VEP-FRD-36 A

CONTROL ROD REACTIVITY WORTH DETERMINATION BY THE ROD SWAP TECHNIQUE

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December, 1980

8101200235

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

NOV 7 1980

Mr. W. N. Thomas, Vice President
Fuel Resources
Virginia Electric Power Company
Richmond, Virginia 23261

Dear Mr. Thomas:

SUBJECT: ACCEPTANCE FOR REFERENCING OF TOPICAL REPORT VEP-FRD-36 "CONTROL ROD REACTIVITY WORTH DETERMINATION BY ROD SWAP TECHNIQUE"

The Nuclear Regulatory Commission (NRC) staff has completed its review of the Virginia Electric and Power Company Topical Report number VEP-FRD-36 entitled "Control Rod Reactivity Worth Determination by Rod Swap Techniques" and the amendment attached to your letter dated June 26, 1980 and serial No. 569. The Report describes the methodology for determining control rod reactivity worth utilizing the rod swap technique. Data obtained during the startup of Surry Unit 1, Cycle 5 and North Anna Unit 1, Cycle 2 are presented to validate the methodology. The report also provides the two level criteria by which the results are judged and the remedial actions if these criteria are not met.

As a result of our review of the use of the rod swap technique as presented by VEPCO for the Surry Units 1 and 2 and for the North Anna Units 1 and 2 plants, we conclude this technique an acceptable method for verifying shutdown margin provided the following conditions are met:

1. VEPCO submits the data to NRC within 45 days of the first use of the rod swap after this approval for each unit, and

2. The On-Site Safety Review Committee compares the VEPCO prediction for total rod worth and shutdown margin with the prediction by the organization performing the safety analysis and that the effect of any differences is evaluated. This comparison and evaluation is to be done for each cycle prior to initial criticality.

We do not intend to repeat the review of the safety features described in the report and its amendment as found acceptable herein. Our acceptance applies only to the use of features described in the topical report and its amendment as discussed herein.

In accordance with established requirements, it is requested that Virginia Electric and Power Company issue a revised version of this report within three months of the receipt of this letter. The revised version is to appropriately incorporate the information submitted in your June 26, 1980 letter. This evaluation letter is to be included in the revised version between the title page and the abstract and the approved report will carry the identifier VEP-FRD-36A.

Should Nuclear Regulatory Commission criteria or regulations change such that our conclusions as to the acceptability of the report are invalidated, Virginia Electric and Power Company will be expected to revise and resubmit the topical report or submit justification for the continued effective applicability of the topical report without revision.

If you have any questions about the review or our conclusion, please contact us.

Sincerely,

R Tedesco

Robert L. Tedesco, Assistant Director
for Licensing
Division of Licensing

CLASSIFICATION/DISCLAIMER

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ABSTRACT

The methodology for determining control rod reactivity worth utilizing the rod swap technique is presented. Data obtained during the startup of Surry Unit 1, Cycle 5 and North Anna Unit 1, Cycle 2, which validates the methodology, is also presented. This methodology is applicable for conducting control rod reactivity worth tests at Surry and North Anna.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the cooperation and support of the Surry and North Anna Power Station personnel in performing the tests documented in this report. Additionally, we would like to acknowledge the effort of Mr. M. C. Cheok in providing the North Anna design data. We would like to thank Ms. C. E. Bullock for her patience and accurate typing of the entire report.

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Section 1

INTRODUCTION

The purpose of the control rod bank worth tests, which are performed as part of the startup physics testing program, is to verify selected design statepoint calculations and thereby demonstrate the validity of the results of the calculational models used to predict control rod bank reactivity worths as part of the design process. This is done through a comparison of measured and predicted results for those selected design statepoints. The Vepco control rod bank worth tests traditionally have been performed using the dilution/boration technique. The dilution/boration technique involves exchanging the reactivity associated with the control rod bank of interest with the reactivity associated with the boron in the reactor coolant system (RCS), i.e., as control rods are inserted into the core, primary grade water is put into the RCS so that the boron concentration of the reactor coolant system is diluted. During this process, the core is kept nominally critical. The amount of each control rod bank motion is strictly limited such that the reactivity value associated with each movement is within the reliability range of the reactivity computer, which is used to monitor core reactivity and directly measure the reactivity worth of the control rod banks. The dilution/boration rate is established such that the reactivity exchange rate is compatible with the operational requirements of the reactivity computer. Typically, the reactivity exchange rate is 300 to 500 pcm/hour. For a typical reload cycle, the measured control rod bank reactivity has been approximately 5500 pcm (four control banks successively inserted). This results in a measurement time of between 22 and 37 hours (measurements are made during control rod bank insertion and withdrawal).

The measurement of the reactivity worth of the control rod banks using the rod swap technique is an alternate method that can be used to verify control rod worths. The rod swap technique has been devised in order to reduce the amount of time associated with the measurement of the reactivity worth of the control rod banks without sacrificing any of the essential information that is derived from the performance of these tests relative to the current test methods. The benefits associated with the rod swap technique include:

1) the reactivity worths of all the rod banks (control and shutdown) are determined (in the past, the reactivity worths of the shutdown banks were not measured).
2) the time associated with the measurement of the reactivity worths of the control rod banks is greatly reduced, and
3) the boron recovery processing requirements (associated with RCS boration/dilution) are greatly reduced.

Implementatio -f this program enhances overall nuclear availability.

In ad...tion to the conventional control rod bank reactivity tests, reactivity tests using the rod swap technique were performed during the initial startup of Surry 1, Cycle 5 and North Anna 1, Cycle 2. These side-by-side demonstration programs were performed in order to establish the technical basis for validating the rod swap methodology. The purpose of this report is to present a description of the rod swap methodology and the results of the side-by-side demonstration programs mentioned above; and show that the results of these programs validate the use of the rod swap methodology in future Vepco physics testing programs.

Section 2 of this report contains a description of the rod swap test procedu and the associated data analysis methodology. Section 3 describes the calculational methods used to predict the rod swap test results. Section 4 contains a description of the rod swap test results evaluation methodology and review criteria. Section 5 presents the rod swap test results. Section 6 presents the validation of the rod swap methodology through a comparison of the results of the side-by-side demonstration programs, and Section 7 presents the conclusions that can be drawn from the validation of the rod swap methodology. The Appendix provides a description of the changes to the zero power physics testing program that will occur as a result of implementing the rod swap program.

The applicability of this report encompasses the use of the rod swap methodology by Vepco for the Surry and North Anna Power Stations.

Section 2

ROD SWAP REACTIVITY TESTS

2.1 Test Description

The objective of the rod swap tests is to measure the reactivity worth of each control rod bank. The first step in the rod swap procedure is to dilute the most reactive control rod bank (hereafter referred to as the reference bank) into the core and measure its reactivity worth using conventional test techniques. The dilution rate is selected so that the rate of change of core reactivity is approximately 300 pcm per hour. At the completion of the reference bank reactivity worth measurement, the reactor coolant system temperature and boron concentration are stabilized such that the reactor is critical with the reference bank at or near full insertion. At this point, a boron endpoint determination is made, and an isothermal temperature coefficient test is performed. Initial statepoint data for a rod swap maneuver are obtained by moving the reference bank to its fully inserted position, if necessary, and recording the core reactivity and moderator temperature. A rod swap maneuver is performed by withdrawing the reference bank while one of the other control rod banks (i.e., a test bank) is inserted. The core is kept nominally critical throughout this rod swap and the maneuver is continued until the test bank is fully inserted and the reference bank is at the position at which the core is just critical. This measured critical position (MCP) of the reference bank with the test bank fully inserted is the major parameter of interest since it is a measure of the reactivity worth of the test bank. Statepoint data (core reactivity and moderator temperature) are recorded with the reference bank at the MCP. The reference bank is alternately withdrawn and inserted a small amount about the MCP in order to measure the differential reactivity worth of the reference bank over this region. The rod swap maneuver is performed in reverse order such that the reference bank once again is at or near full insertion and the test bank is once again fully withdrawn from the core. Statepoint data (rod position, core reactivity, and moderator temperature) are recorded in order to confirm RCS boron concentration stability. The rod swap process is then repeated for all of the other control rod banks (control and shutdown).

In summary, conventional dilution/boration test data are obtained in order to determine the reactivity worth of the reference bank inserted alone. Rod swap test data are obtained in order to determine the reactivity worth of each test bank with the reference bank partially inserted in the core.

2.2 Test Data Analysis Methodology

The reactivity worth of the reference bank is determined using the standard analysis techniques associated with dilution/boration rod worth test data. The reactivity worth of each test bank is determined from the measured reference bank reactivity worth data and the measured critical position data.

As outlined in Section 2.1, the data that are recorded during the tests include the following:

1) the integral and differential reactivity worth of the reference bank with all other control rod banks withdrawn from the core,
2) the critical RCS boron concentration associated with the reference bank being fully inserted in the core with all other control rod banks withdrawn from the core,
3) the isothermal temperature coefficient associated with the reference bank being fully inserted in the core with all other control rod banks withdrawn from the core,
4) the critical position of the reference bank associated with each of the control rod banks being individually fully inserted in the core,

5) the core reactivity and moderator temperature associated with the reference bank being fully inserted alone, and the reference bank being at the measured critical positions identified in Item 4,

6) the differential reactivity worth of the reference bank in the region of the measured critical positions identified in Item 4.

Items 1, 2, 3, 5, and 6 represent data that are obtained and analyzed using the current standard testing and analysis procedures. The measured critical reference bank position data, Item 4, are also analyzed in a straightforward manner. The analysis accounts for off-nominal conditions that may have existed during the test. These may include the following:

A) variations in the moderator temperature,

B) variations in the RCS boron concentration,

C) deviations from criticality with the reference bank fully inserted alone, and

D) deviations from criticality with the reference bank at the measured critical position (MCP) and the test bank fully inserted.

The reactivity effects of Items A and B can be minimized through strict control of the RCS temperature and boron concentration during the test and can be quantified based on the test data. The reactivity effects of Items C and D are measured directly by the reactivity computer during the test. Equation (1) is used to adjust the measured critical position data to account for off-nominal test conditions.

$$MCP^A = MCP - \left[\left((\Delta T \times \alpha_T) + (\Delta C_B \times \alpha_{C_B}) + \rho_C^I - \rho_C^{MCP}\right) \times \frac{1}{\left(\frac{\Delta\rho}{\Delta h}\right)}\right] \qquad (1)$$

Where:

MCP^A = the measured critical position of the reference bank adjusted for off-nominal test conditions.

MCP = the measured critical position of the reference bank.

ΔT = the increase in moderator temperature during the test.

α_T = the isothermal temperature coefficient measured with the reference bank fully inserted alone.

ΔC_B = the increase in RCS boron concentration during the test.

α_{C_B} = the boron worth coefficient.

ρ_C^I = the core reactivity measured with the reference bank fully inserted alone.

ρ_C^{MCP} = the core reactivity measured with the reference bank at the MCP and the test bank fully inserted.

$\left(\frac{\Delta\rho}{\Delta h}\right)$ = the measured differential reactivity worth of the reference bank in the region of the MCP.

These data adjustments were quantified as part of the data analysis of the rod swap tests performed during the startup of Surry 1, Cycle 5 and North Anna 1 Cycle 2, and are summarized in Table 2.1. It can be seen from the information in this table that the data adjustments are usually very small.

The reactivity worth of each test bank is determined from the measured reference bank reactivity worth data and the MCP^A of the reference bank for each test bank using the following basic reactivity balance equation:

$$R^M = \Delta R^M(M) + T^M_{\Delta R(M)} \quad (2)$$

Where:

R^M = the measured total integral reactivity worth of the reference bank inserted alone.

$\Delta R^M(M)$ = the measured integral reactivity worth of the reference bank inserted alone from the fully withdrawn position to the MCP^A.

$T^M_{\Delta R(M)}$ = the total integral reactivity worth of the test bank with the reference bank at the MCP^A.

As described previously, the value of the total integral reactivity worth of the reference bank inserted alone, R^M, is determined using the dilution/boration measurement and analysis techniques. The value of $\Delta R^M(M)$ for each test bank is determined from the same measured reference bank worth data using the appropriate adjusted measured critical position, MCP^A. Figures 2.1 and 2.2 present graphs of the measured integral worth of the reference bank for Surry 1, Cycle 5 and North Anna 1, Cycle 2, respectively, and illustrate the determination of the values of $\Delta R^M(M)$. The total integral worth of the test bank with the reference bank at the MCP^A, $T^M_{\Delta R(M)}$, is determined from these measured data using the reactivity balance given in Equation (2). The determination of the measured integral reactivity worth of each test bank from the Surry and North Anna test data is illustrated in Table 2.2.

TABLE 2.1

MEASURED CRITICAL POSITION DATA ADJUSTMENT SUMMARY

Test Bank	Measured Critical Reference Bank Position-MCP (steps)	Measured Data Adjustments (pcm)	Differential Rod Worth (pcm/step)	Adjusted Measured Critical Reference Bank Position - MCP^A (steps)
Surry 1, Cycle 5				
D	186	-8	-5.4	185
C	123	-9	-6.4	122
A	96	-14	-9.0	94
SB	138	-14	-6.0	136
SA	171	-6	-5.6	170
North Anna 1, Cycle 2				
C	164	+1	-5.6	164
B*	228	+16	——	228
A	189	-10	-11.4	188
SB	159	-3	-5.3	159
SA	200	-6	-9.0	199

$$MCP^A = MCP - \frac{\text{(Measured Data Adjustment)}}{\text{(Differential Rod Worth)}}$$

*The Measured Data Adjustment for B bank is not applied to the MCP value (228 steps) since the MCP^A value can be no greater than 228 steps. This Measured Data Adjustment is the amount of reactivity by which the total worth of B bank, inserted alone, exceeds the total worth of the reference bank, inserted alone.

