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February 2, 1982

Director of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
7920 Norfolk Avenue
Bethesda, MD 20014

Attention: Mr. Steven A. Varga, Chief
Operating Reactors Branch 1
Division of Licensing

Gentlemen:

SAFETY EVALUATION OF THE PSE&G
ROD EXCHANGE MEASUREMENT PROCEDURE
FACILITY OPERATING LICENSES DPR-70 & DPR-75
UNITS 1 AND 2
SALEM NUCLEAR GENERATING STATION
DOCKET NOS. 50-272 AND 50-311

This transmittal documents the Safety Evaluation of the PSE&G Rod Exchange Measurement Procedure. This procedure represents a new technique for measuring control rod worth for the purpose of design verification. It has been developed by PSE&G for application to the Salem Units.

The attached Safety Evaluation has been reviewed by PSE&G and it has been concluded that the implementation of the Rod Exchange Procedure does not represent an unreviewed safety question as defined by 10CFR50.59. Therefore, subject to comments received in response to this transmittal, PSE&G intends to implement the Rod Exchange Measurement Procedure beginning with Salem 1, Cycle 4, which is scheduled for startup in March, 1982.

Very truly yours,

E. A. Liden
Manager - Nuclear Licensing
& Regulation

EAL:ea

CC: Mr. Leif Norrholm
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PSEG

The Energy People

SAFETY EVALUATION

OF THE

PSE&G

ROD EXCHANGE METHODOLOGY

NFTG 81-206 RAB

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OF THE

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PSE&G ROD EXCHANGE METHODOLOGY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

This report describes the safety evaluation of a methodology for measuring control rod worths which PSE&G intends to implement for the purpose of design verification and license compliance for Salem Units 1 and 2 beginning with Unit 1, Cycle 4, currently scheduled for startup in March of 1982.

This methodology, termed rod exchange, is intended to replace the traditional procedure of control bank measurements via boron dilution.

Section 3.1 of this report describes the mechanics of the plant test procedures.

Section 3.2 describes the PSE&G core physics models and general calculational procedures used to generate the analytical data used to infer the rod worths from the measurements described in Section 3.1.

Section 3.3 describes the procedures for inferring the rod worths using measurements from Section 3.1 and the analytical data from Section 3.2; Key Notation conventions are defined in Table 3.1.

Section 4 presents the benchmark results, which include comparisons of dilution measurements, exchange measurements, and design calculations for Salem 1, Cycles 1 and 3.

Section 5 presents the safety evaluation of the exchange measurement technique as defined by Sections 3.1-3, based on the benchmark results from Section 4. Test acceptance criteria are also defined.

2.0 SUMMARY AND CONCLUSIONS

The PSE&G Rod Exchange Measurement procedure has been developed as a replacement for the currently used dilution method of measuring rod worths. The development objective was to improve the degree of design verification and to reduce test time for future reloads.

The degree of design verification is the product of the measurement accuracy and the fraction of the total rod worth measured. A procedure which measures half of the available rod worth with measurement uncertainty of 10% verifies only 45% (0.9x50%=45%) of the total rod worth.

The dilution procedure utilizes a reactivity computer to measure the worth of a rod bank as it is slowly inserted into the core. During this insertion, the boron concentration in the reactor coolant system is diluted to maintain the reactor nearly critical. The insertion of the rod bank causes a spatial redistribution of the flux distribution. This redistribution causes significant errors in the reactivity computer solution. The current dilution procedure measures only four of the eight Salem rod banks.

The exchange procedure measures all eight rod banks for each reload and is designed to minimize the effects of flux redistribution. The procedure uses a reactivity computer only to measure one rod bank, referred to as the reference bank. This bank is then used as a yardstick to measure the remaining seven rod banks without the use of the reactivity computer.

The performance of the exchange measurement procedure has been demonstrated experimentally in two separate benchmark tests. The first was performed during the Salem 1, Cycle 1, startup and included measurements of all eight rod banks using both the dilution and exchange procedures. The second test was performed during the Cycle 3 startup and included exchange and dilution measurements for four rod banks. The results from these tests support the conclusion that the measurement accuracy of the exchange procedure represents an improvement over the dilution procedure.

Assuming that the exchange measurement accuracy is at least equivalent to that of the dilution technique, the exchange procedure provides a significantly greater degree of design verification than the dilution procedure on the basis that it measures twice as many rod banks for each reload cycle.

The question of plant safety associated with the implementation of the PSE&G Rod Exchange Test has been evaluated. It has been determined that the implementation does not represent an unreviewed safety question as defined by 10CFR50.59.

3.0 METHODOLOGY

The PSE&G Rod Exchange Methodology consists of three components; 1) the plant test or measurement procedure, 2) the analytical methods, and 3) the inferencing procedure. Each of these components is described in the following subsections.

3.1 Test Procedure

The PSE&G Rod Exchange Test Procedure(1) consists of two steps:

First, the most worthy of the eight rod banks is chosen as a reference bank and is diluted from the full out to the full in (or nearly full in) position with all other rod banks remaining in the full-out position. The worth of the reference bank is measured during this dilution using an on-line reactivity computer and standard data reduction techniques.

The second step is to perform a critical exchange between the reference bank and the bank to be measured. This is accomplished by withdrawing the reference bank at constant boron concentration and temperature and inserting the bank to be measured, referred to as Bank x, in a manner such as to maintain the reactor nearly critical. When Bank x is fully inserted, the position of the reference bank is adjusted to make the reactor just critical. This just critical position is noted, and the reference bank is then exchanged with Bank x in the opposite direction until the reference bank is again inserted and Bank x withdrawn.

