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FARLEY UNIT 1 CYCLE 15

THIMBLE DELETION STUDY

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FARLEY UNIT 1 CYCLE 15

EVALUATION OF THIMBLE DELETION ON PEAKING FACTORS

INTRODUCTION

A study has been undertaken to assess incremental peaking factor measurement uncertainties associated with a reduction to a minimum of 25 of the 50 movable detector (M/D) thimbles for Farley Unit 1 Cycle 15. Due to a large database used in the study, it is intended that the uncertainties quantified herein are to be considered of a generic nature and applicable to subsequent cycles.

Section 1 of this study presents the methodology and results of randomly deleting thimbles from actual INCORE maps to quantify the uncertainties. Section 2 quantifies the minimum number of thimbles per quadrant required in order to improve the ability to distinguish between random and systematic thimble deletion events and to establish the bounds of applicability of Section 1.

For Farley Unit 1 Cycle 15, an evaluation was performed to confirm applicability of this cycle to the study described herein. Review of current cycle flux maps indicate that measurement to predicted peaking factors are well within the required measurement uncertainties and indicate the core is behaving as predicted. Based on this, it is anticipated that the core will perform as expected for the remainder of the cycle. It is not expected that the additional uncertainties on the peaking factors will result in any violation of the limits. Even with the increased measurement uncertainty applied as a result of the thimble detection study, the Farley Unit 1 Cycle 15 F_Q and $F_{\Delta H}$ Surveillance Technical Specifications will provide necessary protection.

When referring to percentages in Sections 1 and 2, they refer to the percentage from a total of 50 thimbles unless otherwise specified.

SECTION 1

METHODOLOGY - GENERAL

To assess the additional peaking factor measurement uncertainties associated with as few as 50% of the M/D thimbles available, eight full core INCORE flux maps from the operating cycles of Farley Unit 1 and Unit 2 (4 maps per unit) were used. The selection of these maps was made to cover the entire cycle burnup range. For each of the INCORE maps, ten separate random deletions were made, giving a total of 80 thimble deletion cases with 50% of the thimbles available. Ten separate random deletions were also done with this same set of 8 INCORE maps giving 80 thimble deletion cases with 75% of the thimbles available. The INCORE code was used to analyze the cases with randomly deleted thimble locations. The measured peaking factors for the thimble deletion maps were then compared with the measured peaking factors in the reference maps, i.e., the INCORE maps employing all or most of the 50 movable detector thimbles. Figure 1 shows the movable detector (M/D) locations for the Farley plants considered and Table 1 provides additional information on the 8 maps used in the study (although the thermocouple locations for Figure 1 differ between Units 1 and 2, the movable detector locations are identical for the two units). For those maps with less than 100% of available thimbles (e.g., 76.0%), thimble deletion cases were run deleting an additional 50% (e.g. leaving 26.0%). These comparisons yielded the additional measurement uncertainties to be applied to $F_{\Delta H}$ and F_Q. Thimble deletion effects on the INCORE measured axial offset and quadrant tilt were addressed in a similar manner.

METHODOLOGY - STATISTICAL

The percent error between the reference peaking factor value, $F\alpha$, (Reference), and the thimble deletion case peaking factor value, $F\alpha$, (T.D.) is defined in Equation 1 as

$$\%\ \text{Error (T.D.)} = \left(1 - \frac{F\alpha\,(\text{T.D.})}{F\alpha\,(\text{Reference})}\right) \times 100 \qquad \text{(Eq. 1)}$$

where $F\alpha$ is $F_{\Delta H}$, or F_Q and T.D. refers to 75% or 50% of available thimbles in the reference case. A positive value of error implies that the peaking factor from the thimble deletion map is non-conservative relative to the reference. In the following paragraphs the error will be denoted X_{ij} where i refers to one of the 8 flux maps and j refers to one of the 10 thimble-deletion cases for each map. The percent error between the reference value and the thimble deletion case value for quadrant tilt and axial offset are defined in Equations 2 and 3 as

$$\text{Error (T.D.)} = (\text{Ref.} - \text{Deleted}) \times 100 \text{ for QUAD Tilt} \qquad \text{(Eq. 2)}$$

$$\text{Error (T.D.)} = (\text{Ref.} - \text{Deleted}) \text{ for A.O.} \qquad \text{(Eq. 3)}$$

