2.0 ANALYTICAL VERIFICATION

2.1 Introduction

Control rod bank worths are currently measured at the startup of every cycle of a nuclear plant. The information from these measurements and others are used to confirm that the calculation models and assumptions used in the safety analysis of the core are valid.

The purpose of the analysis described in this section is to examine the validity of the rod exchange concept for rod worth measurement. The analysis addresses the use of the rod exchange concept for individual and cumulative rod bank worth measurement. For the purpose of this study, the validity of the rod exchange concept rests on whether it gives results which are comparable to those of the currently accepted measurement technique of rod bank dilution. This comparison of measurement methods includes the areas of individual rod bank measurement, cumulative rod bank measurement, and the information inferred from these results concerning N-1 rod worth. The related question is addressed regarding whether different acceptance criteria or other measurement requirements must be stipulated for the rod exchange concept over and above those required for the rod dilution concept.

Before further discussion of the analysis some preemptory remarks are included here concerning the source of observed differences between calculated and measured rod bank worths.

One major source of these differences is measurement uncertainty. It should be noted that there are normally measurement uncertainties in both rod worth measurement techniques being discussed here. In the analysis presented in this section this effect is removed, thereby permitting a closer examination of the fundamental similarities or differences between the rod bank exchange and rod bank dilution concepts.

The other major source of measured deviations from calculated values lies in differences between the calculation model and the physical core. These model-to-core differences are expected and are accounted for in design (Reference 1). Typically, the as-built fissile content of the freshly loaded fuel is not exactly the nominal value assumed in design. Also, the accumulated burnup on each fuel assembly is not exactly that assumed in design, primarily because the exact length of the plant cycle previous to the design cycle is not known at the time of design. These model-to-core differences produce small differences in core power distribution and neutron spectrum which can affect rod bank worths. For example the peripheral loading of fresh fuel with slightly higher-than-nominal enrichment will cause some slight shift of power toward the periphery of the core and radially away from the center of the core. This in turn weighs slightly more heavily the peripheral rod bank worths and may cause some slight decrease in centrally located rod bank worths. For a sequence of rod banks inserted evenly throughout the core there may be no change at all in their cumulative worth in this example.

These types of effects are examined in this study. It is emphasized that the results presented here employ Westinghouse calculational techniques ver i by experiment (Section 3.0) and do not apply to measurement pre ns calculated with other models.

2.2 Methods of Analysis

The analysis presented here essentially examines the effects of core perturbations on rod worth measurements. The model used to calculate rod exchange quantities is consistent with those used in the core design and safety evaluation. The NRC would be notified if there were significant changes in this process. The scope of this study covers all of the control rod banks and the N-1 configuration. This analysis can be divided into two parts. First, "predictions" of rod bank worths are calculated for the nominal core. This set of information includes he N-1 rod worth which is considered an observed variable in the analysis. For the rod bank dilution method, the individual rod bank worths are calculated as banks are inserted into the core in sequence. For the rod bank exchange method the rod bank worths are calculated [

] +a,c,f This body of information represents what the experimentor knows before the rod bank worth measurements.

The second part of the analysis provides simulated measurements of the same core design but with some perturbations introduced into the core model. In order to show clearly the trends introduced by these perturbations, unrealistically large changes were made to the model. The perturbations used are 0.05 w/o U-235 deviations in the average feed enrichment, [

] +a,c, and large changes in previous cycle burnup. These effects are combined so as to produce the largest perturbation in core power distribution. As alluded to in Section 2.1, such changes in the previous cycle burnup are expected and accounted for in the Westinghouse safety analysis (Reference 1).

After these perturbations are introduced into the model pseudo-measurement information is generated. For the rod bank dilution method worths are calculated with rod banks inserted in sequence, and for the rod bank exchange method [ ] +a,c, bank worths are calculated. This body of information represents what the experimentor would know after the measurement. In addition, the N-1 rod worth is calculated for comparison to the nominal case.