Another bank is then chosen for measurement, and the whole process of critical exchange is repeated. Each bank is in this fashion "measured" against the calibrated reference bank. The measurement data consists of the absolute worth of reference bank and the relative worth of the other banks in terms of the critical position of the reference bank when displaced by the measured bank. These relative worths are converted to absolute bank worths using the Analytical Methods described in Section 3.2 and the Inferencing Techniques described below in Section 3.3

3.2 Analytical Methods

The PSE&G analytical methods for Rod Exchange Measurements consists of a core model and a set of procedures for the application of that model.

PSE&G utilizes the ARMP[(2)] Code Package for the core model in all Rod Exchange applications. Since ARMP has become an industry standard code, no further description of the code package will be given here.

The PSE&G ARMP model of the Salem reactors represents a full core, three dimensional geometry with 12 axial nodes and one radial node per assembly. This model is applied to a Rod Exchange Measurement for a given cycle by simulating both the Rod Exchange Test and the Standard Boron Dilution Test sequences.

The Standard Boron Dilution Test sequence is simulated by calculating the worth of each rod bank in the sequential, nonoverlap insertion mode. In this calculation, Bank D is inserted first, Bank C is inserted next with D remaining in, Bank B is then inserted with D and C remaining in, etc. The RCS boron concentration is varied during this simulation to maintain the core model nearly critical. These bank worths are referred to as the "calculated dilution mode" worths.

The Rod Exchange Test is simulated in two parts.

The first step in the simulation is to compute the worth of each bank with all other rods out. These bank worths are used to identify the reference bank.

Second, the core reactivity is calculated as a function of the reference bank position when the bank being measured, Bank x, is fully inserted. The "calculated exchange mode" rod worths are obtained from these results.

3.3 Inferencing Techniques

This section describes the procedure(3) for inferring the "measured dilution mode" bank worths from test data described in Section 3.1, using the analytical results described in Section 3.2. For the purpose of clarity, a set of Rod Exchange Notation Conventions is introduced and used in the derivation of the inferencing techniques as well as in later sections. These conventions are defined in Table 3.1.

3.3.1 Exchange Mode Worths

A typical rod exchange test maneuver begins with the core just critical, the reference bank nearly fully inserted, and all other rods out. The maneuver ends with the core again just critical, boron unchanged, the reference bank nearly withdrawn , and the bank to be measured (bank x) fully inserted, all other rods out. Since the core begins and ends in a critical configuration, the negative reactivity due to the insertion of bank x must be exactly equal in magnitude to the positive reactivity due to withdrawal of the reference bank. The absolute value of either reactivity component is referred to as the "exchange mode rod worth" to be associated with bank x.

The predicted exchange mode rod worth for bank x, $W^{cal}_{exc,x}$ (refer to Table 3.1) is obtained as the calculated integral worth of the reference bank as it moves from its initial position (nearly inserted, all other rods out) to the predicted critical position, in the presence of bank x (bank x fully inserted prior to moving reference bank). An example is presented in Figure 3.1 in which the reference bank, bank D, moves from an initial position of fully inserted to a predicted position of 166 steps, in the presence of bank C. The predicted exchange worth of bank C is therefore 895 pcm.

The measured exchange mode worth is obtained in a manner similar to the predicted value above with two differences. First, the calculated integral worth of the reference bank is obtained using the measured position, and second, the calculated reference bank worth is adjusted, or calibrated, to match the measured dilution worth. In the example in Figure 3.1, the measured position was 185 steps and the reference bank calibration factor was 0.975. Therefore, the measured exchange worth would be;