The mean error for reference map i, $\overline{X}_i$; and the percent relative sample standard deviation for reference map i, S_i, are defined in Equations 4 and 5, respectively.

$$\overline{X}_i = \frac{1}{10} \sum_{j=1}^{10} X_{ij} \qquad \text{(Eq. 4)}$$

$$S_i = \left(\frac{\sum_{j=1}^{10} (x_{ij} - \overline{x}_i)^2}{10-1} \right)^{1/2} \qquad \text{(Eq. 5)}$$

After computing $\overline{X}_i$ and S_i for each map, for each parameter of interest, and for both 50% and 75% thimble deletion cases, the data is combined. The combined mean for all reference maps, $\overline{X}_{combined}$, is given by Equation 6 as:

$$\overline{X}_{combined} = \frac{1}{8} \sum_{i=1}^{8} \overline{X}_i \qquad \text{(Eq. 6)}$$

The combined percent relative sample standard deviation of all maps is given by Equation 7 as:

$$S_{combined} = \left(\left(\frac{\sum_{i=1}^{8} \left((N_i - 1) S_i^2 + N_i \overline{X}_i^2 \right)}{N_T} - \overline{X}_{comb}^2 \right) \frac{N_T}{N_T - 1} \right)^{1/2} \quad \text{(Eq. 7)}$$

where:

N_i = Number of random deletion cases of each map = 10 and
N_T = Total number of datapoints = 8 maps x 10 deletions/map = 80

Equations 6 and 7 are constructed in such a manner that if one were to directly compute the mean and standard deviation for all 80 datapoints, the same numeric results would be obtained.

After $\overline{X}_{combined}$ and $S_{combined}$ have been obtained for each parameter of interest, and for both 50% and 75% thimble deletion cases, 95% confidence/ 95% probability one-sided upper tolerance limits are constructed to quantify the thimble deletion uncertainty component (See Equation 8).

$$\text{Thimble Deletion Uncertainty Component (\%)} = \overline{X}_{combined} + kS_{combined} \quad \text{(Eq. 8)}$$

where k = the one-sided 95% confidence/95% probability tolerance limit factor for 79 degrees of freedom = 1.964.

Application of the above methodology is presented in the "Results" section of this report. The statistical combination of the thimble deletion uncertainty component with INCORE measurement is discussed in the "Thimble Deletion Uncertainty" section of this report.

RESULTS

Table 2a provides the peaking factors sample mean (%) for each map (see Equation 4) and the sample standard deviation (%) for each map (see Equation 5) for the 50% thimbles available case. The combined sample mean (%) and the combined standard deviation (%) for each parameter of interest, as calculated per Equations 6 and 7, is also shown. Table 2b presents the analogous information for the 75% thimbles available case. Tables 2c and 2d provide the sample mean and the sample standard deviation for quadrant tilt and axial offset over the same database.

Thimble deletion uncertainty components (i.e. the 95% probability, 95% confidence tolerance limit) for $F_{\Delta H}$, and F_Q are calculated in Appendix A using Equation 8 and are based upon the data of Tables 2a and 2b. The total Thimble Deletion Peaking Factor Uncertainty (%) is plotted in Figure 2 as a function of Percentage of Thimbles Available. This figure shows the linear application of the thimble deletion uncertainty factor.

THIMBLE DELETION UNCERTAINTY

Current flux map peaking factor measurement uncertainties include allowance for down to 75% thimbles available. Accordingly, an incremental thimble deletion uncertainty component penalty from 75% to 50% of thimbles available could be considered to be appropriate. However, for conservatism and simplicity, the full thimble deletion uncertainty component penalty from 100% to 50% thimbles available will be used. The Thimble Deletion Uncertainty Component (50% T.D.) discussed in the preceding section is combined with the appropriate flux map measurement uncertainty to obtain a total uncertainty.

