GE Nuclear Energy

175 Curtner Avenue
San Jose, CA 95125

NEDO-32465-A
Class I
August 1996

Licensing Topical Report

# Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology for Reload Applications

**Prepared for the
Boiling Water Reactor Owners' Group
by**

**C. R. Lehmann (PP&L)
M. P. LeFrancois (Yankee Atomic)
W. R. Mertz (Southern Nuclear)
Hung Le (GE)
Jason Post (GE)**

**Approved:**
**H.C. Pfefferlen, Program Manager
BWROG Detect & Suppress Methodology Committee**

# Important Notice Regarding Contents of the Report

## Please Read Carefully

## Participation and Ownership

This document was prepared by and for the BWR Owners' Group Detect and Suppress Methodology Committee. In accordance with established BWROG procedures, use of the information in this report is limited to the participating utilities that have sponsored this activity. The participating utilities of the BWROG Detect and Suppress Methodology Committee are:

- Cleveland Electric Illuminating
- Commonwealth Edison
- Detroit Edison
- IES Utilities
- Illinois Power
- Nebraska Public Power District
- New York Power Authority
- Niagara Mohawk Power Corp.
- Northeast Utilities Service
- Northern States Power
- Pennsylvania Power & Light
- Public Service Electric & Gas
- Southern Nuclear Operating
- Tennessee Valley Authority
- Vermont Yankee Nuclear Power

## Acknowledgment

GE wishes to acknowledge the significant contributions made by Chet Lehmann (PP&L), Ted Shannon (ComEd), Tom Rausch (ComEd), Joan Wieging (ComEd), Mark LeFrancois (Yankee Atomic), and Wally Mertz (Southern Nuclear). These individuals met frequently as a subcommittee of the BWROG Detect and Suppress Methodology Committee, and were instrumental in development of this methodology. Mr. Lehmann also contributed significant authorship to this licensing topical report.

# TABLE OF CONTENTS

# TABLE OF CONTENTS
(Continued)

# TABLE OF CONTENTS
(Continued)

# LIST OF TABLES

# LIST OF FIGURES

# ABSTRACT

The Boiling Water Reactor (BWR) Owners' Group has developed several different stability long-term solutions. Several of the solutions depend upon automatic reactor instability detection and suppression to show compliance with licensing requirements. A licensing methodology is defined which may be used to determine the minimum critical power ratio (MCPR) for BWRs which employ a detect and suppress solution. The calculated MCPR may be compared to the MCPR Safety Limit to determine the acceptability of the selected detection system features and setpoints.

A simplified initial application process has been developed based on that previously described in NEDO-31960 and NEDO-31960 Supplement 1. It consists of three elements: (1) a plant-specific pre-oscillation MCPR, (2) a cycle-specific peak hot bundle oscillation magnitude before the instability is suppressed, and (3) a generic representative curve for hot bundle MCPR performance vs. oscillation magnitude. A reload review process is also specified utilizing these three elements.

# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| A | Average value of an oscillating signal |
| ABA | Amplitude Based Algorithm |
| AOO | Anticipated Operational Occurrence |
| APRM | Average Power Range Monitor |
| ATWS | Anticipated Transient Without Scram |
| BWR | Boiling Water Reactor |
| DIVOM | Delta CPR Over Initial MCPR Versus Oscillation Magnitude |
| FMCPR | Final Minimum Critical Power Ratio |
| FSAR | Final Safety Analysis Report |
| GDC | General Design Criteria |
| GLRWOB | Generator Load Rejection Without Bypass |
| GRA | Growth Rate Algorithm |
| IMCPR | Initial Minimum Critical Power Ratio |
| LTR | Licensing Topical Report |
| LTS | Long-Term Solution |
| LPRM | Local Power Range Monitor |
| LUA | Lead Use Assembly |
| M | Minimum value of an oscillating signal |
| MCPR | Minimum Critical Power Ratio |
| MCPR OL | MCPR Operating Limit |
| MCPR SL | MCPR Safety Limit |
| NRC | Nuclear Regulatory Commission |
| OPRM | Oscillation Power Range Monitor |
| P | Peak (maximum) value of an oscillating signal |
| PBDA | Period Based Detection Algorithm |
| RPS | Reactor Protection System |
| RPT | Recirculation Pump Trip |
| RWE | Rod Withdrawal Error |
| SER | Safety Evaluation Report |

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 4, 1996

R. A. Pinelli, Chairman
BWR Owners' Group
c/o GPU Nuclear
MCC Building E
One Upper Pond Road
Parsipanny, NJ 07054

SUBJECT: ACCEPTANCE FOR REFERENCING OF TOPICAL REPORT NEDO-32465, "BWR OWNERS GROUP REACTOR STABILITY DETECT AND SUPPRESS SOLUTIONS LICENSING BASIS METHODOLOGY AND RELOAD APPLICATIONS" (TAC M92882)

Dear Mr. Pinelli:

The staff has completed its review of Topical Report NEDO-32465, "BWR Owners' Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology and Reload Applications," submitted by the Boiling Water Reactor Owners' Group (BWROG) by letter dated June 28, 1995. This report describes the detect and suppress methods used in both Options III and I-D.

We find the detect and suppress methods documented in NEDO-32465 acceptable for referencing in license applications to the extent specified, and under the limitations delineated in NEDO-32465 and the associated NRC technical evaluation. The enclosed safety evaluation defines the basis for acceptance of the topical report.

We do not intend to repeat our review of the matters found acceptable as described in NEDO-32465 when the report appears as a reference in license applications, except to assure that the material presented is applicable to the specific plant involved. Our acceptance applies only to the matters described in the application of NEDO-32465.