$$W^{exc}_{exc,x} = 0.975 * 980 \text{ pcm} = 956 \text{ pcm.}$$

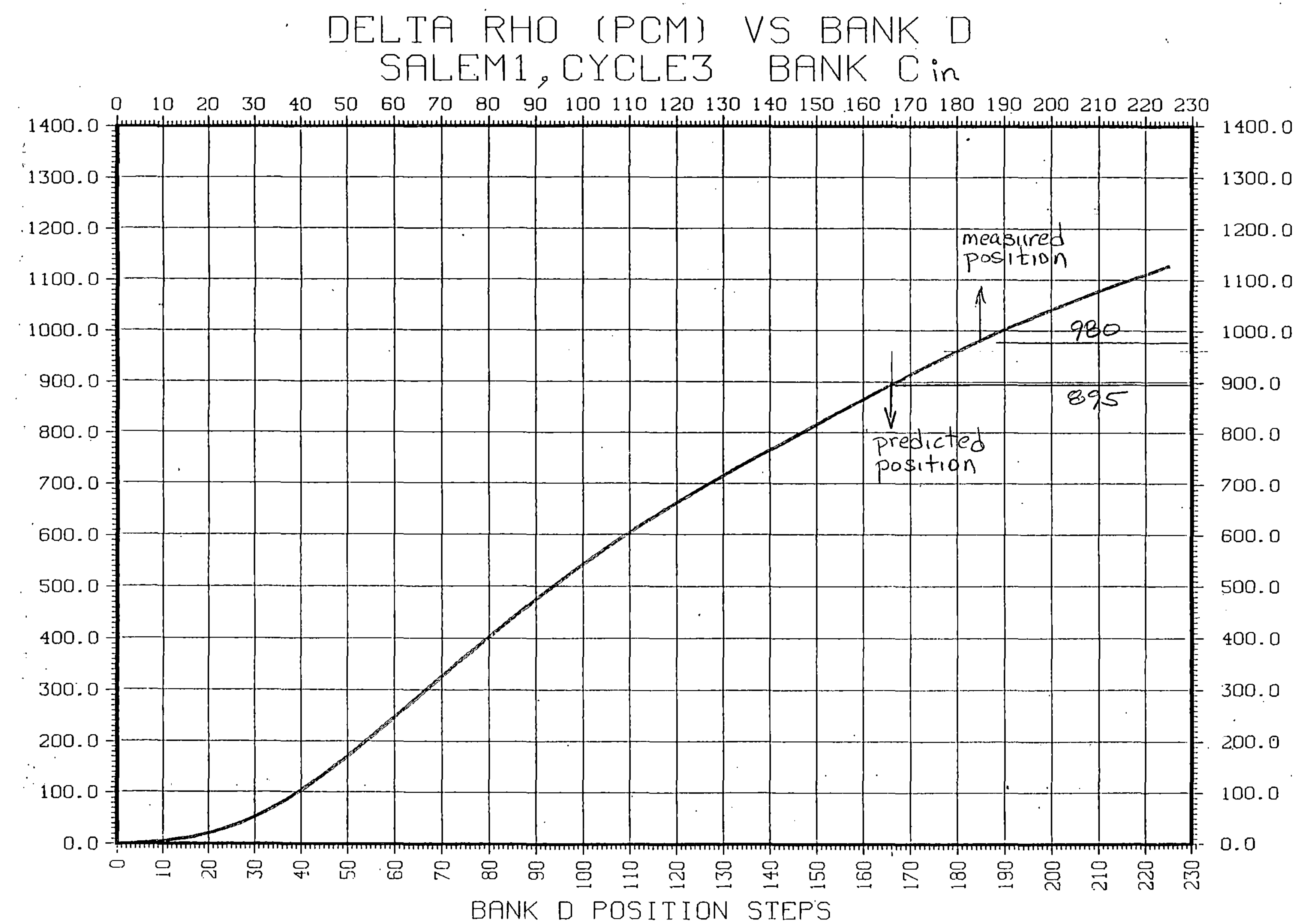

FIGURE 3.1
EXAMPLE OF EXCHANGE MODE ROD WORTHS

3.3.2 Dilution Mode Worths

Dilution mode rod worth differs from exchange mode worth due to the presence of a greater number of rod banks. In general, the worth of a rod bank in the presence of other rod banks is greater than the worth with all other banks withdrawn. The total measured dilution mode rod worth for Salem 1, Cycle 1, was 30% larger than the exchange mode worth. The ratio of the dilution worth to the exchange worth for any bank x is referred to as βx (refer to Table 3.1). βx is calculated from the simulations described in Section 3.2 as;

Equation 3.1

$$\beta_x^{cal} = W_{dil,x}^{cal} / W_{exc,x}^{cal}$$

(Refer to notation conventions in Table 3.1)

The dilution mode rod worths are inferred from the measured exchange worths as follows;

Equation 3.2

$$W_{dil,x}^{exc} = \beta_x^{cal} \cdot W_{exc,x}^{exc}$$

TABLE 3.1

ROD EXCHANGE NOTATION CONVENTION

1) $W^{s}_{m,x}$ = rod bank worth obtained from Source s, representing bank x, in the core configuration or mode, m.

possible sources, s

- s = act; actual worth, not observable
- s = cal; calculated worth, using models
- s = dil; measured worth obtained via standard boron dilution using sequential, nonoverlap insertion
- s = exc; measured worth obtained via rod exchange test.

possible modes, m

- m = dil; rod bank configuration as required for sequential, nonoverlap insertion
- m = exc; measured bank inserted, reference bank in critical exchange position, all other rods out.

possible banks, x

- ref = reference bank
- x = any bank, including the reference bank

2) h^{s}_{x} = critical position of reference bank in the exchange mode when the measured bank, x, is fully inserted, obtained from Source s.

3) $\rho_x^s(h)$ = core reactivity in the exchange mode as a function of reference bank position, h, when the measured bank, x, is fully inserted, assuming the pre-exchange reference bank position to be fully inserted and no changes in boron or moderator temperature during the exchange.

4) β_x = ratio of dilution worth of Bank x to the exchange worth

4.0 BENCHMARK RESULTS

The Rod Exchange Test Procedure has been developed by PSE&G as a repacement for the dilution measurement procedure. The objective for this development was to increase the degree of design verification and to shorten the test time for future reloads.

The benchmark comparisons presented in this section provide confirming evidence that the Rod Exchange Test Procedure is at least as accurate as the current dilution measurement technique. The evidence presented includes comparisons of all three of the only independent sources of rod worth information available. These are:

a) Dilution Measurements,
b) Vendor Design Calculations,
c) Exchange Measurements.

The results of the comparisons consistently support the following conclusions:

1) The differences between the dilution and exchange measurements are due primarily to flux redistribution errors associated with the dilution measurements. The exchange measurement errors are small by comparison.

2) The exchange measurements are in significantly better agreement with vendor design rod worths than are the dilution measurements. Since all three data sources are independent, this indicates that the exchange measurements are more accurate than the dilution measurements.

4.1 Benchmark Data

There are only three independent sources of rod worth information. These are:

a) Dilution Measurements
b) Vendor Design Calculations
c) Rod Exchange Measurements

The benchmark of the Rod Exchange Measurement Procedure includes intracomparisons of all three data sources for Salem 1, Cycles 1 and 3.

Comparisons of dilution measurements and exchange measurements are presented in Table 4.1. The differences between these measurements represent the combined effects of the measurement errors for each measurement. These effects are investigated in Sections 4.2 through 4.4 below. The Cycle 1 data includes measurements of all rod banks for the entire N-1 rod worth (all rods in less the worst stuck rod).

The comparisons of the dilution and exchange measurements to vendor design calculations are presented in Table 4.2 and 4.3. The significance of these comparisons is discussed in Section 4.4.

