BAW-10122A

Topical Report
November 1979

NORMAL OPERATING CONTROLS

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BAW-10122A

Topical Report
November 1979

NORMAL OPERATING CONTROLS

by

G. E. Hanson
Fuel Engineering

1548 241

BABCOCK & WILCOX
Power Generation Group
Nuclear Power Generation Division
P. O. Box 1260
Lynchburg, Virginia 24505

Babcock & Wilcox

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

SEP 14 1979

Mr. James H. Taylor
Manager, Licensing
Babcock & Wilcox Company
Nuclear Power Generation
P. O. Box 1260
Lynchburg, Virginia 24505

Dear Mr. Taylor:

SUBJECT: EVALUATION OF BAW-10122

We have completed our evaluation of Babcock & Wilcox Topical Report BAW-10122, "Normal Operating Controls." We have determined that BAW-10122 is acceptable for reference to describe the criteria and methods used to establish the limits for normal reactor core operation. A summary of our evaluation is enclosed.

If our criteria or regulations change, such that our conclusions concerning BAW-10122 are invalidated, we will notify you and provide you with an opportunity to revise and, if you desire, resubmit this report for our review.

We request, that within three months, you issue a revised version of BAW-10122 incorporating this letter and your responses to our requests for additional information.

Sincerely,

L S Rubenstein

L. S. Rubenstein, Acting Chief
Light Water Reactors Branch No. 4
Division of Project Management

Enclosure:
As stated

cc w/enclosure:
Mr. Robert B. Borsum
Babcock & Wilcox Company
7735 Old Georgetown Road
Bethesda, Maryland 20014

1548 242

Evaluation of Babcock and Wilcox Licensing Topical Report BAW-10122, "Normal Operating Controls"

Report No.: BAW-10122
Report Title: Normal Operating Controls
Report Date: July 1978
Originating Organization: Babcock & Wilcox
Reviewed By: Core Performance Branch/W. Brooks

The Power Generation Group of Babcock and Wildox has submitted licensing topical report BAW-10122 entitled, "Normal Operating Controls" for our review. This report describes the techniques and procedures used to establish core related limiting conditions of operation (LCOs). It is one of a series of topical reports which have been submitted by Babcock and Wilcox in order to provide the staff with generic information on the nuclear design of B&W reactors and to facilitate the review of such designs.

1. Summary of Report

Topical Report BAW-10122 describes the criteria and methods used by Babcock and Wilcox to establish the limits for normal reactor core operation - the limiting conditions for operation (LCOs). Core operating limits are established which assure that transients or accidents which are initiated from the limiting conditions do not violate appropriate acceptable limits. As a practical matter, the most restrictive operating limits on power distributions are currently imposed by the requirements of the loss of coolant accident as expressed in Appendix K of 10 CFR 50. Limits on control rod positions are imposed by the necessity of having an adequate shutdown margin and of limiting the reactivity worth of a potential ejected rod in addition to the power distribution restriction.

The calculational methods employed in the analysis are briefly described. They have been fully described in other topical reports in the series. Most of the calculations are three-dimensional and are performed with the PDQ07 and/or FLAME3 codes. Total rod worths and detailed radial power distributions are performed with the PDQ07 code in two dimensions.

The control philosophy of the bleed-and-feed reactor system is described and differences between bleed-and-feed and rodded plants pointed out. The core parameters which are investigated in the analysis of operating limits are listed and the analyses performed are described. In general, the parameter is varied over a range larger than is expected and the effect on the core operating condition determined.

For the LOCA limited heat generation rates the effects of five operating parameters are considered - axial offset, quadrant power tilt, control rod position, transient xenon, and fuel depletion. The manner in which each of these parameters affects the core peaking is described. The uncertainties applied to the calculated results are listed and typical values given. The manner in which the various limits are combined to obtain final operating limits is also described.

The procedures followed in determining the rod insertion limits relative to the shutdown margin requirements are described. Briefly, the reactivity increase in going from the operating power to zero power is calculated and one percent reactivity change is added to achieve the required shutdown margin. This is the amount of reactivity which must be held in control rods at the operating power. The fraction of rods which must be withdrawn to obtain this amount of reactivity then determines the insertion limit.

Another restraint on the amount of reactivity that may be held in control rods is the worth of a rod that could possibly be ejected from the core. In general this worth is larger for more inserted rod worth. Acceptable ejected rod worths are determined from the analysis of the ejected rod event and are currently one percent reactivity change at zero power and 0.65 percent reactivity change at full power, varying linearly at intermediate powers.

In summary there are three restraints on the amount of inserted rod worth; LOCA-limited power peaking, shutdown margin requirements, and ejected rod worths. The final insertion limits are obtained by combining the most limiting portions of the three insertion limit curves. In general at low power ejected rod worth considerations will be limiting and at high power the limit will be established by the LOCA.

The uncertainties to be applied to the operating limits are described - both calculational and measurement uncertainties are considered. Measurements of quadrant tilt and axial offset are performed with the incore monitoring system. The measurement uncertainties are described and typical values are presented.

The final step in the process of establishing operating limits is the conversion of the computed limits to alarm settings. The power dependence of the limits is represented by a series of straight line segments and entered into the alarm unit of the plant computer system. Audible and visual alarms are provided as well as an alarm message at the computer console. The algorithms used to calculate the various limited parameters are given. The calculated values are compared to the error-corrected limits and appropriate alarms sounded.

Finally, an example of the normal operating limits for the standard B&W plant, Babcock-205 cycle 1 is presented. An appendix to the report describes the differences between the current techniques and those used for current generation plants with 177 fuel assemblies. The chief difference is in the use of axial imbalance rather than offset to characterize the axial power distribution where imbalance is the product of offset and the fraction of full power in the core.

2. Summary of Evaluation

We have reviewed the description of methods and techniques used for obtaining normal operating limits given in topical report BAW-10122. The following comments summarize our evaluation.

The calculational methods and procedures employed for obtaining the information on power distributions, control rod worths, and core reactivity balances have been described in other topical report supplied by Babcock and Wilcox. These reports have been reviewed and approved and their use for establishing limiting conditions of operation is acceptable.

The choice of parameters to be considered for establishing LOCA power distribution limits is state-of-the-art and is acceptable. The use of axial offset to characterize the axial power distribution is an industry-wide practice and is acceptable. Allowance is made in the power distribution limits for a quadrant tilt of the order of five percent. This is conservative since normally the core will have negligible tilt. A further conservatism in the analysis is the fact that when the limit for a particular parmeter is derived all other parameters are assumed to be at their respective limits. The uncertainties applied to the determination of power peaking are state-of-the-art and the values for these uncertainties have been shown to be bounding. On the basis of the stated conservatisms and the use of appropriate uncertainties we conclude that the procedure and techniques are used to establish LOCA related limiting operating parameters are acceptable.

Calculations of the number of control rods that must be withdrawn in order to assure that the shutdown margin is adequate have been reviewed. The available rod worth is first corrected for the assumed stuck rod and for loss of reactivity due to burnout and the corrected value is reduced by ten percent to account for calculational uncertainty. Comparisons to measured values have shown that this is a conservative value of the uncertainty. The reactivity defect is calculated and a flux redistribution correction added. The corrected available rod worth and the corrected reactivity defect are then compared to obtain the rod withdrawal limits. This is an acceptable procedure.

The power dependent values of the ejected rod worth limiting values are reduced by fifteen percent to account for calculational uncertainty in the rod worth. Comparisons between calculated and measured ejected rod worths have shown that this is a conservative uncertainty value. The comparison of calculated ejected rod worth to the error-corrected limit establishes the withdrawal limit. This is an acceptable procedure.

The use of the most limiting of the withdrawal curves at each power level is an acceptable procedure which is industrywide practice.

Measurement uncertainties are applied in addition to the calculated ones described above. The incore monitoring system and rod position indication system measurement uncertainties are described in sufficient detail to permit the conclusion that proper techniques and methods are used in their evaluation. Algorithms are presented for certain portions of the errors and typical values given for other portions. We conclude that an acceptable discussion of measurement errors has been given.

The calculational and measurement errors are combined and the limiting conditions of operation (Technical Specification limits) are adjusted by the amount of the combined error. It is these error-adjusted limits to which core parameters are compared in order to give alarms. This is an acceptable procedure.

3. Evaluation Procedure

The review of topical report BAW-10122 has been conducted within the guidelines provided by the Standard Review Plan, Section 4.3. Sufficient information is included to permit a knowledgeable person to conclude that the methods and techniques employed are state-of-the-art and are acceptable. The parameters chosen to characterize the core power distribution are those widely used in the industry and are acceptable. The calculational and measurement uncertainties have been shown to be conservative and are appropriately applied.

4. Regulatory Position

Based on our review of licensing topical report BAW-10122 we conclude that it is acceptable for referencing in licensing actions by Babcock and Wilcox with respect to the establishment of limiting conditions of operation for the parameters discussed above.

Babcock & Wilcox

Power Generation Group

P.O. Box 1260, Lynchburg, Va. 24505
Telephone: (804) 384-5111

January 31, 1979

Mr. S. A. Varga, Chief
Light Water Reactors Branch No. 4
Division of Project Management
United States Nuclear Regulatory Commission
Washington, D.C. 20555

Subject: Response to Questions on Topical Report BAW-10122

Dear Mr. Varga:

The responses to the questions in your November 22, 1978 letter are attached. We hope this adequately answers your questions, however, if you desire additional information please contact Mr. R. J. Finnin (Ext. 2892) of my staff.

Very truly yours

James H Taylor

James H. Taylor
Manager, Licensing

JHT/fw
cc: R. B. Borsum (B&W)

Attachments: As stated

Question 232.1: (Sect. 2.1) The implication in this section is that the power distribution operating limits are always defined by the requirements of the LOCA analysis. Please comment.

ANSWER: The statement above is true in general. For example, initial DNB assumptions used in the analysis of other, DNB-limited accidents are, in our experience, preserved through adherence to the normal operating limits (offset and rod position) defined by the LHR limits from the LOCA analysis. Current practice for B&W operating plants is to check the power peaking allowed within the LOCA-related control rod and imbalance limits to insure that the initial condition DNB ratio assumed for the DNB limited accidents is preserved. Every check has indicated that the LOCA-related operating limits are the most restrictive. A preliminary analysis for the Babcock-205 core has also indicated that the LOCA-related operating limits are the most restrictive. However, a flat statement that this will always be the case should not be inferred from Section 2.1. Should an instance arise where part of the normal operating limits are set by other, non-LOCA accident criteria, it will be so noted in the appropriate licensing submittal.

QUESTION 232.2: (Fig. 4-5) Presumably the shape of this curve depends on the location of the other rods in the core and on core burnup. How are these effects handled in establishing operating limits?

ANSWER: Figure 4-5 was included for illustration only and represents the peaking response for beginning of cycle conditions with a nominal (12.5% insertion) position for the Bank 7 control rods. As described in Section 4.1.2.1, when operating limits are established, APSR scans are run for various control rod (Bank 7) insertions at several, selected core burnups. Control rod and offset limits are developed for each burnup, and the most restrictive limits are specified for the burnup interval chosen (either all or part of a cycle, as discussed in Section 4.1.1.5.).

1548 252

QUESTION 232.3: (4.1.1.4) It is implied in this section that the APSRs are used to minimize offset while the core is at low power. However, Figure 2-6 of BAW-10118 shows no movement of the APSRs during this time. Please clarify.

ANSWER: Figure 2-6 of BAW-10118 starts with the core power already reduced to 60% and APSRs already inserted to ∿12.5% withdrawn; had this figure started with core power at 100% the APSR would have been ∿25% withdrawn and their movement into the core upon power reduction would have been evident. Once placed in the minimum offset position (∿12.5% wd), no further movement at reduced power is beneficial, as the xenon burnout in the lower half of the core allows more power to be produced there. APSR movement about the initial, reduced power minimum offset position has little effect until after power recovery. Then the ASPR's are moved to damp the resulting xenon-induced axial power oscillation.

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QUESTION 232.4: (4.1.2)

The term H(X,Y,Z) in the equation on page 4-4 appears to be the linear heat rate in the peak rod in the node at (X,Y,Z). Please clarify.

ANSWER:

The term H(X,Y,Z) represents the <u>peak</u> linear heat rate within each node. Multiplication of the factors F_1-F_7 and the radial-local peaking factor, P_{R-L}, times the nodal average linear heat rate $(P_t X\overline{P})$ results in a product, H(X,Y,Z), which is the maximum linear heat rate for a pellet within the node at (X,Y,Z). As described on page 4-5, the H value for each node in the core is then compared to the LOCA Kw/ft limit at the appropriate axial location. The resulting margins are searched to find the minimum margin in the core. It is this single valve that is associated with the core offset for each unique calculation (rod position, xenon concentration, burnup), as in Figure 4-9).

QUESTION 232.5 (Fig. 4-9)

APSR positions are not indicated on this figure. Is the inference to be made that the most adverse APSR position is to be associated with each point? Cr, are all points for the same APSR position?

ANSWER:

Each point on the Figure represents a single calculation for a fixed APSR and Bank 7 position. The different Bank 7 positions are represented by different symbols. Each point shown with a given symbol represents a different APSR position. In general, one can follow an APSR scan by connecting the points with identical symbols. This is most easily observed by considering three points for 100% withdrawal of Bank 7. Starting with the point at ∿11% positive offset and ∿0% margin, this represents an APSR position of 12.5% withdrawn. Moving to the point at ∿1% positive offset and ∿5% positive margin, this represents an APSR position of 25% withdrawn. Similarly, the point at ∿14% negative offset and ∿5% negative margin is for an APSR position of 37.5% withdrawn. Other points for 100% Bank 7 withdrawal are either continuations of this ASPR scan for equilibrium xenon, or are scans at other xenon conditions, as discussed in paragraph two of Section 4.1.2.3. Only a representative sample of end of cycle cases are plotted on Figure 4-9, in order to show different symbols for the different Bank 7 positions and the behavior of the offset/minimum margin points for various APSR positions and xenon conditions.

(6)

QUESTION
232.6:
(4.4)

The statement that BNL-NUREG-22333 constitutes approval of the approach to setting operating limits is incorrect. Approval can be provided only by NRC. BNL-NUREG provides verification of the procedure. Please correct the report to reflect this fact.

ANSWER:

The use of the word "approved" was intended only in the context of technical verification. In the last sentence of Section 4.4, the word "verified" will be substituted for word the word "approved".

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

NOV 22 1978

Mr. James H. Taylor
Manager, Licensing
Babcock & Wilcox Company
Nuclear Power Generation
P. O. Box 1260
Lynchburg, Virginia 24505

Dear Mr. Taylor:

SUBJECT: REVIEW OF TOPICAL REPORT BAW- 10122

In order to complete our review of the subject report, we require adequate responses to the enclosed requests for additional information. If you have any questions on this matter, please contact us.

Sincerely,

Steven A. Varga

Steven A. Varga, Chief
Light Water Reactors Branch No. 4
Division of Project Management

Enclosure:
As stated

cc: Mr. Robert B. Borsum
7735 Old Georgetown Road
Bethesda, MD 20014

1548 257

ENCLOSURE

NOV 22 1978

Request for Additional Information - BAW-10122

232.1 (Sect. 2.1) The implication in this section is that the power distribution operating limits are always defined by the requirements of the LOCA analysis. Please comment.

232.2 (Fig. 4-5) Presumably the shape of this curve depends on the location of the other rods in the core and on core burnup. How are these effects handled in establishing operating limits?

232.3 (4.1.1.4) It is implied in this section that the APSRs are used to minimize offset while the core is at low power. However, Figure 2-6 of BAW-10118 shows no movement of the APSRs during this time. Please clarify.