POOR ORIGINAL

TABLE 2.2

MEASURED TEST BANK INTEGRAL WORTH SUMMARY

Test Bank	Adjusted Measured Critical Reference Bank Position – MCP^A (steps)	Reference Bank Worth to MCP^A – $\Delta R^M(M)$ (pcm)	Reference Bank Total Worth – R^M (pcm)	Test Bank Total Worth – $T^M_{\Delta R(M)}$ (pcm)
Surry 1, Cycle 5				
D	185	148	1405	1257
C	122	524	1405	881
A	94	756	1405	649
SB	136	428	1405	977
SA	170	227	1405	1178
North Anna 1, Cycle 2				
C	164	385	1069	684
B*	228	0	1069	1085
A	188	226	1069	843
SB	159	420	1069	649
SA	199	139	1069	930

$T^M_{\Delta R(M)} = R^M - \Delta R^M(M)$

*As indicated in the note on Table 2.1, the total integral worth of B bank, inserted alone, is greater than the total integral worth of the reference bank, inserted alone, by the amount of it's Measured Data Adjustment (16 pcm). The total integral worth of B bank, $T^M_{\Delta R(M)}$, was determined with the reference bank at it's MCP^A (i.e., fully withdrawn); $T^M_{\Delta R(M)}$ = 1069 pcm + 16 pcm = 1085 pcm.

FIGURE 2.1

SURRY UNIT 1 - CYCLE 5
MEASURED REFERENCE BANK WORTH
B BANK WITH ALL OTHER BANKS OUT

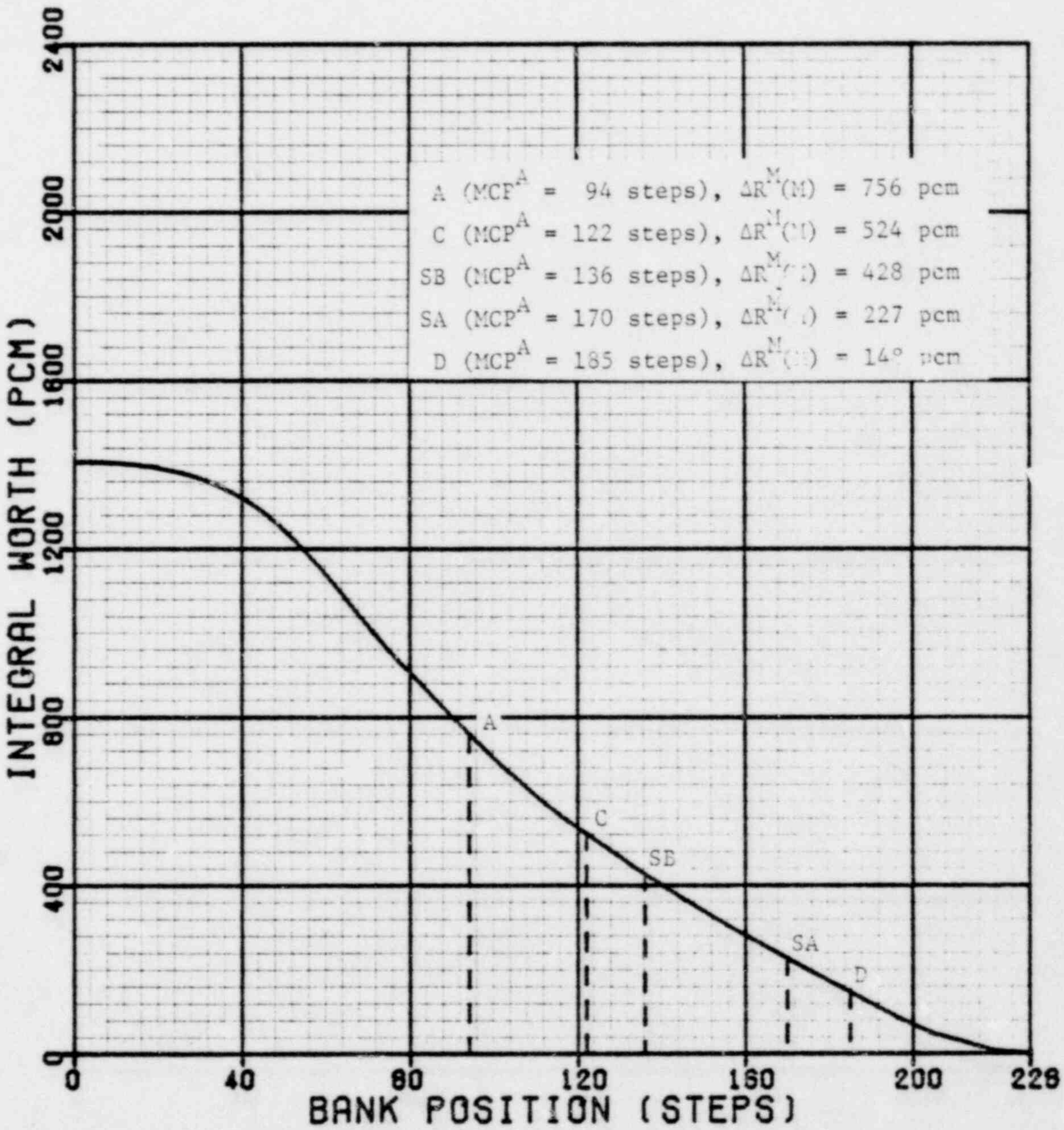
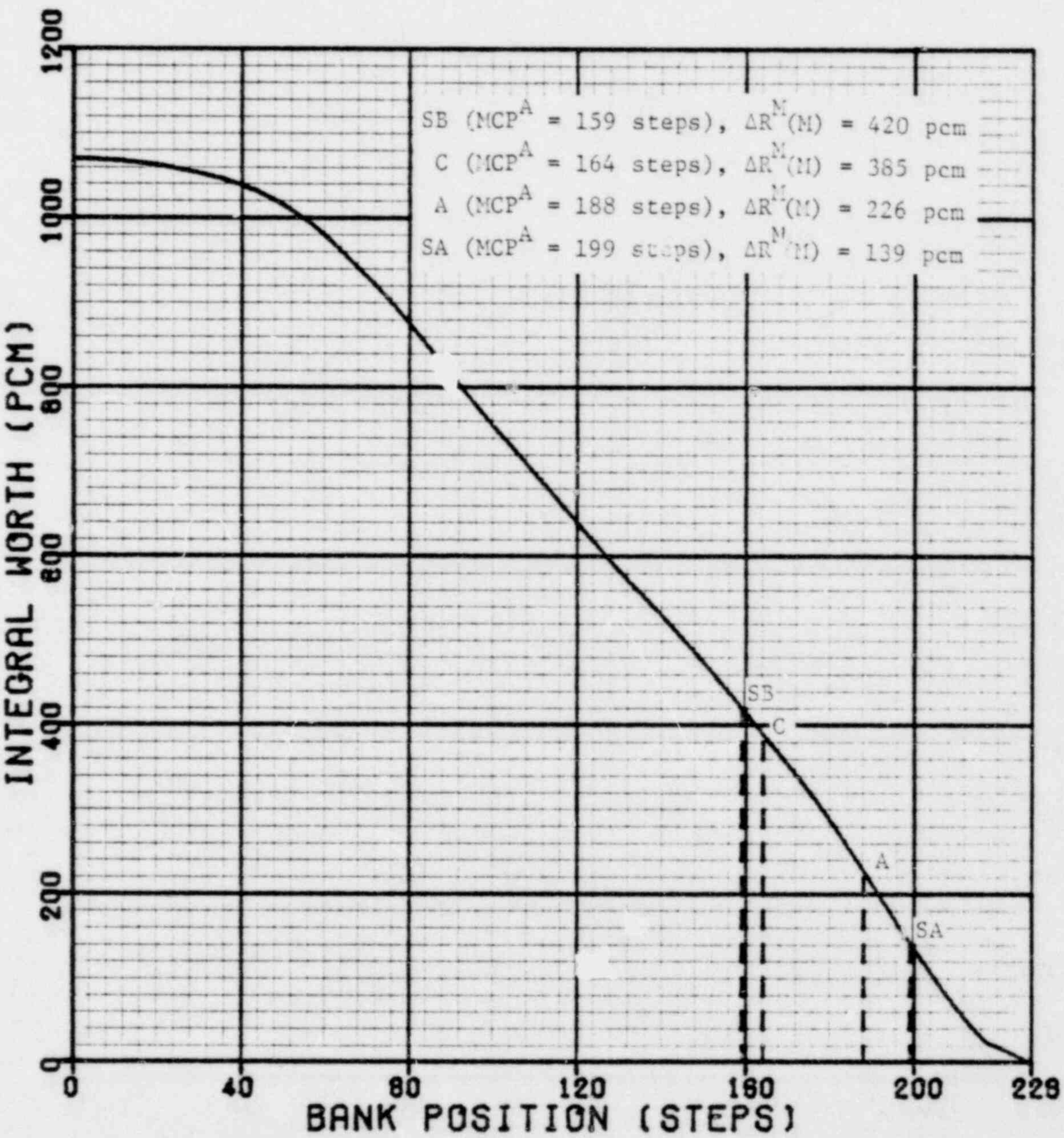


FIGURE 2.2

NORTH ANNA UNIT 1 - CYCLE 2
MEASURED REFERENCE BANK WORTH
D BANK WITH ALL OTHER BANKS OUT



Section 3

CALCULATIONAL METHODOLOGY

3.1 Introduction

The design information required to support the rod swap tests consists of individual control rod bank worths, predicted critical reference bank positions, and test bank total integral worths. The design data required to produce this information are generated using the Vepco PDQ07 Discrete [1] and FLAME [2] models. The PDQ07 model calculates core reactivity and power distributions in two dimensions (x,y). For data requiring an axial representation (e.g., any core configuration with control rods partially inserted), the FLAME model is employed.

The design predictions, which are required for the rod swap test, are determined from the following sets of calculations:

1) the total integral reactivity worth of each control rod bank individually inserted in the core,
2) the critical boron concentration with the reference bank fully inserted in the core,
3) the differential and integral reactivity worth of the reference bank as a function of bank position with all other banks withdrawn from the core, and
4) the differential and integral reactivity worth of the reference bank as a function of bank position with each test bank individually inserted in the core.

Items 1 and 2 are calculated with the PDQ07 Discrete model. Items 3 and 4 are calculated with the FLAME model.

The design predictions for the critical reference bank position with each test bank fully inserted in the core and for the total integral worth of each test bank are determined from the above design data and basic reactivity balance equations. The methodologies used to generate these data are described in detail below.

3.2 PDQ07 Discrete Calculations

The total integral reactivity worth of each control rod bank individually inserted in the core is required in order to determine the identity of the reference bank. In addition, these bank worths are used in the reactivity balance equations described in Sections 3.4 and 3.5. The total integral worth of a control rod bank individually inserted in the core is calculated by the following equation:

$$\text{Bank Worth (pcm)} = \frac{k_i - k_o}{k_i \times k_o} \times 10^5 \qquad (3)$$

Where:

k_o = eigenvalue from a PDQ07 Discrete run at hot zero power, all rods out critical boron concentration, with all rods out.

k_i = eigenvalue from a PDQ07 Discrete run at hot zero power, all rods out critical boron concentration, with one control rod bank fully inserted in the core.

The critical boron concentration with the reference bank fully inserted, C_B (ref), is obtained by performing a poison search with the PDQ07 Discrete model.

The calculation of the total integral worth of the reference bank with each test bank fully inserted requires two PDQ07 Discrete runs per test bank: 1) a run with the test bank fully inserted and a boron concentration of C_B (ref); and 2) a run with the reference bank and the test bank fully inserted and a boron concentration of C_B (ref). The reference bank worths are computed using the same technique as in Equation (3). The reference bank worths determined in this manner provide normalization for the FLAME model calculations discussed in Section 3.3.

3.3 FLAME Calculations

The differential and integral worths of the reference bank with all other banks out, and with each of the test banks fully inserted are calculated using the FLAME model. The same methodology is used for both sets of calculations. First, a series of cases is run with the FLAME3 code in which only the reference bank moves:

1) reference bank out,
2) reference bank inserted in the top node of the appropriate assemblies,
3) reference bank inserted in the top 2 nodes of the appropriate assemblies,

n+1) reference bank inserted in the top 'n' nodes of the appropriate assemblies,

last) reference bank fully inserted.

For the reference bank worths with all other banks out, the all rods out critical boron concentration is used. For the reference bank worths with the test banks inserted, the reference bank in critical boron concentration, C_B(ref), is used. The change in core reactivity resulting from each movement of the reference bank is a direct indication of its differential worth.

The second step in the process is the normalization of the total integral worth calculated by FLAME3 to the reference bank worth given by the PDQ07 Discrete model (Section 3.2 above). Based on this methodology, the following equations are used to compute the reference bank worths:

$$\text{Differential Worth at Node 'i' (pcm/step)} = \frac{k_{i-1} - k_{i+1}}{k_{i-1} \times k_{i+1}} \times \frac{10^5}{2 \times SPN} \times N_j \qquad (4)$$

$$\text{Integral Worth at Node 'i' (pcm)} = \frac{k_o - k_i}{k_o \times k_i} \times 10^5 \times N_j \qquad (5)$$

Where:

k_o = eigenvalue given by FLAME3 for the reference bank out

k_i = eigenvalue given by FLAME3 for the reference bank inserted in the ith node

SPN = number of steps of control rod movement per node

N_j = total integral worth of the reference bank from the PDQ07 Discrete model divided by the total integral worth from FLAME3 for similar conditions of boron concentration and rod configuration

For these calculations, there are six (6) normalization factors (N_j). Five of these are for the cases with the reference bank being inserted with a test bank fully inserted. The other is for the reference bank inserted alone. Equations (4) and (5) are used to calculate the differential and integral worths of the reference bank as a function of bank position.

3.4 Design Predictions of the Critical Reference Bank Positions

The determination of the predicted critical position (PCP) of the reference bank with a test bank fully inserted is based on the following reactivity balance equation:

$$R^P = T^P + \Delta R_T^P(P) \qquad (6)$$

Where:

R^P = the total integral worth of the reference bank inserted alone

T^P = the total integral worth of the test bank inserted alone

$\Delta R_T^P(P)$ = the integral worth of the reference bank from the fully withdrawn position to the PCP with the test bank fully inserted

The values of R^P and T^P are calculated with the PDQ07 Discrete model as discussed in Section 3.2 and the value for $\Delta R_T^P(P)$ is determined using Equation (6). The design prediction of the reference bank worth as a function of bank position with the test bank fully inserted (calculated with the FLAME model as discussed in Section 3.3) is then used to determine the bank position at which the reference bank worth equals the value of $\Delta R_T^P(P)$. This bank position is the predicted critical position of the reference bank with the test bank fully inserted.