In accordance with procedures established in NUREG-0390, it is requested that the BWROG publish an accepted version of this topical report within 3 months of receipt of this letter. The accepted version shall include an "A" (designating accepted) following the report identification symbol.

Should our criteria or regulations change so as to invalidate our conclusions concerning the acceptability of the report, the BWROG or the applicants referencing the topical report will be expected to revise and resubmit their respective documentation, or submit justification for the continued effective applicability of the topical report without revision of their respective documentation.

Sincerely,

Timothy E. Collins for

Robert C. Jones, Chief
Reactor Systems Branch
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

Enclosure:
Safety Evaluation Report

# SAFETY EVALUATION REPORT

## NEDO-32465, "BWR OWNERS GROUP REACTOR STABILITY DETECT SUPPRESS SOLUTIONS LICENSING BASIS METHODOLOGY AND RELOAD APPLICATIONS

## 1.0 INTRODUCTION

By letter dated June 28, 1995, Boiling Water Reactor Owners Group (BWROG) submitted a licensing topical report (LTR) NEDO-32465, "BWR Owners Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology and Reload Applications" for NRC review. This LTR relates to reactor stability long term solution Option III and Option I-D. The LTR describes the licensing basis and related licensing methodology to demonstrate that the proposed hardware/software systems and the specified setpoints provide a high confidence that the MCPR safety limit will not be violated for anticipated oscillations.

## 2.0 EVALUATION

Topical report NEDO-32465 (Ref. 1) describes the methodology proposed by the BWROG to define setpoints for Solution III algorithms and to confirm that hose setpoints are applicable for future reloads. The topical report also describes the methodology used to confirm that the flow-biased APRM scram provides protection for the most likely instability mode (core-wide) in Solution I-D plants.

The staff was assisted in its review by its consultant, Oak Ridge National Laboratory (ORNL), who wrote the attached technical evaluation report (TER). The review conducted by ORNL indicated that the proposed methodology to define detect-and-suppress setpoints is adequate and satisfies the requirements for an acceptable long term stability solution. The review also finds that the proposed implementations of the methodology are adequate for both the first application and reload confirmation as described in the topical report. The staff reviewed the attached TER and adopts the findings recommended by ORNL.

## 3.0 CONCLUSIONS

On the basis of its review in conjunction with the consultant's evaluation (Attachment 2), the staff concludes that:

1. The detect-and-suppress setpoint methodology proposed in NEDO-32465[1] should produce setpoint values that will result in a very low likelihood of exceeding CPR safety limits during instability events in Solution III plants.

2. The proposed delta-CPR correlation based exclusively on the core-wide instability mode is acceptable for Solution I-D plants because the likelihood of out-of-phase instabilities is very low in these plants if power-distribution controls are in place. The methodology proposed in NEDO-32465[1] is acceptable to confirm that the flow-biased APRM scram provides protection for core-wide instabilities should they occur in a Solution I-D plant.

3. The proposed setpoint confirmation for reload cores is acceptable for both Solution III and Solution I-D plants. This confirmation is accomplished by dividing the setpoint calculation process in three steps: a cycle-dependent initial MCPR determination, a cycle-dependent confirmation that the statistical peak bundle power oscillation estimation is applicable, and by the use of a generic delta-CPR correlation that is applicable to all current fuel designs.

4. The statistical input ranges proposed in NEDO-32465[1] to estimate the peak bundle power oscillation are acceptable and should result in a conservative value with 95-95 confidence level.

5. The initial application methodology proposed in Section 5 of NEDO-32465[1] is acceptable.

6. The reload review methodology proposed in Section 6 of NEDO-32465[1] is acceptable.

## 5.0 REFERENCES

1. NEDO-32465, "BWR Owners' Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology And Reload Applications," General Electric Company Report, May 1995.

ORNL/NRC/LTR-96/07

| | |
|---|---|
| Contract Program: | **Technical Support for the Reactor Systems Branch (L1697/P2)** |
| Subject of Document: | **Review of Licensing Basis and Reload Applications for Stability Detect and Suppress Methodologies** |
| Type of Document: | **Technical Evaluation Report** |
| Author: | **José March-Leuba** |
| Date of Document: | **December, 1995** |
| NRC Monitor: | **T. L. Huang, Office of Nuclear Reactor Regulation** |

Prepared for
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
under
DOE Interagency Agreement 1886-8169-7L
NRC JCN No. L1697, Task 18

Prepared by
Instrumentation and Controls Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6010
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No.DE-AC05-96OR22464

## SUMMARY

This report documents our review of NEDO-32465,[1] a licensing topical report that defines the licensing basis methodology and reload applications for detect-and-suppress long term stability solutions. Our review is based on data presented in the submitted topical report and during a number of meetings with the boiling water reactor Owners' Group (BWROG) and General Electric (GE). The main conclusion from this review is that the proposed methodology to define detect-and-suppress setpoints is adequate and satisfies the requirements for an acceptable long term stability solution. We also find that the proposed implementations of the methodology are adequate for both the first application and reload confirmation as described in the topical report.

## BACKGROUND

Following the March 1988 instability event in the LaSalle boiling water reactor (BWR), the BWROG initiated a task to investigate actions that industry should take to resolve the BWR stability issue as an operational concern. Through analysis,[2] the BWROG found that the current plant protection system, which is based on a scram on high average power range monitor (APRM) signal, may not provide enough protection against out-of-phase modes of instability; thus, the BWROG decided that a new automatic instability suppression function was required as a long-term solution and that this function should have a rapid and automatic response which does not rely on operator action.