$F_{\Delta H}$ UNCERTAINTY, $F_{\Delta H}{}^U$

The appropriate equation for combining statistically independent uncertainty components is

$$F^U_{\Delta H}(50\%) = 1 + F_{\Delta H\,T.D.\,Bias} + ((F^{MU}_{\Delta H} - 1)^2 + (kS_{combined})^2_{T.D.})^{1/2} \quad \text{(Eq. 9)}$$

where $F_{\Delta H\,T.D.\,Bias}$ is the combined mean of the database population and $F^{MU}_{\Delta H}$ is the measurement uncertainty factor from the Technical Specifications.

For conservatism, a negative value of T.D. Bias will be treated as zero. Analogous equations apply to $F_Q{}^U$. Evaluating the above expression yields the following result

[ ] (a,c)

For conservatism to support generic application to subsequent cycles and to support Unit 1 Cycle 15, $F_{\Delta H}{}^U$ (50%) will be rounded up to 1.055. This value can be interpreted as a 95% probability tolerance limit at a high confidence level. This one and one-half percent incremental thimble deletion penalty is linearly applied from 75% to 50% thimbles available (i.e., 1.04 at 38 thimbles and 1.055 at 25 thimbles available).

F_Q UNCERTAINTY, F_Q^U

[ ] (a,c)

For conservatism to support generic application to subsequent cycles and to support Unit 1 Cycle 15, F_Q^U (50%) will be rounded to 1.07. This two percent incremental thimble deletion penalty is linearly applied from 75% to 50% thimbles available (i.e., 1.05 at 38 thimbles and 1.07 at 25 thimbles available).

AXIAL OFFSET AND QUADRANT TILT

The mean change in quadrant tilt with 25 of the thimbles available was found to be only [ ]a,c. Similarly, the mean change in axial offset with 50% of the thimbles available was also quite small at [ ]a,c. Note that all uncertainties on A.O. and tilt are absolute values and not percentages of A.O. nor tilt. These values indicate that thimble deletion has a negligible impact on the core average axial power shape measurement. Changes of this magnitude are not significant and will not adversely affect excore detector calibration.

CONSERVATIVE ASSUMPTIONS

For convenience a summary of conservative assumptions employed in this study are provided below:

1) The total thimble deletion penalty from 100% to 50% of the available thimbles was utilized rather than the incremental penalty from 75% to 50% of the available thimbles.

2) Thimble deletion uncertainty results were rounded up and negative bias values were set to zero.

3) [

]a,c

4) [

]a,c

5) [

]a,c

SECTION 2

This section quantifies the number of thimbles per quadrant required for Farley Unit 1 in order to improve the ability to distinguish between random and systematic thimble deletion events and to establish the bounds of applicability of the incremental peaking factor uncertainties. The peaking factor measurement uncertainty analysis described in Section 1 makes the assumption that thimbles were randomly deleted from the core. If thimbles are somehow systematically deleted from the core then the calculated peaking factor measurement uncertainties will not apply.

The assumption of random deletion of thimbles is an important one. If removal of instrumentation thimbles in the core is completely random then each thimble in the core has an equal probability of being removed from operation. Therefore, if 50 percent of the thimbles in the core were to be deleted randomly, a random pattern of thimbles would result. On the other hand, if there were some function driving the removal of the thimbles the result would not be a random pattern of thimbles. This systematic deletion of thimbles could conceivably result in large areas of the core being uninstrumented.

If less than 75% of the installed thimbles are used, the current Technical Specification requirement of a minimum of 2 M/D thimbles per core quadrant is not sufficient to distinguish between random and systematic deletion events with high confidence. To help insure that thimble deletion is random, a restriction can be placed on the number of thimbles that must remain operable in each quadrant. By defining the quadrant in such a manner as to essentially place a requirement on each 1/8th core, the ability to distinguish between random and systematic events will be significantly enhanced.

If, for example, for 50% thimbles remaining, the requirement of 3 or more thimbles per quadrant is satisfied, then in all likelihood a random deletion occurred and incremental thimble deletion peaking factor measurement uncertainties are appropriate. On the other hand, if there are less than three thimbles per quadrant, then it is possible that a systematic thimble deletion occurred and that the impact on measured quadrant peaking factors, may be larger than quantified in Section 1.

