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CONTROL ROD WORTH ANALYSIS

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CHAPTER 1

INTRODUCTION

A steady state reactor physics methodology has been developed by TU Electric to be utilized in support of reload design, licensing, and operation of Comanche Peak Steam Electric Station (CPSES) Units 1 and 2. The generalized methodology is documented in Reference 1. As described in that report, TU Electric has selected state-of-the-art computer codes and has focused on application of the codes using modeling details appropriate for power reactors. This methodology has been extended to the calculation of control rod worth. The applicability of the methodology is demonstrated by comparison of calculated control rod bank worths to control rod bank worths measured with the boron dilution technique and with the control rod swap technique.

Included in Reference 1 are the results of pre-startup calculations for CPSES Unit 1, Cycle 1 using the TU Electric methodology. After the issuance of Reference 1, TU Electric elected to incorporate the flexibility of utilizing control rod swap as an alternative method of measuring control rod worth. In order to maintain such flexibility for reload cycles, TU Electric developed an analytical methodology to support control rod worth measurements using either the boron dilution technique or the control rod swap technique. The TU Electric control rod swap methodology was provided in Reference 2 along with pre-test predictions of CPSES Unit 1, Cycle 1 control rod bank worths to be compared to control rod bank worths measured with the control rod swap technique. In order to clearly demonstrate the capability of the methodology when applied in the predictive mode, Reference 2 was issued prior to the CPSES Unit 1, Cycle 1 startup physics testing.

This report presents comparisons of calculated and measured control rod bank worths for several power reactors. CPSES Unit 1, Cycle 1 results are included. The test procedures are summarized for both measurement techniques and, in addition, test review and acceptance criteria are identified.

CHAPTER 2

SUMMARY

The steady state reactor physics methodology described in Reference 1 has been extended to include calculation of control rod bank worths. To that end, TU Electric has developed an analytical methodology to support control rod bank worth measurements at CPSES using either the boron dilution technique or the control rod swap technique.

Presented in this report are the analytical methodology for evaluation of control rod bank worth and the validation of the methodology by comparisons between calculated results and measured data for large power reactors (Catawba Unit 1, Prairie Island Unit 1, and CPSES Unit 1). The methodology was applied to eight cycles of operation: Catawba Unit 1, Cycles 1 and 2, Prairie Island Unit 1, Cycles 5 through 7 and Cycles 9 through 10, and CPSES Unit 1, Cycle 1. For five of these cycles, the boron dilution technique was utilized to measure the control rod bank worths. For four cycles the control rod swap technique was utilized. Prairie Island Unit 1, Cycle 9 control rod bank worths were measured using both techniques.

Control rod bank worths calculated with the methodology presented in this report show good agreement with measured values. For measurements made with the boron dilution technique (23 control rod banks in 5 cycles), the average difference between calculated and measured control rod bank worths is 2.32% with a standard deviation of 4.04%. The average difference between calculated and measured worth of the sum of the banks is 2.08% with a standard deviation of 2.40%. For measurements made with the rod swap technique (28 control rod banks in 4 cycles), the average difference between calculated and measured control rod bank worths is 0.50% with a standard deviation of 6.03%. The average difference between calculated and measured worth of the sum of the banks is 0.66% with a standard deviation of 5.74%. All results are well within the review and acceptance criteria for control rod bank worth measurement tests.

It is concluded that the TU Electric control rod worth analysis methodology accurately predicts control rod worths as demonstrated by comparisons to control rod bank worths measured by both the boron dilution technique and the control rod swap technique. Further, it is concluded that the test formulations presented herein can be utilized by TU Electric to measure control rod bank worth by either the boron dilution or the control rod swap technique. The analytical methodology will be used in the design, licensing, and operation of CPSES while the test criteria will be applied for control rod worth measurements.

CHAPTER 3

ANALYTICAL METHODOLOGY

3.1 Core Model

The TU Electric three-dimensional core model was employed to calculate the control rod bank worths. The nodal model is described in Reference 1 and utilizes the computer codes MICBURN-3, CASMO-3, TABLES-3, and SIMULATE-3.