The BWROG is currently pursuing three different options, and it is up to the individual licensees to choose which solution will be implemented in their reactor. These options have been documented in references 3 and 4 and can be summarized as follows.

I    <u>Exclusion Region</u>. A region outside which instabilities are very unlikely is calculated for each representative plant type using well-defined procedures. If the reactor is operated inside this exclusion region, an automatic protective action is initiated to exit the region. This action is based exclusively on power and flow measurements, and the presence of oscillations is not required for its initiation. Two concepts of type I have been pursued by the BWROG:

- I-A   Immediate protection action (either scram or select rod insert) upon entrance to the exclusion region.

- I-D   Some small-core plants with tight inlet orifices have a reduced likelihood of out-of-phase instabilities. For these plants, it is claimed that the existing flow-biased high APRM scram provides a detect and suppress function to avoid safety limits violation for the expected instability mode. In addition, administrative controls are proposed to maintain the reactor outside the exclusion region.

II    <u>Quadrant-Based APRM Scram</u>. In a BWR/2, the quadrant-based average-power-range monitor is capable of detecting both in-phase and out-of-phase oscillations with sufficient sensitivity to initiate automatic protective action to suppress the oscillations before safety margins are compromised.

III LPRM-Based Detect and Suppress. Local power range monitor (LPRM) signals or combinations of a small number of LPRMs are analyzed on-line by using three diverse algorithms. If any of the algorithms detects an instability, automatic protective action is taken to suppress the oscillations before safety margins are compromised.

The four above solutions have been reviewed and accepted in principle by the NRC.[4,5] The present review applies to Long Term Solutions III and I-D, which satisfy General Design Criteria GDC-10 and GDC-12 by detecting the oscillations and suppressing them. This review concentrates in the methodology proposed to define detect-and-suppress setpoints that guarantee that safety limits are not compromised during oscillations.

## EVALUATION

The application of the detect-and-suppress setpoint methodology proposed by the BWROG consists on three major steps:

(1) Define the minimum critical power ratio (MCPR) that exists prior to the onset of the oscillation. This is a plant- and cycle-specific calculation that determines the minimum expected MCPR based on two calculations: (a) a two recirculation pump trip, and (b) steady-state operation at 45% flow and the highest available rod line. We find this proposed methodology acceptable.

(2) Determine the magnitude of the peak fuel bundle power oscillation. This is a plant-specific calculation, and it is performed in a statistical basis for a range of parameters which include sensor failures. The applicability of this calculation is reviewed every cycle, and the calculation is performed again if it is found not applicable. The bases for statistical model used for this step was reviewed and accepted previously in refs 5 and 6. The details of the implementation, as described in NEDO-32465[1] Section 4.3.2.4, "Statistical inputs," are acceptable and these proposed Monte Carlo input ranges should cover all expected instability events. These ranges are: (a) Growth rate (or decay ratio) is sampled from a $\chi^2$ distribution with mean 1.1. (b) Power overshoot is sampled from a uniform distribution between 0% and 100%. (c) The oscillation period is sampled from a $\chi^2$ distribution between 1.4 and 3.3 seconds an a 2 second mean. (d) No LPRM failures are assumed. (e) The oscillation contours are seelcted randomly from a set of six non-cycle-specific contours representative of the plant analyzed.

(3) Determine the final MCPR by using a "generic" correlation that defines the loss in CPR for a given peak fuel bundle power oscillation. The use of a "generic" delta-CPR correlation would not be possible if a "bounding" answer was required; however, the proposed methodology is based on a 95-95 statistical approach. We find that the use of a "fairly-conservative" delta-CPR correlation in conjunction with a statistical distribution of operating conditions results in a high-likelihood that fuel integrity will not be compromised for the likely instability events. We must note, however, that this statistical approach allows for a 5% probability that the CPR limit will be reached during an instability event. The consequences of this, however, should be minor given the oscillatory nature of the power, where periodic cladding rewet is expected if the oscillations are suppressed promptly.

A key unresolved issue in our previous review[6] was the lack of reload confirmation procedures, which would ensure that the setpoints are still applicable to the new fuel loading. The latest submittal (NEDO-32465[1]) describes these reload confirmation analyses, and we find them acceptable from a technical point of view. These analyses include: recalculation of the initial MCPR using cycle-specific parameters (step 1), and an evaluation of cycle parameters which may invalidate the statistical analyses performed to define the peak bundle power oscillation (step 2).

The validity of the generic delta-CPR correlation for different types of fuels and loading patterns has been studied via sensitivity analyses and the BWROG has found it acceptable. This conclusion is not unexpected since the loss of CPR during oscillations is mostly caused by flow oscillations that are largely uncorrelated with fuel parameters. Based on the sensitivity studies and the above observation, we concur with the BWROG conclusion that their proposed delta-CPR correlation applies to all current commercially-available fuels.

## EVALUATION OF SOLUTION I-D METHODOLOGY

As opposed to Solution III, Solution I-D is based on prevention of instabilities by avoiding a conservatively-defined exclusion region. Because this region is avoided using only administrative procedures, it is expected that the reactor will operate inside the region some fraction of the time (e.g. following a two-pump trip). Solution I-D is acceptable because the unfiltered flow-biased APRM scram provides automatic protection for the most likely mode of instability in this plants - the core-wide mode. The out-of-phase mode of oscillation is judged very unlikely in these plants because of the tight inlet orifice, the relatively small-size cores, and because power distribution controls are maintained during startup that make out-of-phase instabilities very unlikely.