METHODOLOGY - COMPUTER SIMULATION

A short computer program for determining the probability distribution of thimbles remaining was written. The program allows for different number of thimbles per quadrant and keeps track of interior, axis, and diagonal thimbles (see 3-loop description). This program has been used to determine the number of thimbles per quadrant for all of Westinghouse Thimble Deletion Analyses.

Starting with n_T thimbles in the core and randomly deleting down to r_T thimbles constitutes one case. After deleting n_T - r_T thimbles from the core, the number of thimbles remaining in each of the eight quadrants is determined. The minimum number of thimbles remaining over all 8 quadrants is then found. A large number of cases is run in order to determine the probability distribution of thimbles remaining.

3-LOOP PROBLEM DESCRIPTION

The maximum possible number of available thimbles for a 3-loop Westinghouse PWR is 50. The initial distribution of these thimbles is provided in the following table. Figures 3 and 4 should also help in visualization.

No. of Interior Thimbles in Q1	9	
No. of Interior Thimbles in Q2	10	
No. of Interior Thimbles in Q3	11	
No. of Interior Thimbles in Q4	8	
No. of Axis Thimbles Q1-Q2	4	
No. of Axis Thimbles Q2-Q3	3	
No. of Axis Thimbles Q3-Q4	2	
No. of Axis Thimbles Q4-Q1	3	
	50	Total

No. of Interior Thimbles in QA	11	
No. of Interior Thimbles in QB	12	
No. of Interior Thimbles in QC	9	
No. of Interior Thimbles in QD	9	
No. of Diagonal Thimbles QA-QB	3	
No. of Diagonal Thimbles QB-QC	3	
No. of Diagonal Thimbles QB-QD	1	
No. of Diagonal Thimbles QD-QA	2	
	50	Total

Note that all thimbles are counted as whole values even if they lie on an axis or diagonal. Provided the technical specification value and computer simulation are consistent this is appropriate. Twenty-five (25) thimbles are randomly deleted from each case.

3-LOOP PROBLEM RESULTS

A 3000 case simulation was run to obtain the probability distribution of the minimum number of thimbles left after having reduced to 50% of the thimbles available. Results are summarized in Table 3.

[

]a,c Therefore, a requirement that 3 or more thimbles per quadrant for 50% be available is appropriate. Assuming random thimble deletion, it is unlikely that with 25 thimbles remaining overall, fewer than 3 thimbles will be available over the 8 quadrants.

CONCLUSION

With the inclusion of the additional peaking factor uncertainties, it is concluded that operation of the movable detector system with a minimum of 50% of the thimbles available is acceptable provided that an additional 1.5% for $F_{\Delta H}$ and 2.0% for F_Q be applied to the INCORE measured peaking factors. However, when fewer than 75% of the thimbles are available there should be a minimum of 3 thimbles per quadrant where quadrant includes both horizontal-vertical quadrants and diagonally bounded quadrants. This requirement increases the ability to distinguish between random and systematic thimble deletion events. In addition, the confidence on the appropriateness of the incremental thimble deletion peaking factor uncertainty values is increased provided that 3 or more thimbles per quadrant are observed to be available, and counting thimbles on the axis and diagonal as whole values. The applicability of these conclusions to Farley Unit 1 Cycle 15 has been confirmed.

TABLE 1

INCORE DETECTOR THIMBLE REDUCTION STUDY MAPS

		Burnup (MWD/MTU)	Core Power %	Percent Thimble Available (Ref.)
Unit 1 Cycle 15				
MAP	372	151	100.0	86
MAP	373	1304	100.0	82
MAP	374	2299	100.0	76
MAP	375	2662	100.0	76
Unit 2 Cycle 12				
MAP	305	1300	100.0	94
MAP	308	4018	100.0	90
MAP	311	7026	100.0	96
MAP	313	9140	100.0	96

TABLE 2a

SAMPLE STANDARD DEVIATION AND MEAN FOR INCORE MAPS
WITH 50% OF THE THIMBLE AVAILABLE FOR FARLEY UNITS
REACTOR CORE PARAMETERS