Percentage differences between "predictions" (P) and "measurements" (M) are calculated by the relationship

$$\% \text{ Difference} = \frac{M-P}{P} \times 100.$$

For rod exchange, measured bank worths are inferred by the following relationship:

+a

Cumulative bank worths for either measurement method are obtained by summing the individual bank worths and percentage differences found as for individual banks.

The results obtained below were derived using a 4-loop core model.

2.3 Results

A core perturbation consisting of 0.05 w/o U-235 reduction in feed enrichment and a 2000 MWD/MTU reduction in the previous cycle burnup was introduced into the core model after "prediction" calculations were completed on the nominal core. Pseudo-measurement data was then generated and is presented in Tables 2.1, 2.2, 2.3, and 2.4, along with the "prediction" data for the nominal core.

In Table 2.1, the changes in core power distribution and reactivity are indicated by the changes in the radial peaking factor and critical boron concentration between the nominal core and the perturbed core, termed "measured core #1" in the Tables. As can be seen the magnitude of these differences verge on anomalous behavior and would be detected easily in startup flux mapping and critical boron measurements. This information indicates that actual model-to-core deviations in individual rod worth are very unlikely to be of the magnitude shown in this analysis, as has been demonstrated previously (Reference 2). Observed deviations of magnitude comparable to those in this analysis are most likely to be caused by isolated errors in measurement. As a corollary to this conclusion, the very small changes in N rod worth and N-1 rod worth for such large core perturbations indicate it is unlikely that either value could truly change significantly from model to core.

Table 2.2 presents the comparison of rod bank dilution and rod bank exchange results for individual bank worths. The percentage differences between "measurement" and "prediction" (abbreviated M/P) range from [ ]+a,c with some banks remaining almost unchanged. The M/P values for rod exchange behave essentially the same as those for the rod dilution method.

Cumulative rod bank worths are presented in Table 2.3. It is seen that the cumulative rod bank worths vary significantly less than individual rod banks, as would be expected from the discussion in Section 2.1. Again, the M/P values from the rod exchange method are very comparable to those from the rod dilution method.

The N-1 rod worth, in Table 2.4, behaves much like the other cumulative bank worths in that its M/P value tends to vary little compared to individual rod bank M/P values.

To verify that these observed trends are reproducible, a series of different core perturbations were used to provide three more "measured cores" for comparison. These additional cases, termed "measured core #2", "measured core #3", and measured core #4" are presented in Table 2.5. The values for "measured core #1" and the nominal core are reproduced in Table 2.5 for reference. As shown in the table, "measured core #4" represents a change from nominal of the same magnitude as "measured core #1" but in the opposite direction. The remaining two cases lie between these two extremes.

M/P values for all of the measured cores, again with "measured core #1" data reproduced for reference, are given in Table 2.6. Examination of these data will indicate clearly that the trends observed above with "measured core #1" are quite reproducible and predictable.

2.4 Conclusions

The results presented in Section 2.3 demonstrate that there is no analytical reason to expect less informative data from a rod bank exchange measurement than a rod bank dilution measurement. Furthermore comparison of any series of successive rod exchange measurements to prediction is expected to provide the same cumulative worth information as the corresponding M/P comparison for rod bank dilution.

Thus, there is no analytical basis to support a different acceptance criteria for one method over the other for the same number of bank measurements

There is also strong evidence in the data presented that the tentatively proposed acceptance criterion of ± 15% on individual bank worth M/P is far too restrictive with respect to N-1 rod worth preservation. The results of this study show that large, core power perturbations resulting in [ ]+a,c deviations in individual rod bank worths affect N-1 rod worth by only [ ]+a,c It is likely that individual bank worth M/P values of [ ]+a,c could be experienced before the N-1 rod worth varied ± 10%. There is certainly no basis for tightening the ± 15% acceptance criteria on individual banks for either measurement method discussed here. It has been proposed that utilities measure all the control banks and then continue making successive rod worth measurements down to the N-1 configuration unless or until the cumulative worth M/P is within ± 10%. The results presented in Section 2.3 demonstrate that rod exchange and rod dilution will perform comparably to satisfy such requirements.