Figures 3.1 through 3.10 are graphs of the predicted integral worths of the reference bank with each test bank fully inserted[3,4]. Also shown is an illustration of the determination of each PCP based upon the value of $\Delta R_T^P(p)$ for each test bank. Table 3.1 presents a summary of the predicted critical position of the reference bank associated with each test bank[3,4,5].

3.5 Design Predictions of the Integral Worth of Each Test Bank

The determination of the predicted total integral worth of the test bank with the reference bank at the PCP is based on the following reactivity balance equation:

$$R^P = \Delta R^P(P) + T^P_{\Delta R(P)} \qquad (7)$$

Where:

R^P = the total integral worth of the reference bank inserted alone

$\Delta R^P(P)$ = the integral worth of the reference bank inserted alone from the fully withdrawn position to the PCP

$T^P_{\Delta R(P)}$ = the total integral worth of the test bank with the reference bank at the PCP

The value of R^P is calculated with the PDQ07 Discrete model as discussed in Section 3.2. The values of $\Delta R^P(P)$ are determined using the calculations of the integral reference bank worth as a function of bank position with all other banks out (calculated with the FLAME model as discussed in Section 3.3) and the PCP values determined in Section 3.4. Figures 3.11 and 3.12 are graphs of the predicted integral worth of the reference bank for Surry 1, Cycle 5[3] and North Anna 1, Cycle 2[4], respectively. The determination of the values of $\Delta R^P(P)$ based upon the PCP for each test bank is illustrated on these figures. The total integral worth of each test bank with the reference bank at the appropriate PCP, $T^P_{\Delta R(P)}$, is determined using Equation (7). Table 3.2 presents an illustration and summary of the determination of these reactivity worth values.

As described in Section 2.2, the measured total integral worth of each test bank, $T^M_{\Delta R(M)}$, is determined with the reference bank inserted to the adjusted measured critical position, MCP^A. Whenever the MCP^A is not identical to the predicted critical position, PCP, the predicted worth of the test bank, with the reference bank at the MCP^A, $T^P_{\Delta R(M)}$, must be determined in order to put the design values and the test results on the same basis. The values for $T^P_{\Delta R(M)}$ are determined from design data using the following reactivity balance equation:

$$T^P_{\Delta R(M)} + \Delta R^P(M) = T^P + \Delta R^P_T(M) \qquad (8)$$

Where:

$T^P_{\Delta R(M)}$ = the total integral worth of the test bank with the reference bank at the MCP^A

$\Delta R^P(M)$ = the integral worth of the reference bank from the fully withdrawn position to the MCP^A inserted alone

T^P = the total integral worth of the test bank inserted alone

$\Delta R^P_T(M)$ = the integral worth of the reference bank from the fully withdrawn position to the MCP^A with the test bank fully inserted

The values of T^P are calculated with the PDQ07 Discrete model. The values of $\Delta R_T^P(M)$ are determined using the calculations of the integral reference bank worth as a function of position with each test bank fully inserted and the MCP^A values. Figure 3.13 is a graph of the North Anna 1, Cycle 2 predicted reference bank (D bank) integral worth with test bank C fully inserted. This figure provides an illustrative example of the determination of the $\Delta R_T^P(M)$ values. Similarly, the values of $\Delta R^P(M)$ are determined using the calculations of the integral reference bank worth as a function of position with all other banks out and the MCP^A values. Figure 3.14 is a graph of the North Anna 1, Cycle 2 predicted integral worth of the reference bank (D bank) with all other banks out. This figure provides an illustrative example of the determination of the $\Delta R^P(M)$ values. Table 3.3 presents an illustration and summary of the determination of the predicted reactivity worth of the test banks with the reference bank at the MCP^A, $T^P_{\Delta R(M)}$. The test bank worths determined for Surry 1, Cycle 5 and North Anna 1, Cycle 2 are summarized in Table 3.4 and illustrate that the test bank worths are insensitive to small changes in the position of the reference bank.

TABLE 3.1

PREDICTED CRITICAL POSITION SUMMARY

Test Bank	Reference Bank Total Worth (Inserted Alone)- R^P (pcm)	Test Bank Total Worth (Inserted Alone)- T^P (pcm)	Reference Bank Worth to PCP (Test Bank In)- $\Delta R_T^P(P)$ (pcm)	Predicted Critical Reference Bank Position - PCP (steps)
Surry 1, Cycle 5				
D	1374	1188	186	181
C	1374	867	507	123
A	1374	631	743	98
SB	1374	964	410	133
SA	1374	1149	225	172
North Anna 1, Cycle 2				
C	1095	687	408	167
B	1095	1089	6	222
A	1095	789	306	195
SB	1095	713	332	162
SA	1095	941	154	203

TABLE 3.2

PREDICTED TEST BANK INTEGRAL WORTH WITH THE REFERENCE BANK AT THE PCP

Test Bank	Reference Bank Total Worth (Inserted Alone)- R^P (pcm)	Reference Bank Worth to PCP (Inserted Alone)- $\Delta R^P(P)$ (pcm)	Test Bank Total Worth (Ref Bank at PCP)- $T^P_{\Delta R(P)}$ (pcm)
Surry 1, Cycle 5			
D	1374	165	1209
C	1374	521	853
A	1374	739	635
SB	1374	453	921
SA	1374	215	1159
North Anna 1, Cycle 2			
C	1095	458	637
B	1095	7	1088
A	1095	210	885
SB	1095	495	600
SA	1095	131	964

$$T^P_{\Delta R(P)} = R^P - \Delta R^P(P)$$

TABLE 3.3

PREDICTED TEST BANK INTEGRAL WORTH WITH THE REFERENCE BANK AT THE MCP[A]

Test Bank	Test Bank Worth (Inserted Alone)- T^P (pcm)	Reference Bank Worth to MCP[A] (Test Bank In)- $\Delta R_T^P(M)$ (pcm)	Reference Bank Worth to MCP[A] (Inserted Alone)- $\Delta R^P(M)$ (pcm)	Test Bank Worth Ref Bank at MCP[A]- $T^P_{\Delta R(M)}$ (pcm)
Surry 1, Cycle 5				
D	1188	164	147	1205
C	867	520	531	856
A	631	772	766	637
SB	964	393	432	925
SA	1149	235	226	1158
North Anna 1, Cycle 2				
C	687	429	479	637
B	1089	0	0	1089
A	789	393	277	905
SB	713	407	520	600
SA	941	192	167	966

$$T^P_{\Delta R(M)} = T^P + \Delta R_T^P(M) - \Delta R^P(M)$$

TABLE 3.4

PREDICTED TEST BANK INTEGRAL WORTH SUMMARY

Test Bank	Predicted Critical Reference Bank Position-PCP (steps)	Adjusted Measured Critical Reference Bank Position-MCP^A (steps)	Test Bank Worth Ref Bank at PCP- $T^P_{\Delta R(P)}$ (pcm)	Test Bank Worth Ref Bank at MCP^A – $T^P_{\Delta R(M)}$ (pcm)
Surry 1, Cycle 5				
D	181	185	1209	1205
C	123	122	853	856
A	98	94	635	637
SB	133	136	921	925
SA	172	170	1159	1158
North Anna 1, Cycle 2				
C	167	164	637	637
B	222	228	1088	1089
A	195	188	885	905
SB	162	159	600	600
SA	203	199	964	966