3.2 Delayed Neutron Parameters

Control rod bank worths are measured with a reactivity computer. Core average delayed neutron parameters are required as input to the reactivity computer which then determines reactivity through the Inhour equation.

3.2.1 Selection of Delayed Neutron Parameters

The basic delayed neutron data currently coded into CASMO-3 is derived from ENDF/B-V. However, the ENDF/B-V delayed neutron parameters are being re-evaluated at the Oak Ridge National Laboratory while the conversion from delayed neutron yield per fission to delayed neutron fraction of total fission neutrons is being re-evaluated by Studsvik. Revisions to ENDF/B-V and subsequently to CASMO-3 are anticipated, but several years may elapse before the revisions are released for general use.

Because of the uncertainty associated with the ENDF/B-V delayed neutron parameters, alternative delayed neutron parameter data sets were reviewed to identify the data to be employed in the TU Electric methodology. As a result of the review, the delayed neutron parameters originally encoded in CASMO-2 were selected to replace those in CASMO-3. These delayed neutron parameters are based on ENDF/B-III and therefore rely heavily on the work of Keepin (Reference 3).

3.2.2 Determination of Core Average Delayed Neutron Parameters

With SIMULATE-3, the core effective delayed neutron parameters are determined using two-group adjoint flux weighting of assembly average parameters calculated with CASMO-3. However, the CASMO-3 assembly depletions required for the control rod worth caculations reported herein were completed before the selected delayed neutron data set described in Section 3.2.1 had been installed in CASMO-3.

Therefore, for this report, the measured control rod bank worths have been corrected based on a power and volume weighting of assembly average delayed neutron parameters. In future applications, the core average values will be determined directly from SIMULATE-3.

CHAPTER 4

CONTROL ROD BANK REACTIVITY DETERMINATION

4.1 Boron Dilution

4.1.1 Measurement Technique

Control rod bank worth has traditionally been measured using the boron dilution technique. When that technique is employed, the control rod bank is stepped in with the boron concentration being continuously diluted. System temperature and pressure are maintained constant. The control rod bank worth is obtained by summing the incremental worths output from the reactivity computer.

4.1.2 Analytical Technique

The control rod bank worth is calculated as the change in reactivity between the control rod bank fully withdrawn statepoint and the control rod bank fully inserted statepoint. In addition, the differential and integral worths can be determined as a function of control bank po[illegible] by performing a series of statepoint calculations at the positions of interest.

4.2 Control Rod Swap

4.2.1 Measurement Technique

To evaluate control rod bank worths using the control rod swap technique, two measured quantities are required: the reference bank worth and the reference bank critical position with each test bank fully inserted. The measurements proceed as follows. The reference bank worth is measured by boron dilution. Before beginning the rod swap maneuvers, the reactor is stabilized with the reference bank fully inserted, all other banks fully withdrawn, and the boron concentration such that the reactor is just critical. Then the reference bank is incrementally withdrawn while a test bank is incrementally inserted, maintaining nominal criticality. When the test bank is fully inserted with the reactor critical, the position of the reference bank is recorded. The procedure is repeated until all test bank measurements are completed.

4.2.2 Definitions

Reference bank - the highest worth control rod bank, measured by the traditional boron dilution method.

Test bank - the control rod bank which is swapped with the reference bank.

MCP (Measured Critical Position) - position of the reference bank when the test bank is fully inserted and the reactor is just critical, including corrections as required.

R - total worth of reference bank, inserted alone.

T - total worth of test bank, inserted alone.

ΔR - worth of reference bank from MCP to fully withdrawn, inserted alone.

$T_{\Delta R}$ (rod worth parameter) - test bank worth, with reference bank inserted to the MCP.

ΔR_T - worth of reference bank from MCP to fully withdrawn, with test bank inserted.