Core-wide instabilities result in smaller channel-flow oscillations than out-of-phase instabilities. For this reason, Solution I-D plants can use a different delta-CPR correlation, which is based exclusively on core-wide oscillation and results in a lower delta-CPR penalty for a given power oscillation than the generic correlation that is based mostly on out-of-phase instability data.

Section 7 of NEDO-32465[1] describes the delta-CPR correlation and the overall methodology to be used by Solution I-D plants. The only significant difference between this methodology and the Solution-III methodology is the delta-CPR correlation.

A review of the data presented to support the "core-wide" delta-CPR correlation indicates that this correlation is conservative and its application is acceptable for Solution I-D plants.

## CONCLUSIONS AND TECHNICAL RECOMMENDATIONS

The main conclusion from this review is that the proposed methodology to define detect-and-suppress setpoints is adequate and satisfies the requirements for an acceptable long term stability solution. Specifically, we conclude the following:

(1) The detect-and-suppress setpoint methodology proposed in NEDO-32465[1] should produce setpoint values that will result in a very low likelihood of exceeding CPR safety limits during instability events in Solution III plants.

(2) The proposed delta-CPR correlation based exclusively on the core-wide instability mode is acceptable for Solution I-D plants because the likelihood of out-of-phase instabilities is very low in these plants if power-distribution controls are in place. The methodology proposed in NEDO-32465[1] is technically acceptable to confirm that the flow-biased APRM scram provides protection for core-wide instabilities should they occur in a Solution I-D plant.

(3) The proposed setpoint confirmation for reload cores is technically acceptable for both, Solution III and Solution I-D plants. This confirmation is accomplished by dividing the setpoint calculation process in three steps: a cycle-dependent initial MCPR determination, a cycle-dependent confirmation that the statistical peak bundle power oscillation estimation is applicable, and by the use of a generic delta-CPR correlation that is applicable to all current fuel designs.

(4) The statistical input ranges proposed in Section 4.3.2.4 of NEDO-32465[1] to estimate the peak bundle power oscillation are technically acceptable and should result in a conservative value with 95-95 confidence level.

(5) The initial application methodology proposed in Section 5 of NEDO-32465[1] is technically acceptable.

(6) The reload review methodology proposed in Section 6 of NEDO-32465[1] is technically acceptable.

## REFERENCES


1. NEDO-32465, *BWR Owners' Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology And Reload Applications*. General Electric Company, May 1995.

2. *General Electric Company, Fuel Thermal Margin During Core Thermal Hydraulic Oscillations in a Boiling Water Reactor, NEDO-31708, June 1989*

3. NEDO-31960, *BWR Owners' Group Long-Term Stability Solutions Licensing Methodology*, General Electric Company, May 1991.

4. NEDO-31960 Supplement 1, *BWR Owners' Group Long-Term Stability Solutions Licensing Methodology*, General Electric Company, March 1992.

5. Letter Ashok C. Thadani (NRC) to L. A. England (BWROG Chairman), *Acceptance for Referencing of Topical Reports NEDO-31690 and NEDO-31960 Supplement 1, 'BWR Owner's Group Long-Term Stability Solutions Licensing Methodology' (TAC No. M75928)*. July 12, 1993.

6. ORNL/NRC/LTR-92/15 "Licensing Basis for Long-Term Solutions to BWR Stability Proposed by the BWR Owners' Group" Jose March-Leuba, ORNL letter report. August 1992

# 1.0 INTRODUCTION

## 1.1 BACKGROUND

Under certain conditions, boiling water reactors (BWRs) may be susceptible to coupled neutronic/thermal-hydraulic instabilities. These instabilities are characterized by periodic power and flow oscillations and are the result of density waves (i.e., regions of highly voided coolant periodically sweeping through the core). If the flow and power oscillations become large enough, and the density wave contains a sufficiently high void fraction, then the fuel cladding integrity safety limit could be challenged. Analytical studies have shown that, for some plants, existing reactor protection systems may not assure automatic protection for these events.

Stability Long Term Solution (LTS) Option III is described in Licensing Topical Reports NEDO-31960 (Reference 1) and NEDO-31960 Supplement 1 (Reference 2). The Option III solution consists of hardware and software that provide for reliable, automatic detection and suppression of stability related power oscillations. The Option III hardware initiates control rod insertion to terminate the power oscillation while it is still small. The combination of hardware, software, and system setpoints will provide protection against violation of the MCPR safety limit for anticipated oscillations. Thus, compliance with General Design Criteria 10 and 12 of 10CFR50, Appendix A will be accomplished via an automatic action.

The Option I-D solution (also described in References 1 and 2) takes credit for unique plant characteristics to demonstrate, using portions of the Detect and Suppress methodology, that the existing Reactor Protection System (RPS) provides a sufficient automatic detect and suppress function. The features of the Option I-D solution are described in more detail in Section 7.

Descriptions of the Detect and Suppress methodology and the Option III solution were provided for NRC review in References 1 and 2. NRC acceptance of the concepts and associated recommendations are contained in the NRC Safety Evaluation Report (Reference 3). Specific hardware/software designs and related Technical Specifications will be addressed in hardware Licensing Topical Reports which will be submitted separately for NRC approval. The Option III licensing analysis methodology is fully described in this report. Section 7 of this report contains a description of the portions of this methodology which may be utilized to support Option 1-D.