FIGURE 3.1

SURRY UNIT 1 - CYCLE 5
PREDICTED REFERENCE BANK WORTH
B BANK WITH D BANK IN

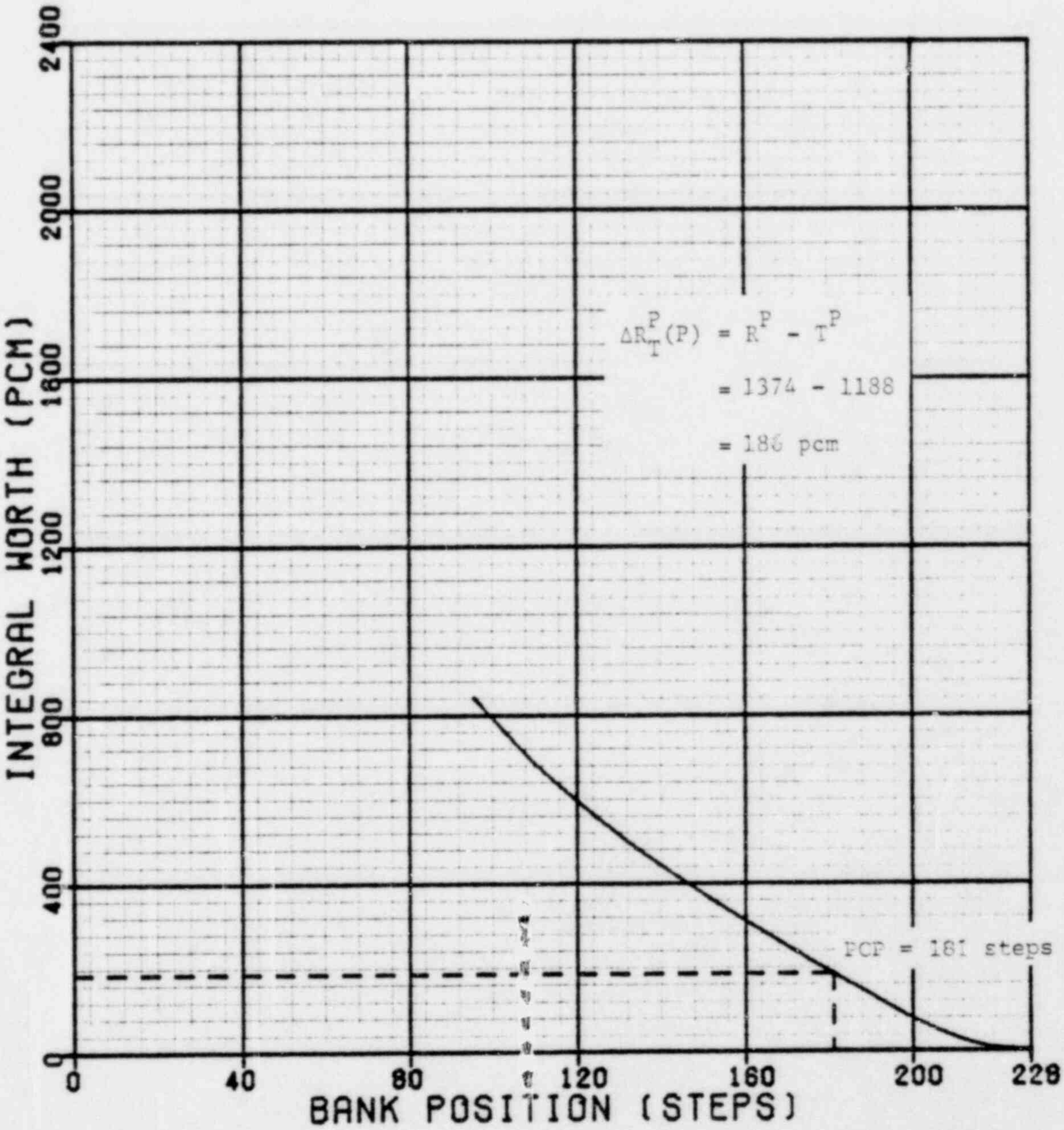


FIGURE 3.2

SURRY UNIT 1 - CYCLE 5

PREDICTED REFERENCE BANK WORTH

B BANK WITH C BANK IN

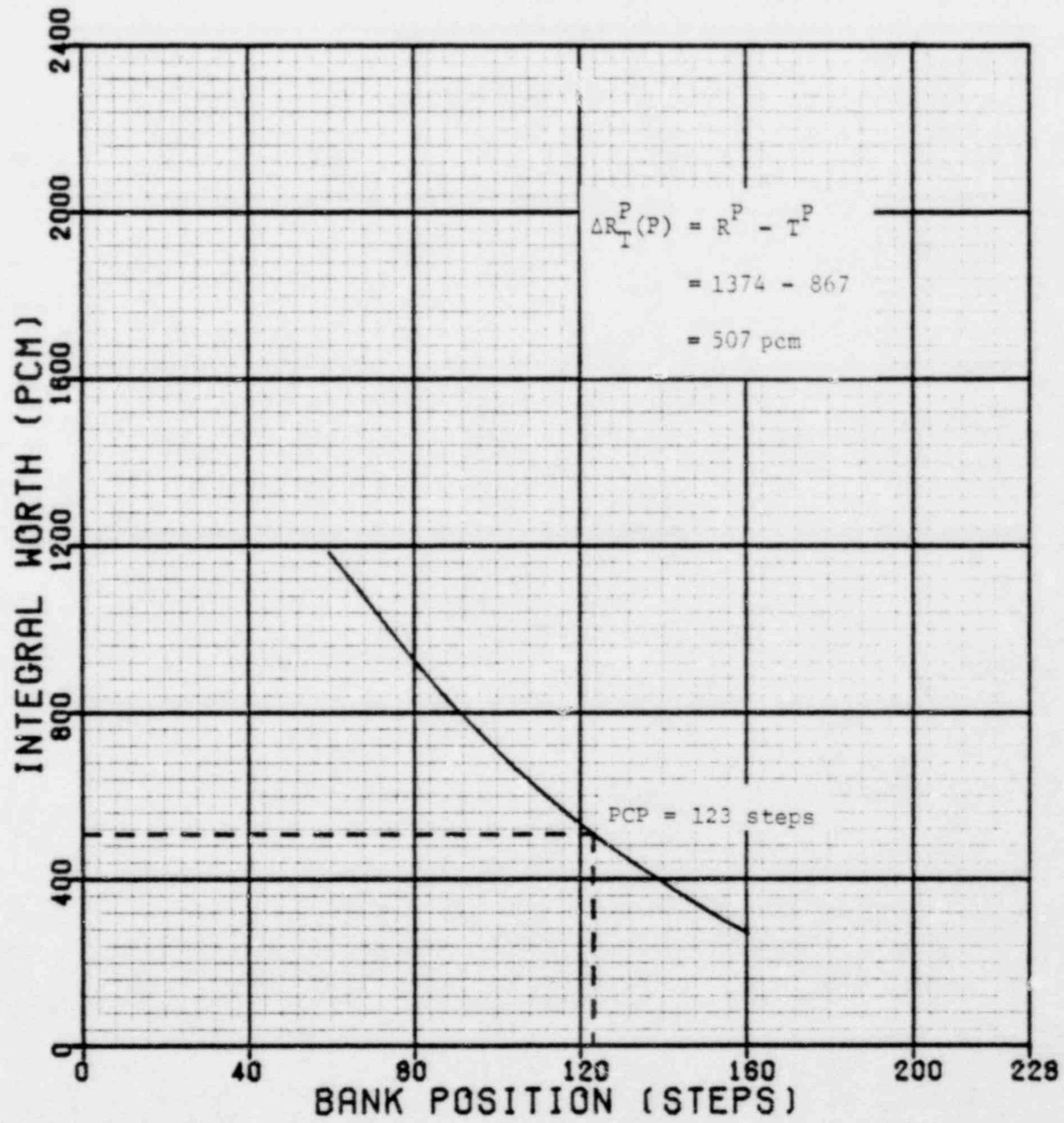


FIGURE 3.3

SURRY UNIT 1 - CYCLE 5
PREDICTED REFERENCE BANK WORTH
B BANK WITH A BANK IN

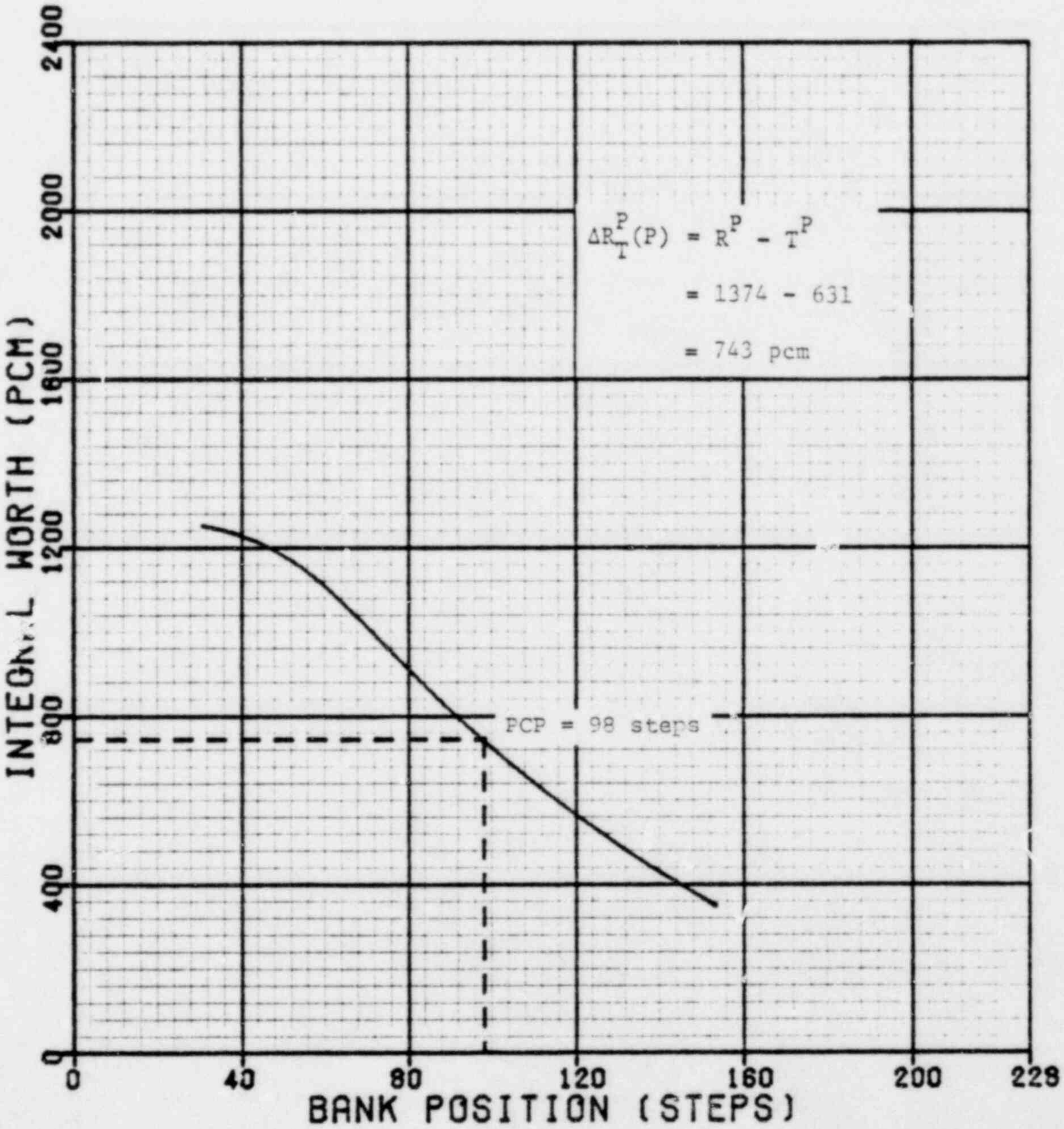


FIGURE 3.4

SURRY UNIT 1 - CYCLE 5
PREDICTED REFERENCE BANK WORTH
B BANK WITH SB BANK IN

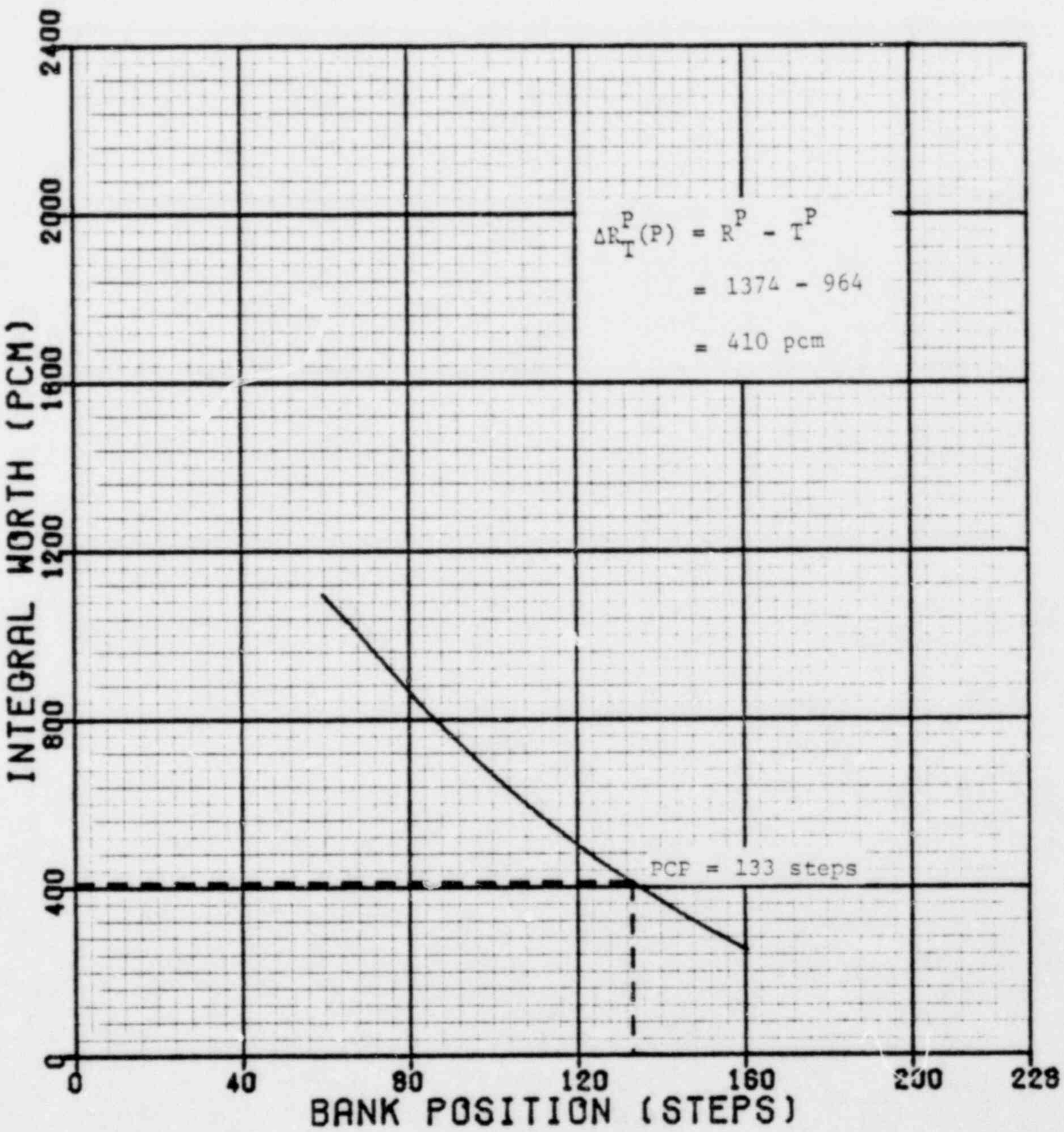


FIGURE 3.5

SURRY UNIT 1 - CYCLE 5
PREDICTED REFERENCE BANK WORTH
B BANK WITH SA BANK IN

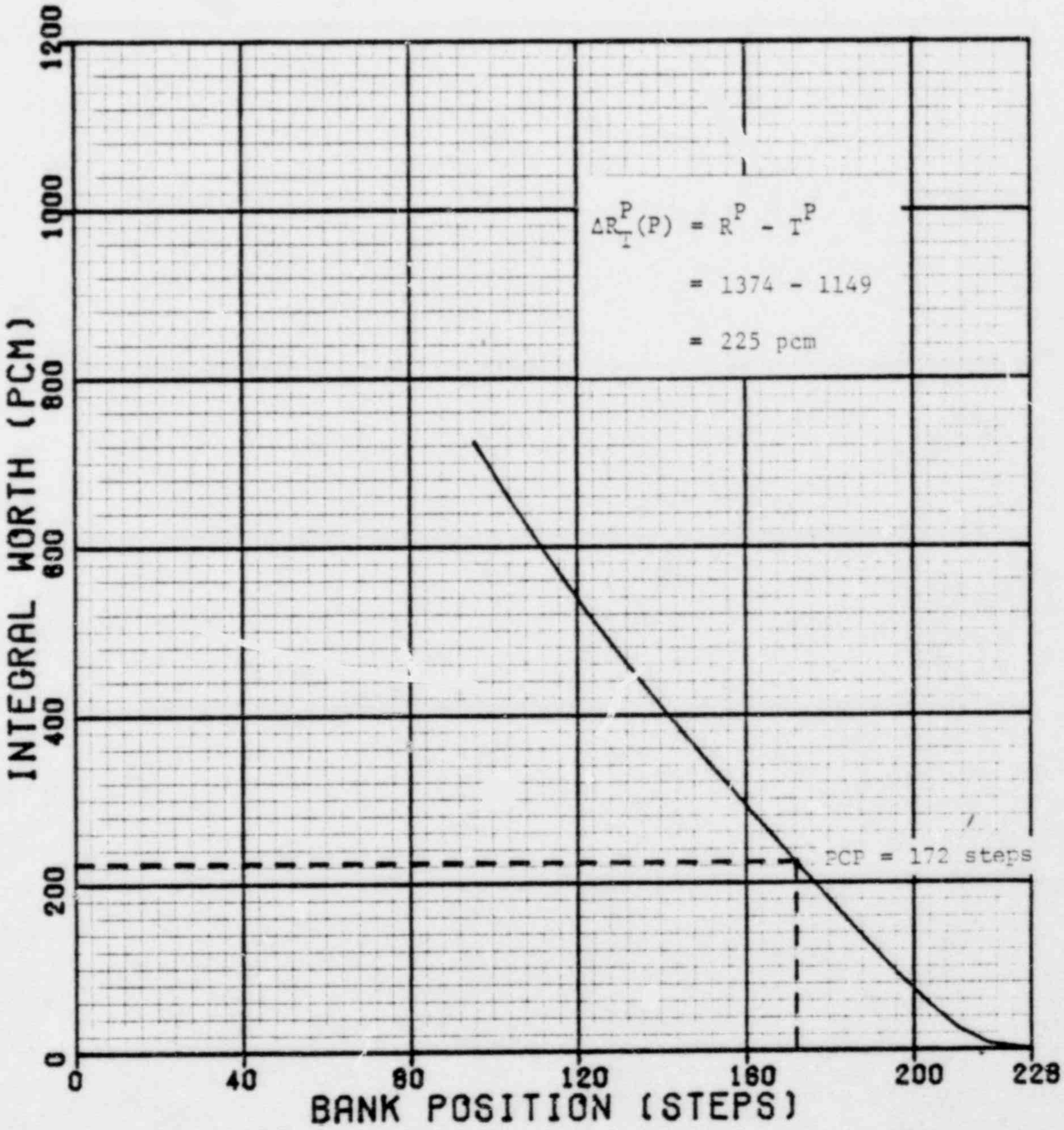


FIGURE 3.6

NORTH ANNA UNIT 1 - CYCLE 2
PREDICTED REFERENCE BANK WORTH
D BANK WITH C BANK IN

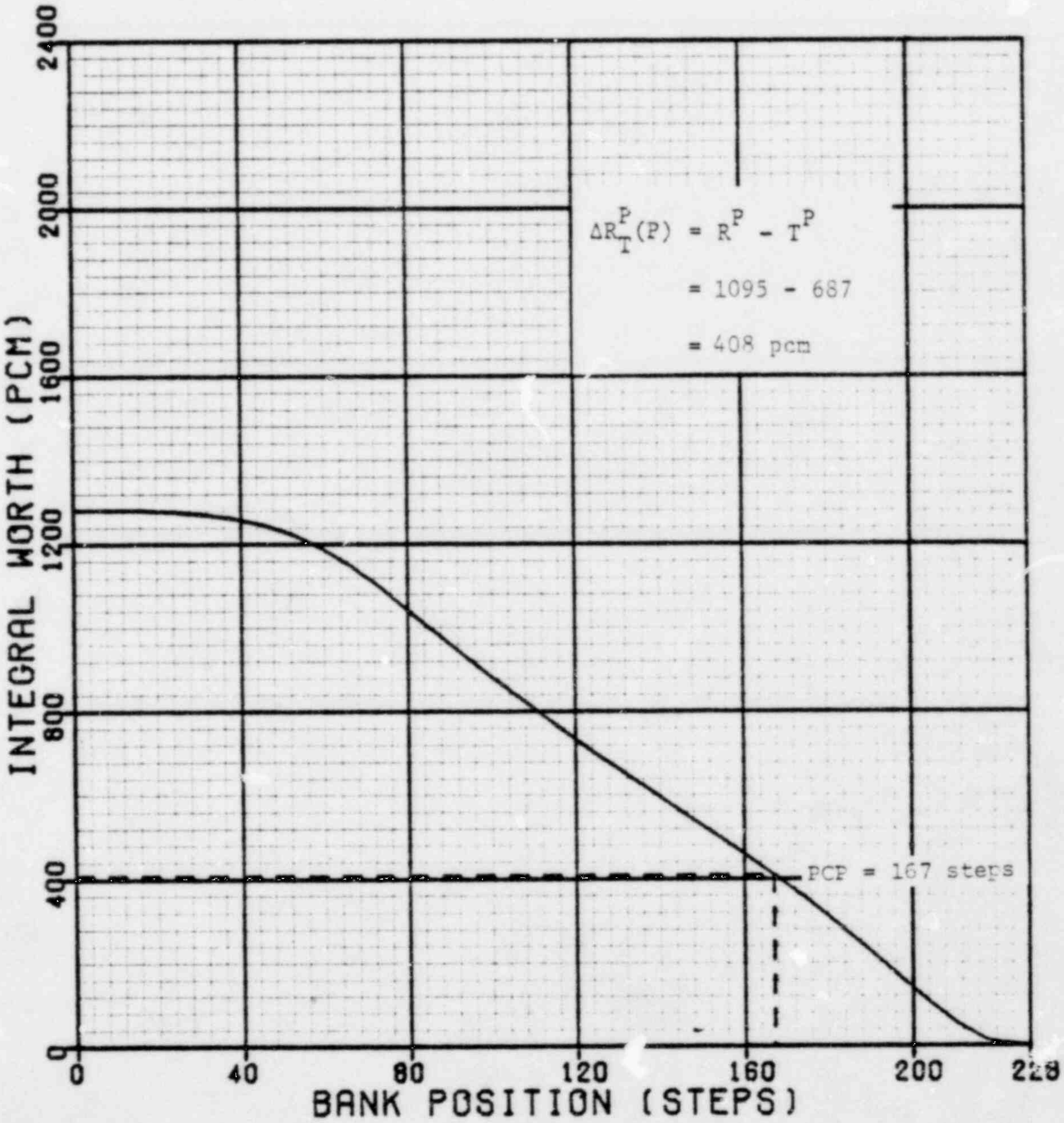


FIGURE 3.7

NORTH ANNA UNIT 1 - CYCLE 2
PREDICTED REFERENCE BANK WORTH
D BANK WITH B BANK IN

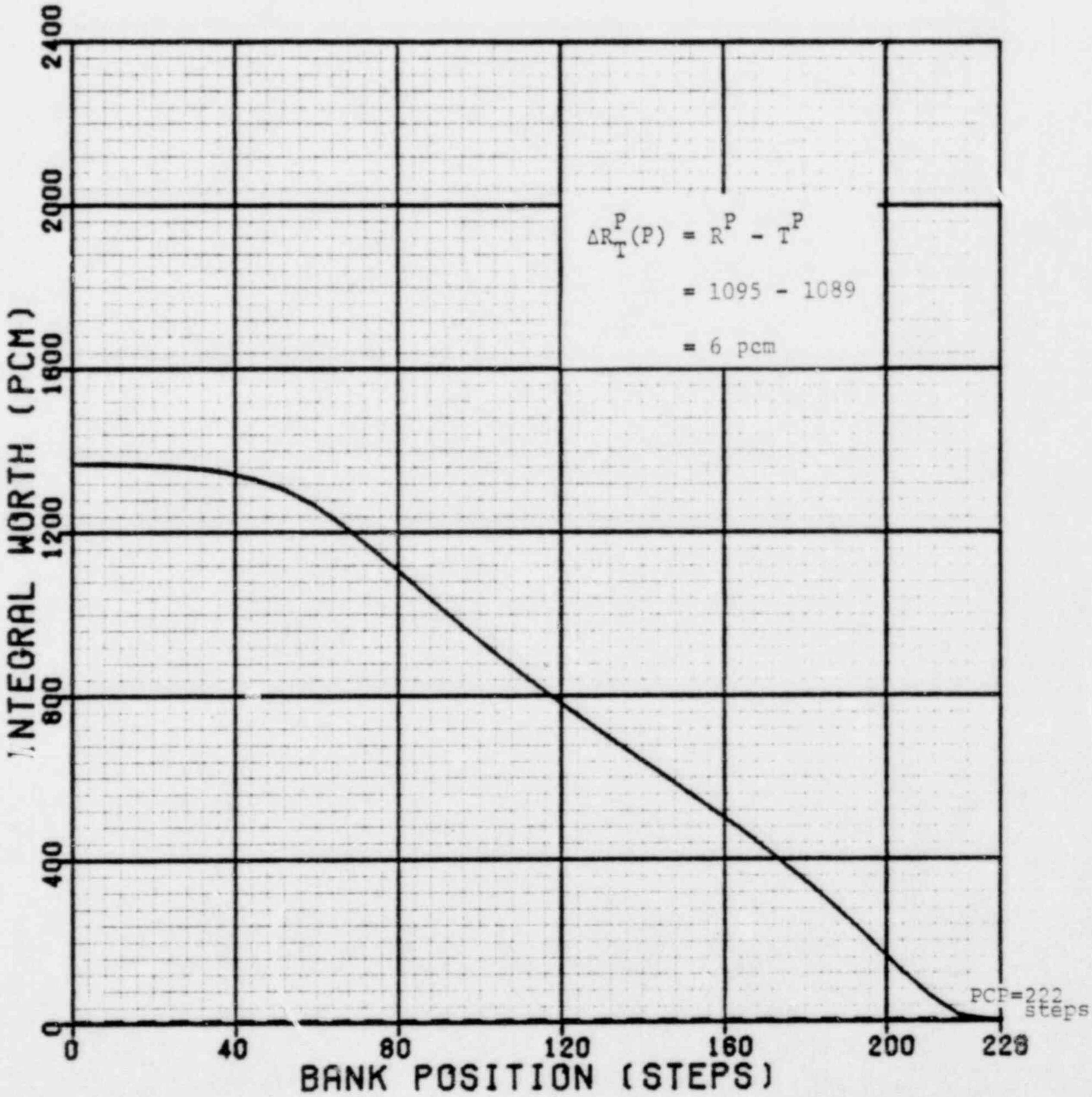


FIGURE 3.8

NORTH ANNA UNIT 1 - CYCLE 2
PREDICTED REFERENCE BANK WORTH
D BANK WITH A BANK IN

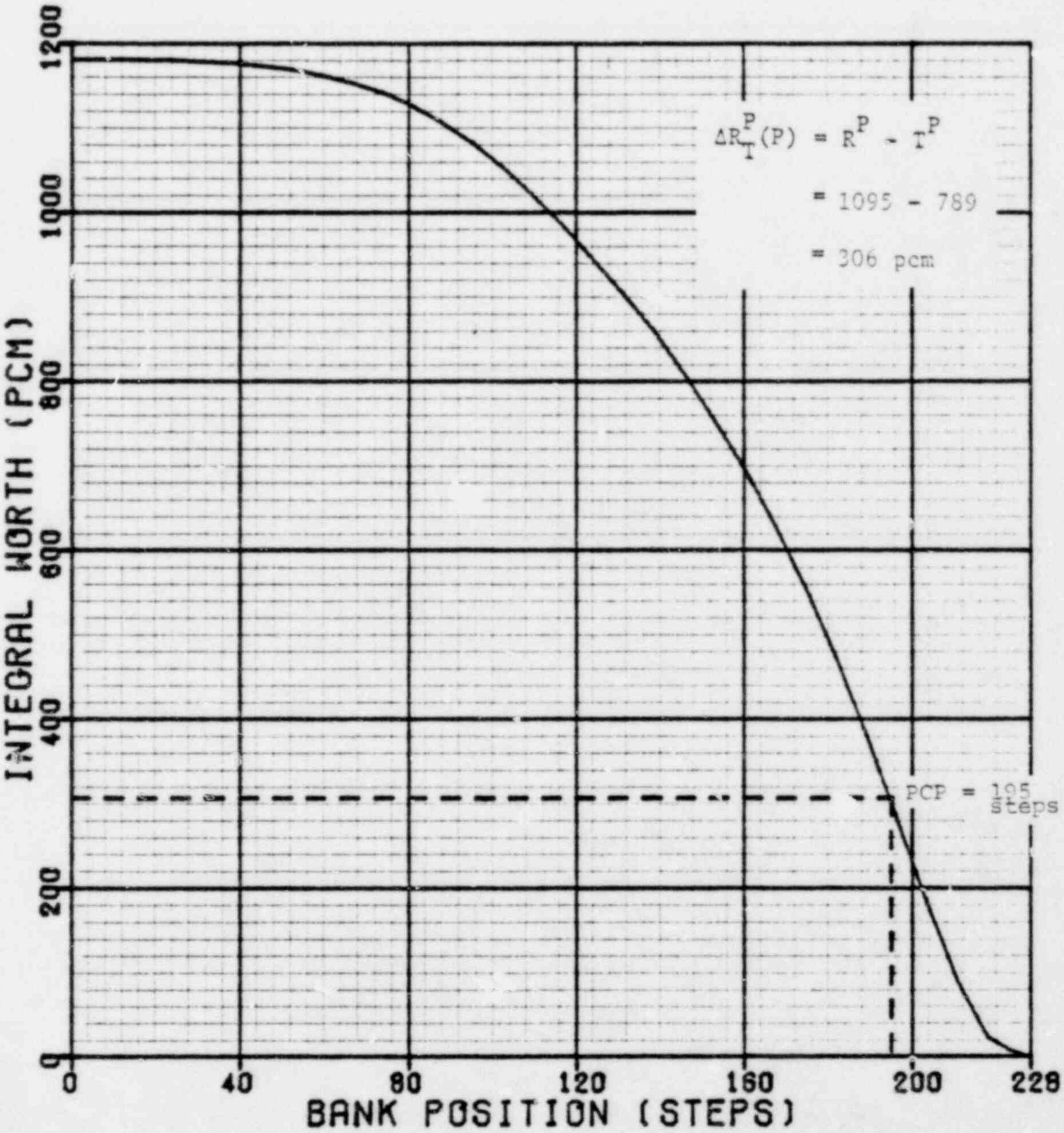


FIGURE 3.9

NORTH ANNA UNIT 1 - CYCLE 2
PREDICTED REFERENCE BANK WORTH
D BANK WITH SB BANK IN

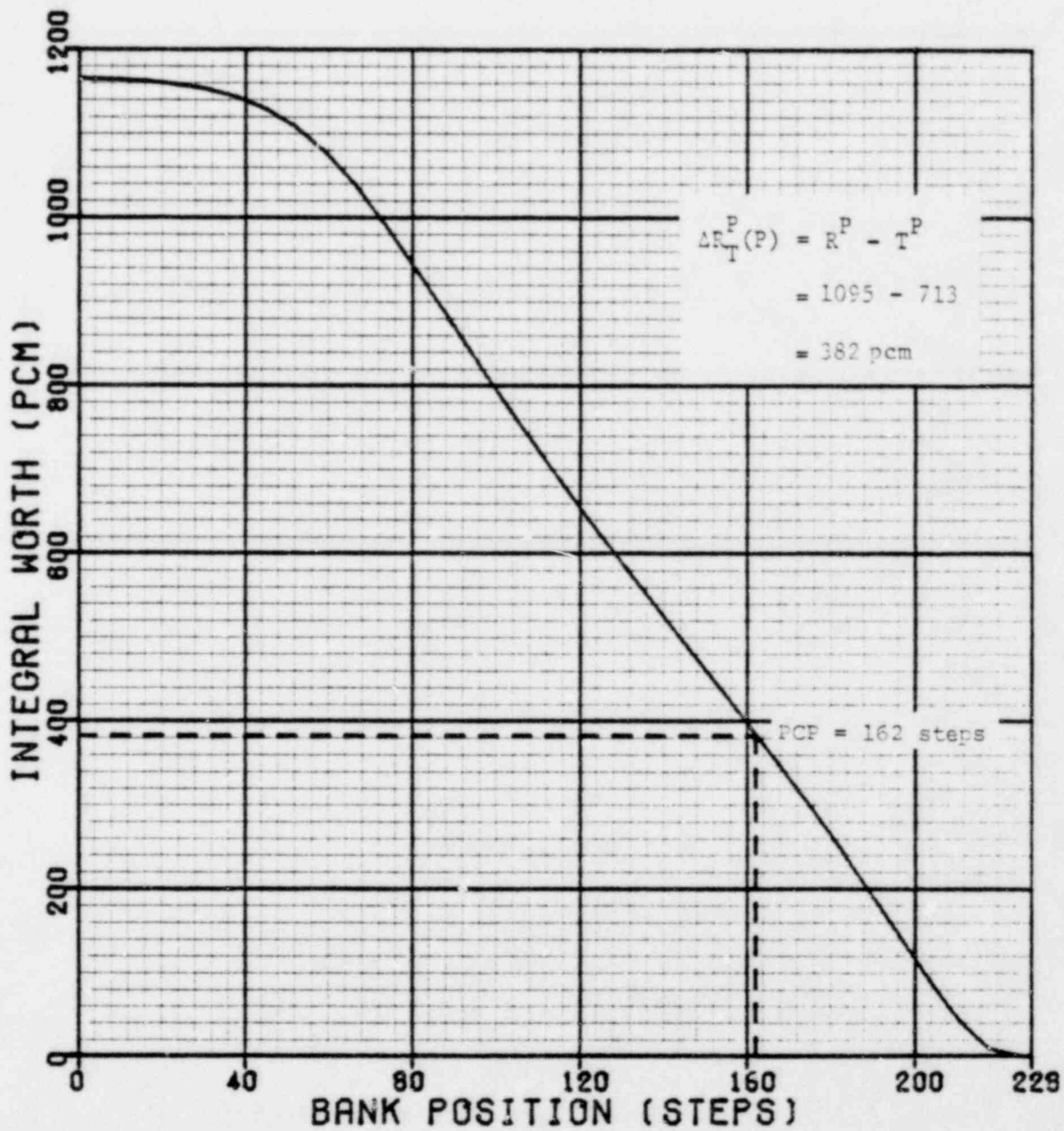


FIGURE 3.10

NORTH ANNA UNIT 1 - CYCLE 2
PREDICTED REFERENCE BANK WORTH
D BANK WITH SA BANK IN

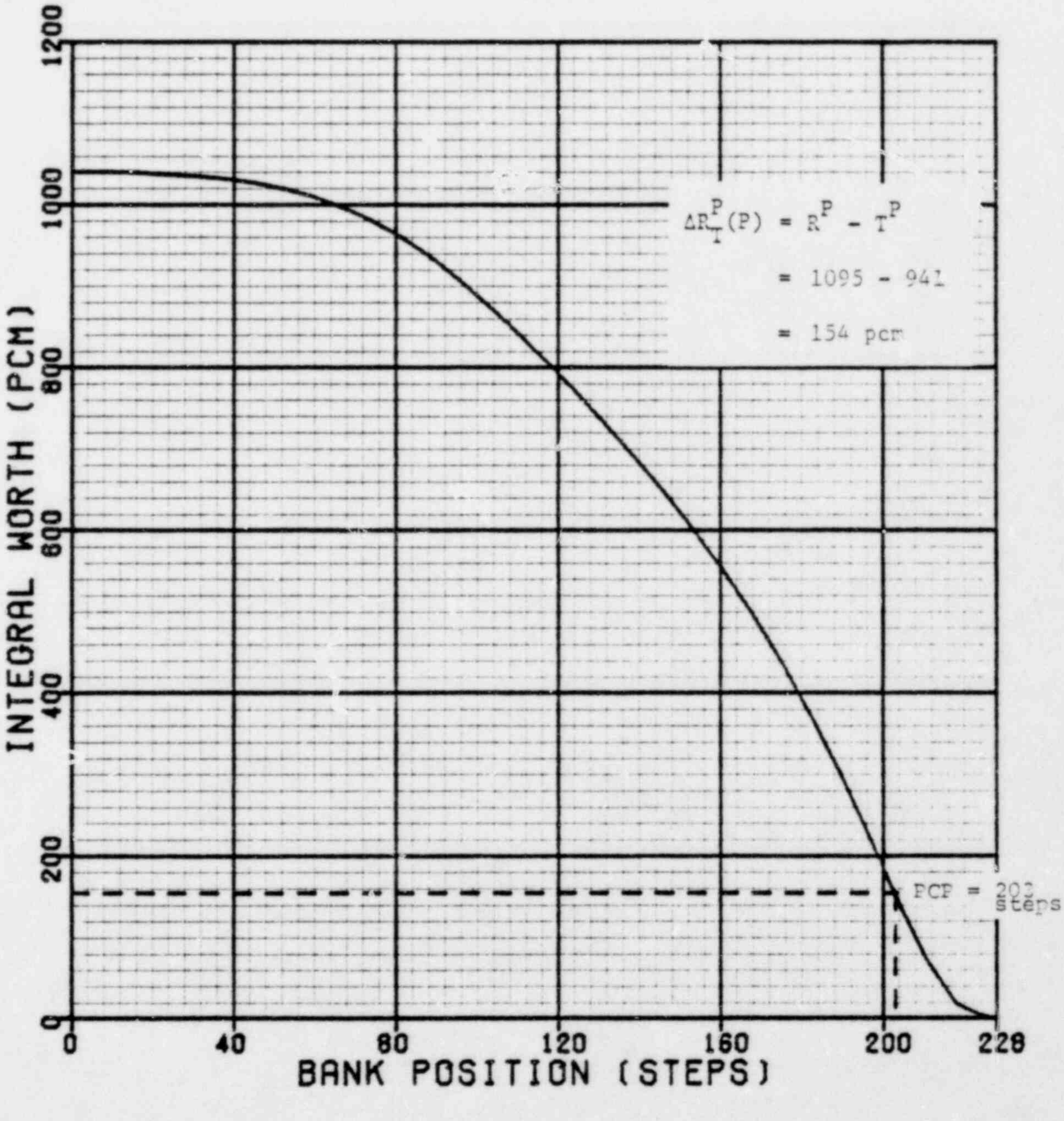


FIGURE 3.11

SURRY UNIT 1 - CYCLE 5
PREDICTED REFERENCE BANK WORTH
B BANK WITH ALL OTHER BANKS OUT

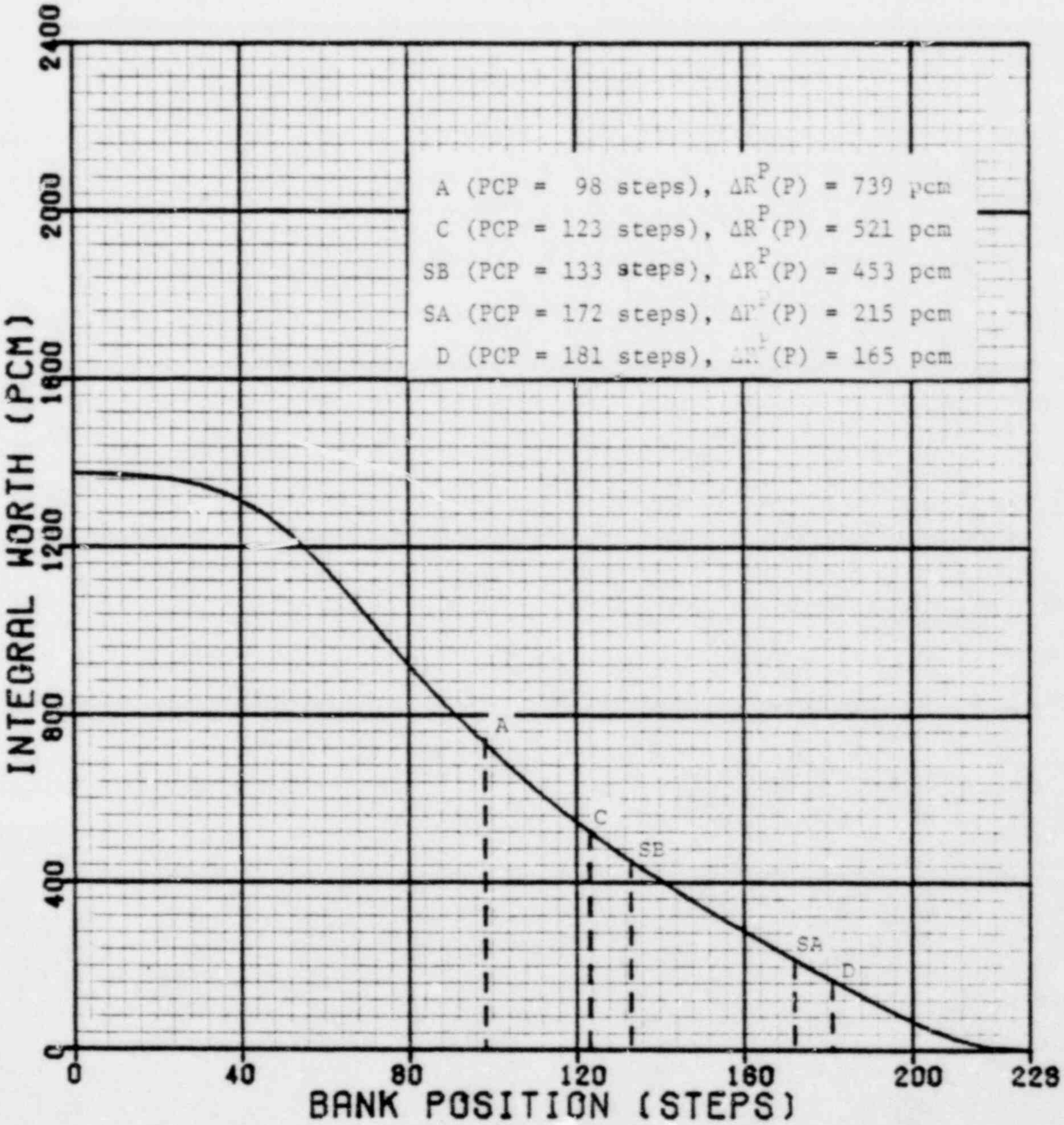


FIGURE 3.12

NORTH ANNA UNIT 1 - CYCLE 2

PREDICTED REFERENCE BANK WORTH

D BANK WITH ALL OTHER BANKS OUT

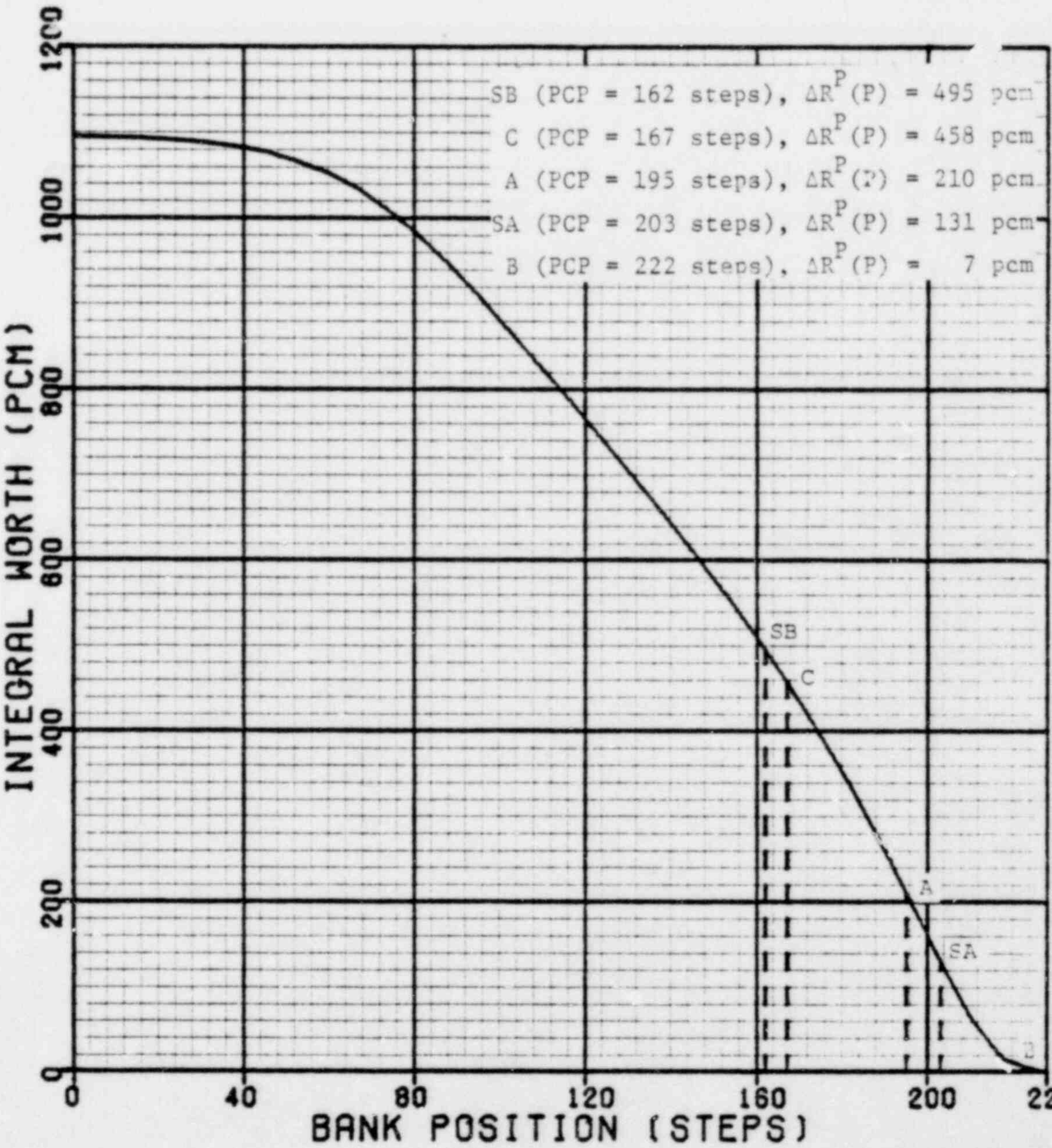


FIGURE 3.13

NORTH ANNA UNIT 1 - CYCLE 2

DETERMINATION OF $\Delta R_T^P(M)$

FOR TEST BANK C

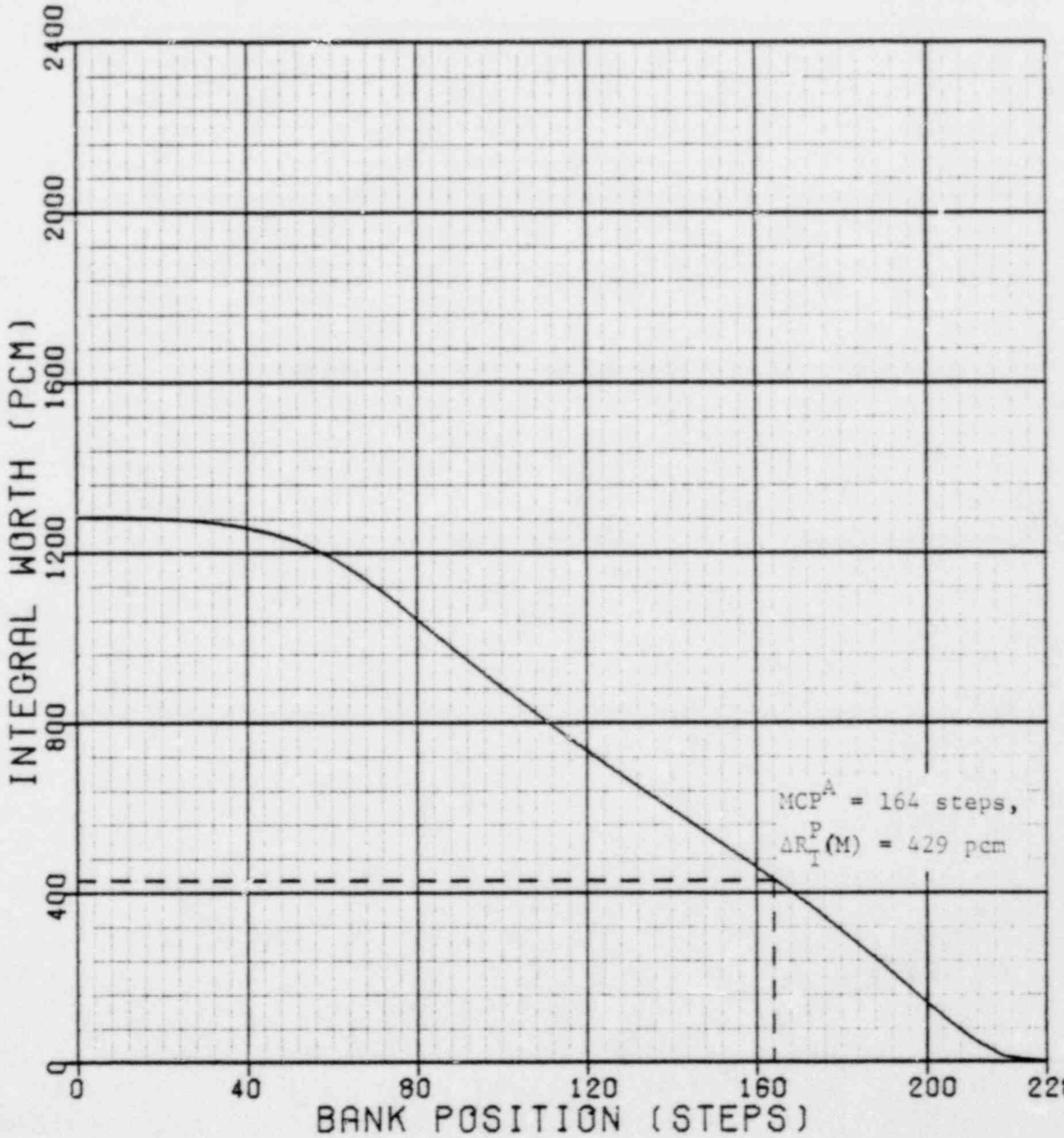
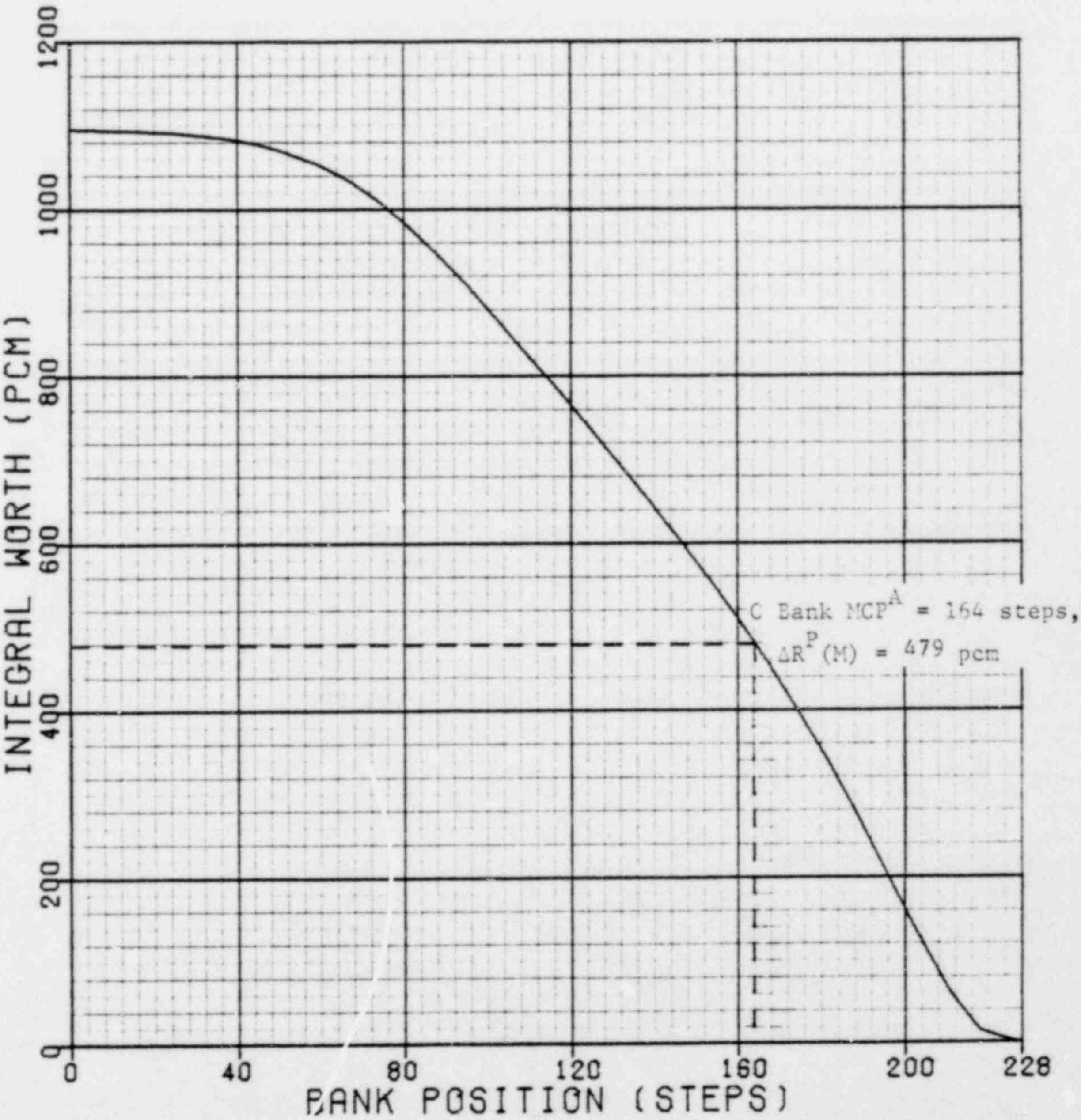


FIGURE 3.14

NORTH ANNA UNIT 1 - CYCLE 2

DETERMINATION OF $\Delta R^P(M)$

FOR TEST BANK C



Section 4

TEST RESULTS EVALUATION METHODOLOGY AND REVIEW CRITERIA

4.1 Background

As described earlier in this report, the acceptability of the results of the control rod bank worth tests serves to demonstrate the validity of the results of the calculational models used to predict control rod bank worths as part of the design process. Traditionally, the evaluation of the acceptability of the results of control rod bank worth tests has been based on a comparison of the measured and predicted control rod bank worths. This comparison has typically been expressed in terms of the percent difference between the measured and predicted result as shown in Equation (9).

