 1.113 -1.73%	0.946 0.955 0.94%	0.683 0.695 1.76%	
13	+++++ 1.222 1.216 -0.46% +++++	***** 1.235 1.209 -2.07% *****	--- --- ---	1.142 1.125 -1.45%	--- --- ---	1.019 1.008 -1.05%	0.642 0.612 -4.73%	
14	1.173 1.159 -1.24%	1.183 1.182 -0.12%	1.172 1.160 -1.07%	--- --- ---	0.696 0.694 -0.30%	0.623 0.611 -1.97%		
15	0.858 0.858 -0.04%	0.000 0.767	--- --- ---	0.523 0.513 -1.79%				

Error Summary

R.M.S. =	1.90%
Worst Assembly =	4.73%

Burnup (GWD/MTU):	1.226
Power Level (MWt):	3411
Power Level (%):	95.7%
Bank D Position (Steps):	208

****

Peak Assm (Measured) : 1.235

****

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Peak Assm (SIMULATE) : 1.216

++++++++++++++++++

KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 42

CALLAWAY CYCLE 3

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
8	--- --- ---	1.229 1.233 0.30%	1.272 1.273 0.05%	1.126 1.146 1.80%	1.192 1.192 0.02%	1.075 1.080 0.42%	1.014 1.013 -0.13%	0.662 0.677 2.20%
9	1.229 1.233 0.30%	1.262 1.251 -0.81%	1.143 1.157 1.21%	1.247 1.248 0.07%	1.097 1.107 0.94%	--- --- ---	1.052 1.067 1.41%	0.656 0.664 1.12%
10	1.272 1.273 0.05%	1.1[illegible]3 1.156 0.68%	*+*+* 1.283 1.279 -0.30% *+*+*	--- --- ---	1.256 1.245 -0.86%	1.111 1.104 -0.61%	--- --- ---	0.657 0.668 1.66%
11	1.126 1.146 1.80%	--- --- --	1.240 1.260 1.61%	1.150 1.151 0.11%	--- --- ---	1.172 1.149 -1.99%	--- --- ---	0.478 0.478 -0.04%
12	1.192 1.192 0.02%	1.095 1.106 1.03%	--- --- ---	--- --- ---	1.228 1.191 -3.01%	1.005 0.999 -0.59%	0.690 0.699 1.27%	
13	1.075 1.080 0.42%	1.132 1.137 0.41%	--- --- ---	1.164 1.148 -1.40%	--- --- ---	1.013 1.003 -0.98%	0.590 0.580 -1 63%	
14	1.014 1.013 -0.13%	1.062 1.067 0.45%	1.075 1.052 -2.09%	--- --- ---	0.705 0.699 -0.75%	0.583 0.579 -0.53%		
15	0.662 0.677 2.20%	0.654 0.664 1.43%	--- --- --	0.482 0.478 -0.77%				

Burnup (GWD/MTU): 9.897
Power Level (MWt): 3530
Power Level (%): 99.0%
Bank D Position (Steps): 215

****
Peak Assm (Measured) : 1.283
****

++:++++++++++++++
Peak Assm (SIMULATE) : 1.279
+++++++++++++++++

Error Summary

R.M.S. =	1.20%
Worst Assembly =	3.01%

KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Rea[illegible]n Rate

% Error
(S-M)/M

Figure 43

CALLAWAY CYCLE 3

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
8	--- --- ---	1.143 1.170 2.32%	+++++ 1.244 1.254 0.76%	1.124 1.135 0.95%	1.192 1.199 0.55%	1.069 1.069 0.02%	1.031 1.029 -0.20%	0.664 0.673 1.24%
9	1.143 1.170 2.32%	1.210 1.212 0.21%	+++++ 1.108 1.119 1.00%	1.220 1.238 1.47%	1.086 1.094 0.73%	--- --- ---	1.041 1.055 1.32%	0.678 0.689 1.53%
10	+++++ 1.244 1.254 0.76%	[illegible].093 1.118 2.31%	1.231 1.243 0.96%	--- --- ---	***** 1.256 1.244 -0.98%	1.099 1.102 0.22%	--- --- ---	0.661 0.668 1.17%
11	+++++ 1.124 1.135 0.95%	--- --- ---	1.172 1.198 2.19%	1.103 1.107 0.36%	***** --- --- ---	1.208 1.177 -2.56%	--- --- ---	0.528 0.523 -0.90%
12	1.192 1.199 0.55%	1.088 1.094 0.[illegible]%	--- --- ---	--- --- ---	1.246 1.214 -2.54%	1.050 1.026 -2.31%	0.745 0.741 -0.59%	
13	1.069 1.069 0.02%	1.130 1.134 0.36%	--- --- ---	1.203 1.177 -2.15%	--- --- ---	1.050 1.034 -1.59%	0.611 0.596 -2.44%	
14	1.031 1.029 -0.20%	1.047 1.056 0.83%	1 104 1 068 -[illegible].27%	--- --- ---	0.747 0.741 -0.86%	0.606 0.596 -1.62%		
15	0.664 0.673 1.24%	0.685 0.688 0.34%	--- --- ---	0.526 0.523 -0.52%				