232.4 (4.1.2) The term H(X,Y,Z) in the equation on page 4-4 appears to be the linear heat rate in the peak rod in the node at (X,Y,Z). Please clarify.

232.5 (Fig. 4-9) APSR positions are not indicated on this figure. Is the inference to be made that the most adverse APSR position is to be associated with each point? Or, are all points for the same ASPR position?

232.6 (4.4) The statement that BNL-NUREG-22333 constitutes approval of the approach to setting operating limits is incorrect. Approval can be provided only by NRC. BNL-NUREG provides verification of the procedure. Please correct the report to reflect this fact.

Babcock & Wilcox

Power Generation Group

P.O. Box 1260, Lynchburg, Va. 24505
Telephone: (804) 384-5111

August 4, 1978

Mr. S. A. Varga, Chief
Light Water Reactor Branch #4
Division of Project Management
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Mr. Varga:

Enclosed are fifty copies of the Topical Report BAW-10122, "Normal Operating Controls." This report describes the criteria and methods used by B&W to establish the limits for normal reactor core operation.

BAW-10122 is one of a series of topical reports that has been requested by the NRC to supply generic information on the nuclear design of B&W Nuclear Steam Supply Systems. Use of this information on B&W reactors will be addressed in the individual license applications filed by our customers.

Very truly yours

Edward R Kane

for James H. Taylor
Manager, Licensing

JHT/fw

Enclosures: As stated

cc: R. B. Borsum - B&W

1548 259

Babcock & Wilcox
Power Generation Group
Nuclear Power Generation Division
Lynchburg, Virginia

Topical Report BAW-10122A

November 1979

Normal Operating Controls

G. E. Hanson

Key Words: Criteria, Methods, Techniques, Limits, Normal Operation, B-SAR-205

ABSTRACT

The criteria, methods and techniques employed by B&W in setting the limits for normal reactor core operation are described. The data used and references cited are consistent with the B-SAR-205. The techniques and types of restrictions are, however, applicable to all B&W cores.

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1. INTRODUCTION

This report describes the criteria used in setting the normal operating controls that maintain various limiting conditions for operation (LCOs) for all Babcock & Wilcox cores, the analyses that determine the restrictions applied, and the means by which these restrictions are enforced. All data and references used in the body of this report are consistent with the Babcock-205 core described in the B-SAR-205.[1] However, the methods used and the types of restrictions applied are generic to all B&W cores. Data and references specific to B&W 177-assembly cores are given in the Appendix.

The criteria used to set the controls are discussed in section 2. The methods of analysis and the techniques used to derive the controls are described in sections 3 and 4. Section 5 lists the various monitoring systems and the measurement uncertainties inherent in each. The method of combining this information with the calculated operating limits is discussed in section 6. An example of the techniques described in sections 2-6 is given in section 7 for cycle 1 of the Babcock-205.

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2. CRITERIA

This section describes the criteria used to set the normal operating controls. Three primary criteria are maintained by these controls: (1) kW/ft limits based on initial condition assumptions used in the analysis of ECCS performance during a postulated LOCA; (2) regulating rod bank position limits, which preserve a 1% Δk/k shutdown margin at all times; and (3) regulating rod bank position limits, which prevent a postulated ejected rod accident from inserting more than a fixed amount of reactivity into the core. Each criterion is detailed below.

2.1. LOCA Linear Heat Rate

The effectiveness of the emergency core cooling system (ECCS) for B&W's 205-FA NSS during a postulated LOCA was evaluated using the B&W ECCS evaluation model as documented in BAW-10104.[2] This model is constructed to comply with the requirements of Appendix K of 10 CFR 50. Calculations utilized the CRAFT2[3] computer code during the blowdown period, the REFLOOD[4] code during the refill and reflooding periods, and the THETA1-B[5] code for the fuel rod heatup calculation. Typical results of this analysis for B&W's 205-FA NSS are given in BAW-10102.[6]

Figure 2-1 graphically shows the typical results of the LOCA limits analysis. The locus of points generated by this analysis defines the allowable linear heat rate versus axial position and ensures that the criteria for 10 CFR 50.46 are satisfied.

2.2. Shutdown Margin

Sufficient control rod assembly (CRA) worth must be available to shut down the reactor with at least a 1% Δk/k subcritical margin in the hot conditions at any time during the life cycle with the most reactive CRA stuck in the fully withdrawn position.

2.3. Ejected Rod Worth

The worth of the most reactive CRA in each rod group is determined for various control rod axial configurations. When the reactor is shut down, the boron concentration is maintained at a level ensuring that the reactor is at least 1% subcritical with the control rod of greatest worth fully withdrawn from the core. Thus, a rod ejection will not cause a nuclear excursion when the reactor is shut down and all the other rods are in the core. As criticality is approached, the worth of the remaining rods decreases, so that at criticality the maximum reactivity addition from a rod ejection would be less than 1% $\Delta k/k$. However, for this startup condition, ejected rod worths up to 1.0% $\Delta k/k$ were analyzed. At rated power, BOL, the maximum rod worth is expected to be less than 0.5% $\Delta k/k$. A maximum ejected rod worth of 0.65% $\Delta k/k$ has been considered as a limiting value at rated power to demonstrate the inherent ability of the system to safely terminate this postulated rod ejection transient.

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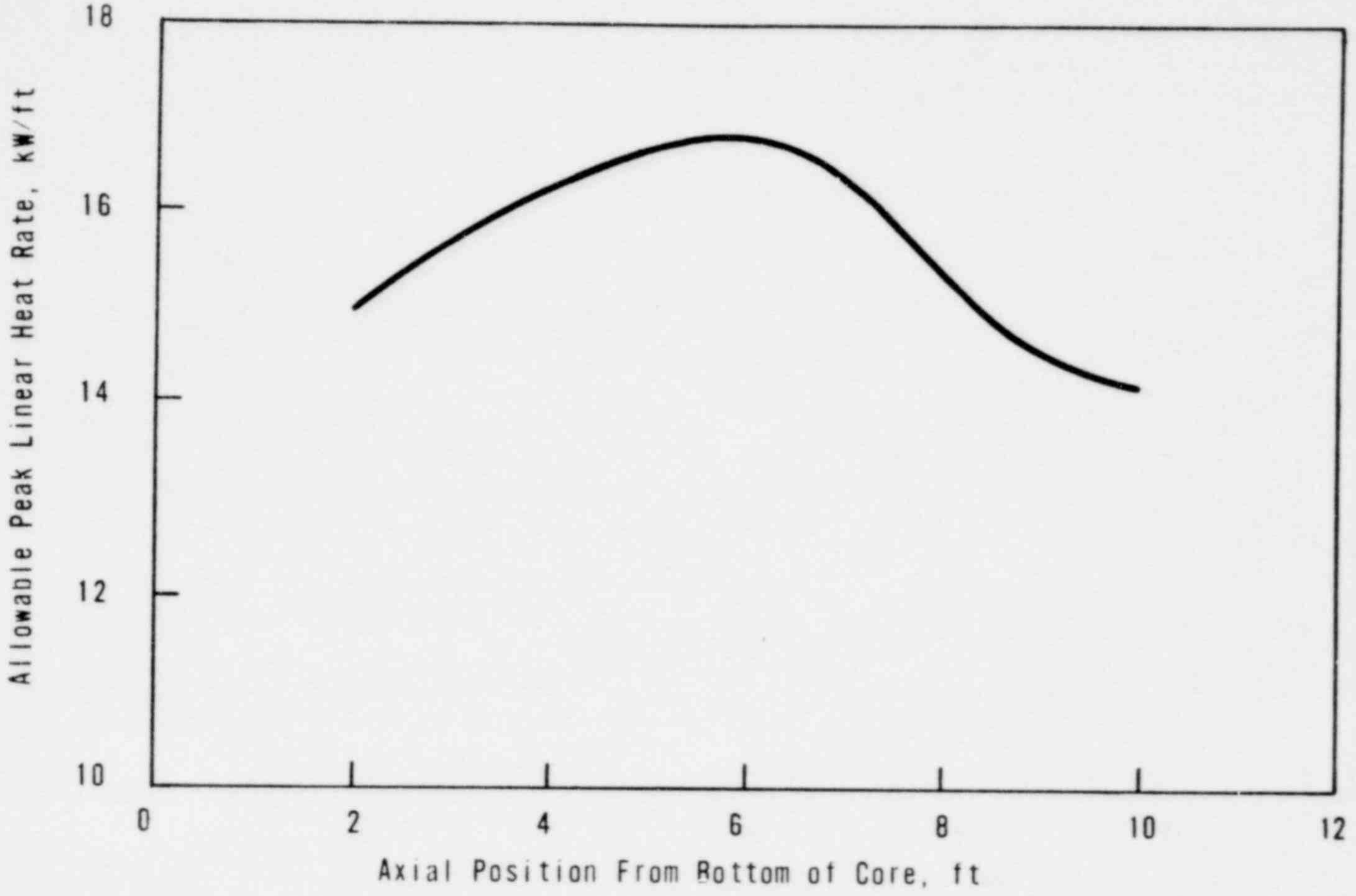
Figure 2-1. LOCA Limits — Allowable Peak Linear Heat Rates Vs Axial Position From Bottom of Core



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3. METHODS

3.1. PDQ07

The PDQ07 code, as described in BAW-10117[7], is used in developing parameter limits that maintain all the criteria listed in section 2. The fitted nuclear data used in the various PDQ07 model calculations is described in BAW-10116.[8]

3.1.1. Two-Dimensional Geometry

The PDQ07 code is used in two-dimensional, discrete pin geometry to obtain core radial power distributions and radial-local (peak pin power/assembly average power) peaking factors for use in the determination of parameter limits that maintain the LOCA kW/ft criteria. It is also used to determine total, stuck, and ejected rod worths, which are used to develop rod position limits that maintain the shutdown margin and ejected rod worth criteria. Details of the code utilization in performing the various calculations are discussed in BAW-10118.[9]

3.1.2. Three-Dimensional Geometry

PDQ07 calculations are performed in three-dimensiona (3-D) quarter-core geometry for first-of-a-kind analyses using the one-zone model[8] for assembly cross section homogenization. Up to 6 × 6 radial mesh blocks per assembly can be used with the axial mesh spacing as defined in BAW-10118. Total peaking factors are derived from the resulting power distributions and are used in conjunction with radial-local peaking factors from section 3.1.1 and other peaking augmentation factors, as discussed in section 4.1.2, to obtain peak kW/ft values. Parameter limits are then established to prevent these values from exceeding the LOCA kW/ft criteria. Also, in first-of-a-kind analyses, total and individual group rod worths and integral shapes may be calculated with this 3-D model. BAW-10118 includes a detailed discussion of 3-D PDQ utilization.

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3.2. FLAME3

The FLAME3 code[10,11] is the primary design tool for 3-D analyses, both for total peaking factors and integral rod worth shapes. Again, BAW-10118 describes how the calculations are performed, including the determination of albedo values and the mechanics of computing the nominal fuel cycle depletion and design power transients.

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4. DERIVATION OF OPERATING CONTROLS

The control philosophy for the Babcock-205 reactor makes extensive use of boron dilution control rather than control rods for excess reactivity compensation. The following reactivity is controlled by the regulating banks during plant operaton:

1. Power level changes (Doppler).
2. Moderator temperature changes between 0 and 15% power.
3. The additional reactivity held by the partial insertion of the control rods allows periodic rather than continuous boron dilution as the fuel is depleted.

An operating position range is specified as a function of reactor power level. Figure 4-1 shows a typical range. Boron is added or diluted to maintain the rods within the range to account for the following:

1. Reactivity deficit from ambient to operating temperatures.
2. Equilibrium xenon and samarium.
3. Transient xenon resulting from load changes.
4. Excess reactivity required for fuel burnup and fission product buildup.

This section defines how measurable operating parameters are related to the criteria listed in section 2, and gives the mechanics of deriving the limits for these parameters.

4.1. LOCA Linear Heat Rate

To generate the operating power peaks for the Babcock-205, the methods described in section 3 are used. In the analysis, the effects of five operating parameters are considered and are as follows:

1. Axial offset.
2. Quadrant power tilt.
3. Control rod position (both regulating bank and APSRs).
4. Transient xenon.
5. Fuel depletion.

Each of these effects is discussed in section 4.1.1 to establish the general effect on power peaking of each parameter, while the procedures used to establish the parameter limits are given in 4.1.2.

4.1.1. Basis for Controls

4.1.1.1. Axial Offset

The core axial offset is defined as power(top) - power(bottom)/power(top) + power(bottom), where power(top) = power in top half of core, and power(bottom) = power in bottom half of core. The relationship between axial offset and total peaking is shown in Figure 4-2. Data points are obtained from rod positions both in and beyond the normal operating range. The effects of mispositioned APSRs are included simultaneously. As seen in the figure, if the core is in a balanced condition with power equally distributed in the top and bottom of the core, linear heat rates are minimized. The ability to bound the behavior of power peaks with increasing offset (either positive or negative) is a key to using measured offset as a limiting parameter for LOCA kW/ft criteria.

4.1.1.2. Quadrant Power Tilt

Quadrant power tilt is defined as

$$\%\ \text{QPT} = 100 \times \left(\frac{\text{power in any core quadrant}}{\text{avg power in all quadrants}} - 1\right).$$

Quadrant tilts indicate deviations from core radial symmetry. Core radial symmetry is established during startup tests using incore instrumentation. The relationship of quadrant tilt and increased peaking is shown in Figure 4-3. The relationship of measured peaking and quadrant tilt was studied for numerous dropped rod cases since these produce the highest peaking increases. The data are conservatively bracketed by the lines shown in the figure.

4.1.1.3. Control Rod Position

Although only minimal regulating bank insertion is maintained at full power, the effects of movement away from this nominal position as well as the effects of deeper rod insertions at reduced powers must be examined. Figure 4-4 shows the behavior of the total power peak with rod movement at beginning- and end-of-cycle conditions. Control rod shadowing causes the increase in heat rate as the rods move from nominal insertion to fully withdrawn at the end of the cycle as illustrated in Figure 4-4.

Likewise, movement of the axial power shaping rods (APSRs) affects total power peaking as shown in Figure 4-5.

4.1.1.4. Transient Xenon

Figure 4-6 shows the variation in xenon concentration as a function of time for the design power maneuver, defined as 50% insertion of the regulating bank, which results in a reduction from 100% to about 60% power until peak xenon occurs (about 6 hours later), then a return to 100% power. Also illustrated is the axial redistribution of the xenon caused by regulating rod control of the core Doppler reactivity changes at the beginning of the transient. The reader is referred to Figure 2-6 of BAW-10118[9] for details of the control rod positions and offset values versus time in the transient. The Babcock-205 reactor compensates for the relatively slow changes in the reactivity held by xenon with changes in soluble boron concentration. Thus, after the initial rod movement to compensate for Doppler reactivity, the regulating rod position is nearly constant. APSRs minimize power offset between the upper and lower portions of the core. However, the resultant minimized negative offset will produce a xenon mismatch between the top and bottom core halves. The xenon builds up in the controlled top half of the core and burns out in the bottom half, which is producing more power than the top half at the reduced power level. The design power maneuver maximizes the axial redistribution of xenon; thus, maximum peaking results. Power changes that cause a lower axial offset result in reduced peaking. Figure 4-7 is based on power recovery at maximum axial xenon mismatch (6 hours after reduction of power). If power is changed and if the axial redistribution of xenon is allowed to stabilize before full power recovery, the power peaking will be reduced.