Superscripts "M" and "C" may be included on the last five defined quantities to denote "measured/inferred" and "calculated," respectively.

4.2.3 Description of the Rod Worth Parameter

There are two rodded statepoints at which criticality is established: 1) reference bank in, all other rods out, and 2) test bank fully inserted, reference bank at the MCP for that test bank. The total net change in reactivity associated with transitioning from one state to another is zero and is independent of the path. From an analytical point of view, two paths can be addressed: 1) withdraw the reference bank, insert the test bank, insert the reference bank to the MCP, and 2) withdraw the reference bank, insert the reference bank to the MCP, insert the test bank. Writing equations for the two paths:

$$-R + T + \Delta R_T = 0 \qquad (1)$$

$$-R + \Delta R + T_{\Delta R} = 0 \qquad (2)$$

From these two equations, three relationships can be determined:

$$R = T + \Delta R_T \qquad (3)$$

$$R = \Delta R + T_{\Delta R} \tag{4}$$

$$T + \Delta R_T = \Delta R + T_{\Delta R} \tag{5}$$

With the control rod swap technique, values of R and ΔR are measured by boron dilution, so a measured value of $T_{\Delta R}$ can be determined from equation (4). Equation (4) is then rearranged as:

$$T^M_{\Delta R} = R^M - \Delta R^M \tag{6}$$

As noted above, $T^M_{\Delta R}$ is the measured/inferred rod worth parameter.

4.2.4 Measurement Corrections

Although every effort is made to maintain the plant conditions constant during the control rod bank worth measurements, it is possible that the boron concentration or moderator temperature could drift slightly, or that the reactor could be other than exactly critical either at the MCP or at the reference bank inserted condition. In addition, it is possible that the reference bank could be less than fully inserted at the start of the test. A deviation in any of these parameters affects the reactivity balances of equations (1) through (6). The rod worth parameter can be corrected for deviations in plant conditions by correcting the MCP to what it would have been had the plant conditions not changed.

Effects to be accounted for include drifts in temperature or boron concentration. Since the isothermal temperature coefficient (ITC) is generally negative, an increase in temperature results in a negative reactivity insertion. Similarly, an increase in boron concentration also results in a negative reactivity insertion. If temperature or boron concentration increases during the test, then the insertion required of the reference bank to maintain criticality is less than it would have been had there been no increase. Thus, the MCP corrected for temperature and boron concentration drift will be lower in the core than the actual measured critical position. The MCP corrected only for temperature and boron concentration drift is:

$$MCP = MCP^{*} - [\Delta T * ITC + \Delta B * BW]/[\Delta\rho/\Delta h] \qquad (7)$$

where

MCP is the critical position corrected for temperature and boron changes,

MCP^*	is the measured critical position,
ΔT	is the change in temperature during the test,
ITC	is the reference-bank-in isothermal temperature coefficient,
ΔB	is the change in boron concentration during the test,
BW	is the boron worth, and
$\Delta\rho/\Delta h$	is the differential worth of the refei .nce bank in the vicinity of the MCP.

ITC, BW, and $\Delta\rho/\Delta h$ are typically negative.

Much of the time, the reference bank may not be fully inserted at the start of the test. In that case, a reactivity correction is needed, since R^M in equation (6) requires that the reference bank be fully inserted. The correction can be applied to the MCP:

$$MCP = MCP^* - [\Delta T*ITC + \Delta B*BW + R^M_i]/[\Delta\rho/\Delta h] \qquad (8)$$

where R^M_i is the reactivity worth of the reference bank from the initial configuration to the bottom of the core. The reactivity bias can be thought of as equivalent to an increase in boron concentration, and R^M_i is negative.

The temperature correction is usually negligible. In addition, the boron concentr' ion measurement has an uncertainty of approximately 10 ppm, so a small drift in the boron concentration during the test might not be detected. Unless there is a very large change in boron concentration during the test, the boron concentration correction provided in equations (7) and (8) should not be used. The largest correction term in equation (8) is anticipated to be R^M_i, which accounts for the reference bank not being fully inserted at the start of the control rod swap test.