TABLE 4.1

COMPARISONS OF DILUTION AND EXCHANGE MEASUREMENT

CYCLE	BANK	MEASURED WORTH (pcm) Dilution	MEASURED WORTH (pcm) Exchange	Δ %	$(\Delta-\bar{\Delta})$ %
1	D	1107	1107	reference	
	C	1183	1095	-7.5	-2.8
	B	766	754	-1.6	+3.1
	A	1241	1175	-5.3	-0.6
	SD	745	707	-5.1	-0.4
	SC	1181	1141	-3.4	+1.3
	SB+SA less B6	751	712	-5.2	-0.5
				$\bar{\Delta}$ = -4.7 s = 2.0	
3	D	834	834	reference	
	C	960	967	+0.7	-2.9
	B	565	616	+9.0	+5.4
	A	1023	1033	+1.0	-2.6
				$\bar{\Delta}$ = +3.6 s = 4.7	

$$\Delta = \frac{\text{Exchange - Dilution}}{\text{Dilution}} \times 100\%$$

$$\bar{\Delta} = \frac{1}{n}\sum \Delta_i \qquad \text{mean difference}$$

$$s = \left[\frac{1}{n-1}\sum\left(\Delta_i-\bar{\Delta}\right)^2\right]^{1/2} \qquad \text{standard deviation}$$

TABLE 4.2

COMPARISONS OF MEASUREMENTS TO VENDOR DESIGN

CYCLE	ROD BANK	VENDOR DESIGN	DILUTION MEAS. pcm	DILUTION MEAS. Δ%	EXCHANGE MEAS. pcm	EXCHANGE MEAS. Δ%
1	D	1076	1107	+2.9	1107	+2.9
	C	1014	1183	+16.7	1095	+8.0
	B	770	766	-0.5	754	-2.0
	A	1155	1241	+7.4	1175	+1.7
	SD	725	745	+2.8	707	-2.5
	SC	1183	1181	-0.2	1141	-3.6
			$\bar{\Delta}$ =	+4.9	$\bar{\Delta}$ =	0.8
			s =	6.5	s =	4.4
3	D	885	834	-5.8	834	-5.8
	C	947	960	+1.4	967	+2.1
	B	630	565	-10.4	616	-2.2
	A	1081	1023	-5.4	1033	-4.4
			$\bar{\Delta}$ =	-5.1	$\bar{\Delta}$ =	-2.6
			s =	4.9	s =	3.5

Δ = (Meas - Design)/Design * 100%

$$\bar{\Delta} = \frac{1}{n}\sum \Delta$$

$$S = \left[\frac{1}{n-1}\sum\left(\Delta - \bar{\Delta}\right)^2\right]^{1/2}$$

TABLE 4.3

COMPARISONS OF DILUTION MEASUREMENTS TO DESIGN

CYCLE	BANK	DILUTION MEAS. (pcm)	VENDOR DESIGN (pcm)	Δ %	$(\Delta - \bar{\Delta})$ %
1	D	1107	1076	-2.8	+1.6
	C	1183	1014	-14.4	-10.0
	B	766	770	+0.5	4.9
	A	1241	1155	-6.9	-2.5
	SD	745	725	-2.7	1.7
	SC	1181	1183	+0.2	4.6
				$\bar{\Delta}$ = -4.4	
				s = 5.6	
3	D	834	885	+6.1	0.6
	C	960	947	-1.4	-6.9
	B	565	630	+11.5	6.0
	A	1023	1081	+5.7	0.2
				$\bar{\Delta}$ = +5.5	
				s = 5.3	

$$\Delta = \frac{\text{W - Dilution}}{\text{Dilution}} \times 100\%$$

$$\bar{\Delta} = \frac{1}{n}\sum_i \Delta_i$$ mean difference

$$S = \left[\frac{1}{n-1}\sum_i (\Delta - \bar{\Delta})^2\right]^{1/2}$$ standard deviation

4.2 Dilution Measurement Error Sources

The purpose of this section is to describe the various sources of error associated with the dilution measurement process.

Significant dilution measurement errors can result from two sources;

1) the reactimeter (or reactivity computer) calibration error, and
2) the effects of flux redistribution.

The reactimeter is typically calibrated only once during a reactor startup. Therefore, a calibration error will affect all dilution measurements in the same way for a given cycle. The calibration error can, therefore, only contribute to the mean dilution error and not to the standard deviation errors about the mean. However, because the reactimeter is recalibrated for each cycle, the contribution to the mean dilution error may vary from one cycle to another.

The magnitude of the calibration error is estimated by the reactimeter manufacturer to be ± 4%.

The flux redistribution error mechanism is inherent in the dilution measurement. The reactimeter input signal is obtained from an excore neutron detector which is sensitive only to leakage neutrons from the core periphery. The proper operation of the reactimeter requires that the excore detector signal be proportional to the average incore neutron population. The problem is that this proportionality is altered by the radial flux redistribution caused by the insertion of the control rod being measured via the dilution process. The magnitude and sign of the measurement error caused by redistribution depends on the spatial geometry of the rod bank relative to the excore detector, the specific fuel arrangement, and also the specific test technique used (rate of dilution, size of rod step, interpretation of reactivity strip chart). Typically, the test technique is the dominant factor affecting the mean redistribution error, and the rod bank/detector geometry is the dominant factor affecting the variation of redistribution errors about the mean error.

4.3 Exchange Measurement Error Sources

Exchange measurement errors can result from three sources;

1) the reactimeter calibration error associated with the dilution measurement of the reference bank,

2) the flux redistribution error associated with the dilution measurement of the reference bank,

3) the error associated with the inferencing procedure used to convert the critical exchange rod positions into rod worth for banks other than the reference bank.