$$\Delta(\%) = \frac{\rho_{meas} - \rho_{design}}{\rho_{design}} \times 100 \qquad (9)$$

In the past, the measured control rod bank worths were obtained by using the dilution/boration technique. The review criteria (design tolerance) used for this comparison has been $\pm 15\%$ for the measurement of the reactivity worth of individual control rod banks as shown by Equation (10).

$$|\Delta(\%)| \leq 15\% \qquad (10)$$

For individual control rod banks with relatively low reactivity worths, i.e., ≤ 600 pcm, the difference between the measured and predicted reactivity worth has been expressed in terms of absolute reactivity as shown by Equation (11).

$$\Delta(pcm) = \rho_{meas} - \rho_{design} \qquad (11)$$

The review criteria used for this comparison has been ±100 pcm as shown by Equation (12).

$$|\Delta(\text{pcm})| \leq 100 \text{ pcm} \tag{12}$$

Finally, in order to address additional concerns regarding shutdown margin verification, a review criteria has been established that the percent difference between the measured and predicted total reactivity worth of all four control banks be within ±10% as shown by Equation (13).

$$|\Delta(\%)|_{\text{A thru D}} = \left| \frac{\rho^{A-D}_{meas} - \rho^{A-D}_{design}}{\rho^{A-D}_{design}} \times 100 \right| \leq 10\% \tag{13}$$

4.2 Rod Swap Test Evaluation and Review Criteria

The rod swap test evaluation and review criteria have been established at two levels. The first level addresses the individual bank worth test results. The second level addresses the test results for the total reactivity worth of all of the control rod banks.

Level I Review Criteria

The measurement of the reactivity worth of the reference bank is performed using the dilution/boration technique. Therefore, the standard test result evaluation methodology and review criteria for individual bank worths using the dilution/boration technique, as described above, could be used to evaluate the results of that test. However, since the results of the reference bank reactivity worth test are used in the determination of the reactivity worth of each test bank, a more restrictive review criteria is used to evaluate that test result as shown by Equation (14).