Figure 4-7 shows the effects of transient xenon on linear heat rate (LHR) during the design power maneuver. The increase in LHR above the equilibrium condition depends on the magnitude of the perturbation of the axial power shape by xenon mismatch and rapid xenon burnout. During the first 4 hours after power recovery, the xenon redistribution reaches a maximum, which yields the maximum increase in peaking above the equilibrium case (∿20%). This is followed by a rapid, substantial decrease in the peak LHR. The principal cause of the abrupt change is the movement of the APSRs back to their approximate pre-maneuver position as the xenon mismatch is burned out and the core offset changes from negative to positive. For the Babcock-205 core, the APSRs can be raised and the peak LHR returns to within 10% of the equilibrium value within 5 hours of return to full power. This observation is valid at any time during the cycle.

4.1.1.5. Fuel Depletion

As mentioned in the discussions above, the effects of fuel depletion on operating power peaks were examined. The peak LHR generally decreases as a function of burnup as shown in Figure 4-8. In determining operating restrictions, the maximum peaks during the chosen interval must be used. To gain operating flexibility during part of a fuel cycle, burnup-dependent limits on offset and rod position may be used.

4.1.2. Calculational Procedures and Assumptions

The axial dependence of the LHR limit is given in Figure 2-1. The maximum operating LHRs are maintained less than the axially dependent limits by restrictions on axial offset, control rod and APSR position and quadrant power tilt. These restrictions are selected with respect to maximum peaking conditions that occur during the design power maneuver at any time during the interval chosen, as mentioned in section 4.1.1.5.

For comparison to the limits of Figure 2-1, the LHR is calculated for each node (or mesh block) as follows:

$$H(X,Y,Z) = P_t \times P_{R-L} \times \bar{P} \times F_1 \times F_2 \times F_3 \times F_4 \times F_5 \times F_6 \times F_7$$

where

$H(X,Y,Z)$ = nodal LHR at 102% power,

$P_t(X,Y,Z)$ = total peaking factor as calculated by 3-D FLAME or PDQ,

$P_{R-L}(X,Y)$ = radial-local peaking factor as calculated by discrete mesh, 2-D PDQ,

$\bar{P}$ = average LHR, 5.73 kW/ft,

F_1 = nuclear uncertainty factor, 1.075,[12]

F_2 = hot channel factor obtained by statistical combination of manufacturing tolerances (1.025),

F_3 = quadrant power tilt factor from section 4.1.2.2, (1.091),

F_4 = axial shrinkage factor due to densification (1.02),*

F_5 = power uncertainty due to calorimetry (1.02),

F_6 = transient xenon factor, if used (see section 4.1.2.3),

F_7 = axial peaking factor due to presence of grids (1.030).

Special care is taken in the assignment of $P_{R-L}(X,Y)$ to APSR locations. Peaking in an APSR assembly occurs above or below the active poison length. Values for an unrodded condition are used, augmented to account for burnup shadowing. The peaking increase due to postulated worst-case fuel rod bowing is inherently included by the multiplication of F_1 and F_2, as approved in reference 13. The calculation of the peak LHR, H, and the resultant peaking margin to the LOCA kW/ft limit is obtained from the B&W in-house data processing code FLUT. This program accesses a FLAME3 history tape and, using input values for all the factors listed above as well as the axially dependent limits, calculates H and

$$\%\ \text{LOCA margin} = \frac{\text{CLOCA}(Z) - H(X,Y,Z)}{\text{CLOCA}(Z)}\ (100)$$

where CLOCA(Z) = axially dependent LOCA kW/ft limits for every node in the calculation. It then searches these values for the minimum margin at each axial level as well as the overall minimum in the core. This approach eliminates the possibility of arriving at the incorrect margin, which can occur by selecting the largest calculated $P_t(X,Y,Z)$ and applying its radial-local factor $P_{R-L}(X,Y)$ without checking whether some other combination of a slightly lower $P_t^1(X,Y,Z)$ and its radial-local factor $P_{R-L}^1(X,Y)$ might yield a larger product.

4.1.2.1. Limiting Offset and Rod Position Selection

Planned sets of many calculations are processed in the above manner for various control rod and APSR configurations at various times during the cycle. The resultant LOCA margin data can be plotted versus core offset as shown in Figure 4-9. The advantage of using margin instead of the total peak as shown in Figure 4-2 is that the need of a plot like Figure 4-2 for every axial plane is eliminated. The individual points can be identified with respect to the control rod and APSR positions that produced them. In this manner, limiting

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[*] The factor given is approximate and for illustration only.

offsets and rod positions can be chosen within which positive margins to LOCA limits are preserved. As can be observed in Figure 4-9, various trade-offs exist between allowable regulating rod positions, APSR positions, and offset limits. For example, if all regulating rod positions between 75 and 100% withdrawn are allowed, the allowable offset window will be rather narrow (approximately -7 to +10%). However, if a "rod-out" restriction of about 95% withdrawn is imposed, the points for 100% withdrawn may be ignored (or the graph replotted without them), and new, wider offset limits derived. This may be necessary near the end of the cycle, as the example in Figure 4-9 shows, because of the "shadowing" of the fuel in the top of the core by depletion with the regulating rods inserted to their nominal position ($\sim$10% inserted). Similarly, APSR positions may be restricted to avoid axial power "pinch" effects whereby large peaks are produced at relatively small offsets by positioning APSRs too low in the core and axially "pinching" the core power distribution between them and the partially inserted regulating rods. Repetition of this iterative selection process at different power levels gives rise to the familiar offset and rod position envelopes as are currently provided in operating plant Technical Specifications.

Conversion of the limits derived in this manner to alarm set points is discussed in sections 5 and 6.

4.1.2.2. Quadrant Tilt

The effects of a quadrant power tilt on power peaking are shown in Figure 4-3. For a 5% actual quadrant power tilt, the graph would indicate that a maximum increase in power peaking of 9.1% could be expected. The conversion of this actual tilt limit to an alarm limit for the incore monitoring system is also discussed in sections 5 and 6. Three separate limits may be defined as in B&W Standard Technical Specification 3.2.4:

1. A "steady-state" tilt limit, such as that defined above.
2. A "transient" limit with somewhat greater limit values.
3. A "maximum" limit which, if exceeded, requires reduction to ≤ 15%FP within two hours.

These three limits provide increasingly more stringent action requirements for an increasing amount of control rod misalignment or other causes of quadrant tilt.

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4.1.2.3. Transient Xenon

As discussed in section 4.1.1.4 and shown in Figure 4-7, for a design power maneuver the increase in power peaking from equilibrium steady-state operation is initially about 20% and drops to about 10% after 5 hours following the return to power. These peaking effects can be accommodated within the other operating limits at full power in two ways: either include cases from all times following a power maneuver in the data base or limit the return to full power until the peak returns to an acceptable value. In the latter case the data base is limited to steady-state peaking cases only, and the factor F_4 listed at the beginning of section 4.1.2 is used.

The typical LOCA margins plot shown in Figure 4-9 includes the full peaking effects of transient xenon at return to full power from the design power maneuver. Thus, no power level hold would be necessary with operating limits derived from these data.

Alternately, as discussed in the Appendix, operating B&W reactors routinely make use of the hold at the power level cutoff for the amount of time necessary to reduce the transient xenon-induced peaking to below a preselected level. In this manner, the operating limits of rod position and offset are not excessively penalized for infrequently occurring power peaks.

4.1.2.4. Relationship of Operating Restrictions

In defining any single limit of operation, it is assumed that the other operating conditions are at their respective limits. For example, in defining the offset limits, it is assumed that the control rods and APSRs are at their respective withdrawal limits, a full 5% quadrant tilt exists, and transient xenon conditions exist to increase peaking by the maximum amount allowed. Furthermore, the operating limits are defined at the worst time for peaking in the burnup period chosen.

4.2. Shutdown Margin

The 1% $\Delta k/k$ subcritical margin requirement defined in section 2.2 is preserved at all times during the cycle by a second set of control rod insertion limits, derived independently from those obtained in the preceeding section. The basis for and derivation of these limits are discussed below.

4.2.1. Basis for Control

The basis for a rod insertion limit to ensure a 1% shutdown margin is simply the relationship between rod bank position and inserted rod worth, as illustrated by the integral rod worth curve in Figure 4-10. Using the net total rod worth and the worth required to shut down the core at any given time in the cycle, the allowable inserted worth, which still preserves the 1% Δk/k margin, can be calculated (as illustrated in section 4.2.2). Then using the appropriate integral rod worth curve for the power level and time in the cycle of interest, the rod insertion limits of the regulating banks are established.

4.2.2. Calculational Procedures and Assumptions

The calculational procedures used to derive shutdown margin rod insertion limits are most easily discussed by reference to Table 4-1. The calculation of total and stuck rod worths is described in section 3 of BAW-10118. The nvt (or depletion) correction accounts for the loss in rod worth in individual rods as they are used for bank 7 rods and are kept partially inserted during the cycle. In the Babcock-205 this value is quite small since bank 7 is only inserted about 10%.

The power deficit, PD, is normally calculated with 2-D PDQ. A generic, conservative flux redistribution term, established by special 3-D PDQ studies, is added to obtain a total 3-D reactivity deficit.

Following the Table 4-1 procedure for various times during the cycle and power levels between 0 and 100% FP allows burnup- and power-dependent rod insertion limits to be established by the use of the appropriate integral rod worth curves. Section 7 illustrates shutdown margin limits.

4.3. Ejected Rod Worth

Ejected rod worth criteria are preserved by insertion limits on the regulating banks in a manner similar to that described in section 4.2.

4.3.1. Basis for Control

As in section 4.2.1, the integral rod worth curves of the regulating banks are used to establish insertion limits so that an ejected rod would not exceed the power-level-dependent limits of section 2.3. The relationship, which is established through calculations, is that of the inserted rod worth to the ejected rod worth.

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4.3.2. Calculational Procedures and Assumptions

The calculation of ejected rod worths is also described in detail in section 3 of BAW-10118. Sufficient calculations are performed at various power levels with various regulating bank insertions, so that the resultant ejected rod worths can be plotted against inserted worth and a bounding line can be drawn. Picking the inserted worths for points on the line corresponding to the ejected rod worth limits for various power levels and using the appropriate integral rod worth curves, the rod position limits which preserve the ejected rod worth criteria can be established. Table 4-2 gives the power-level-dependent ejected rod worth limits and adjusted limits, which include a 15% calculational uncertainty. The adjusted limits are used to establish the rod position limits. Section 7 includes an example of ejected rod worth position limits.

4.4. Combined Limits

Rod position limits based on each criterion are plotted and the plant is controlled to the most restrictive position. The combined effects of applying the limits described in 4.1-4.3 in cycle 1 of the Babcock-205 reactor (as defined in the B-SAR-205) are illustrated in section 7. The overall approach to setting operating limits described in this section was reviewed and verified in BNL-NUREG-22333.[14]

Table 4-1. Calculation of Shutdown Margin Limits

$ARW = (TW - nvt - SRW)\ 0.9$

ARW = available rod worth including 10% calculational uncertainty,

TW = total worth of all full-length rods,

SRW = worth of most reactive stuck rod,

nvt = control rod depletion correction.

$PD = PD(2D) + \phi$

PD = power deficit,

PD(2D) = 2-D power deficit,

ϕ = axial flux redistribution term.

SM = ARW - PD = shutdown margin

IRW = SM - 1%

IRW = inserted rod worth limit,

1% = design shutdown margin.

Table 4-2. Ejected Rod Limits

% FP	Accident analysis ERW limit, % $\Delta\rho$	Adjusted ejected rod worth limit, % $\Delta\rho$
100	0.65	0.55
50	0.82	0.70
15	0.95	0.81
0	1.00	0.85