The dilution measurement of the reference bank enters linearly into the calculation of the exchange rod worths of all other banks. Therefore, the dilution measurement error sources No. 1 and No. 2 above can only influence the mean exchange measurement error and not the standard deviation of the errors about the mean. However, the errors resulting from the inferencing procedure can conceivably contribute to both the mean and standard deviation of errors.

4.4 Evaluation of Benchmark Measurements

The benchmark data presented in Table 4.1 are comparisons of two sets of measurements. The observed differences between these measurements represent the combined effects of the individual errors in each of the measurements. For each cycle of comparisons there is a mean observed difference, $\overline{\Delta}$, and also a standard deviation of differences, s. Each of these components is considered below.

4.4.1 Standard Deviation of Observed Differences

Only two sources of error can contribute to the standard deviation of differences in Table 4.1. One is the flux redistribution error associated with the dilution measurements (refer to Section 4.2), and the other is the inferencing error associated with the exchange measurements (refer to Section 4.3). These two error sources are independent of each other.

The magnitude of the flux redistribution errors can be evaluated from Figure 4.1. In this figure, the variations in the observed differences between the dilution measurements and the other two data sources are plotted as a function of the amount of flux redistribution occurring during the dilution measurements. The other two data sources, exchange measurements and design calculations, are totally independent of the dilution measurements and each other and are not affected by flux redistribution errors. The differences presented in Figure 4.1 are obtained from Tables 4.1 and 4.3. The estimated redistribution is obtained from the changes in the radial core power distribution caused by the insertion of the rod bank being measured during the dilution measurements. The effect on the excore detector signal is estimated by making the simplifying assumption that the detector signal is directly proportional to the average flux level in the three peripheral fuel assemblies closest to the detector. The accuracy of this estimate is anticipated to be ± 10% of the detector signal.

Three facts are obvious from Figure 4.1:

1. There is a correlation of the observed differences with the estimated flux redistribution. The correlation is verified by comparisons to two independent data sources.

2. Qualitatively, the correlation is consistent with the anticipated effects of flux redistribution. This is explained further below.

3. The magnitude of the scatter in the correlation is consistent with the anticipated uncertainties of estimating the effects of the flux redistribution on the excore detector signal. This implies that the redistribution error is the dominant factor in the observed differences between the exchange and dilution measurements.

The anticipated effects of flux redistribution are that a negative redistribution such as for bank C, in Figure 4.1, should cause a negative difference in the sense of the data in the right hand columns of Table 4.1 and 4.3. As an example, consider the bank C measurements. The Cycle 1 and Cycle 3 dilution measurements were too high relative to the exchange measurements as seen from the negative value in the right hand column of Table 4.1 (all differences considered relative to the mean difference). This is to be expected from the Bank C/excore detector geometry shown in Figure 4.2. It is apparent that the insertion of Bank C will cause a redistribution of flux away from the excore detector (negative redistribution as shown in Figure 4.1). The change in the excore detector signal, therefore, has two components. One is a decrease due to redistribution, and the other is a decrease due to the negative reactivity of the Bank-C insertion. The reactimeter cannot distinguish between the two components. It simply computes core reactivity as if the total decrease was due to the negative reactivity worth of Bank C. The reactimeter, therefore, computes a bank C worth that is too high in absolute magnitude (the reactimeter output value will be too negative). By similar arguments, the insertion of Bank B would cause a positive redistribution thereby causing the reactimeter to read too low in absolute value.

Another way to evaluate the exchange measurements is to make a three-way comparison of the exchange, dilution, and design rod worth data. Since all three are mutually independent, agreement between any two is a verification of each. These comparisons are presented in Table 4.2. The key results are summarized in Table 4.4 below. It is apparent from Table 4.4 that the agreement between the exchange measurement and the design values are consistently better than between the dilution measurements and design. This is especially true for the average and maximum differences. These results are somewhat anticipated from the correlation presented in Figure 4.1. on the premise that the dilution measurements contain significant redistribution errors which are not present in the exchange measurements.