$$|\Delta(\%)|_{\substack{\text{Reference}\\ \text{Bank}}} \leq 10\% \qquad (14)$$

As described in Section 3 of this report, the design predictions of the individual test bank reactivity worths are on exactly the same basis as the measured test results. Therefore, it is appropriate to use the same test result evaluation methodology for the rod swap test results as for test results obtained using the dilution/boration technique. The measured test bank worths, $T^M_{\Delta R(M)}$, are compared to the design predictions, $T^P_{\Delta R(M)}$, and the difference between the two is expressed either in terms of percent difference or in terms of absolute reactivity as appropriate. Additionally, since the individual test bank worth determinations are essentially the same in nature as the individual control rod bank reactivity worth tests using the dilution/boration technique, it is appropriate to use the same review criteria for the individual test bank worths determined through rod swap as shown by Equations (15a) and (15b).

$$|\Delta(\%)|_{\substack{\text{Test}\\ \text{Bank}}} \leq 15\% \text{ for bank worths } > 600 \text{ pcm} \qquad (15a)$$

$$|\Delta(\text{pcm})|_{\substack{\text{Test}\\ \text{Bank}}} \leq 100 \text{ pcm for bank worths } \leq 600 \text{ pcm} \qquad (15b)$$

Level II Review Criteria

A review criteria has been established to confirm that the percent difference between the measured and predicted total reactivity worth of all of the control rod banks (i.e., the summation of the individual bank worths, control and shutdown) be within ±10%; i.e.,

$$\left|\Delta(\%)\right|_{Total} = \left| \frac{\rho^T_{meas} - \rho^T_{design}}{\rho^T_{design}} \times 100 \right| \leq 10\% \qquad (16)$$

In summary, a test result evaluation methodology and review criteria have been established to evaluate the control rod bank worth test results obtained by using the rod swap technique. The evaluation methodology and review criteria are appropriate with respect to the test procedure, the test data analysis methods, and the design methods; and are consistent with those used to evaluate the results of control rod bank worth tests using the dilution/boration technique.