If the reference bank is swapped for the test bank after the determination of each MCP, drift in boron concentration and temperature can be determined from the difference in the initial and final reference bank positions, where initial and final refer to the configuration with the reference bank inserted alone before and after swap with a test bank. Assuming that the reactivity computer shows the plant to be critical at the initial, final, and MCP statepoints, and further recognizing that the reactivity change due to drifting core conditions is typically quite small, the following approximation is made:

$$R^M_i + 2(\Delta T * ITC + \Delta B * BW) = R^M_f \qquad (9)$$

where R^M_f is the worth of the reference bank from its final position to fully inserted (a negative value), and ΔT and ΔB are defined as in equation (7), between the initial and MCP statepoints. Thus, drift in the boron concentration and temperature in equation (8) can be replaced by the quantity $\frac{1}{2}(R^M_f - R^M_i)$, leading to:

$$MCP = MCP^* - [\tfrac{1}{2}(R^M_f + R^M_i)]/[\Delta\rho/\Delta h] \qquad (10)$$

If the reference bank is re-swapped for the test bank following determination of the MCP, equation (10) can be used to correct the MCP for drifting core conditions; otherwise equation (8) should be used.

4.3 Rod Worth Tests

4.3.1 Measured Rod Worth Parameter

R^M is available upon completion of the reference bank worth measurement by boron dilution. Following each rod swap maneuver, the MCP is available. The value of ΔR^M can then be obtained from the reference bank worth measurei data. Equation (6) is used to define the measured rod worth parameter for each test bank.

4.3.2 Calculated Rod Worth Parameter

The calculated reactivity change between the initial statepoint and the MCP statepoint is zero only if the calculated critical position is identical to the measured critical position. Therefore, equations (3) and (4) may not be applicable. However, equation (5) can be utilized in the evaluation of the calculated rod worth parameter, leading to:

$$T^C_{\Delta R} = T^C + \Delta R^C_T - \Delta R^C \qquad (11)$$

Using the three-dimensional core model, the worth of the reference bank is calculated prior to testing as a function of rod position, which permits the value of ΔR^C to be extracted once the MCP is determined. The worth of each test bank, T^C, is also calculated prior to testing. In addition, the integral worth of the reference bank in the presence of the test bank is calculated for reference bank positions about the calculated critical position. Once the MCP is established, equation (11) is used to determine the calculated rod worth parameter.

4.3.3 Data Reduction and Evaluation

For a given test bank, the procedure for determining the calculated and measured rod worth parameters is as follows:

1. Obtain the MCP, corrected for changes in core conditions, using equation (8) or equation (10).

2. From the measured reference bank integral worth data, obtain ΔR^M and R^M.

3. Determine the measured rod worth parameter $T^M_{\Delta R}$ using equation (6).

4. Obtain ΔR^C from the calculated reference bank worth curve, reference bank inserted alone.

5. Obtain ΔR^C_T from the calculated reference bank worth curve with the test bank inserted.

6. Obtain T^C.

7. Determine the calculated rod worth parameter $T^C_{\Delta R}$ using equation (11).

The calculated and measured rod worth parameters are compared to verify that the plant is performing as expected.

4.3.4 Other Considerations

It is possible that the calculated reference bank will not be the highest worth bank if any other control rod bank has a similar worth. Under those circumstances, when the highest worth bank is swapped with the reference bank, the reference bank will be fully withdrawn before the test bank is fully inserted. In that case, after the reference bank has been fully withdrawn, the test bank should be fully inserted and the incremental worth measured with the reactivity computer. The measured rod worth $T^M_{\Delta R}$ will be $R^M + \Delta\rho$, where $\Delta\rho$ is the incremental worth of the test bank after the reference bank has been fully withdrawn. The calculated rod worth remains T^C.