Figure 4-1. Control Rod Operating Range

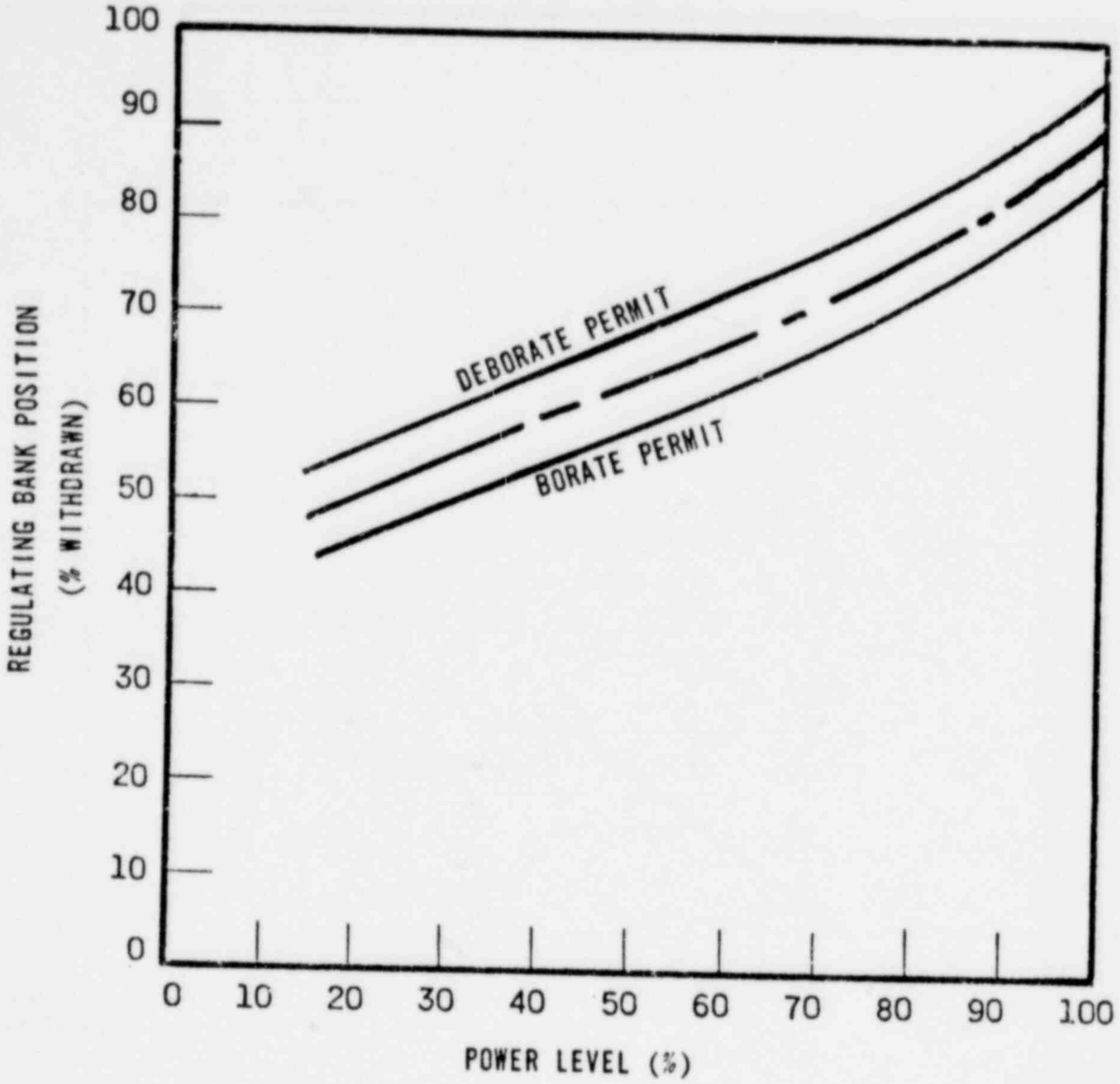

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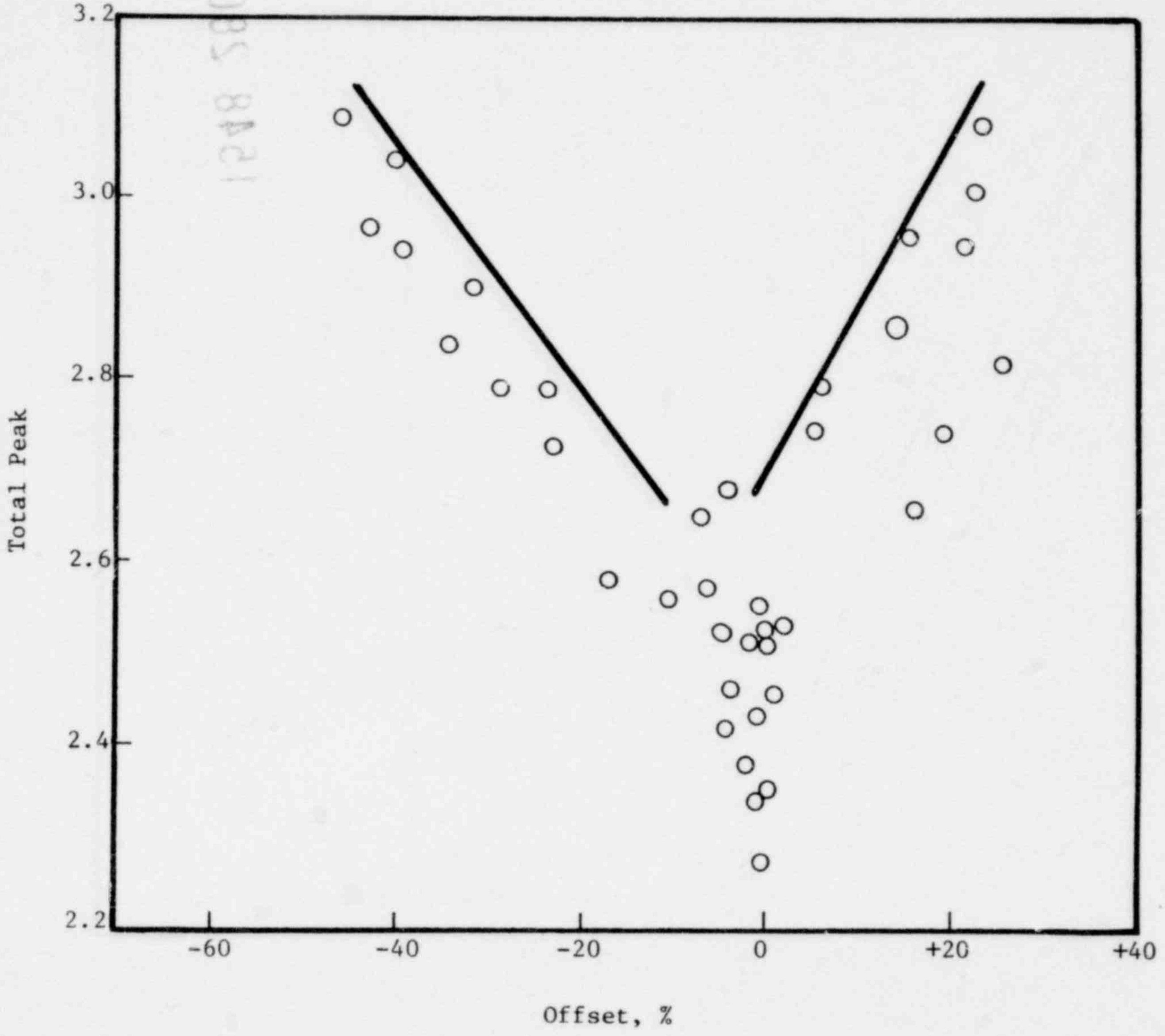
Figure 4-2. Typical Peaking Vs Offset Behavior



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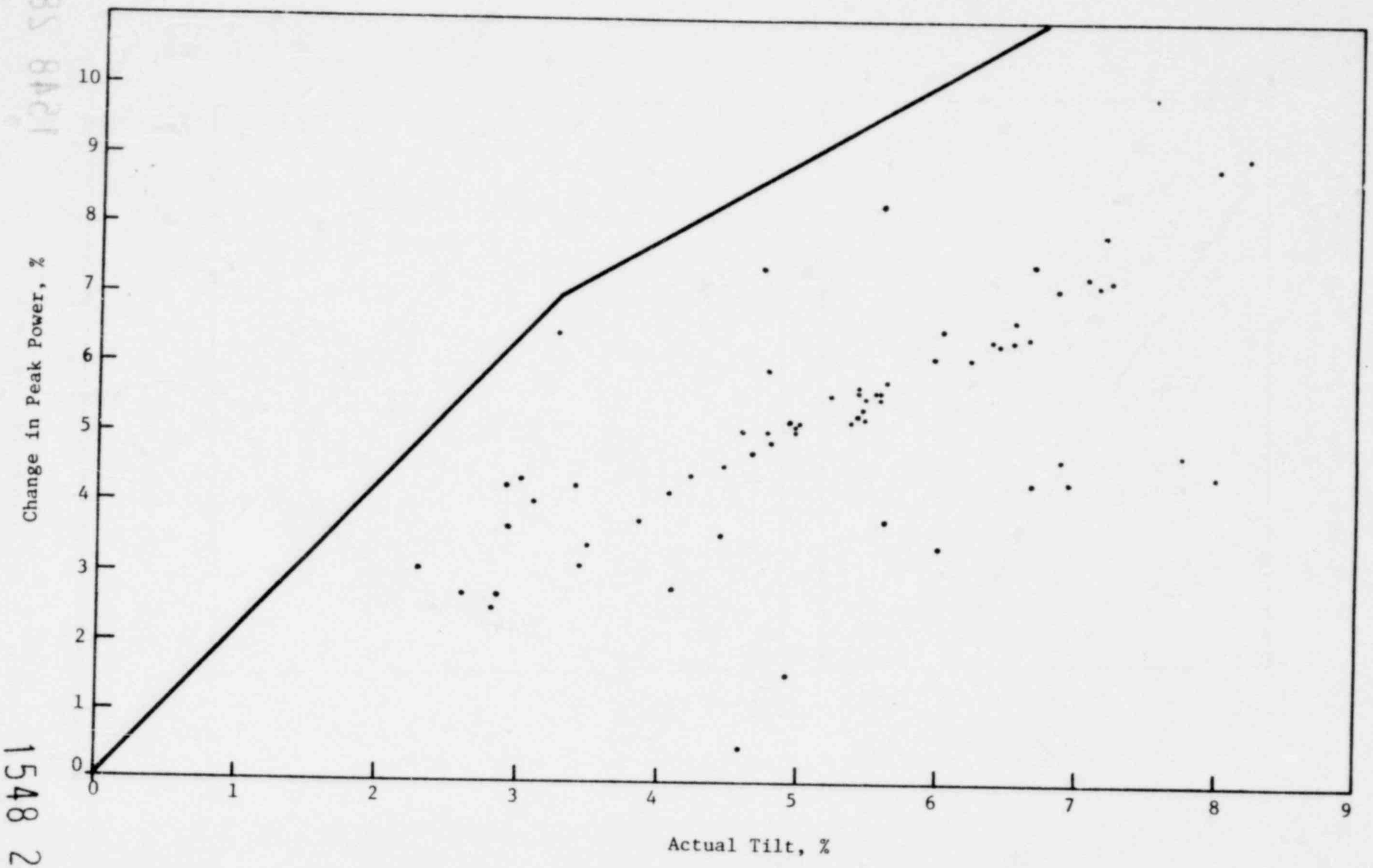

Figure 4-3. Change in Peak Power Vs Radial Tilt

Figure 4-4. Linear Heat Rate Vs Rod Insertion, BOL and EOL

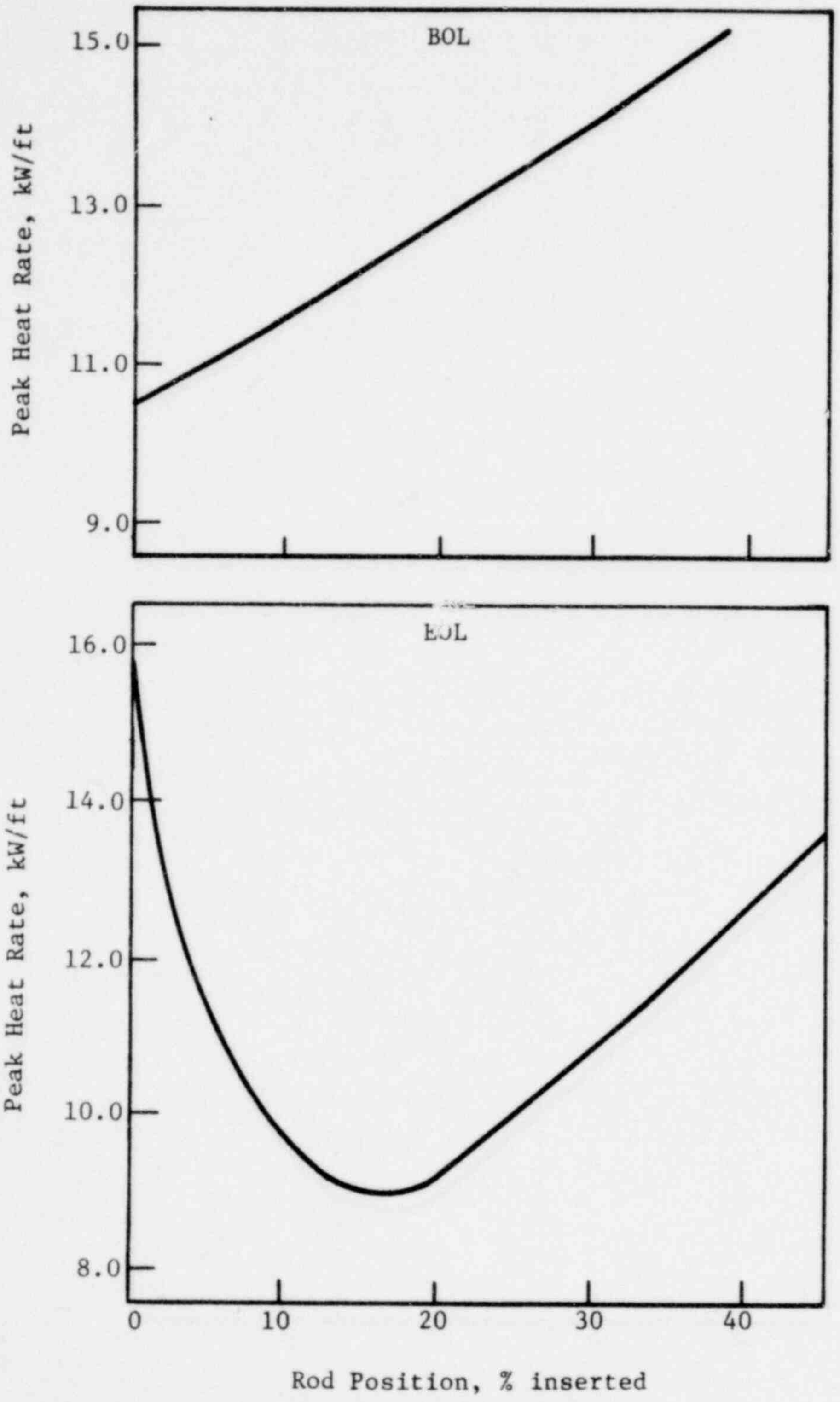

Figure 4-5. Linear Heat Rate Vs APSR Position

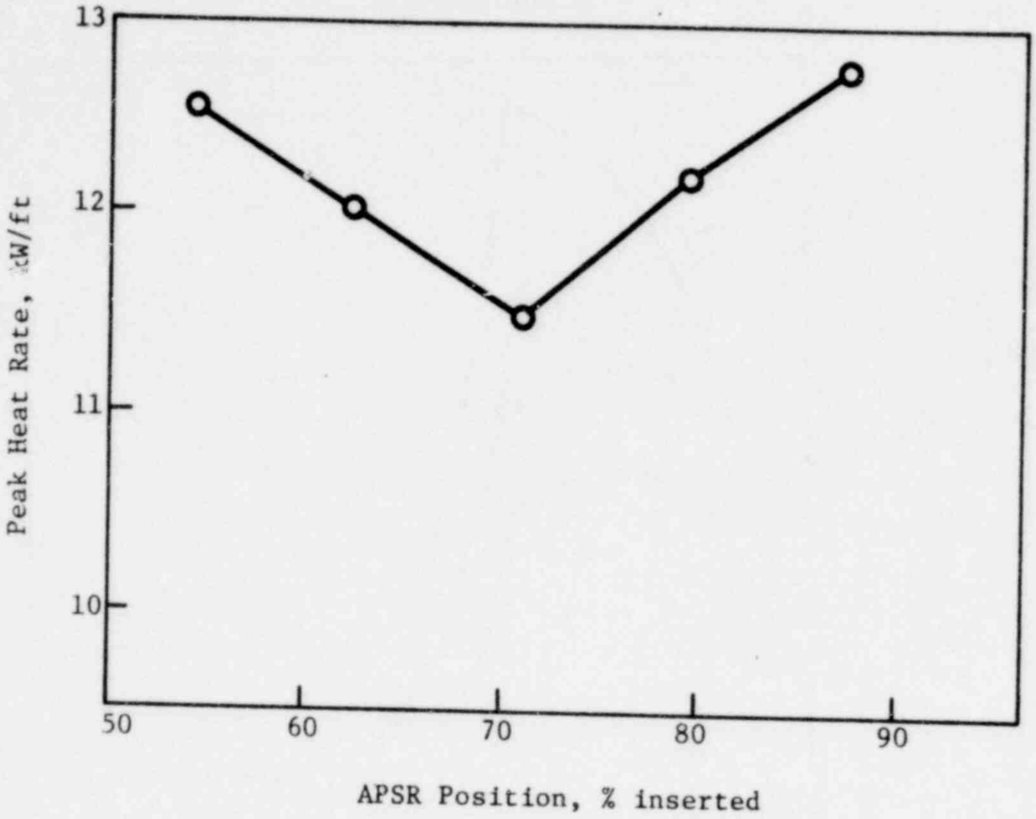

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Figure 4-6. Transient Xenon During BOL Design Power Maneuver, BOL