As in the case of the current testing programs, should the results of the rod swap tests fail to meet the established review criteria, the Station Nuclear Safety and Operating Committee will be informed as required by the Vepco Nuclear Power Station Quality Assurance Manual. A test result that fails to meet the Level I review criteria shall be reviewed by the Station Nuclear Safety and Operating Committee. Final resolution shall be based on the composite of plant startup data and an evaluation of the impact of the discrepancy on the results of the analyses of the applicable events considered in the FSAR. Based on the results of this review, the Committee may decide to perform additional testing. This additional testing may be a repeat of the original test or the performance of other appropriate confirmatory tests. Should the test results fail to meet the Level II review criteria, the reactivity worth of control rod banks D thru A shall be measured (and also the remainder of the rod banks to N-1 if required) by successive insertion using the dilution/boration technique. This will be done in order to validate the results of the calculational models used to predict the control rod bank reactivity worths.

Section 5

ROD SWAP TEST RESULTS

The Surry 1, Cycle 5 and North Anna 1, Cycle 2 rod swap test data were analyzed using the methodology presented in Section 2.2. The design predictions associated with these tests were performed using the methodology presented in Section 3. Figures 5.1 and 5.2 provide a comparison of the measured and predicted integral worth of the reference bank for Surry 1, Cycle 5 and North Anna 1, Cycle 2, respectively. The results of the test bank worth measurements, together with the associated design predictions and test review criteria are summarized on Table 5.1. As can be seen from the information presented on this table, all of the test results met the test review criteria and were acceptable.

TABLE 5.1

ROD SWAP TEST RESULTS

SURRY 1, CYCLE 5

Control Rod Bank	Bank Worth (pcm) Measured	Bank Worth (pcm) Predicted	Δ(pcm)	Δ(%)	Review Criteria (%)
B-reference bank	1405	1374	31	+2.3	±10
D	1257	1205	52	+4.3	±15
C	881	856	25	+2.9	±15
A	649	637	12	+1.9	±15
SB	977	925	52	+5.6	±15
SA	1178	1158	20	+1.7	±15
Total	6347	6155	192	+3.12	±10

NORTH ANNA 1, CYCLE 2

Control Rod Bank	Bank Worth (pcm) Measured	Bank Worth (pcm) Predicted	Δ(pcm)	Δ(%)	view Criteria (%)
D-reference bank	1069	1095	-26	-2.4	±10
C	684	637	47	+7.4	±15
B	1085	1039	-4	-0.4	±15
A	843	905	-62	-6.9	±15
SB	649	600	49	+8.2	±15
SA	930	966	-36	-3.7	±15
Total	5260	5292	-32	-0.6	±10