CHAPTER 5

METHODOLOGY VALIDATION

5.1 Background

Prior to CPSES Unit 1, Cycle 1 startup testing, TU Electric methodology for control rod worth analysis was validated through comparisons with measured data from Prairie Island Unit 1, Cycles 5 through 7 and Cycles 9 through 10, and Catawba Unit 1, Cycles 1 and 2. Although the CPSES Unit 1, Cycle 1 startup testing was supported with analytical results provided by Westinghouse, analyses (including control rod swap) were also performed utilizing the TU Electric methodology. TU Electric predictions for the CPSES startup tests except the control rod swap measurements were documented in Reference 1. The TU Electric control rod swap pre-test predictions were documented in Reference 2.

5.2 Prairie Island Comparisons

5.2.1 Core Description

Prairie Island Unit 1 is a Westinghouse two-loop, 1650 MWth pressurized water reactor. The core consists of 121 fuel assemblies, each with a 14x14 fuel pin array. Each assembly has 16 guide tubes and one off-center instrument thimble. Fuel assemblies manufactured by Westinghouse were used in the initial core and in the first three reloads. In Cycles 5 through 10, fuel assemblies fabricated by Advanced Nuclear Fuels (ANF) were loaded in the core. In the ANF supplied reloads, burnable absorbers in the form of gadolinia blended in uranium dioxide were employed. Natural uranium axial blankets, 6 inches top and bottom, were incorporated into the Cycles 7 through 10 reload designs. These reload designs also had a higher water-to-fuel ratio than did previous reload fuel.

5.2.2 Analytical Approach

Each cycle was depleted at hot full power (HFP) with all rods out (ARO). Plant coastdown was modeled, as well as fission product decay after shutdown. Coastdown was utilized at the end of Cycles 5, 6, 7, and 9. Calculations of control rod bank worths at hot zero power (HZP) were compared to measured control rod bank worths provided by Northern States Power Company.

5.2.3 Comparisons to Plant Data

Control rod bank worths were measured using the boron dilution technique for Cycles 5 through 9 and with the rod swap technique for Cycles 9 and 10. Results of the control rod worth comparisons for Prairie Island are presented in Table 5.1 for measurements using the boron dilution technique and in Table 5.2 for measurements which employed the control rod swap technique.

5.3 Catawba Comparisons

5.3.1 Core Description

Catawba Unit 1 is a 4-loop Westinghouse plant rated at 3411 MWth. The core contains 193 fuel assemblies each with a 17x17 fuel pin array. Cycles 1 and 2 utilized Westinghouse Optimized Fuel Assembly (OFA) fuel, standard burnable absorbers, and B_4C control rods. The burnable absorbers in the Cycle 1 assemblies were removed prior to Cycle 2 operation.

5.3.2 Analytical Approach

Each cycle was depleted at hot full power (HFP) with all rods out (ARO) Coastdown at the end of Cycle 1 was modeled, as well as fission product decay after shutdown. Removal of the burnable absorber clusters between Cycles 1 and 2 was accounted for in the analysis. Hot zero power (HZP) calculated control rod bank worths were compared to measured control rod bank worths provided by Duke Power Company.

5.3.3 Comparisons to Plant Data

Control rod bank worths were measured using the boron dilution technique in Cycle 1 and by the rod swap technique in Cycle 2. Results of the control rod worth comparisons for Catawba are presented in Table 5.3 for measurements using the boron dilution technique and in Table 5.4 for measurements made with the control rod swap technique.

5.4 Comanche Peak Comparisons

5.4.1 Core Description

CPSES Unit 1 is a 4-loop Westinghouse plant rated at 3411 MWth. Cycle 1 utilizes Westinghouse standard fuel with 17x17 pins per assembly, standard burnable absorbers, and Ag-In-Cd control rods. The core contains 193 assemblies.

5.4.2 Analytical Approach

As this was a fresh core, no depletion calculations were required. The control rod bank worth calculations were initiated directly from the beginning-of-life core model.