			$F_{\Delta H}$		F_Q		
Unit	Cycle	MAP	$\overline{X}_i$ (%)	S_i (%)	$\overline{X}_i$ (%)	S_i (%)	
1	15	372					(a,c)
1	15	373					
1	15	374					
1	15	375					
2	12	305					
2	12	308					
2	12	311					
2	12	313					
S_{comb}							
$\overline{\overline{X}}_{comb}$							

TABLE 2b

SAMPLE STANDARD DEVIATION AND MEAN FOR INCORE MAPS
WITH 75% OF THE THIMBLE AVAILABLE FOR FARLEY UNITS
REACTOR CORE PARAMETERS

			$F_{\Delta H}$		F_Q	
Unit	Cycle	MAP	$\overline{X}_i$ (%)	S_i (%)	$\overline{X}_i$ (%)	S_i (%)
1	15	372				
1	15	373				
1	15	374				
1	15	375				
2	12	305				
2	12	308				
2	12	311				
2	12	313				
S_{comb}						
$\overline{X}_{comb}$						

(a,c)

TABLE 2c

SAMPLE STANDARD DEVIATION AND MEAN FOR INCORE MAPS WITH 50% THIMBLES AVAILABLE FOR FARLEY UNITS REACTOR CORE PARAMETERS

Unit	Cycle	MAP	A.O.* $\overline{X}_i$ (%)	A.O.* S_i (%)	QUAD TILT+ $\overline{X}_i$ (%)	QUAD TILT+ S_i (%)
1	15	372				
1	15	373				
1	15	374				
1	15	375				
2	12	305				
2	12	308				
2	12	311				
2	12	313				
S_{comb}						
$\overline{X}_{comb}$						

(a,c)

\+ Standard deviation for QUAD TILT about ΔTilt = (Ref. - Deleted) x 100%.

* Standard deviation for A.O. about ΔA.O. = (Ref. - Deleted).

TABLE 2d

SAMPLE STANDARD DEVIATION AND MEAN FOR INCORE MAPS WITH 75% OF THE THIMBLE AVAILABLE FOR FARLEY UNITS REACTOR CORE PARAMETERS

			A.O.*		QUAD TILT+	
Unit	Cycle	MAP	$\overline{X}_i$ (%)	S_i (%)	$\overline{X}_i$ (%)	S_i (%)
1	15	372				
1	15	373				
1	15	374				
1	15	375				
2	12	305				
2	12	308				
2	12	311				
2	12	313				
S_{comb}						
$\overline{X}_{comb}$						

(a,c)

+ Standard deviation for QUAD TILT about ΔTilt = (Ref. - Deleted) x 100%.

* Standard deviation for A.O. about ΔA.O. = (Ref. - Deleted).

TABLE 3

3-LOOP CORE SUMMARY

3000 CASE THIMBLE DELETION SIMULATION

50% THIMBLES AVAILABLE

Minimum No. of Thimbles Left	Number of Cases	Percent of Cases	Cumulative Percentage

(a,c)