FIGURE 5.1

SURRY UNIT 1 - CYCLE 5
REFERENCE BANK WORTH
B BANK WITH ALL OTHER BANKS OUT

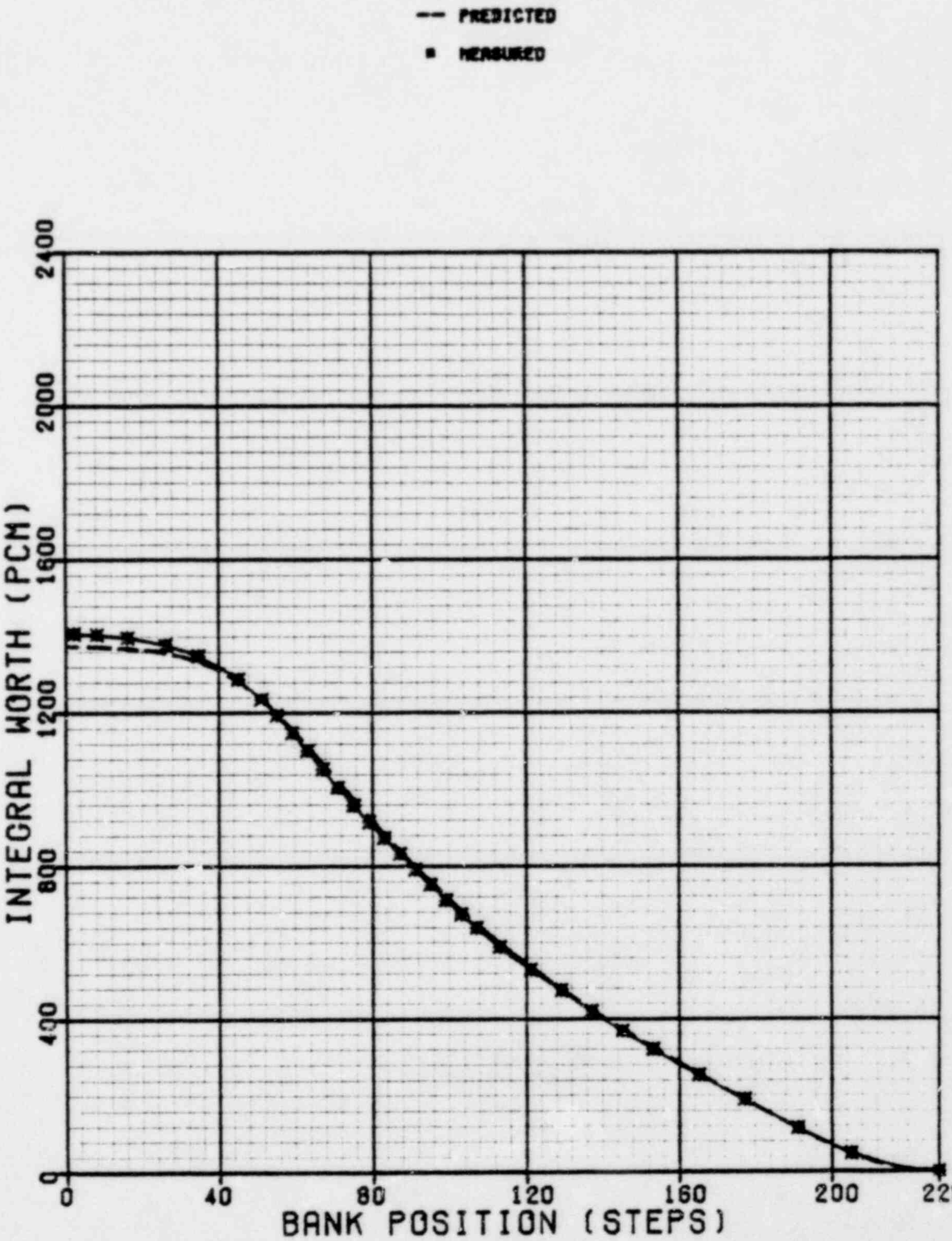
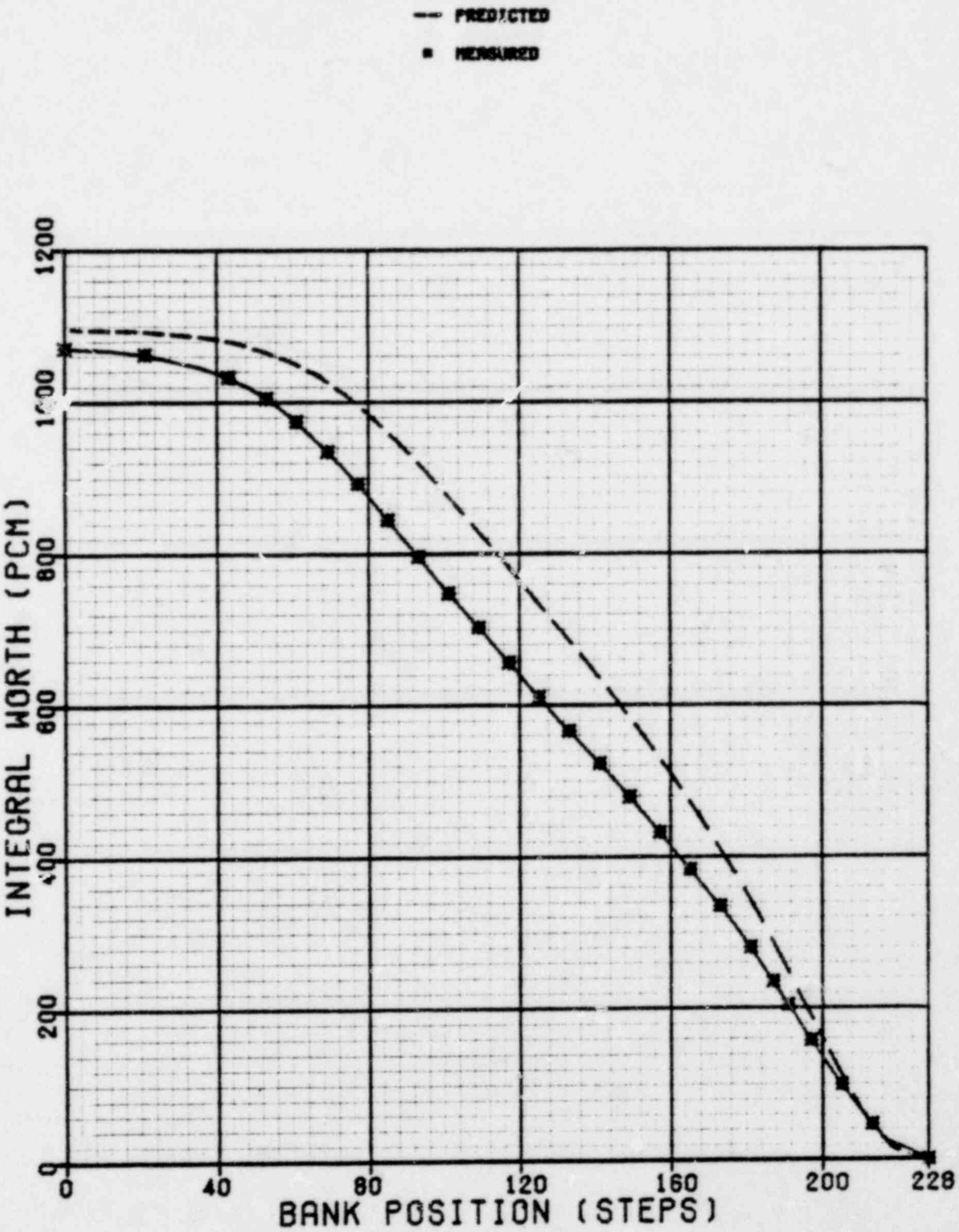


FIGURE 5.2

NORTH ANNA UNIT 1 - CYCLE 2

REFERENCE BANK WORTH

D BANK WITH ALL OTHER BANKS OUT



Section 6

VALIDATION OF THE ROD SWAP METHODOLOGY

As mentioned earlier in this report, in addition to the control rod bank reactivity tests that were performed using the rod swap technique, control rod bank reactivity tests were performed using the conventional dilution/boration technique during the reload startup of Surry 1, Cycle 5 and North Anna 1, Cycle 2. The purpose of performing these side-by-side programs was to establish the technical basis for validating the rod swap methodology. The results of these tests are presented in Tables 6.1 and 6.2, respectively, for Surry and North Anna. The design values for these tests together with the test review criteria are also shown.

The data on these tables indicate the basic similarities that exist between the results of these two test techniques with respect to the acceptability of the test results, and therefore, the verification of the design calculations. More specifically, for the Surry 1, Cycle 5 test results, the average absolute percent difference for the individual bank worth tests was 2.78% for the dilution/boration tests and 3.12% for the rod swap tests. The percent difference associated with the total reactivity worth of the control rod banks that were measured was 1.2% for the dilution/boration tests and 3.12% for the rod swap tests. For the North Anna 1, Cycle 2 tests results, the average absolute percent difference for the individual bank worth tests was 3.46% for the dilution/boration tests and 4.83% for the rod swap tests. The percent difference associated with the total reactivity worth of the control rod banks that were measured was -1.7% for the dilution/boration tests and -0.6% for the rod swap tests. In summary, the results of all of the tests were acceptable since all of the review criteria were met. Therefore, the results of both test techniques demonstrated the validity of the results of the design calculations for control rod bank worths.

Since the reactivity worth of all of the control rod banks is determined as part of the rod swap methodology, and since the same conclusions are reached regarding the verification of the results of the design calculations for control rod bank worths, the results of the side-by-side programs demonstrate the validity of using the rod swap methodology in future Vepco startup physics testing programs.

TABLE 6.1

SURRY 1, CYCLE 5 ROD WORTH RESULTS

ROD SWAP TECHNIQUE

Control Rod Bank	Bank Worth (pcm) Measured	Bank Worth (pcm) Predicted	Δ(pcm)	Δ(%)	Review Criteria (%)
B-reference bank	1405	1374	31	+2.3	±10
D	1257	1205	52	+4.3	±15
C	881	856	25	+2.9	±15
A	649	637	12	+1.9	±15
SB	977	925	52	+5.6	±15
SA	1178	1158	20	+1.7	±15
Total	6347	6155	192	+3.12	±10

$\overline{|\Delta(\%)|} = 3.12\%$

DILUTION/BORATION TECHNIQUE (6)

Control Rod Bank	Bank Worth (pcm) Measured	Bank Worth (pcm) Predicted	Δ(pcm)	Δ(%)	Review Criteria (%)
D	1207	1188	19	+1.6	±15
C-Bank D in	1082	1056	26	+2.5	±15
B-Banks C+D in	1999	2040	-41	-2.0	±15
A-Banks B+C+D in	1304	1242	62	+5.0	±15
Σ A→D	5592	5526	66	+1.2	±10

$\overline{|\Delta(\%)|} = 2.78\%$

Table 6.2

NORTH ANNA 1, CYCLE 2 ROD WORTH RESULTS

ROD SWAP TECHNIQUE

Control Rod Bank	Bank Worth (pcm) Measured	Bank Worth (pcm) Predicted	Δ(pcm)	Δ(%)	Review Criteria (%)
D-reference bank	1069	1095	-26	-2.4	±10
C	684	637	47	+7.4	±15
B	1085	1089	-4	-0.4	±15
A	843	905	-62	-6.9	±15
SB	649	600	49	+8.2	±15
SA	930	966	-36	-3.7	±15
Total	5260	5292	-32	-0.6	±10

$\overline{|\Delta(\%)|} = 4.83\%$

DILUTION/BORATION TECHNIQUE(7)

Control Rod Bank	Bank Worth (pcm) Measured	Bank Worth (pcm) Predicted	Δ(pcm)	Δ(%)	Review Criteria (%)
D	1069	1095	-26	-2.4	±15
C-Bank D in	908	873	35	+4.0	±15
B-Banks C+D in	1321	1434	-113	-7.9	±15
A-Banks B+C+D in	1651	1649	2	+0.1	±15
SB-Banks A+B+C+D in	933	907	26	+2.9	±15
N-1	5942	6044	-102	-1.7	±10

$\overline{|\Delta(\%)|} = 3.46\%$

Section 7

CONCLUSIONS

Based on the results of the side-by-side demonstration programs, it has been concluded that it is appropriate to use the rod swap methodology to demonstrate the validity of the results of the calculational models used to predict control rod bank reactivity worths. Additionally, the rod swap tests that were performed during the initial startup of Surry 1, Cycle 5 and North Anna 1, Cycle 2 demonstrated that the implementation of the test procedure was very straightforward and that the data acquisition and analysis were no more difficult or complex than that associated with control rod bank reactivity worth tests using the dilution/boration technique. The potential savings in testing time and boron recovery processing requirements were also demonstrated.

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3) W. C. Beck, "Rod Swap Design Data for Surry Unit 1, Cycle 5," NFE Technical Report No. 73, April, 1978.

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5) J. G. Miller, S. A. Ahmed, R. T. Robins, H. H. Barker, "Design Predictions for Surry Unit No. 1, Cycle 5," NFE Technical Report No. 74 (Parts 1 and 2), May, 1978.

6) T. J. Kunsitis, J. H. Leberstien, "Surry Unit 1, Cycle 5 Startup Physics Test Report," VEP-FRD-30, September, 1978.

7) T. J. Kunsitis, J. H. Leberstien, T. K. Ross, "North Anna Unit 1, Cycle 2 Startup Physics Test Report," VEP-FRD-35, June, 1980.

APPENDIX
IMPACT OF THE ROD SWAP TESTS ON THE HOT ZERO POWER STARTUP PHYSICS TESTING PROGRAM FOR RELOAD CORES

Table A.1 identifies the series of tests that have been routinely performed as part of the Vepco reload hot zero power physics testing programs. Table A.2 identifies the series of tests that will be performed in the future. As can be seen from the information presented on these two tables, a basic trade-off is taking place. Through the implementation of the rod swap program, more control rod bank reactivity worth information will be obtained in lieu of several boron endpoint measurements. This is justified for the following reason. The boron endpoint data is supplementary to the control rod bank reactivity worth data in that the change in the boron endpoint values is merely another way of measuring the reactivity change associated with a change in the configuration of the control rod banks. Since the rod swap tests provide a mechanism for measuring the reactivity worths of all of the control rod banks, the elimination of selected boron endpoint measurements does not represent a loss of significant information.

In summary, the implementation of the rod swap tests will change the composition of the reload hot zero power startup physics testing program. However, this change will result in more control rod bank reactivity worth data being obtained. The elimination of selected boron endpoint measurements does not result in the loss of required data.

TABLE A.1

HOT ZERO POWER STARTUP PHYSICS TESTING PROGRAM

Reactivity Computer Checkout

Boron Endpoint - ARO

Temperature Coefficient - ARO

M/D Flux Map - ARO

Bank D Worth

Boron Endpoint - D in

Temperature Coefficient - D in

M/D Flux Map - D in

Bank C Worth - D in

Boron Endpoint - C+D in

*Temperature Coefficient - C+D in

Bank B Worth - C+D in

Boron Endpoint - B+C+D in

Bank A Worth - B+C+D in

Boron Endpoint - A+B+C+D in

Banks A→D Worth in Overlap

*Only performed when it is necessary to supply measured data to establish control rod bank withdrawal limits in order to meet the Technical Specification limits for the moderator temperature coefficient.

TABLE A.2

HOT ZERO POWER STARTUP PHYSICS TESTING PROGRAM WITH ROD SWAP

Reactivity Computer Checkout

Boron Endpoint - ARO

Temperature Coefficient - ARO

M/D Flux Map - ARO

Reference Bank Worth

Boron Endpoint - Reference Bank In

Temperature Coefficient - Reference Bank In

M/D Flux Map - Rodded

Control Rod Bank Worths (Control and Shutdown)