## 1.2 PURPOSE

This report describes the licensing basis and the related licensing methodology to demonstrate the adequacy of the Option III hardware/software designs being developed by GE and ABB. Sections 2 through 6 describe the Option III licensing basis and licensing methodology for reload evaluations. Specific Option III methodology is described for a "first application" (i.e., the first cycle that the system is to operate) and for a "reload application". The portions of the Option III methodology to support Option I-D applications are discussed in Section 7. The goal of the evaluations is to demonstrate that the hardware/software system and specified setpoints provide a high confidence that the MCPR Safety Limit (MCPR SL) will not be violated for anticipated oscillations. Plant-specific hardware setpoints will be included as part of individual utility submittals.

Included in this report are responses to NRC comments contained in Reference 3.

It should be noted that the Option III methodology described herein is conceptually the same as that described in References 1 and 2. This report contains a full description of the Option III methodology for use in reload evaluations. A small number of changes have been made to the methodology described in References 1 and 2 to simplify its application. These changes to the Reference 1 and 2 methods are described in this report.

## 1.3 OVERVIEW

The licensing methodology described in this report (Sections 2 through 6) is designed to demonstrate that the Option III features will reliably detect and suppress anticipated stability related power oscillations while providing a high degree of confidence that the MCPR safety limit is not violated, thus satisfying the requirements of GDC 10 and 12. The detection algorithm for this purpose is called the Period Based Detection Algorithm (PBDA). The PBDA monitors groups of LPRMs and confirms that stability related oscillations exist by detecting periodic behavior typical of reactor instability events. Upon confirmation that an instability exists, the PBDA initiates a trip when the signal's oscillation amplitude exceeds a specified value.

The Option III licensing analysis methodology consists of three major components:

a. <u>A determination of the MCPR margin that exists prior to the onset of the oscillation:</u> The plant and cycle specific MCPR will be evaluated to determine the margin to the MCPR safety limit prior to the oscillation.

b. <u>A statistical treatment of various parameters which influence the magnitude of the peak fuel bundle power oscillation:</u> The statistical methodology considers power distributions, oscillation contours, oscillation growth rates, frequencies, trip overshoot, and LPRM failures. The result of the statistical evaluation is a conservative value of the peak bundle power oscillation magnitude for anticipated reactor instability events. For a given combination of LPRM assignments to OPRM cells and trip setpoint, this statistical analysis calculates the hot bundle oscillation magnitude prior to termination of the instability.

c. A conservative relationship between the change in CPR and the hot bundle oscillation magnitude: This relationship is derived from 3-D TRACG analyses performed over a range of conditions selected to represent all current fuel designs.

The statistical methodology (modified as applicable) and the use of a 3-D TRACG based relationship between $\Delta$CPR and hot bundle oscillation magnitude are both applicable to the Option 1-D methodology (Section 7).

In order to provide defense in depth, the Option III solution also contains amplitude and growth rate algorithms. Both the amplitude and growth rate algorithms are capable of initiating a scram (or SRI) to limit the size of an oscillation. These algorithms are not credited in the licensing methodology but are included as additional protection against unanticipated oscillations. Appendix A describes these two additional algorithms. Neither the amplitude nor the growth rate algorithm is considered part of the licensing basis. Thus, no Technical Specification actions are required if either or both of these "defense in depth" algorithms does not function.

# 2.0 SOLUTION DESIGN PHILOSOPHY

## 2.1 DESIGN APPROACH

The design philosophy used in the development of Stability Long-Term Solution Option III (both hardware/software and licensing methodology) has a number of key features, which are discussed in this section.

The Option III design provides ***automatic*** detection and suppression of reactor instability events. Thus, reliance on the operator to suppress instability events is minimized. The provision of an extremely reliable automatic system makes Option III "operator friendly" in that protection does not rely on operator action. However, alarms are provided to alert the operator of an increase in the number of confirmed period counts so actions can be taken to avoid a scram.

The Option III design provides a high degree of defense in depth. Each of four independent trip channels monitors signals from a large number of LPRM detectors. A local group of LPRMs (1 to 8 LPRM detectors) is called an Oscillation Power Range Monitor (OPRM) cell. Each trip channel consists of many OPRM cells distributed throughout the core so that each trip channel provides monitoring of the entire core. Thus, the system is fully capable of detecting both core wide and regional modes of oscillation. The system is "robust" in that it provides protection despite LPRM failures, OPRM cell inoperability (e.g., from too few inputs), or OPRM channels being out of service.

The PBDA is capable of recognizing an instability and initiating rod insertion before the power oscillations increase much above the noise level. Further defense in depth is provided by two other algorithms for detecting stability related oscillations. These two additional algorithms examine an aspect of the oscillation (oscillation amplitude and oscillation growth rate) different from the PBDA. The amplitude and growth rate algorithms are included in the design as a means of detecting oscillations which are not anticipated and are, therefore, not part of the Option III licensing basis.

Based on the analyses presented in this report, it is expected that the PBDA setpoint for an individual plant will be slightly above the normal LPRM noise level. This setpoint will be low enough to provide a high confidence that the MCPR safety limit will not be violated for anticipated oscillations, while minimizing the possibility of non-stability related scrams.

Conservatism is introduced in the design philosophy by selecting the MCPR Safety Limit to demonstrate protection of fuel cladding integrity for anticipated stability events. The MCPR SL is a conservative limit for this application because the fuel and clad responses to stability related oscillations are relatively mild even if the critical power ratio falls below the MCPR SL. The Option III initiated rod insertion will assure that the hot bundle will only experience a few oscillations above the setpoint prior to scram. If a rod actually experienced boiling transition, the cyclic nature of the event would result in clad rewet approximately every two seconds. A few oscillations in which the clad rewets would result in a nearly negligible cladding temperature transient. This fact has been demonstrated in the assessment of NEDO-32047, "ATWS Rule Issues Related to BWR Core Thermal-Hydraulic Stability" (Reference 4). This assessment showed that, as long as the clad rewets between cycles, the clad temperature increase is typically less than 100°F for oscillations up to 200% of rated power. Therefore, use of the MCPR SL as the acceptance criterion is extremely conservative in protecting the fuel.