FIGURE 1
MOVEABLE DETECTOR, THERMOCOUPLE AND FLOW MIXING DEVICE LOCATIONS

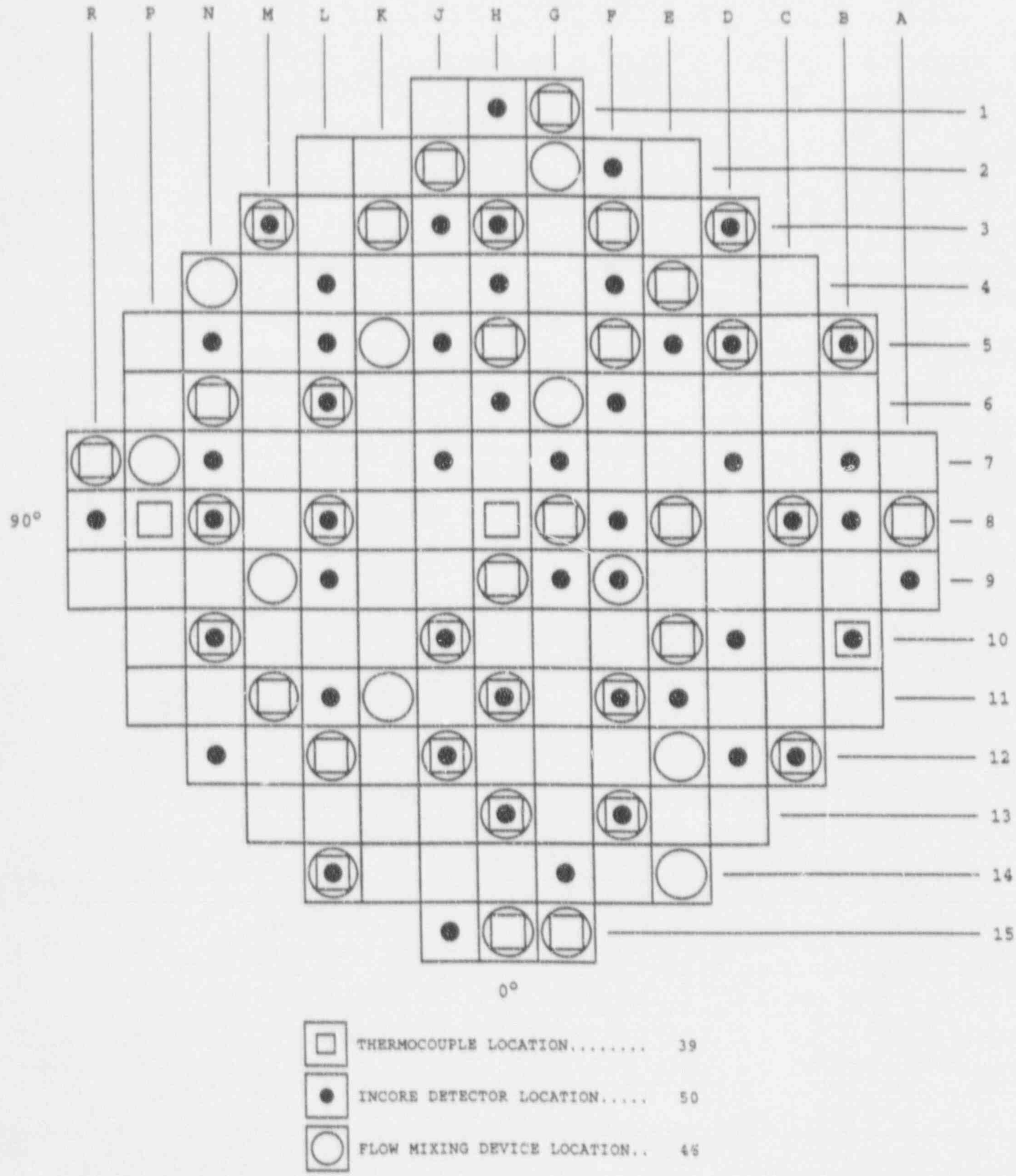


FIGURE 2
TOTAL THIMBLE DELETION PEAKING FACTOR UNCERTAINTY VERSUS PERCENTAGE OF THIMBLES AVAILABLE

(a,c)