Error Summary

R.M.S. =	1.47%
Worst Assembly =	3.27%

Burnup (GWD/MTU):	17.931
Power Level (MWt):	3565
Power Level (%):	100.0%
Bank D Position (Steps):	216

****

Peak Assm (Measured) : 1.256

****

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Peak Assm (SIMULATE) : 1.254

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KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 44

CALLAWAY CYCLE 4

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
	---	1.205	1.189	1.221	1.167	1.246	1.134	0.589
8	---	1.278	1.221	1.171	1.105	1.210	1.107	0.585
	---	6.08%	2.68%	-4.04%	-5.30%	-2.88%	-2.32%	-0.70%
		+++++						
	1.205	1.268	1.286	1.126	1.219	---	1.093	0.544
9	1.278	1.315	1.273	1.094	1.194	---	1.074	0.534
	6.08%	3.73%	-1.02%	-2.86%	-2.02%	---	-1.67%	-1.97%
		+++++				*****		
	1.189	1.239	1.149	---	1.177	1.311	---	0.507
10	1.221	1.275	1.164	---	1.150	1.303	---	0.500
	2.68%	2.91%	1.36%	---	-2.29%	-0.59%	---	-1.33%
						*****		
	1.221	---	1.211	1.191	---	1.252	---	0.390
11	1.171	---	1.200	1.191	---	1.272	---	0.382
	-4.04%	---	-0.86%	-0.01%	---	1.59%	---	-2.27%
	1.167	1.263	---	---	1.250	1.187	0.668	
12	1.105	1.248	---	---	1.259	1.199	0.671	
	-5.30%	-1.18%	---	---	0.76%	1.07%	0.52%	
	1.246	1.121	---	1.269	---	0.877	0.409	
13	1.210	1.140	---	1.298	---	0.902	0.410	
	-2.88%	1.77%	---	2.26%	---	2.80%	0.25%	
	1.134	1.093	1.128	---	0.673	0.409		
14	1.107	1.104	1.137	---	0.681	0.414		
	-2.32%	1.08%	0.82%	---	1.31%	1.01%		
	0.589	0.561	---	0.380				
15	0.585	0.547	---	0.389				
	-0.70%	-2.55%	---	2.34%				

Error Summary

R.M.S. =	2.35%
Worst Assembly =	6.08%

Burnup (GWD/MTU):	0.277
Power Level (MWt):	3547
Power Level (%):	99.5%
Bank D Position (Steps)	215

****
Peak Assm (Measured) : 1.311
****

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Peak Assm (SIMULATE) : 1.315
+++++++++++++++++

KEY:

Measured Assembly Reaction Rate
SIMULATE-3P Predicted Assembly Reaction Rate
% Error (S-M)/M

Figure 45

CALLAWAY CYCLE 4

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISON

	H	G	F	E	D	C	B	A
	---	1.133	1.183	1.228	1.193	1.280	1.156	0.623
8	---	1.147	1.209	1.212	1.170	1.285	1.156	0.626
	---	1.28%	2.23%	-1.32%	-1.90%	0.41%	-0.08%	0.46%
	1.133	1.200	1.251	1.142	1.235	---	1.166	0.592
9	1.147	1.204	1.254	1.133	1.240	---	1.162	0.589
	1.28%	0.35%	0.22%	-0.78%	0.36%	---	-0.37%	-0.50%
						++*		
	1.183	1.240	1.163	---	1.174	1.289	---	0.533
10	1.209	1.250	1.184	---	1.166	1.300	---	0.531
	2.23%	0.78%	1.83%	---	-0.70%	0.84%	---	-0.42%
						++*		
	1.228	---	1.217	1.188	---	1.172	---	0.397
11	1.212	---	1.214	1.198	---	1.170	---	0.392
	-1.32%	---	-0.26%	0.78%	---	-0.18%	---	-1.22%
	1.193	1.253	---	---	1.174	1.162	0.663	
12	1.170	1.255	---	---	1.185	1.168	0.653	
	-1.90%	0.14%	---	---	0.96%	0.51%	-1.44%	
	1.280	1.163	---	1.176	---	0.896	0.425	
13	1.285	1.156	---	1.173	---	0.887	0.423	
	0.41%	0.64%	---	-0.26%	---	-0.94%	-0.38%	
	1.156	1.159	1.103	---	0.664	0.425		
14	1.156	1.160	1.095	---	0.653	0.423		
	-0.08%	0.06%	-0.75%	---	-1.59%	-0.38%		
	0.623	0.589	---	0.394				
15	0.626	0.586	---	0.391				
	0.46%	-0.34%	---	-0.59%				