A goal in developing the licensing methodology was to make it very simple to use for reload evaluations. To accomplish this goal, some conservatisms were introduced into the methodology to simplify the reload evaluation process.

The Option III licensing methodology uses a Monte Carlo statistical approach to calculate a conservative value of the hot bundle response (hot bundle oscillation magnitude) for anticipated oscillations. The statistical methodology considers power distributions, oscillation contours, oscillation growth rates, frequencies, trip overshoot, and LPRM failures. A large number of Monte Carlo trials are run, and a 95% probability/95% confidence level is selected. Although a number of parameters are treated statistically, plant-specific and cycle-specific inputs are used for a number of key parameters (e.g., setpoints, core size, trip system response time,and LPRM assignments to OPRM cells).

## 2.2 LICENSING COMPLIANCE

The Option III solution and related licensing methodology were developed to comply with the requirements of 10CFR50, Appendix A, "General Design Criteria for Nuclear Power Plants". The Appendix A criteria related to stability are Criteria 10 and 12:

Criterion 10 (Reactor Design) requires that:

> "The reactor core and associated coolant, control, and protection systems shall be designed with appropriate margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated occurrences."

Criterion 12 (Suppression of Reactor Power Oscillations) requires that:

> "The reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillations which can result in conditions

exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed."

The Option III hardware and software system was designed to reliably and readily detect and suppress both core wide and regional mode oscillations prior to violating the MCPR safety limit for anticipated oscillations. The ability to trip the reactor is automatically enabled at power and flow conditions at which stability related oscillations are possible. The trip function will be enabled when both the power level is greater than 30% of rated and the core flow is less than 60%. Based on experience with actual instabilities and decay ratio calculations, instabilities above 60% flow are not expected. Similarly, instabilities occurring below 30% power are also not expected. If an instability were to occur below 30% power, the instability would not be expected to grow large enough to threaten the MCPR SL. This expectation is due, in part, to the large MCPR margin that exists at low power.

Both core wide and regional mode oscillations will be reliably detected and suppressed while the oscillation magnitude is still low. In order to detect all expected oscillation modes, the outputs from a small number of LPRMs in the same area of the core are combined into one OPRM cell signal. Thus, small regions of the core are effectively monitored for instabilities.

Multiple cells distributed throughout the core provide input to each of the RPS channels. This ensures that the system is sensitive to all of the anticipated oscillation modes, and also provides substantial redundancy for the input signals and accommodates out of service or failed LPRMs. A number of LPRM-to-OPRM cell assignments (i.e., number and location of the LPRMs that comprise a cell) are possible within the constraints of the OPRM definition given in Reference 1. The Option III methodology takes plant-specific LPRM assignments into account in calculating the hot bundle oscillation magnitude.

The licensing methodology described in this report is consistent with the one described in References 1 and 2. The methodology is designed to demonstrate that the system and setpoints will result in suppression of the oscillation before the MCPR SL is violated for anticipated oscillations. In this context, anticipated oscillations are those which, based on both experience and analytical simulations, might be expected to occur in a reactor. Specifically, these events approach a limit cycle and gradually increase in amplitude. The period of these oscillations becomes relatively constant (i.e., detectable) prior to the oscillation amplitude significantly exceeding the noise level. This is consistent with the observed behavior of actual plant instability events such as LaSalle-2 and WNP-2 and is consistent with the results of analytical simulations. Oscillations with frequencies between 0.3 and 0.7 Hz and growth rates up to 1.6 are considered anticipated oscillations. Protection against violating the MCPR SL for anticipated oscillations is demonstrated solely by use of the PBDA (i.e., no credit is taken for the other two algorithms which are provided as defense-in-depth protection against unanticipated oscillations).

In summary, the licensing methodology described in this report provides a high degree of confidence that the power oscillation will be terminated at relatively low amplitude by the Option III Solution, and the MCPR SL will not be violated for anticipated oscillations. Thus, the Option III Solution complies with GDC 10 and 12. The Option III Solution enhances overall plant safety by providing a reliable automatic oscillation detection and suppression function while avoiding unnecessary scrams.

# 3.0 SOLUTION DESCRIPTION

This section provides a brief description of the major aspects of the Option III Solution. A more complete description of the solution is contained in References 1 and 2. The arrangement of LPRM detectors into OPRM cells is discussed. The PBDA algorithm is described along with its key setpoints, since it is the algorithm used to show compliance with GDC 10 and 12.

## 3.1 SYSTEM FUNCTION

Option III consists of a combined hardware/software system to detect and suppress stability related power oscillations. The principal inputs to the system are the signals from a large number of LPRM detectors. The signals are filtered, processed, and evaluated for evidence of stability related oscillations. If sufficient evidence exists that the reactor is experiencing unstable operation, a reactor scram is produced by the RPS.

The basic function of the system is to automatically suppress stability related power oscillations to provide a high confidence that the MCPR safety limit would not be violated for anticipated oscillations.

## 3.2 SYSTEM INPUT AND LPRM ASSIGNMENT

The basic unit of the Option III hardware/software system is the OPRM cell. An OPRM cell consists of from one to eight, closely spaced LPRM detectors. The signals from the individual LPRM detectors in a cell are averaged to produce the OPRM cell signal.