5.4.3 Comparisons to Plant Data

Control rod bank worths were measured by the rod swap technique. Comparisons of calculated and measured rod worth parameters are given in Table 5.5.

5.5 Summary of Results

The comparisons of calculated and measured control rod bank worths are summarized in Table 5.6. As shown, the average difference in individual control rod bank worths is -0.77% with a standard deviation of 5.37%. With respect to the sum of the control rod bank worths, the average difference is -1.45% with a standard deviation of 3.97%. The comparisons of calculated and measured control rod bank worths show very good agreement for individual control rod banks as well as for the sum of the banks.

Table 5.1

Control Rod Worth Comparisons for Measurements with Boron Dilution
Prairie Island Unit 1, Cycles 5 Through 7 and Cycle 9, HZP

Cycle	Rods Inserted	SIMULATE-3 (pcm)	Measured+ (pcm)	Difference (%)**
5	D	657	665	- 1.20
	CD	1078	1087	- .83
	BCD	621	633	- 1.90
	ABCD	1789	1794	- .28
	total	4145	4179	- .81
6	D	729	736	- .95
	CD	1283	1319	- 2.73
	BCD	773	740	4.46
	ABCD	1575	1570	.32
	total	4360	4365	- .11
7	D	961	1068	-10.02
	CD	1126	1229	- 8.38
	BCD	860	870	- 1.15
	ABCD	1174	1167	.60
	total	4121	4334	- 4.91
9	A	1292	1356	- 4.72
	BA	977	1024	- 4.59
	DBA	750	778	- 3.60
	CDBA	1734	1817	- 4.57
	total	4753	4975	- 4.46

+ corrected for delayed neutron parameters

** $(\frac{c-m}{m} * 100)$

Table 5.2

Control Rod Worth Comparisons for Measurements with Rod Swap
Prairie Island Unit 1, Cycles 9 and 10, HZP

Cycle	Rod Bank	SIMULATE-3 Rod Worth Parameter (pcm)	Measured+ Rod Worth Param ter (pcm)	Difference (%)**
9	A*	1292	1356	- 4.72
	B	588	653	- 9.95
	C	947	1009	- 6.14
	D	860	915	- 6.01
	total	3687	3933	- 6.25
10	A*	1197	1261	- 5.08
	B	590	544	8.46
	C	1007	1050	- 4.10
	D	706	691	2.17
	SA	648	641	1.09
	SB	652	650	.31
	total	4800	4837	- .76

+ corrected for delayed neutron parameters

* Reference Bank

** $(\frac{c-m}{m} * 100)$

Table 5.3

Control Rod Worth Comparisons for Measurements
with Boron Dilution
Catawba Unit 1, Cycle 1, HZP

Rods Inserted	SIMULATE-3 (pcm)	Measured* (pcm)	Difference (%)**
D	792	797	- .63
CD	1201	1217	- 1.31
BCD	1263	1185	6.58
ABCD	509	554	- 8.12
ABCD+SE	430	466	- 7.73
ABCD+SE+SD	743	781	- 4.87
ABCD+SE+SD+SC	1136	1112	2.16
total	6104	6112	- .13

* corrected for delayed neutron parameters

** $(\frac{c-m}{m} * 100)$

Table 5.4

Control Rod Worth Comparisons for Measurements with Rod Swap
Catawba Unit 1, Cycle 2, HZP

Rod Bank	SIMULATE-3 Rod Worth Parameter (pcm)	Measured+ Rod Worth Parameter (pcm)	Difference (%)**
D	537	499	7.62
C*	1014	979	3.58
B	823	750	9.73
A	26[illegible]	259	3.86
SE	365	334	9.28
SD	461	426	8.22
SC	459	421	9.03
SB	815	754	8.09
SA	532	496	7.26
Total	5275	4918	7.26

+ corrected for delayed neutron parameters

* Reference Bank

** $(\frac{c-m}{m}*100)$

Table 5.5

Control Rod Worth Comparisons for Measurements with Rod Swap
Comanche Peak Unit 1, Cycle 1, HZP