FIGURE 4.1

CORRELATION OF MEASUREMENT DEVIATIONS WITH FLUX REDISTRIBUTION

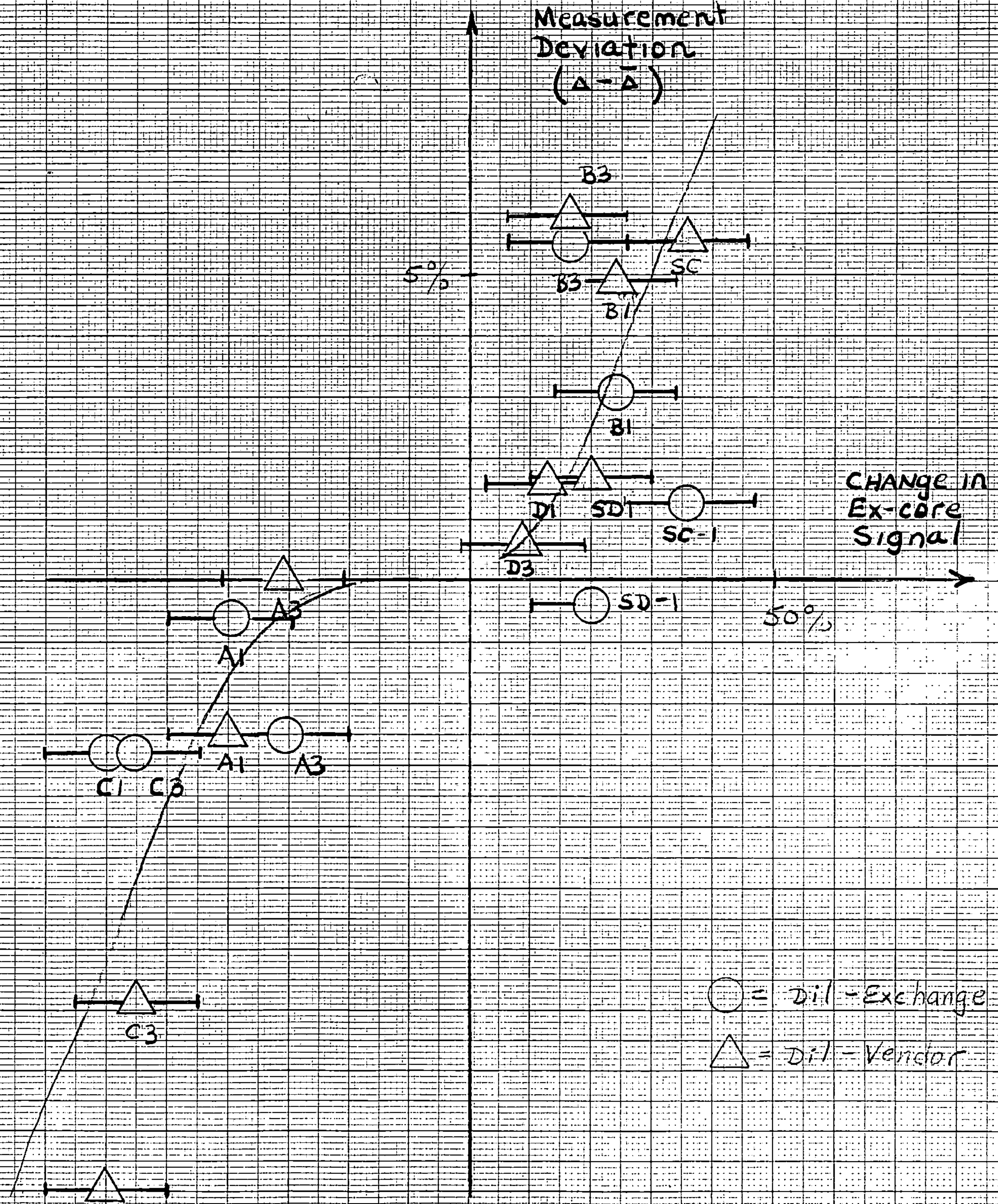

Figure 4.2

Rod Bank / Ex-Core Detector Geometry

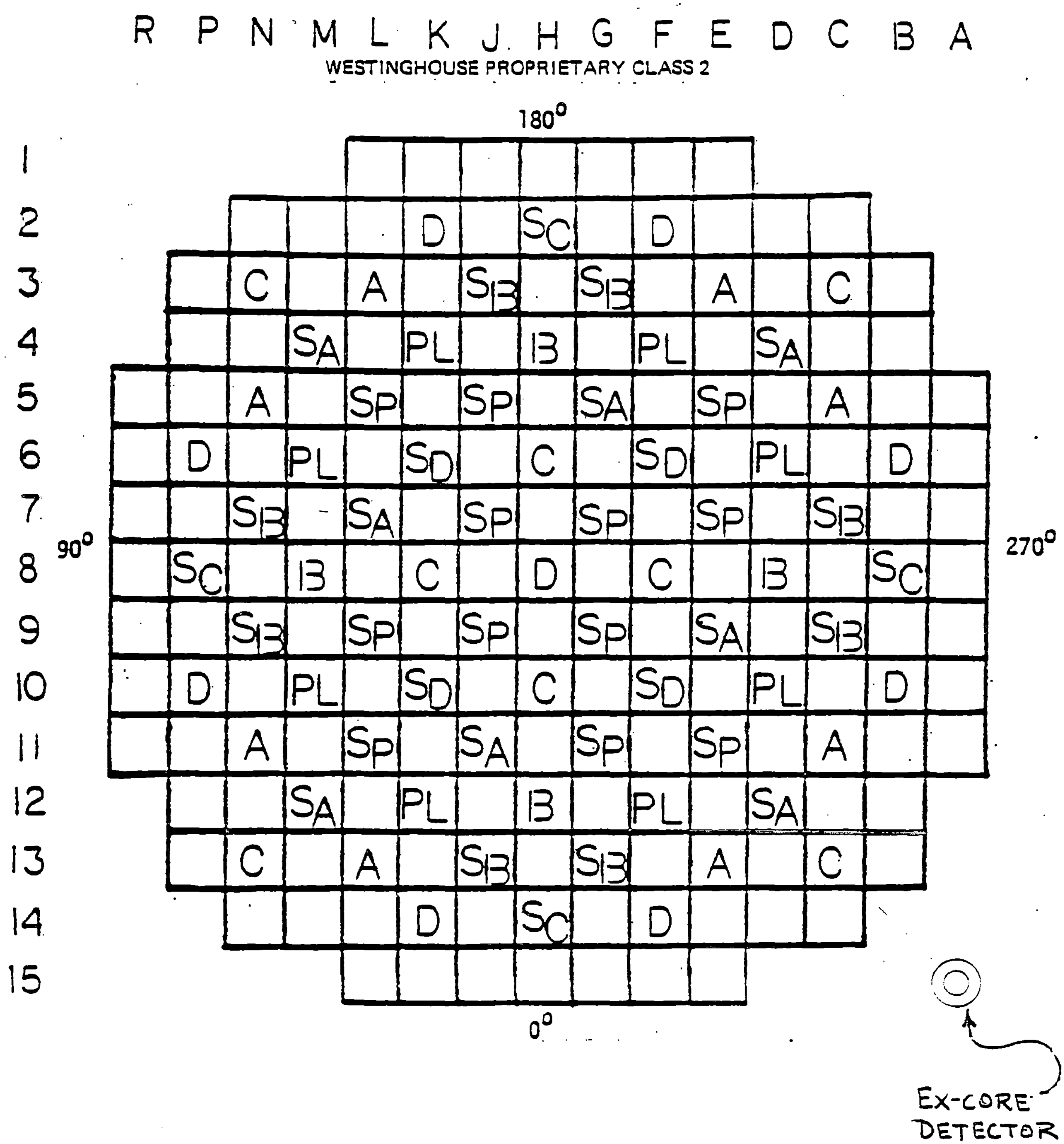

TABLE 4.4

SUMMARY OF COMPARISONS OF MEASUREMENTS TO VENDOR DESIGN CALCULATIONS

DEVIATION PARAMETER	DEVIATIONS FROM DESIGN	
	DILUTION PROCEDURE (%)	EXCHANGE PROCEDURE (%)
Average Difference		
Cycle 1	4.9	0.8
Cycle 3	-5.1	-2.6
Maximum Difference		
Cycle 1	16.7	8.0
Cycle 3	10.4	5.8
Standard Deviation		
Cycle 1	6.5	4.4
Cycle 3	4.9	3.5

$$\text{Deviation} = \frac{\text{Measurement - Design}}{\text{Design}} * 100$$

4.4.2 Mean Observed Differences

The mean difference between the dilution and exchange measurements represents the combined effects of two measurement error components;

a) the flux redistribution error associated with the dilution measurements, and

b) the exchange inferencing error.

The data in Table 4.1 demonstrate that the mean observed difference between the exchange and dilution measurements increased by + 8.2% from Cycle 1 to Cycle 3. The data in Table 4.2 demonstrates that the mean difference between the dilution measurements and the design calculations changed by + 10.0%, while the relationship between the exchange and design data changed by only 3.4%. Since all three data sources are mutually independent, these results strongly suggest that the dominant cause of the observed differences is due to redistribution errors associated with the dilution measurements.

4.5 Measurement Quality Index

As described in Section 3, the exchange measurements rely on correction factors which are computed from PSE&G core physics models. Model inaccuracies might, therefore, contribute to the exchange measurement error. The benchmark results have demonstrated an acceptable level of exchange measurement accuracy. Using these results, it is desirable to develop an index which will relate the model accuracy for future cycles to that observed for the benchmarks.

The rod exchange procedure provides a direct index of the model accuracy in the comparison of measured and calculated exchange mode rod worths. The exchange mode values represent the rod worths for the actual exchange test conditions. They differ from the dilution mode values by the β -factor as described in Section 3.3. These comparisons are presented in Table 4.5 for the benchmark measurements.