FIGURE 3
MOVEABLE DETECTOR, THERMOCOUPLE AND
FLOW MIXING DEVICE LOCATIONS

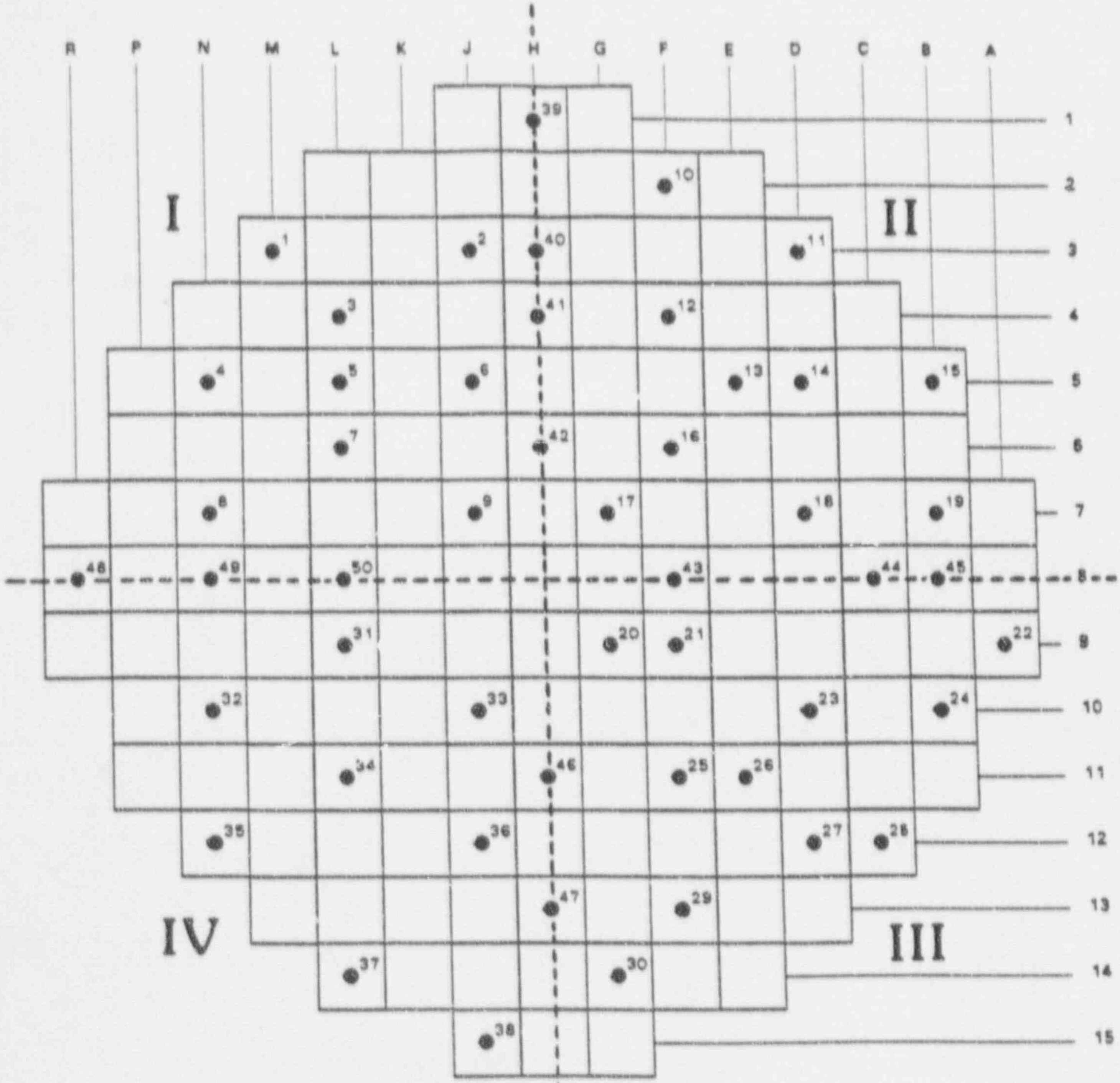
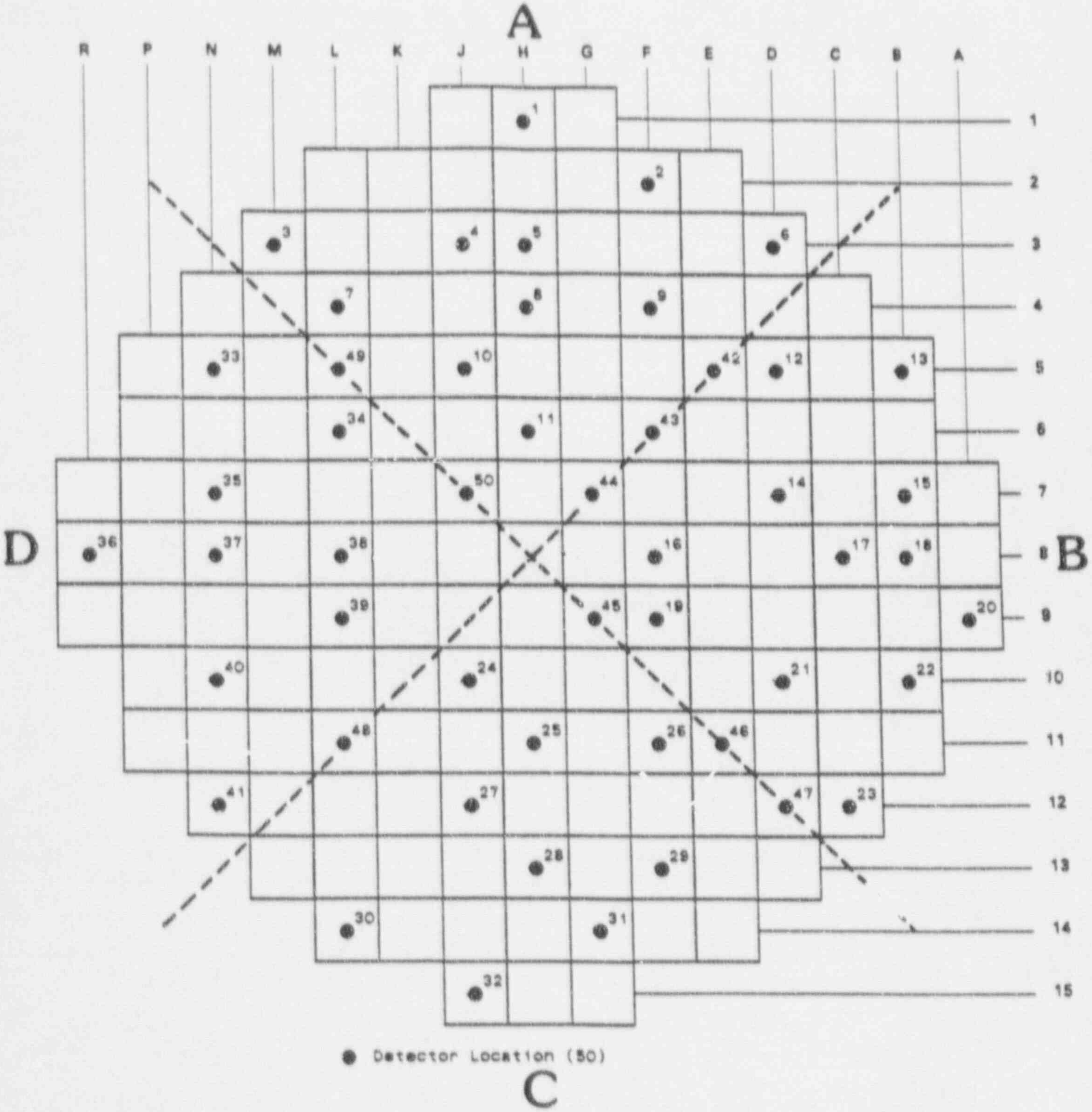


FIGURE 4
MOVEABLE DETECTOR, THERMOCOUPLE AND
FLOW MIXING DEVICE LOCATIONS



APPENDIX A

THIMBLE DELETION UNCERTAINTY COMPONENTS

95% PROBABILITY AND 95% CONFIDENCE ($\overline{X}_{comb} + KS_{comb}$)

NORMAL (TYPICAL) FLUX MAPS

$F_{\Delta H}$ Thimble Deletion Uncertainty Component

[ ] (a,c)

F_q Thimble Deletion Uncertainty Component

[ ] (a,c)

APPENDIX B

TWO-SIDED 95% CONFIDENCE LIMITS ON MEAN ΔTILT AND MEAN ΔA.O.

$\overline{X}_{comb}$ ± $t_{.025}$ s_{comb} / $\sqrt{N}$ (approximate t by z)
tilt or A.O. — tilt or A.O.

Quadrant Tilt Uncertainty Component

[ ] (a,c)

Axial Offset Uncertainty Component

[ ] (a,c)