However, there is also strong evidence in the data that only [ ]+a,c selected control rod banks need be measured to confirm that the models and physical core are analagous, especially with respect to the N-1 rod worth value. As stated before. a reasonable acceptance criterion for such individual bank measurements could very well be much greater than ± 15%. If initial bank worth measurements failed to meet their acceptance criteria then successive bank worth measurements could be performed as has been proposed

[ ]+a

The results of this analysis summarily demonstrate that the rod exchange method performs adequately as a replacement for the rod dilution method of rod worth measurement for either present or proposed test programs and acceptance criteria. It further demonstrates that proposed rod worth measurement acceptance criteria are in general far too restrictive with respect to N-1 rod worth verification.

Again, it is emphasized that the results presented here employ Westinghouse calculational techniques verified by experiment (Section 3.0) and do not apply to measurement predictions calculated with non-Westinghouse models.

TABLE 2.1

CORE CHARACTERISTICS COMPARISON FOR MEASURED CORE #1

	Nominal Core	Measured Core #1
Previous Cycle Burnup (MWD/MT)	13330	11330
Feed Fuel Enrichment (w/o U-235)	3.40	3.35
ARO, HZP $F^N_{\Delta H}$		
ARO, HZP C_B (ppm)		

[ ]+a,c

TABLE 2.2

INDIVIDUAL BANK WORTH PSEUDO-MEASUREMENTS (%ΔK)

	Nominal Core	Measured Core #1	% Difference M/P
Rod Bank Dilution Method			
D			
C with D present			
B with D, C, present			
A with D, C, B present			
SD with D, C, B, A present			
SC with D, C, B, A, SD present			
SB with D, C, B, A, SD, SC present			
SA with D, C, B. A, SD, SC, SB present			
Rod Bank Exchange Method			
+a,c,f			

+a,c

TABLE 2.3

CUMULATIVE BANK WORTH PSEUDO-MEASUREMENTS (%ΔK)

	Nominal Core	Measured Core #1	% Difference M/P
Rod Bank Dilution Method	[		]+a,c
Total Control Banks (D+C+B+A)			
N Rods			
Rod Bank Exchange Method			
Total Control Banks (D+C+B+A)			
N Rods			]

TABLE 2.4

N-1 ROD WORTH (%ΔK)

	Nominal Core	Measured Core #1	% Difference M/P
N-1 Rods	[		]+a,c

TABLE 2.5

CORE MODEL PERTURBATIONS FOR ALL MEASURED CORES

	Nominal Core	Measured Core #1	Measured Core #2	Measured Core #3	Measured Core #4
Previous Cycle Burnup (MWD/MTU)	13330	11330	12330	14330	15330
Feed Fuel Enrichment (w/o U-235)	3.40	3.35	3.35	3.45	3.45

TABLE 2.6

% DIFFERENCE BETWEEN PSEUDO-MEASUREMENT AND PREDICTION (M/P)

	Measured Core #1		Measured Core #2		Measured Core #3		Measured Core #4	
Measured Bank	Bank Dilution	Bank Exchange	Bank Dilution	Bank Exchange	Bank Dilution	Bank Exchange	Bank Dilution	Bank Exchange
D								
C								
B								
A								
SD								
SC								
SB								
SA								
D+C+B+A								
N Rods								
N-1 Rods								

+a,c

REFERENCES

Reference 1: F. M. Bordelon, et al, "Westinghouse Reload Safety Evaluation Methodology", WCAP-9272 (Proprietary) and WCAP-9273 (Non-Proprietary), March 1978.

Reference 2: W. B. Henderson, "Results of the Control Rod Worth Program", WCAP-9217 (Proprietary) and WCAP-9218 (Non-Proprietary), February 1978.

3.2.5 Four Loop Plant C

As part of the initial startup test program of Four Loop Plant C, the individual reactivity worths of RCC control banks D, C, B, and A, and RCC shutdown banks D and C were measured by the boron dilution method as the banks were inserted sequentially in the normal insertion sequence. Prior to and following the insertion of each bank, the critical boron concentration of the reactor coolant system was accurately determined (boron endpoints). During the bank insertion, the stepwise reactivity change was measured with a Westinghouse reactivity computer.