The cell signal is filtered to remove noise components with frequencies above the range of stability related power oscillations. Typically, this is accomplished by a filter with a corner frequency of from 1.5 to 2.5 Hz (referred to as the "conditioning" filter). The conditioned signal is filtered again using a relatively long time constant (typically around 6 seconds) to produce an additional time-averaged value. The conditioned and conditioned/time-averaged signals are used to detect reactor instabilities.

The assignment of LPRM detectors to specific OPRM cells is important to the system's ability to detect an oscillation. For example, a large number of detectors in a cell tends to reduce sensitivity to an oscillation due to the averaging of signals that are slightly out of phase with each other. In fact, analytical results clearly show that single LPRM cells are the most sensitive. However, in order to provide greater assurance against spurious trips, most utilities are expected to use from two to four LPRMs per cell. Examples of possible LPRM to OPRM cell assignments are shown in Appendix D.

Each OPRM cell is permanently assigned to an RPS trip channel (e.g., A1, A2, B1, or B2). If an OPRM cell experiences a "trip" (i.e., if a trip condition is met), then that RPS channel will trip. A reactor scram will occur when the necessary combination of channel trips occurs. For example, in "one-out-of-two-taken-twice" RPS logic, a trip occurs on any of the following channel trips:

A1 & B1
A1 & B2
A2 & B1
A2 & B2

### 3.3 PBDA ALGORITHM DESCRIPTION

The Period Based Detection Algorithm (PBDA) is described in Section B.2 of Reference 1 and Section 6.1 of Reference 2. The PBDA utilizes the fact that LPRM noise becomes coherent at the inception of an instability event, before the amplitude becomes large. The PBDA uses a combination of period confirmation count and amplitude setpoint to determine if a trip is required.

The PBDA focuses on the periodicity of the oscillation in the range from 0.3 to 0.7 Hz. When the time difference between successive peaks (or successive minima) in an OPRM cell signal is consistent with a frequency range of 0.3 to 0.7 Hz, this time difference is defined as the base period, $T_0$. The next period ($T_1$) calculated between successive peaks (or minima) must be within a small time window ($\pm\ \varepsilon$) of $T_0$ to produce a "confirmation" that oscillatory behavior exists. A new base period is defined as the average of all consecutively confirmed periods in that cell. Based on evaluation of plant data, as the decay ratio increases toward 1.0, the oscillation period will become constant, resulting in many consecutive confirmations.

The PBDA detects an instability based on the occurrence of a fixed number of consecutive period confirmations. For example, 10 consecutive confirmations (five complete oscillation cycles) may be considered evidence of a stability related power oscillation. A trip is generated for that OPRM cell (and hence for that RPS channel) if:

1. the number of consecutive period confirmations exceeds its setpoint value ($N_p$), ***and***

2. the relative signal (P/A) exceeds a specified setpoint, $S_p$.

The value of $S_p$ is expected to be set sufficiently above the noise level to minimize the likelihood of an inadvertent scram. In other words, the PBDA generates a trip when oscillatory behavior consistent with an instability exists ***and*** the peak-to-average cell signal has increased to the trip setpoint. This optimizes the probability that the system will both trip when needed to suppress an instability event and will not trip when it is not required. Sample setpoint values are given in Table 3-1. Plant-specific reload evaluations will be performed to confirm that the LPRM assignments and system setpoints provide a high confidence that the MCPR SL will not be violated for anticipated oscillations.

## 3.4 PBDA ALGORITHM SETPOINTS

The licensing methodology assumes that for an anticipated stability related oscillation, the PBDA provides period confirmations greater than or equal to the confirmation count setpoint ($N_P$) at or before reaching the amplitude trip setpoint ($S_P$). Plant data and numerous plant simulations were examined to establish a range of the PBDA setpoints that validate this licensing methodology assumption.

### 3.4.1 Algorithm Period Confirmation Setpoints

The two setpoints which affect period confirmations are the period tolerance ($\varepsilon$) and the conditioning filter cutoff frequency ($F_c$). An acceptable range of these parameters is defined which has been demonstrated to provide continuous confirmations upon transition from stable reactor operation to a growing reactor instability. Since each plant may have a unique LPRM noise characteristics, a range of the setpoints was established to allow an individual plant to tune the sensitivity of their system to avoid spurious alarms on period confirmations. Limiting the setpoint adjustment range provides assurance that the PBDA will provide sufficient confirmations for a growing reactor instability. Based on testing of the algorithm against available plant data, the acceptable setpoint ranges are defined in Table 3-1.

**Table 3-1: PBDA Period Confirmation Setpoints**

| Setpoint | Acceptable Range |
|---|---|
| **Period Tolerance: $\varepsilon$ (seconds)** | 0.100 to 0.300 |
| **Conditioning Filter Cutoff Frequency: $F_c$ (Hz)** | 1.0 to 2.5 |

### 3.4.2 Algorithm Trip Setpoints

The two setpoints which define when the PBDA reaches the trip condition are the confirmation count setpoint ($N_P$) and the amplitude trip setpoint ($S_P$). For an anticipated instability, there is a direct relationship between $N_P$ and $S_P$. If a value of $N_p$ is specified, there is a minimum value of $S_P$ which ensures that the oscillation amplitude trip setpoint will be reached after the count reaches $N_P$. If the amplitude setpoint were lower than the minimum allowed value of $S_P$, then $S_P$ could theoretically be reached before the confirmation count reached $N_P$. Therefore, it is necessary to constrain the value of $S_P$ for given values of $N_P$ to ensure that the confirmation count has reached $N_P$ prior to the amplitude reaching $S_P$ for anticipated reactor instabilities.