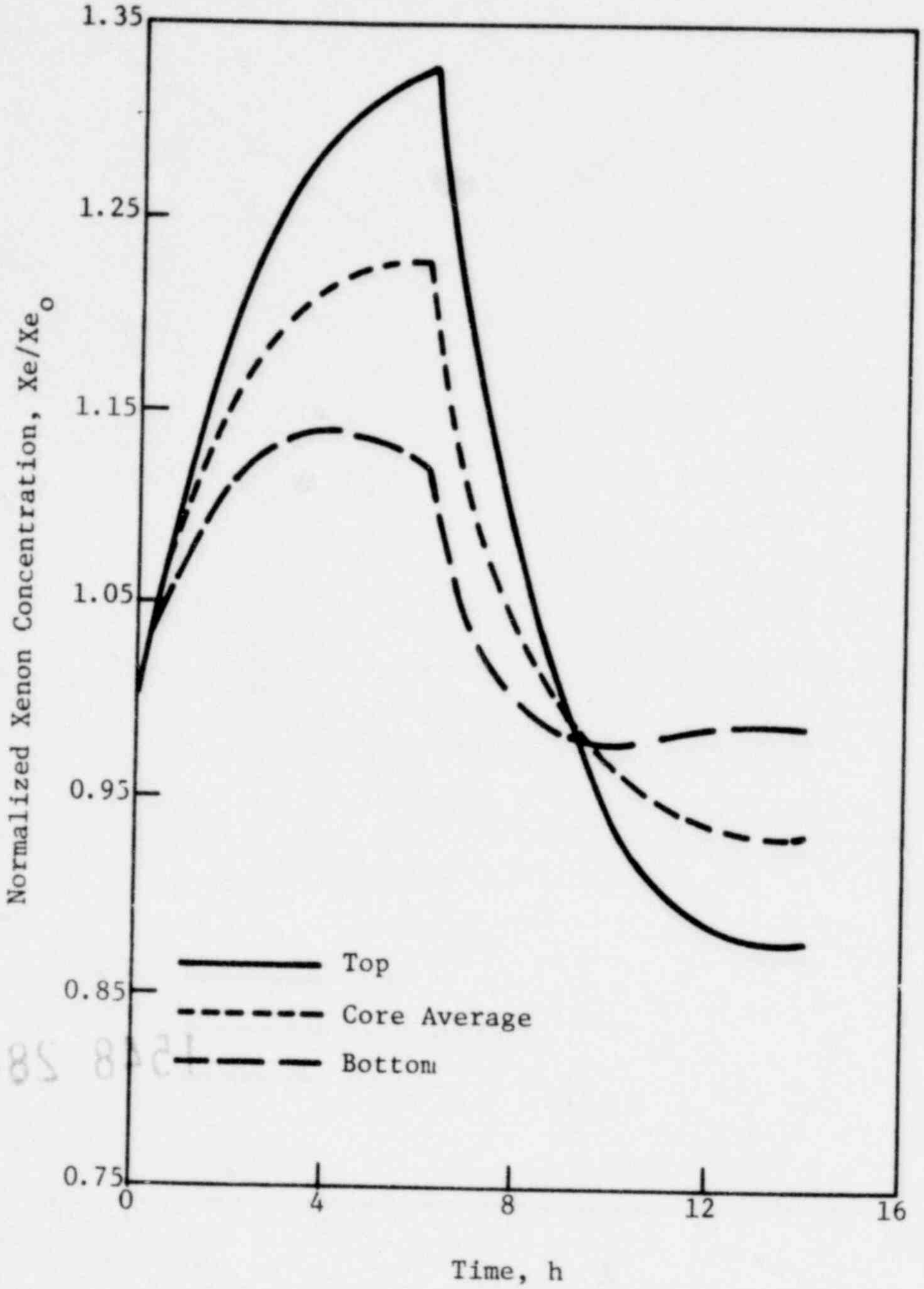

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Figure 4-7. Peak Linear Heat Rate Vs Time for BOL Design Power Maneuver, 100-60-100%

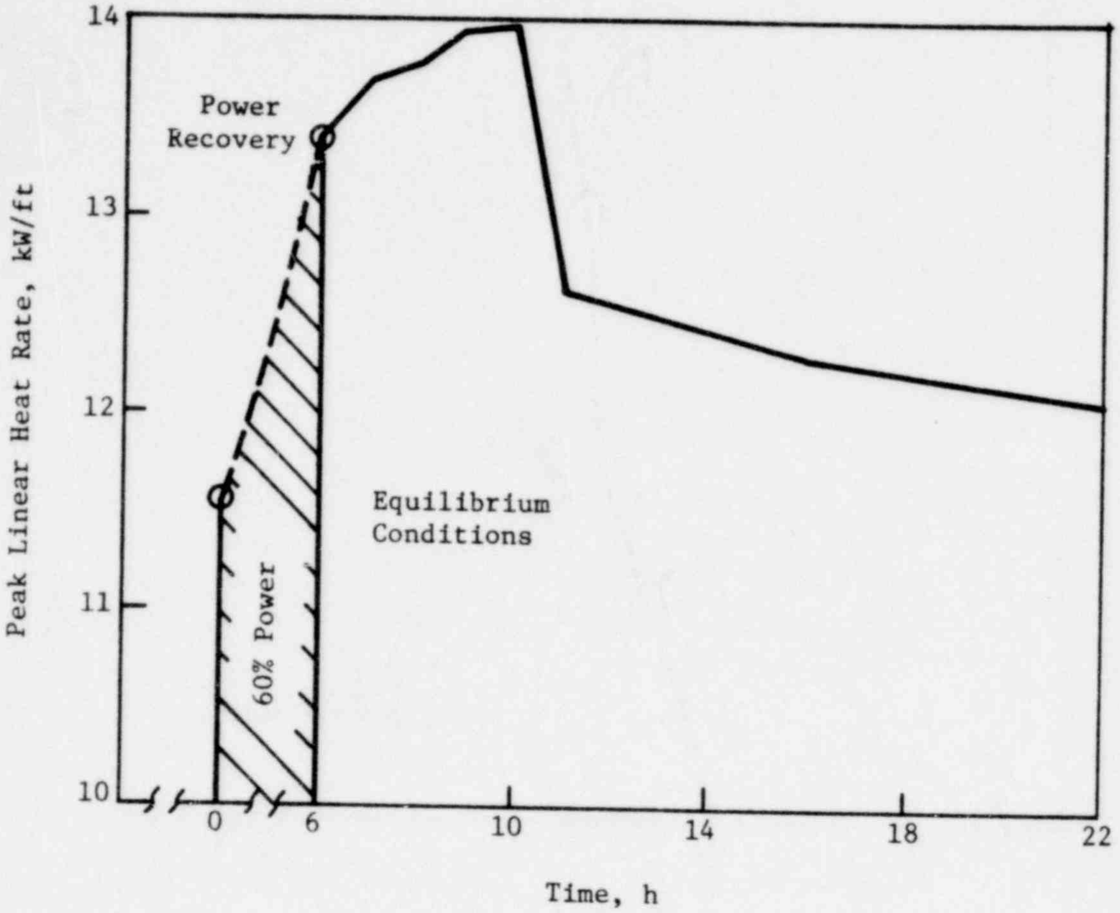


Figure 4-8. Peak Linear Heat Rate at 3800 MWt Vs Cycle 1 Lifetime for Equilibrium Conditions

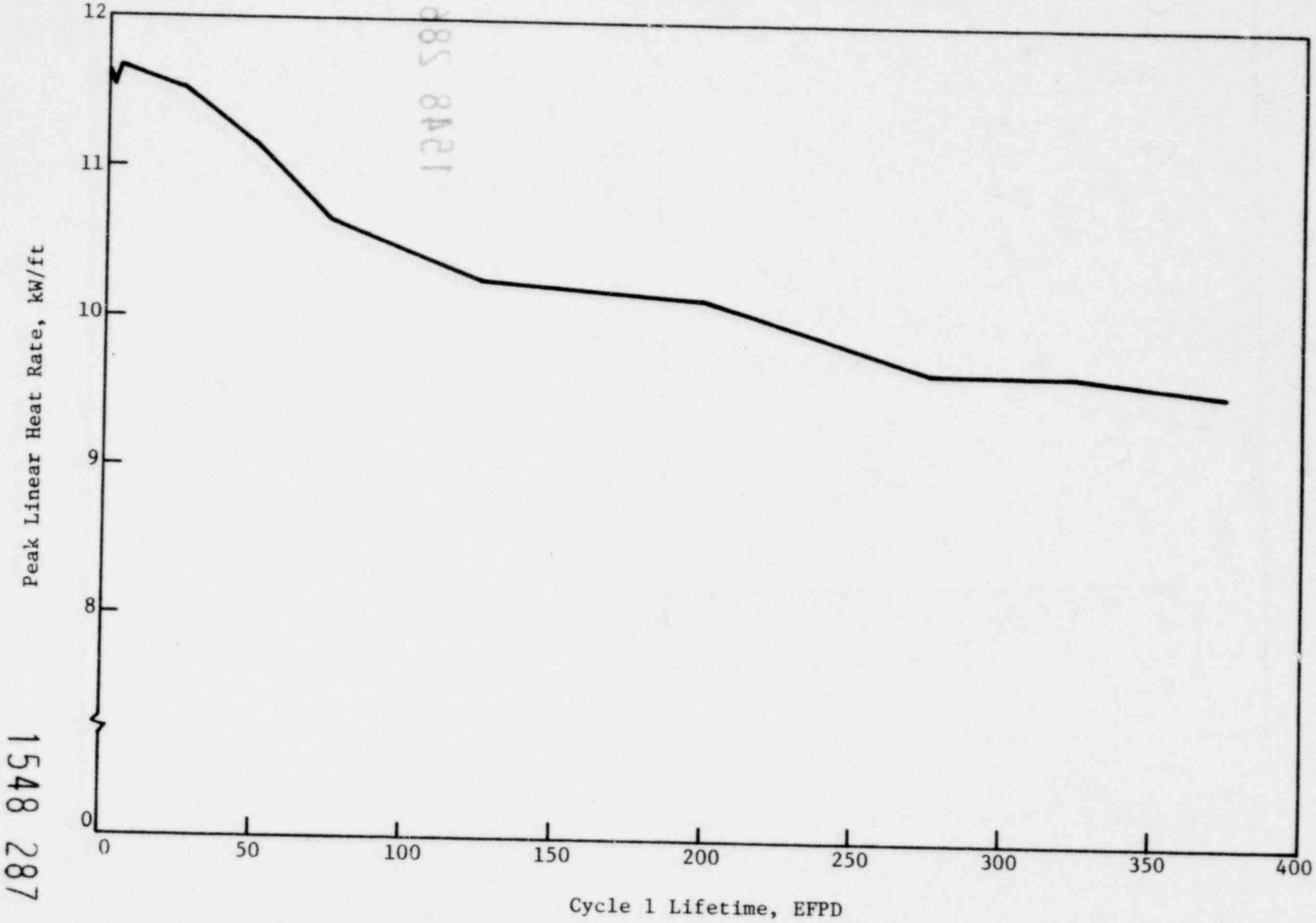


Figure 4-9. Babcock-205 LOCA Margins, 102% Full Power

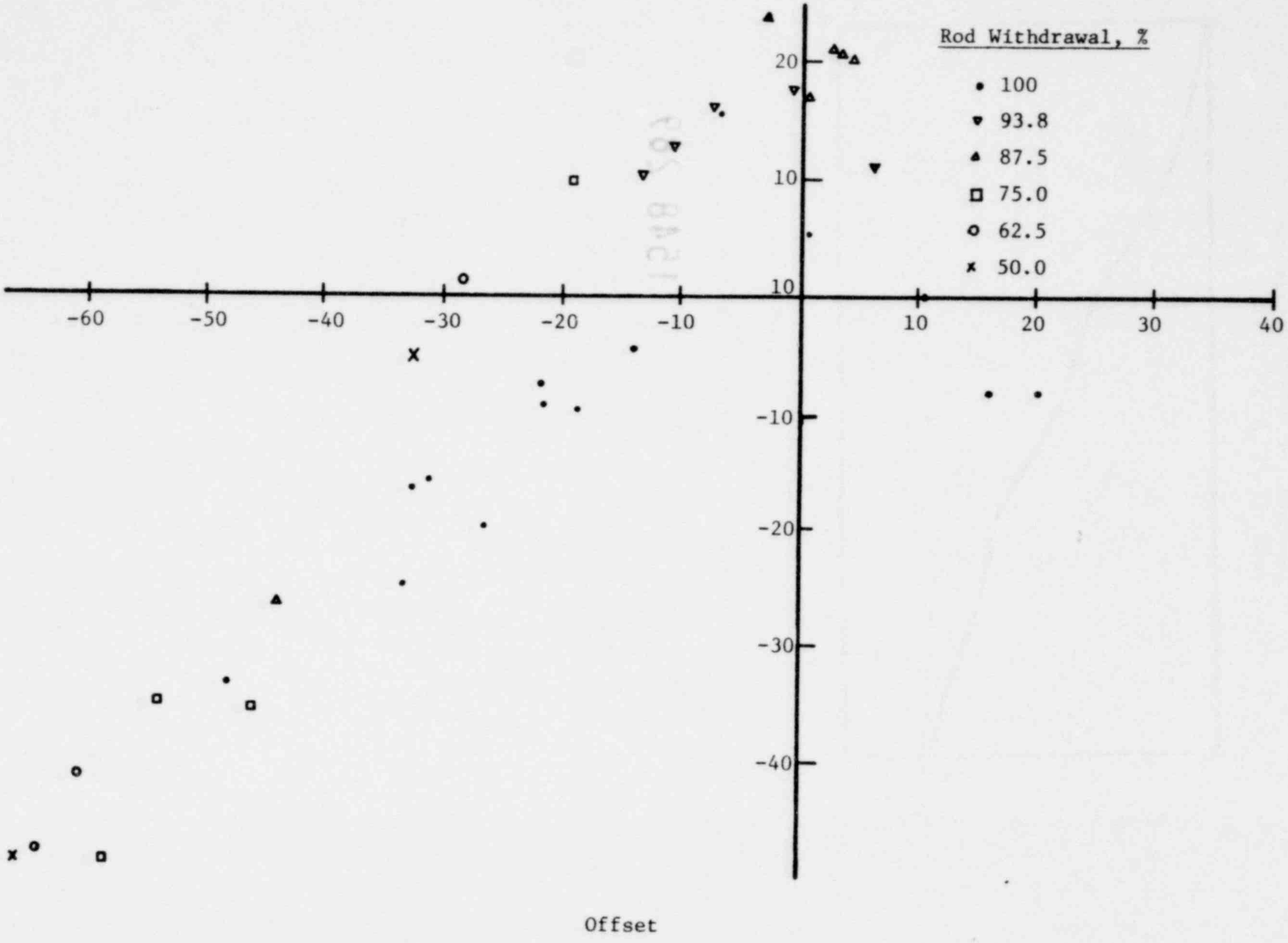
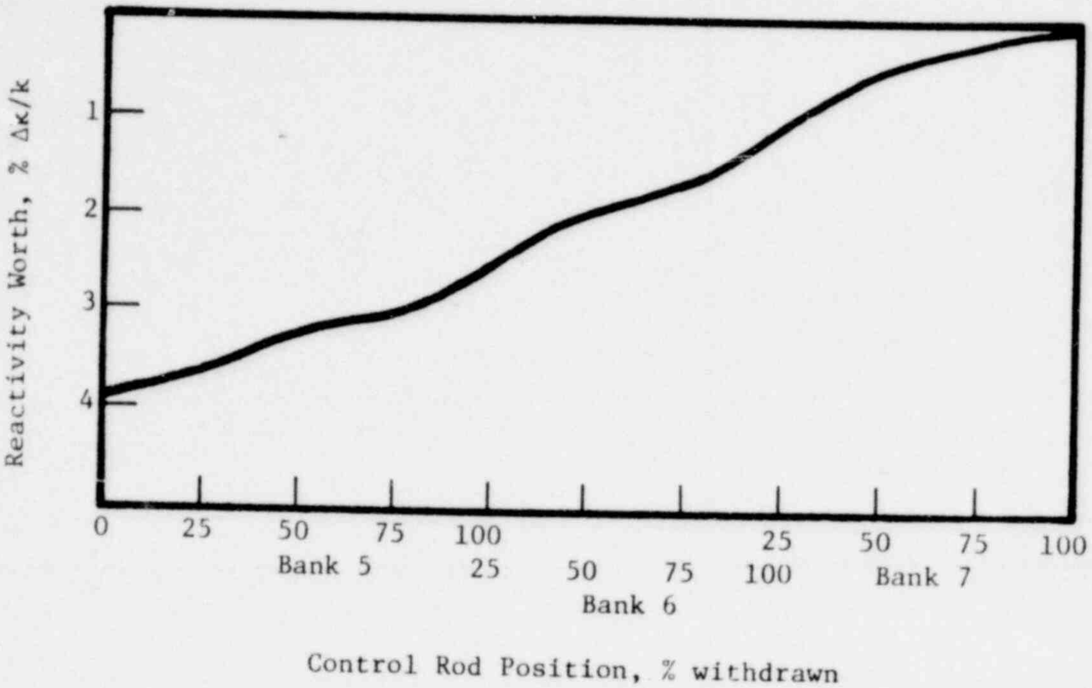


Figure 4-10. Reactivity Worth of Control Rods Vs Withdrawal Position for 0 EFPD Conditions: 541.5F, 2250 psia, APSRs at 37.5% wd



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5. UNCERTAINTIES APPLIED

The uncertainties applied in deriving the operating limits on offset, rod position, and quadrant tilt are twofold: calculational uncertainties and measurement system uncertainties. The effects of the calculational uncertainties on power peaking and rod worth are discussed in Section 4. This section describes the measurement systems and their associated uncertainties.