Following the insertion of shutdown bank C, the remaining reactivity to the N-1 condition (all rods in less the hightest worth stuck rod, RCCA F-10) was determined by a combination of bank interchange and RCS boron dilution.

During these tests, the worth of control bank D was determined to be 1222.6 pcm with an equivalent boron worth of 130 ppm. By comparing the measured boron reactivity worths and the reactivity computer results for all banks to the design predictions, control bank D stood out as inconsistent. That is, with the exception of control bank D, high (or low) reactivity worths were substantiated by the measured boron change. The worth of control bank D was subsequently remeasured using the boron dilution technique, yielding a reactivity worth of

1361.6 pcm and a boron equivalent of 131 ppm. Since the boron reactivity worth agreed with the previous measurement, the new reactivity measurement was taken as valid for use in both the normal dilution measurements and for rod swap analysis. The cause of the first measurement discrepancy is unknown, although some unsubstantiated sources of error have been proposed.

Since control bank D (CD) was predicted to have the highest individual worth of all control and shutdown banks, it was used as the "reference" bank for the rod swap test. Starting with CD near the fully inserted position (11.5 steps), relative worth data were obtained as each RCC bank was swapped for CD.

The inferred worth of each bank x (W_x^I) was obtained from the measured worth of the reference bank, the critical configuration data and the design prediction through the algorithm:

[ ]+a,c

[ ]+a,c

A summary of the results obtained from these measurements is presented in Table 3.11 along with design predictions W_x^P, for the individual reactivity worths for each RCC bank. In both Tables 3.10 and 3.11, ε is defined as:

$$\varepsilon = \left[\frac{\text{(Measured Value) - (Predicted Value)}}{\text{(Predicted Value)}}\right] \times 100.$$

The slight difference (about 8 pcm) between the predicted integral worths of control bank D presented in Tables 3.10 and 3.11 is due to the use of different calculational design models.

As shown in Table 3.11, the rod swap results met all review criteria:

(a) The absolute value of the percent difference between measured and predicted integral worth for the reference bank is ≤ 10%.

(b) The absolute value of the percent difference between inferred and predicted integral worths for all other banks is ≤ 15%.

(c) The absolute value of the percent difference between the sum of the measured/inferred bank worths and the sum of the predicted worths is ≤ 10%.

and all acceptance criteria;

(a) The N rod worth, as determined by rod swap must be greater than or equal to 90% of the predicted N rod worth.

As shown in Table 3.10, the boron dilution test results met all review criteria;

(a) The absolute value of the percent difference between the measured and predicted integral worths for CD, CC, CB, CA, SD and SC is ≤ 15%.

(b) The absolute value of the percent difference between the measured and predicted integral worth of N-1 rod is ≤ 10%.

except for control bank A which measured [ ]+a,c than the predicted value.

Because of the consistency between measurement results and predictions, each set of test results, when taken separately, would lead to the same conclusion, that adequate shutdown margin has been verified.

These results then establish the equivalency of the rod swap technique to the boron dilution technique for 4-loop plants.

Table 3.10

Summary of RCC Bank Worths From Reactivity Measurements

Normal Insertion Sequence

Plant Type: Four Loop Plant C

RCC Bank (x)	W_x^P (pcm)	W_x^M (pcm)	ε (%)
CD	[ ]+a,c	1361.6	[ ]+a,c
CC		997.0	
CB		1330.5	
CA		348.1	
SD		812.0	
SC		1190.2	
N-1		6682.4	

Table 3.11

Summary of RCC Bank Worths From Rod Exchange Tests

Plant Type: Four Loop Plant C

RCC Bank (x)	h_x^P (steps)	h_x^M (steps)	W_x^P (pcm)	W_x^I (pcm)	ε (%)
CD (a)	-	-	+a,c	1361.6 (b)	+a,c
CC	+a,c	110		870.0	
CB		103.5		782.6	
CA		56.5		296.1	
SD		73.5		502.8	
SC		73.5		503.8	
SB		122.5		984.1	
SA		75		500.2	
		Sum		5801.2	

a) Reference Bank

b) Direct measurement based on reactivity computer measurements