The results in Table 4.5 indicate a consistent mean difference or bias between the measured and predicted exchange mode worths. This bias is due to the combined effects of the reactimeter calibration error, the flux redistribution error associated with the dilution measurement of the reference bank, and the model accuracy associated with the predicted exchange mode worth. The standard deviation of the differences about the bias is about 2.3%. This scatter is probably due primarily to model errors.

The exchange measurement procedure is designed to be insensitive to model biases. This is because the analytical factors represent ratios of calculated rod worths in which the bias would tend to cancel out. This has been confirmed for Cycle 1 measurements by performing an additional set of rod exchange calculations in which the model rod worth for all banks had been arbitrarily increased by 10% relative to the benchmark calculations. The Cycle 1 rod exchange test results were then reinterpreted using the new calculations. The resultant N-1 inferred dilution worth, $\sum W^{exc}_{dil,x}$, was found to be within 1% of the value interpreted with the original, unadjusted model calculations used in the benchmarking. This demonstrates that the rod exchange results are insensitive to model biases.

The effect of the scatter in the model errors on the inferred dilution worths was not explicitly investigated. Instead, the approach for future measurements will be to verify that the observed scatter is not significantly different than was observed for the benchmarks.

Based on the benchmark results in Table 4.5, the 95% confidence limits for the standard deviation, σ, of the observed differences is;

$$1.6\% < \sigma < 4.0\%$$

For future measurements, the upper limit of 4% will be used as a Measurement Quality Acceptance Criterion.

TABLE 4.5

EXCHANGE MODE ROD WORTHS

CYCLE	BANK	EXCHANGE MODE WORTH Measured	EXCHANGE MODE WORTH Predicted	Δ%
1	C	1094	1010	-7.7
	B	518	485	-6.4
	A	816	769	-5.8
	SD	528	492	-6.8
	SC	245	232	-5.3
	SB	756	677	-10.4
	SA	1440	1286	-10.7
				$\overline{x}$ = -7.6
				s = 2.2
2	C	956	897	-6.2
	B	539	495	-8.2
	A	760	735	-3.3
	SA	1100	1060	-3.6
				$\overline{x}$ = -5.3
				s = 2.3

5.0 APPLICATIONS

THE PSE&G Rod Exchange Measurement Technique has been developed and benchmarked with the intent of implementation at Salem Units 1 and 2 as a replacement for the currently accepted dilution method. This implementation is scheduled to begin with the startup tests for Salem 1, Cycle 4, in March of 1982. The test procedure and analytical methods to be used are those described in Sections 3.2 and 3.3, respectively.

Sectin 5.1 describes the text acceptance criteria.

Section 5.2 describes the safety evaluation from which it is concluded that this implementation does not represent an unreviewed safety question.