5.1. System Descriptions

5.1.1. Incore Monitoring System

The incore monitoring system (IMS) is described in detail in BAW-10123.[15] Thus, only a brief description is given here for completeness. The IMS provides neutron flux detectors to monitor core performance. Incore, self-powered neutron detectors (SPNDs) measure the neutron flux in the core to provide a history of power distribution during operation. This information is used to monitor core offset and quadrant power tilt. The data obtained also provide power distribution and fuel burnup information for assistance in fuel management. The plant computer gives normal system readout, and a backup readout system is provided for selected detectors.

The IMS comprises assemblies of SPNDs located at 62 positions within the core. The incore detector locations for the Babcock-205 are shown in Figure 5-1. In this arrangement, an incore detector assembly consisting of seven local flux detectors and one background detector is installed in the instrumentation tube of each of 62 fuel assemblies. The local detectors are positioned at seven different axial elevations to provide the axial flux gradient. The background detector provides a signal that can be related to those produced in the detector leadwires. The full incore system is used to monitor offset, and a subset of the full system, the symmetric detectors, is used to monitor quadrant tilt.

5.1.2. Rod Position Indicators

Two methods of rod position indication are provided in the control rod drive control system; absolute and relative position transducers. The absolute

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position transducer consists of a series of magnetically operated reed switches mounted in a tube parallel to the CRDM motor tube extension. Switch contacts close when a permanent magnet mounted on the upper end of the CRA leadscrew extension comes near. As the leadscrew (and the control rod assembly) moves, the switches operate sequentially, producing an analog voltage proportional to position. Other reed switches included in the same tube with the position indicator matrix provide full-in and full-out limit indications. The relative position transducer is a solid-state device that produces a signal proportional to rod position based on the electrical pulse steps that drive the CRDM.

Control rod position-indicating readout devices located in the control room consist of single-CRA-position meters on a wall-mounted position-indication panel and four group-average-position meters on the console. A selector switch permits either relative or absolute position information to be displayed on all of the single-rod meters.

Indicator lights are provided on the single CRA meter panel to indicate when each CRA is fully withdrawn, full inserted, enabled or transferred, and whether a CRA position asymmetry alarm condition is present. Indicators on the operator's console show full insertion, full withdrawal, and enabled for motion for each of the rod groups.

5.2. Calibration Requirements

5.2.1. IMS Calibration

The nature of the self-powered neutron detectors (SPNDs) permits the manufacture of nearly identical detectors, which produces a high relative accuracy between individual units. The detector signals are compensated continuously by the plant computer for burnup of the neutron-sensitive material.

Manual calibration of the SPNDs is not required. The incore SPNDs are controlled to precise levels of initial sensitivity by quality control during manufacturing. The signal magnitude of the detector changes over its lifetime because of detector burnup, control rod positions, fuel burnup, etc. The results of experimental programs to determine the magnitude of these factors have been incorporated into calculations and are used to compensate the outputs of the incore detector for these factors.

The system design permits frequent (once every 6 minutes) computer calculation of the core power distribution. Detector sensitivity as a function of depletion is used to correct detector signals for burnup. The heat balance calculated by the plant computer can be used to normalize the reactor power data derived from the incore detectors. Operation of SPNDs in both power and test reactors has demonstrated that this means of detector compensation provides an accurate readout.

5.2.2. Rod Position Indicator Calibration

No specific calibration requirements are necessary for RPIs. Failures that could result in improper system operation are continuously monitored by fault detection circuits. When failures are detected, indicator lights and alarms on the CRDCS panel alert the operator. Fault indicator lights remain on until the fault condition is cleared by the operator. The indicated faults are as follows:

1. Asymmetric rod patterns (indicator, alarm).
2. Sequence faults (indicator, alarm).
3. Group 6 and 7 misalignment fault (indicator, alarm).
4. Programmer lamp faults (indicators only).

5.3. Uncertainty Models

The conversion of the calculated limits on offset and quadrant tilt to operational setpoints is based on an analysis of the measurement uncertainties. The following items are considered:

1. Observability Error Allowance — This is the error introduced in determining a continuous function with a finite number of samples, i.e., the observed difference in offset or tilt between that calculated by the full set or the symmetric detectors and that calculated by upper and lower half core or quadrant power edits. This error value is developed through PDQ/FLAME simulation since it cannot be determined experimentally. Perfect detectors are assumed.
2. Uncertainty Error Allowance — This is the possible error associated with the uncertainties in the detector signals themselves, in the instrumentation, in the background correction, in the rhodium depletion correction, etc. These errors are statistically combined and used at a high confidence level.

These individual errors are combined and, when applied to the offset and tilt limits, define the error-adjusted limits.

Control rod insertion limits are also error-adjusted. Appropriate margins are allowed for uncertainty in power level and rod position when determining the error-adjusted limits.

5.3.1. Offset Measurement Uncertainty

The offset observability error for the incore detectors of the Babcock-205 was determined from the data plotted in Figure 5-2. Conservatively bounding the plotted points gives rise to the expression

$$E = 0.092|\theta S| + 0.726$$

where

E = |actual offset - offset measured by full incore detector system| = absolute value of observability error in % offset.

$|\theta S|$ = absolute value of actual offset.

The uncertainty error for the measured offset is determined using Monte Carlo statistical methods. The magnitude of the error is a function of the power level and slope of the offset versus power. A typical* value at full power is about 1% at the 95% confidence level.

5.3.2. Quadrant Tilt Measurement Uncertainty

The tilt observability error for the symmetric detectors can be determined from the data plotted in Figure 5-3. The bounding line has the equation:

$$T_A - T_M = 0.345\ T_A$$

where

T_A = actual calculated quadrant tilt, %,

T_M = quadrant tilt measured by symmetric incore detectors, %.

The uncertainty error for the measured quadrant tilt is also determined using Monte Carlo statistical techniques. The magnitude of the tilt error is a function of the symmetric detector depletion. A typical value is about 1% at the 95% confidence level.

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[*] Typical values quoted are for operating B&W cores. The actual values for the Babcock-205 core are being developed.

5.3.3. Control Rod Position Measurement Uncertainty

The measured power uncertainty is used in error-adjusting the control rod and APSR position limits and is ±2% FP, the heat balance uncertainty. The actual control rod position uncertainty for a regulating bank average position has been conservatively determined to be ±1.5% withdrawn, which is $\geq 3\sigma$, depending on the number of control rods in the bank.

Figure 5-1. Standard Incore Detector Arrangement for 205-FA Plant

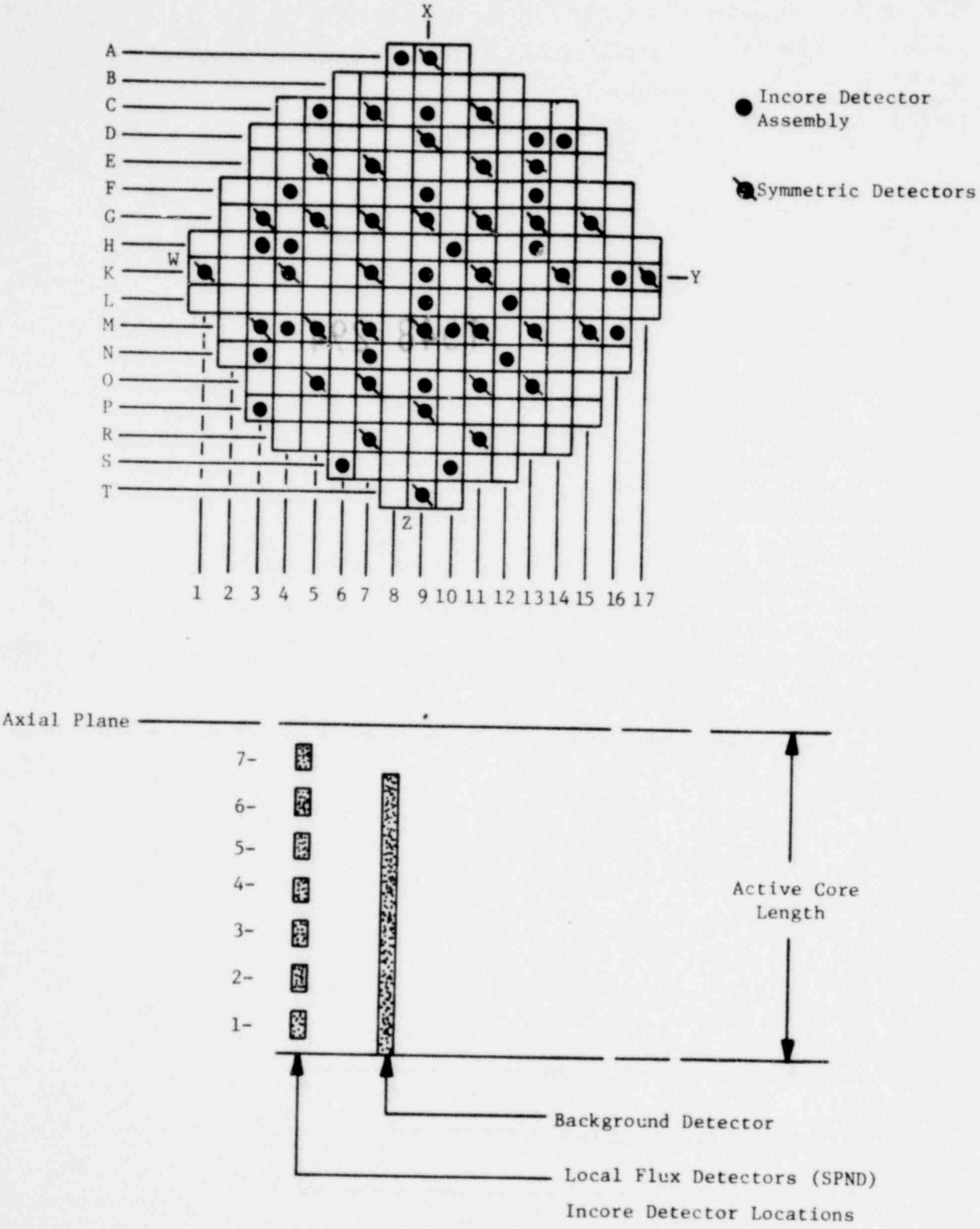

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Figure 5-2. Measured Offset (Full Incore Detector System) Vs Actual Offset