Rod Bank	SIMULATE-3 Rod Worth Parameter (pcm)	Measured+ Rod Worth Parameter (pcm)	Difference (%)**
D	693	699	- .86
C	802	826	- 2.91
B	810	817	- .86
A	322	333	- 3.30
SE	363	380	- 4.47
SD	461	489	- 5.73
SC	461	496	- 7.06
SB*	850	884	- 3.85
SA	624	622	.32
total	5386	5546	- 2.88

+ corrected for delayed neutron parameters

* Reference Bank

** $(\frac{c-m}{m} * 100)$

Table 5.6

Summary of Control Rod Bank Worth Comparisons

	Difference	
	average (%)*	standard deviation (%)
Individual Control Rod Banks		
Dilution Measurements	- 2.32	4.04
Rod Swap Measurements	.50	6.03
Combined	- .77	5.37
Sum of Control Rod Banks		
Dilution Measurements	- 2.08	2.40
Rod Swap Measurements	- .66	5.74
Combined	- 1.45	3.97

* $(\frac{c-m}{m} * 100)$

CHAPTER 6

REVIEW AND ACCEPTANCE CRITERIA FOR MEASUREMENTS

6.1 Evaluation of Test Results

Two levels of criteria are utilized for the evaluation of control rod worth measurement test results. Level 1, or review criteria, is defined for global evaluation and has no direct safety significance. Level 2, or acceptance criteria, is related to assumptions which form the basis of the safety analysis.

If a test result fails to meet the Level 1 criteria, it is reviewed in combination with the balance of the plant startup data. The impact of the discrepancy on the cycle safety analysis is then resolved within 60 Effective Full Power Days (EFPD) following completion of the tests. If a test result fails to meet the Level 2 criteria, a similar resolution must be achieved within 30 EFPD of test completion. In the case of an acceptance test failure, the failure and resolution must be reported to the NRC within 45 EFPD of test completion.

6.2 Level 1 (Review) Criteria

For control rod worth measurement using either measurement technique,

1. For all measured banks, either

   a. the absolute value of the percent difference between inferred and predicted integral worths must be ≤ 15 percent, or

   b. the absolute value of the reactivity difference between inferred and predicted integral worths must be ≤ 100 pcm,

   whichever is greater.

2. The sum of the measured bank worths must be ≤ 110 percent of the sum of the predicted bank worths.

In addition, when using the control rod swap measurement technique,

3. The absolute value of the percent difference between

measured and predicted integral worth for the reference bank must be ≤ 10 percent.

6.3 Level 2 (Acceptance) Criteria

For control rod worth measurements using either measurement technique,

1. The sum of the measured bank worths must be ≥ 90 percent of the sum of the predicted bank worths.

In addition, when using the control rod swap measurement technique,

2. The absolute value of the percent difference between the measured and predicted integral worths for the reference bank must be ≤ 15 percent.

6.4 Additional Constraints

When using the boron dilution measurement technique, at least four control rod banks should be measured. Typically, Control Banks D, C, B, and A are chosen, and are measured in sequential insertion.

When implementing the control rod swap technique, all Control Banks and Shutdown Banks should be measured.

When determining percent differences between measured and calculated control rod worth parameters, the calculated values are used as the bases.

CHAPTER 7

CONCLUSIONS

The TU Electric steady state reactor physics methodology has been shown to accurately predict control rod worths. The applicability of the methodology has been demonstrated by comparisons to measurements performed with the boron dilution technique and with the control rod swap technique. Further, the control rod bank worth measurement requirements have been defined for employment of either the boron dilution technique or the control rod swap tecnnique. Both techniques have been demonstrated to be appropriate by comparisons to applicable startup test results including those obtained for Comanche Peak Unit 1, Cycle 1. All results are well within the recommended review and acceptance criteria for control rod bank worth measurement tests.

CHAPTER 8

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