5.1 Test Acceptance Criteria

Two sets of acceptance criteria will be used in conjunction with the PSE&G Rod Exchange Method. One set deals with the acceptability of the differences between the measured rod worths and those predicted from the models and methods used to perform the Reload Safety Evaluation (RSE). These are "Design Verification Criteria", and those to be used with the rod exchange measurements will remain unchanged from those presently associated with the boron dilution measurements. The current Design Verificaion Criteria are summarized in Table 5.1. Note that notation definition 1, from Table 3.1, has been expanded to include "RSE" as an analytical data source for the purpose of design verification.

A second test criterion to be used is termed the "Measurement Quality Criterion". This criterion is designed to verify that the level of uncertainty associated with a specific exchange measurement is not less conservative than the benchmark results which were used as the basis for the safety evaluation presented in Section 5.2 below.

TABLE 5.1

ROD EXCHANGE MEASUREMENT ACCEPTANCE CRITERIA

DESIGN VERIFICATION CRITERION 1

Maximum difference between the measured rod worth for individual banks and that predicted by the RSE methods should be $\leq$ 15%.

$$\left| W_{dil,x}^{exc} - W_{dil,x}^{RSE} \right| \leq 15\%$$

DESIGN VERIFICATION CRITERION 2

Maximum difference between the total measured rod worth and that predicted by the RSE methods should be $\leq$ 10%.

$$\left| \left(\sum_x W_{dil,x}^{exc} \right) - \left(\sum_x W_{dil,x}^{RSE} \right) \right| \leq 10\%$$

MEASUREMENT QUALITY CRITERION

The standard deviation, s, between the measured and predicted "exchange mode" rod worths should be;

$$s \leq 4.0\%$$

5.2 Safety Evaluation

The PSE&G Rod Exchange Test Procedure represents a measurement technique not described in the FSAR. According to the provisions of 10CFR50.59, the licensee may perform such a test without prior NRC approval if it does not represent an unreviewed safety question. A test would represent an unreviewed safety question if:

1. The probability of occurrence or the consequences of an accident on malfunction of equipment important to safety previously evaluated in the Safety Analysis Report may be increased.

2. A possibility for an accident or malfunction of a different type than any evaluated previously in the Safety Analysis Report may be created.

3. The margin of safety as defined in the basis for any technical specification is reduced.

The purpose of the rod worth measurements is to provide verification that the Reload Safety Evaluation (RSE) is conservative with respect to the core shutdown capability. In this context, the question of safety associated with the implementation of the exchange procedure is related to the degree of verification provided and the margin of safety maintained during the procedure execution. These are related to safety criteria 1 and 3 above. The test does not introduce the possibility for a new type of accident or malfunction and, therefore, Criterion 2 does not apply.

The degree of design verification is the product of the measurement accuracy and the fractionof the total rod worth measured. If half of the total rod worth is measured with a relative uncertainty of 10%, then 45%

$$0.90 \times 50\% = 45\%$$

of the total rod worth has been verified.

If the degree of design verification is too low, then there exists the possibility that the consequences could be increased for one of the transients or postulated accidents which are sensitive to the verifiable rod worth. However, this would require the coincident occurrence of three independent failures, not including the occurrence of the accident itself. First, the reload design engineer would have to choose a reload fuel shuffle pattern that had an inadequate margin of safety associated with a verifiable rod worth parameter. Second, the reload safety evaluation engineer would have to commit a nonconservative calculational error which masked the design error. Third, the degree of design verification provided by the rod worth measurement would have to be too low to detect the design error.

The measurement accuracy of the current dilution measurement procedure cannot be quantitatively determined because there exists no standard for comparison. Until the introduction of the rod exchange measurement procedure, the only experimental verification of the accuracy of the dilution procedure was the degree of mutual agreement with design predictions. Since the two are independent, their degree of mutual agreement is an upperbound estimate of the accuracy of each.

However, the introduction of the exchange measurement technique brings a third, independent source of rod worth information. The benchmark comparisons among these three data sources have been presented in Section 4. The results demonstrate that the exchange procedure is at least as accurate as the dilution procedure.

As discussed above, the degree of design verification is the product of the measurement accuracy and the fraction of rod worth measured. The current dilution measurement procedure typically measures only four of the eight rod banks for each reload cycle. This represents approximately one-half of the total available shutdown capability. The exchange procedure measures all eight rod banks for each reload. Assuming the measurement accuracies to be equivalent, the degree of design verification provided by the exchange procedure is significantly better than that of the dilution procedure. It is concluded, therefore, that the implementation of the rod exchange procedure as a replacement for the dilution procedure will not increase the consequences of transients or postulated accidents considered in the Safety Analysis.

The safety margin parameters of concern during the execution of the rod worth measurement are the shutdown margin and the flux peaking factors. The safety margins associated with both of these parameters are significantly reduced with the insertion of rod banks. The greater the number of rod banks inserted, the greater the margin reduction.

The dilution measurement procedure requires the simultaneous insertion of a minimum of four rod banks. If the measurement results fail to meet acceptance criteria, the simultaneous insertion of additional rod banks would be required. The exchange measurement procedure measures all eight rod banks but never requires the simultaneous insertion of more than two rod banks. Therefore, significantly more margin is maintained during the execution of the exchange procedure than the dilution procedure.

In summary, a greater degree of design verification and margin to safety during the test execution is provided by the exchange measurement procedure than by the current dilution technique. Therefore, it is concluded that the implementation of the exchange procedure as a replacement for the dilution procedure does not represent an unreviewed safety question as defined by 10CFR50.59.

6.0 REFERENCES

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(5) Walpole and Myers, Probability and Statistics for Engineers and Scientists, 2nd ed., Macmillan, 1978.