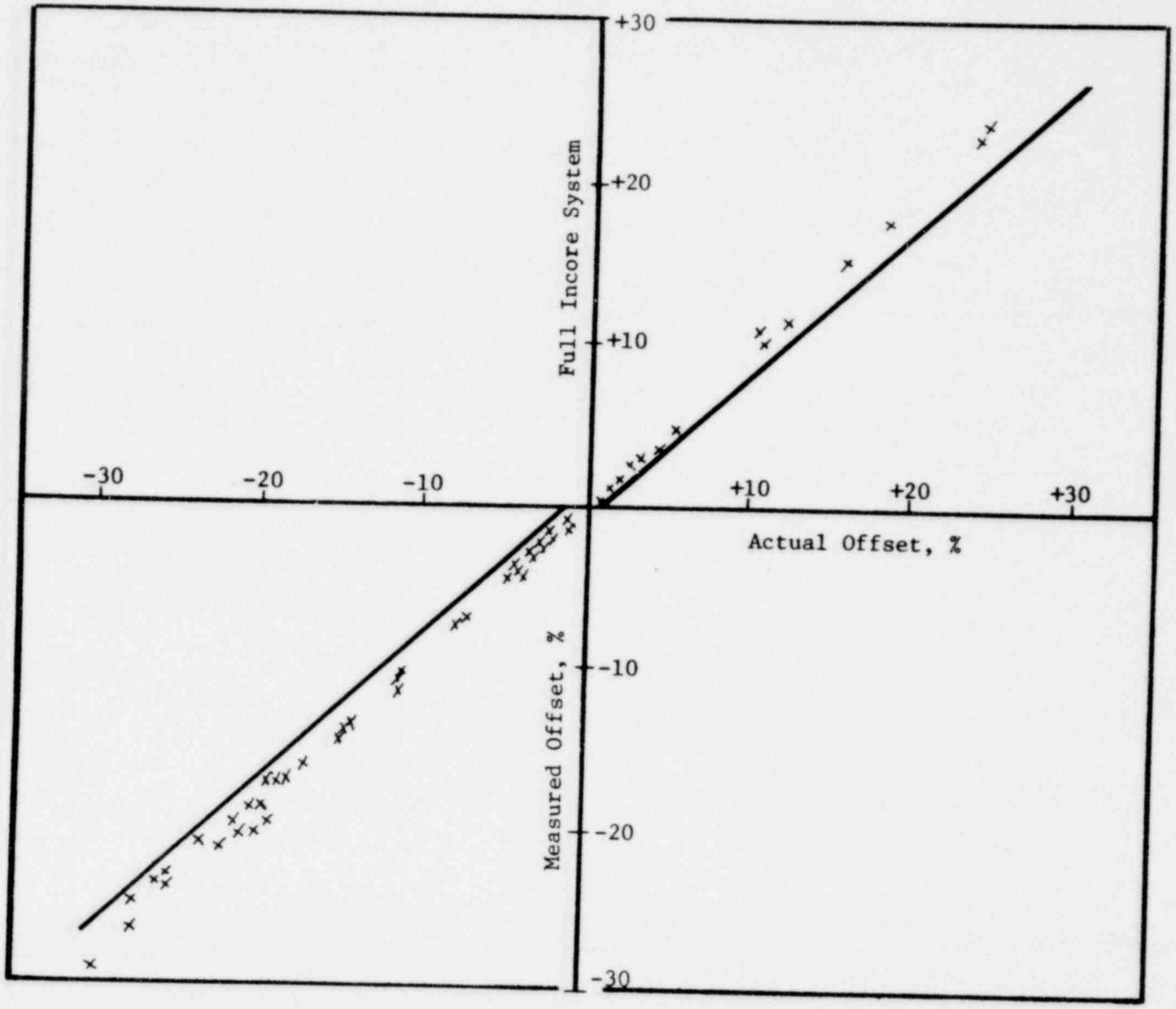

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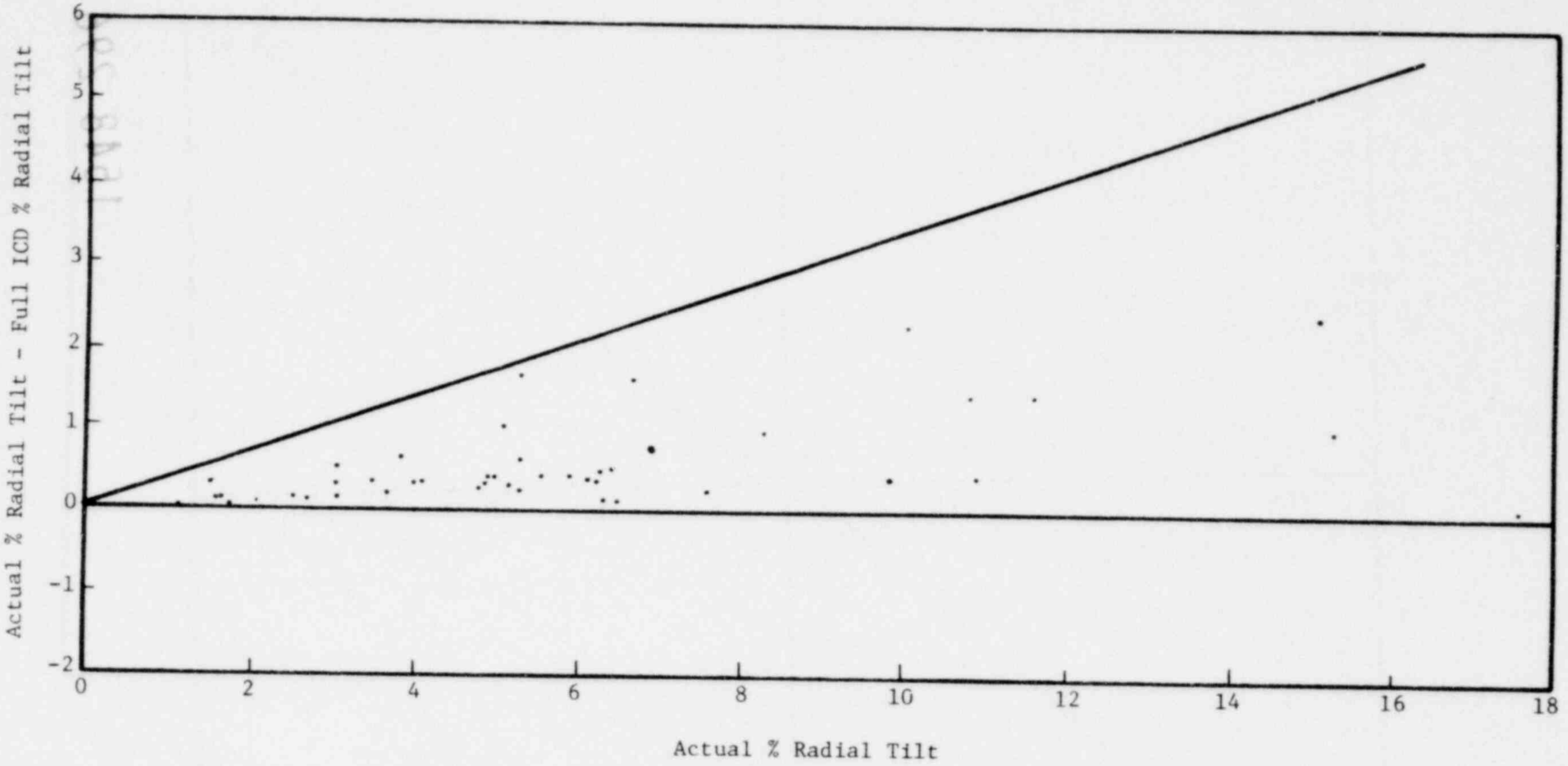
Figure 5-3. Full Incore Detector Measurement Error Vs Actual Tilt



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6. CONVERSION OF CONTROL LIMITS TO ALARMS

The operator will be provided with alarms when limits are exceeded for (1) quadrant tilt versus power level, (2) offset versus power level, (3) rod withdrawal index versus power level, and (4) APSR withdrawal versus power level, and (4) APSR withdrawal versus power level. If a Technical Specification limit is exceeded, the plant computer system will signal the operator in the following manner:

1. Audible alarm
2. Visual alarm
3. Alarm message
4. Annunciator contact

The audible alarm (either normal or high intensity) will remain until acknowledged by the operator. The visual alarm will change from a flashing to a steady indication when acknowledged by the operator. The visual alarm will clear when the detected condition clears. The alarm message will detail the Technical Specification limit exceeded. The alarm message will be displayed once for the detected condition. The annunciator contact for use by others will open when an alarm condition exists. The contact will close when the alarm condition clears.

The alarm setpoints actually used by the computer will be values which are the Technical Specification limits suitably adjusted to account for statistical and other errors as described in section 5. In the following texts "Technical Specification limits" should be understood to mean "error-adjusted Technical Specification limits."

6.1. Description of Alarm Functions

6.1.1. Quadrant Tilt Vs Core Power Level

The quadrant tilt exceeding the Technical Specification limit alarm is provided by using incore detector signals. This method is outlined below:

6.1.1.1. Quadrant Tilt Vs Core Power Level

Quadrant tilt is defined by the following equation and is expressed in percentage

$$\text{TILT} = 100\left(\frac{\text{power in any core quadrant}}{\text{avg power all quadrants}} - 1\right). \qquad (6\text{-}1)$$

The tilt value for each quadrant is calculated for use by the alarms package in the nuclear application software program TILTS.

The nuclear application software is programmed to determine the tilt in each core quadrant using the symmetric detectors as shown in Figure 5-1. Tilt is calculated by the following equation:

$$\text{TILT(N)} = \frac{\sum\limits_{K1=1}^{6} \text{RI(K1)} + 0.5 \sum\limits_{K2=1}^{6} \text{RI(K2)}}{\sum\limits_{K=1}^{36} \text{RI(K)}/4.0} - 1 \qquad (6\text{-}2)$$

where

TILT(N) = tilt in quadrant N determined by instrumented symmetric assemblies,

RI(K1) = normalized symmetric assembly powers for assemblies fully in quadrant N, MW,

RI(K2) = normalized symmetric assembly powers for assemblies half in quadrant N, MW,

RI(K) = normalized symmetric assembly powers, MW,

K1 = indicator of symmetric assemblies fully in quadrant N,

K2 = indicator of symmetric assemblies half in quadrant N.

Note: The center assembly is not used in calculating the tilt from symmetric assemblies.

6.1.1.2. Quadrant Tilt Comparison to Limits

The plant computer system will be programmed to compare QT(1), QT(2), QT(3), and QT(4) to the steady-state quadrant tilt limit and the transient quadrant tilt limit according to the following logic.

If the maximum positive value of QT(J) is less than the steady-state quadrant tilt limit, no computer alarm will be generated.

If the maximum positive value of QT(J) is greater than or equal to the steady-state quadrant tilt limit, but less than the transient quadrant tilt limit, a normal intensity computer alarm and message stating, "the steady-state tilt limit has been violated" will be generated.

If the maximum positive value of QT(J) is greater than or equal to the transient quadrant tilt limit, a high-intensity computer alarm and message stating "the transient tilt limit has been violated" will be generated.

Provision is made for the maximum positive steady-state and transient quadrant tilt limits to be a function of power level. A maximum of 10 (X,Y) coordinates are allowed for both the steady-state and the transient tilt alarm envelopes.

6.1.2. Offset Vs Core Power Level

The alarm for offset versus core power level exceeding Technical Specification limit is provided by using incore detector signals. This method is outlined below:

6.1.2.1. Offset Vs Core Power Level

Offset is defined by the following equation and is expressed in percentage.

$$\text{OFFST} = \%\ \text{measured POWUP} - \%\ \text{measured POWLW}. \qquad (6\text{-}3)$$

The offset value, OFFST, is calculated for use by the alarms package in the nuclear application software program OFST. The plant computer system determines the power in the upper and lower halves of the core (POWUP, POWLW). The total power in the lower half of the core is calculated next by integrating the power shape from the bottom of the active fuel to the fuel midplane for each assembly and maintaining the sum. The power in the upper half of the core is then calculated as the total core power minus the power in the lower half of the core.

$$\text{POWLW} = \sum_{I=1}^{205} \int_{0}^{0.5} \text{SFDLP}(I,L)\,d\ell \qquad (6\text{-}4)$$

where

POWLW = power in lower core half, MW,

SFDLP(I,L) = spline fit of detector level powers at $d\ell$,

ℓ = 0 at bottom of active fuel,

ℓ = 1 at top of active fuel;

and the power in the upper core half is

$$\mathrm{POWUP} = \mathrm{CORPW} - \mathrm{POWLH} \tag{6-5}$$

where POWUP equals power in upper core half.

$$\mathrm{OFFST} = \frac{\mathrm{POWUP} - \mathrm{POWLW}}{\mathrm{CORPW}} (100) \tag{6-6}$$

where

OFFST = core offset, %,

CORPW = total measured core thermal power, MW.

The plant computer system will be programmed to determine the percent full power from the core thermal power by the following equation:

$$\mathrm{PFP} = \frac{\mathrm{CORPW}}{\mathrm{RP}} (100) \tag{6-7}$$

where

PFP = percent full power, %,

RP = rated full power, MW.

6.1.2.2. Offset Comparison to Limits

Measured OFST and PFP will be compared to an envelope. An example of this envelope is described by Figure 7-1. All envelopes allow the entering of up to 10 (X,Y) coordinates.

If the point described by (OFST,PFP) is in the acceptable zone, no computer alarm will be initiated. If this point is at or in the exceeding-Technical Specification-limit zone, a normal-intensity computer alarm and a message stating that "the OFFSET limits have been exceeded" will be initiated.

6.1.3. Rod Withdrawal Index Vs Core Power Level

The rod withdrawal index versus the alarm for core power level exceeding Technical Specification will be provided by the plant computer system by the method described below.

6.1.3.1. Rod Withdrawal Index Vs Core Power Level — Rod Withdrawals

The plant computer system monitors the percent withdrawn of each control rod drive mechanism [RODW(N)]. Also, the assignments of regulating CRDMs into groups is stored within the computer system [RODGP(N)]. From these data, the plant computer system will be programmed to determine the average percent withdrawn for groups 5, 6, and 7 and to compute the rod withdrawal index at the alarm package processing frequency according to the following equations:

$$\mathrm{APWG(K)} = \frac{\Sigma\ \mathrm{RODW(N)\ for\ group\ K}}{\mathrm{No.\ of\ rods\ in\ group\ K}} \tag{6-8}$$

where

K = 5, 6, 7, rod groups 5, 6, 7,

APWG(K) = avg withdrawal for group K, %.

Then

$$\mathrm{RWIND} = \mathrm{APWG(5)} + \mathrm{APWG(6)} + \mathrm{APWG(7)} \tag{6-9}$$

where RWIND = rod withdrawal index, 0-300%.

6.1.3.2. Rod Withdrawal Comparison to Limits

RWIND and PFP will be compared to an envelope such as Figure 7-2 for four-, three-, and two-pump operation. After the comparison, the following logic will be performed: If the point described by (RWIND, PFP) is in the acceptable zone, no computer alarm will be initiated.

If the point described by (RWIND, PFP) is at or is in the exceeding-Technical-Specification-limit zone, a normal-intensity computer alarm and a message stating "the rod index limit has been exceeded" will be initiated.

This limit envelope allows the entering of up to 10 (X,Y) coordinates. This same envelope also applies to two- and three-pump operation.

6.1.4. APSR Bank Withdrawal Vs Core Power Level

The alarm for APSR withdrawal versus core power level exceeding Technical Specification will be provided by the plant computer system:

6.1.4.1. APSR Withdrawal Vs Core Power Level — Rod Withdrawal

The plant computer system monitors the percentage withdrawal of each CRDM [RODW(N)]. The assignment of APSRs is stored in the computer as RODGP(N)=8. From these data, the plant computer will be programmed to determine the average percentage withdrawal of rod group 8 at the alarm package processing frequency according to the following equation:

$$\mathrm{APWG}(8) = \frac{\Sigma\ \mathrm{RODW}(N)\ \text{for group 8}}{\text{No. of rods in group 8}} \qquad (6\text{-}10)$$

where APWG(8) = average withdrawal for group 8, %.

6.1.4.2. APSR Withdrawal Comparison to Limits

APWG(8) and PFP will be compared to an envelope such as Figure 7-3 for four-, three-, and two-pump operation. After the comparison, the following logic will be performed: If the point described by [APWG(8), PFP] is in the acceptable zone, no computer alarm will be initiated. If the point described by [APWG(8), PFP] is at or is exceeding the Technical Specification limit zone, a normal-intesnsity computer alarm and a message stating "the APSR limit has been exceeded" will be generated. This limit envelope allows entering up to 10 (X,Y) coordinates.

6.2. Description of Computer Processing

6.2.1. Application of Figures and Tables

All figures are given as examples only. Updating of X and Y coordinates for the envelopes is required at least once and possibly several times during each fuel cycle.

6.2.2. Processing Frequency

The plant computer system will calculate the alarm functions at a processing frequency equal to or less than every 10 minutes.

6.3. Logging

If no warnings or alarms have been initiated in any 2-hour period, the plant computer alarm CRT will display a status message indicating that the alarm calculations have been performed and found acceptable. The TILT/OFFSET/INSERTION display can be shown at any time on operator demand by keying a group number at the plant computer operator's console. The alarm package will be automatically bypassed when the reactor power is less than 15% rated power.

6.4. Display

Figure 6-1 is the display format required for the macroparameter alarm package.

Figure 6-1. Alarm Display

```
GROUP XX

HH:MM:SS

MM/DD/YY

                    TILT/OFFSET/INSERTION       MM/DD/YY        HH:MM:SS

TILT

Full incore measured tilt                             XX.XX
Steady-state tilt limit at current power level        XX.XX
Transient tilt limit at current power level           XX.XX

OFFSET

Full incore measured offset                          SXX.XY
Steady-state offset limits at current power level
                                       Min = SXX.XX Max = SXX.XX

Rod withdrawal index

Measured rod index                                   XXX.XX
Rod index limit                        Min = XXX.XX Max = XXX.XX

APSR withdrawal index

Measured APSR index                                  XXX.XX
Rod index limit                        Min = XXX.XX Max = XXX.XX

CORPW XXXX.X        POWUP XXXX.X          POWLW XXXX.X
Percent full power XXX.XX
```

7. EXAMPLE

As an example of normal operating limits, the Babcock-205 cycle 1 presented in the B-SAR-205 was analyzed; the resultant limits are presented in this section.

1. Axial offset limits are shown in Figure 7-1.
2. Regulating control rods must be maintained in the rod withdrawal range specified in Figure 7-2. Also shown are the shutdown margin and ejected rod worth limits.
3. Axial power shaping rods must be maintained in the range specified in Figure 7-3.
4. Actual quadrant power tilt must be no greater than 5% when operating above 60% power.

These limits cover the entire cycle and are presented only as illustrations of the methods and techniques described in this report. In actual practice, burnup-dependent limits would be used to maximize operating flexibility. At least two and possibly three burnup intervals would probably be specified, as is routinely done for B&W operating plants.