Error Summary

R.M.S. =	0.91%
Worst Assembly =	2.23%

Burnup (GWD/MTU):	9.581
Power Level (MWt):	3554
Power Level (%):	99.7%
Bank D Position (Steps):	226

****

Peak Assm (Measured) : 1.289

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Peak Assm (SIMULATE) : 1.300

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KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 46

CALLAWAY CYCLE 4

ASSEMBLYWISE REACTION RATE DISTRIBUTION COMPARISCN

	H	G	F	E	D	C	B	A
8	- · · --- ---	1.135 1.148 1.13%	1.221 1.231 0.84%	1.197 1.195 -0.21%	1.201 1.167 -2.84%	1.225 1.232 0.53%	1.124 1.120 -0.29%	0.661 0.656 -0.72%
9	1.135 1.148 1.13%	1.208 1.200 -0.70%	1.222 1.233 0.92%	1.158 1.144 -1.24%	1.197 1.202 0.39%	--- --- ---	1.135 1.142 0.59%	0.650 0.641 -1.39%
10	1.221 1.231 0.84%	1.221 1.228 0.59%	1.198 1.194 -0.37%	--- --- ---	1.165 1.155 -0.87%	*+*+* 1.234 1.245 0.89%	--- --- ---	0.587 0.588 0.10%
11	1.197 1.195 -0.21%	--- --- ---	1.186 1.186 -0.05%	1.184 1.188 0.35%	--- --- ---	*+*+* 1.136 1.133 -0.31%	--- --- ---	0.454 0.446 -1.74%
12	1.201 1.167 -2.84%	1.201 1.207 0.48%	--- --- ---	--- --- ---	1.093 1.137 4.00%	1.127 1.157 2.71%	0.697 0.691 -0.88%	
13	1.225 1.232 0.53%	1.157 1.130 -2.39%	--- --- ---	1.142 1.133 -0.84%	--- --- ---	0.903 0.920 1.87%	0.482 0.488 1.12%	
14	1.124 1.120 -0.29%	1.144 1.137 -0.65%	1.079 1.070 -0.80%	--- --- ---	0.696 0.690 -0.89%	0.484 0.488 0.81%		
15	0.661 0.656 -0.72%	0.647 0.638 -1.40%	--- --- ---	0.447 0.444 -0.76%				

Error Summary

R.M.S. =	1.31%
Worst Assembly =	4.00%

Burnup (GWD/MTU): 19.401
Power Level (MWt): 3437
Power Level (%): 96.4%
Bank D Position (Steps): 202

****
Peak Assm (Measured) : 1.234
****

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Peak Assm (SIMULATE) : 1.245
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KEY:

Measured
Assembly Reaction Rate

SIMULATE-3P Predicted
Assembly Reaction Rate

% Error
(S-M)/M

Figure 47

6.0 CONCLUSIONS

Based on results of explicit rod swap benchmarking for Callaway Cycles 4 and 5, as well as other related benchmark comparisons, Union Electric concludes that its methods for performing bank worth measurements using rod swap are appropriate and valid. Rod swap testing performed thus far at Callaway demonstrates that Union Electric's rod swap procedures can be properly and efficiently implemented, and that data reduction and analysis is less tedious than for boron dilution. Futhermore, Union Electric's rod swap methods are fundamentally equivalent to methods previously licensed by the NRC for other utilites, such as VEPCO and PSE&G. Therefore, in view of the demonstrated validity of the proposed methods as well as their associated benefits, Union Electric requests that rod swap, using the methods described herein, be approved for use at the Callaway Nuclear Plant.

7.0 REFERENCES

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2 ETP-ZZ-ST006, "Bank Reactivity Worth Measurement Using the Rod Swap Technique," Union Electric Co.

3 VEP-FRD-36A, "Control Rod Reactivity Worth Determination By The Rod Swap Technique," Virginia Electric & Power Co., 12/90

4 NFG-004, "Safety Evaluation Of The PSE&G Rod Exchange Methodology," Rev 2, Public Service Electric & Gas Co., 8/22/84

5 "CASMO-3 User's Manual, Version 4.4," Malte Edenius and Bengt H. Forssen, Studsvik AB (Proprietary)

6 "SIMULATE-3 User's Manual, Version 3.0," J. A. Umbarger and A. S. DiGivione, Studsvik of America (Proprietary)

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