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Figure 7-1. Offset Limits

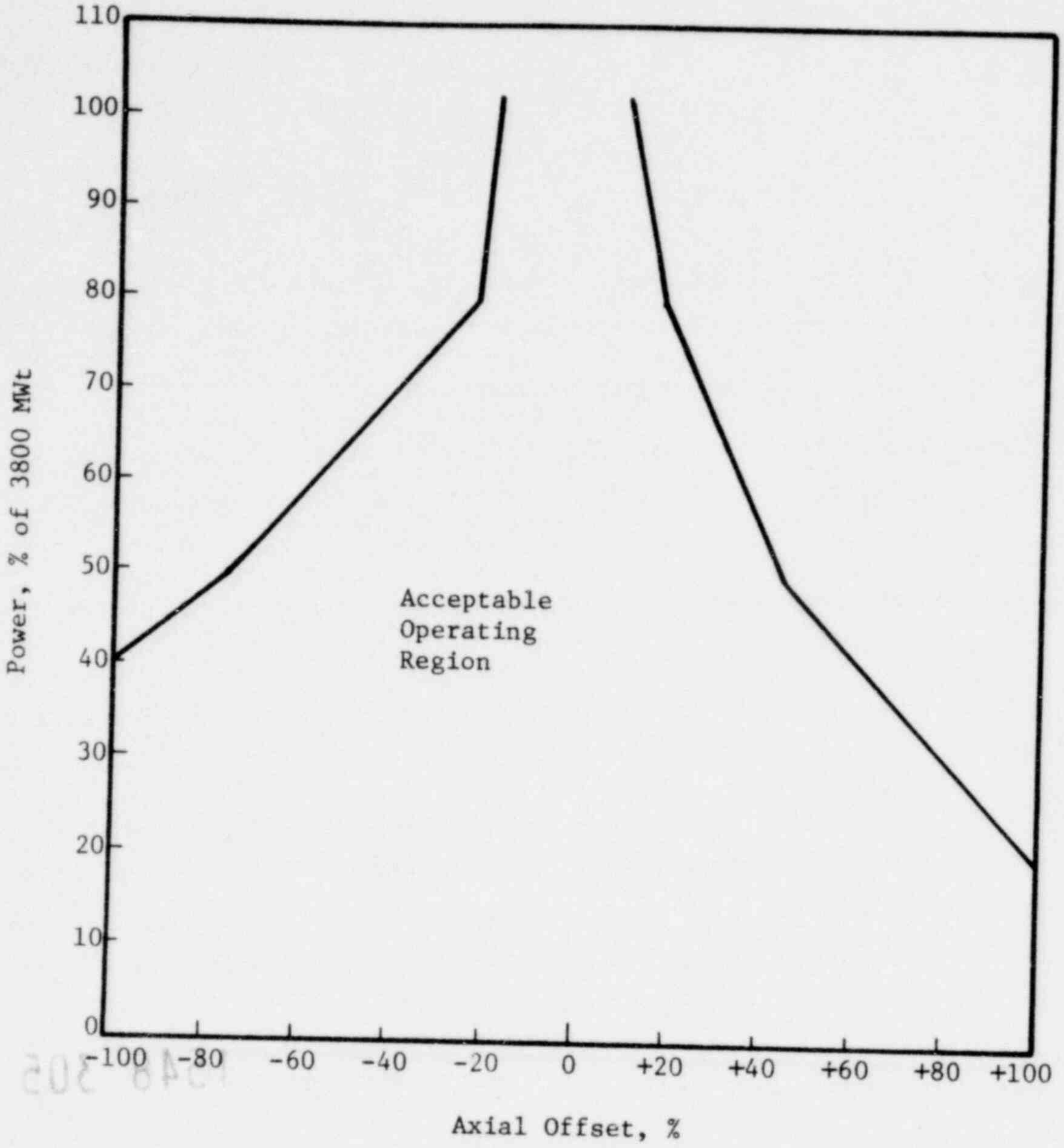


Figure 7-2. Control Rod Insertion Limits for Each Section 2 Criterion

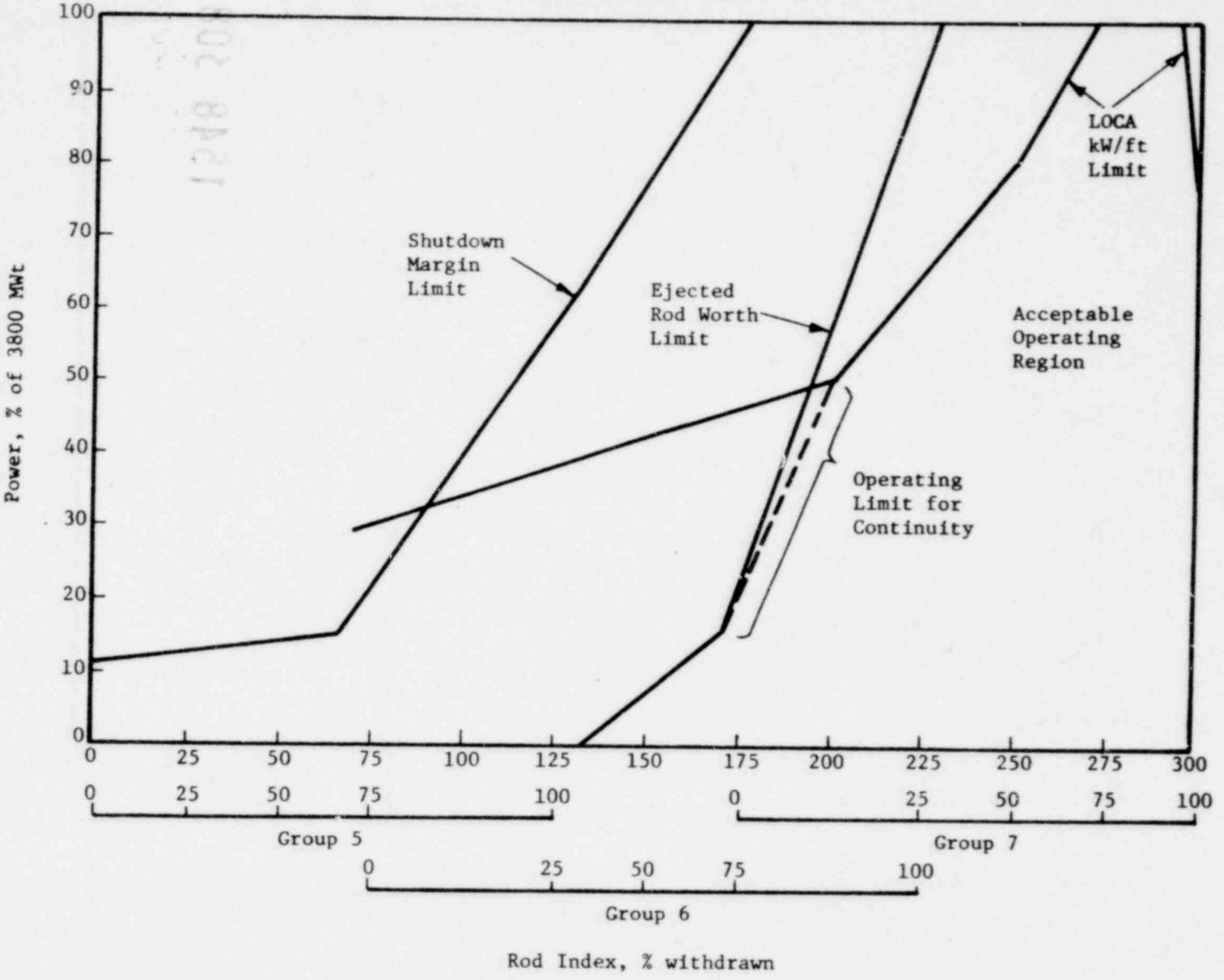
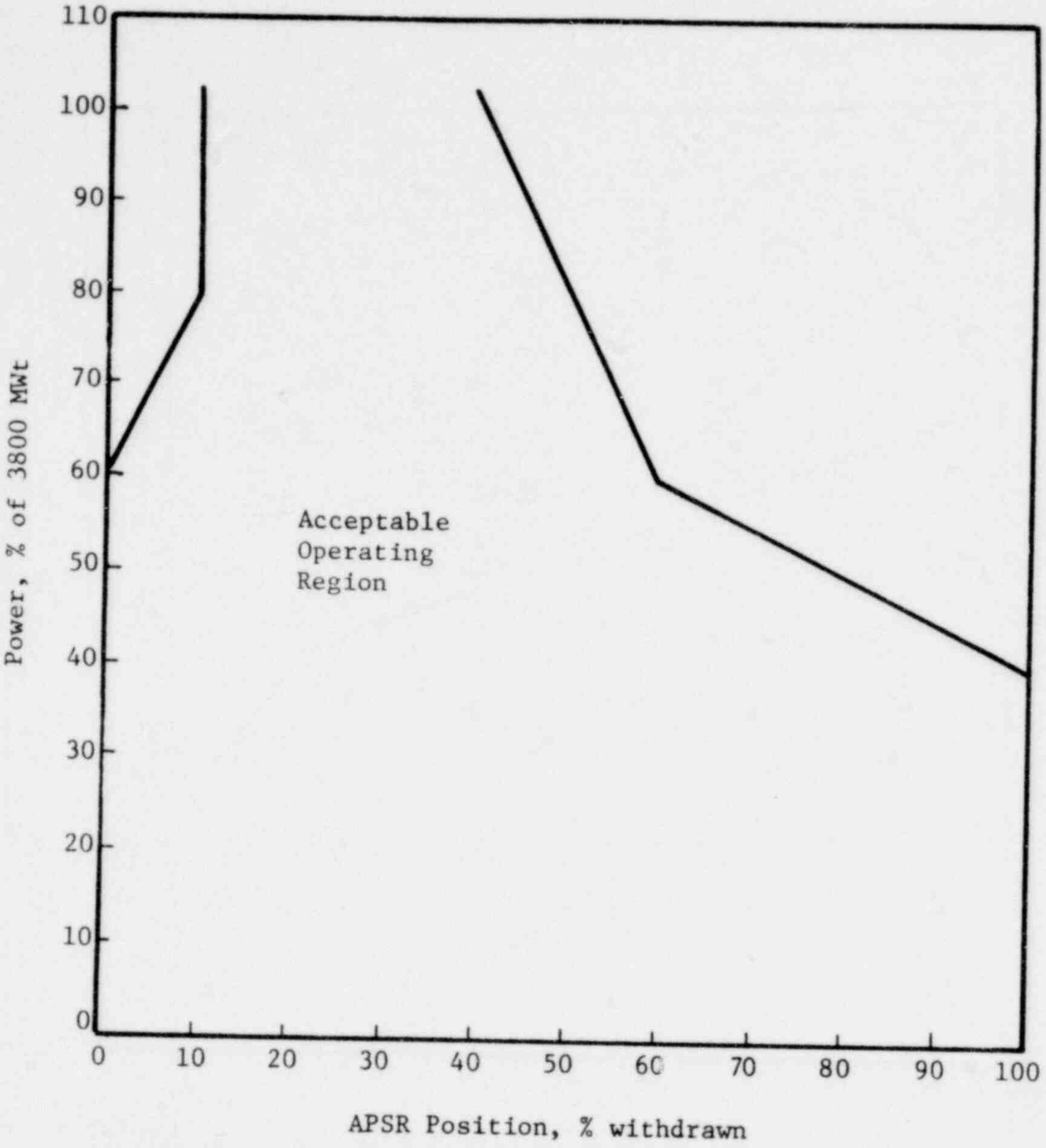


Figure 7-3. APSR Insertion Limits



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APPENDIX

Differences Between This Report and Analyses for Current B&W Operating Plants

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The methods and techniques presented in this report are generally applicable to analyses of B&W operating plants. However, there are certain differences in details which are listed in this section.

1. Criteria

The LOCA (kW/ft) limits analyses for all B&W plants are performed as outlined in section 2.1. The results for the current 177-FA operating plants are given in topical reports BAW-10103A[16] and BAW-10105[17]. Specific kW/ft limits for each plant can be found in the individual plant Technical Specifications.

2. Peaking Factors

Peaking factors used for currently operating plants are the same as those listed in section 4.1.2 for 205-FA plants except as follows:

F_2 = 1.014

F_3 = 1.074 (for allowable real tilt of 4.92%)

F_6 = 1.08 above power level cutoff for rodded cores, 1.05 above power level cutoff for feed-bleed cores

3. Control Rod Position Limits

B&W 177-FA cores operating in the rodded mode will have regulating rod position limits derived in a band about 200% withdrawn, as illustrated in Figure A-1. Once the rods are withdrawn near the end of the cycle, a new set of position limits similar to those shown in this report would be in effect.

4. Measurement System Uncertainties

4.1. Offset (Imbalance)

In currently operating cores, the axial power distribution is measured in terms of imbalance, where

Imbalance = (offset)(fraction of power).

The observability error for this parameter is given by

Error (% imbalance) = +1.8 (FOP) + 0.07 (imbalance).

The observability error was derived from data similar to those shown in Figure 5-2 but plotted as imbalance.

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The following equations have been developed to calculate the imbalance uncertainty error allowance.

For $0 \le N < 0.5$, $E = 1.222 + 11.202C - (10.678C + 0.032)P$, (A-1)

for $0.5 \le N < 1.0$, $E = 1.340 + 10.715C - (10.184C + 0.36)P$, (A-2)

for $N = 1.0$, $E = 1.750 + 10.038C - (9.384C + 1.280)P$

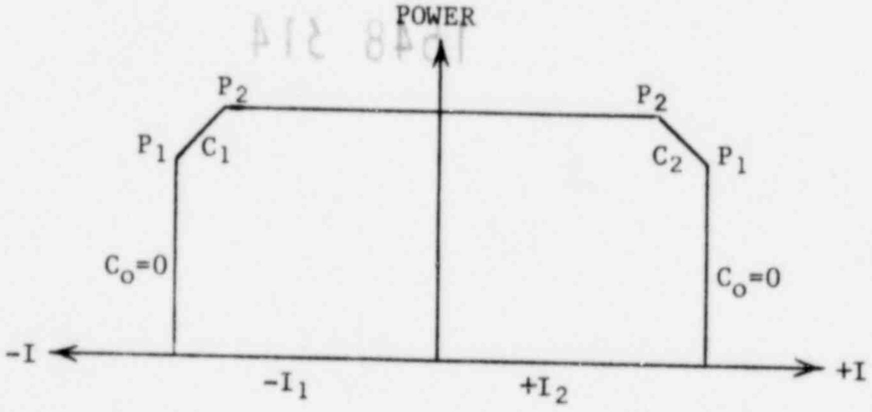
where

E = uncertainty error, % imbalance,

N = No. of Al_2O_3-insulated detector strings in a core ÷ 52,

P = power fraction, the fraction of full power at the point on the imbalance envelope being evaluated; $P = 1.0$ at 100% full power;

C = maximum absolute value of the slope of the imbalance envelope about the point being evaluated after all observability errors have been applied; this value should be determined assuming that the power axis of the envelope is the abcissa and the resultant imbalance limit is the ordinate; an example is given below:



Assume that the imbalance envelope above has had all observability errors applied. Then,

For negative imbalance at P_1: $E = E(C_1,P_1)$ since $C_1 > C_0$, (A-3)

for negative imbalance at P_2: $E = E(C_1,P_2)$. (A-4)

For positive imbalance at P_1: $E = E(C_2,P_1)$ since $C_2 > C_0$, (A-5)

for positive imbalance at P_2: $E = E(C_2,P_2)$. (A-6)

4.2. Quadrant Tilt

The observability error for the measured quadrant tilt is given by

$$\text{error (\%)} = 0.106\ T_A$$

where T_A = actual calculated quadrant tilt, %.

The following equations have been developed for Al_2O_3 detectors to calculate the tilt uncertainty error allowance. These equations are used as indicated.

1. If the plant OLC uses an average background signal proportional to the integrated assembly SPND signal,

$$E = 0.679 + 0.502q - 0.192q^2 + 2.377q^3 \tag{A-7}$$

where q = average end-of-cycle symmetric detector depletion, total coulombs generated at EOC ÷ initial total charge.

2. If the plant OLC uses individual background detector signals,

$$E = 0.860 + 0.635q - 0.243q^2 + 3.009q^3. \tag{A-8}$$

Figure A-1. Rod Position Limits for Four-Pump Operation From 0 to 100 ± 10 EFPD — Oconee 3, Cycle 3