There is limited actual instability data available to develop a correlation between $N_P$ and $S_P$, for example, the data which was provided in Reference 2. Therefore, a conservative theoretical model was used to provide an analytical basis to establish allowable values for $N_P$ and $S_P$. The theoretical model is described in Appendix E. The allowable ranges established for $N_P$ and $S_P$ are shown in Table 3-2.

**Table 3-2: PBDA Trip Setpoints**

| Confirmation Count Setpoint: $N_P$ | Amplitude Setpoint: $S_p$ (Peak/Average) |
|---|---|
| 6 | ≥1.04 |
| 8 | ≥1.05 |
| 10 | ≥1.07 |
| 12 | ≥1.09 |
| 14 | ≥1.11 |
| 16 | ≥1.14 |
| 18 | ≥1.18 |
| 20 | ≥1.24 |

# 4.0 LICENSING METHODOLOGY

## 4.1 APPLICATION OVERVIEW

As stated previously, the purpose of the Option III licensing methodology is to demonstrate that the system and setpoints will result in suppression of an oscillation without violating the MCPR SL for anticipated oscillations. An evaluation will be performed each cycle to assure that this conclusion remains true. The methodology is conceptually identical to that approved by the NRC. Additional conservatisms have been added to streamline the reload review process.

The NRC approved methodology given in References 1 and 2 was restructured somewhat to simplify the first application process and reload review process. The statistical methodology of References 1 and 2 has been divided into three distinct parts. This division is based, in part, on which organization will be responsible for the evaluations (i.e., General Electric, the utility, or the utility's fuel vendor). The three portions of the Option III licensing methodology are:

1. Calculation of Pre-Oscillation MCPR: This portion of the methodology captures the cycle specific MCPR margin to the safety limit. In practice, these calculations will be performed either by the utility or their fuel vendor. In demonstrating that the MCPR SL is not violated for anticipated oscillations, the MCPR margin prior to an event is clearly important.

2. Statistical Calculation of Peak Oscillation Magnitude: This portion of the methodology captures the effect of plant characteristics, trip system definition, and setpoint values on the magnitude of the hot bundle power oscillation (before it is terminated by the scram). In practice, these calculations will be performed using the statistical methodology described in Section 4.3.

3. MCPR Performance of the Hot Bundle: This portion of the methodology captures the effect of fuel design on a fuel bundle's response ($\Delta$CPR) to an oscillation. A number of 3-D TRACG analyses were performed which cover a range of key bundle design characteristics. These ranges were selected to reasonably represent all currently available fuel designs. Results of these analyses are used to produce a generic MCPR performance relationship that represents all current fuel designs.

These three portions which comprise the Option III application methodology are described in Sections 4.2 through 4.4.

## 4.2 PRE-OSCILLATION MCPR

In the Reference 1 and 2 methodology, the pre-oscillation MCPR parameter was calculated as part of the overall statistical method using an assumed statistical distribution for the change in MCPR as a function of the change in flow (i.e., the derivative dMCPR/dFlow). Due to the variation of this relationship for different plants and different fuel types, it was decided that it would be preferable to calculate this parameter for each plant/cycle. Thus, fuel types, CPR correlations, core designs, and cycle-specific MCPR limits will be explicitly treated.

The initial (pre-oscillation) MCPR is referred to as the IMCPR. In determining the IMCPR, two separate scenarios are considered. The first scenario is a two recirculation pump trip from rated power on the highest allowable rod line. The IMCPR for this scenario is the MCPR that exists after the coast down to natural circulation and after the feedwater temperature reaches equilibrium. It is assumed that the reactor is operating at the MCPR Operating Limit (OL) prior to the two recirculation pump trip.

In the second scenario, the plant is assumed to be in steady-state operation at 45% core flow on the highest allowable rod line. It is assumed that the reactor is operating at the MCPR OL corresponding to the specified power and flow conditions. Generally, the IMCPR will be substantially greater for the second scenario than the first scenario due to the increase in the MCPR OL at lower power and flow conditions.

The IMCPR for both scenarios will be determined for each operating cycle using a 3-D nodal simulator code such as SIMULATE, MICROBURN, POLCA, or PANACEA, or by another suitable method. For conservatism, the minimum value of MCPR calculated for both scenarios will be used as the IMCPR for all oscillations. This conservative assumption replaces the assumption (Section 6.3.2 of Reference 1) that 95% and 5% of the cases are initiated from full power and startup, respectively.

## 4.3 STATISTICAL CALCULATION OF HOT BUNDLE OSCILLATION MAGNITUDE

### 4.3.1 OUTLINE

The "hot bundle oscillation magnitude" quantifies the size of the hot bundle power oscillation prior to oscillation suppression. Clearly, the hot bundle oscillation magnitude has a significant effect on the minimum CPR for an instability event. The parameter used to measure the hot bundle oscillation magnitude is defined as:

$\Delta_h = (P_h - M_h) / A_h$, where

$P_h$ = peak hot bundle power for an oscillation cycle
$M_h$ = minimum hot bundle power for an oscillation cycle
$A_h$ = average hot bundle power

The hot bundle oscillation magnitude, $\Delta_h$, is dependent on plant-specific factors. Some of the parameters that affect the hot bundle oscillation magnitude are: core size, LPRM assignments, trip setpoints, growth rate, power distributions (contours), LPRM failures, trip overshoot, and oscillation frequency. A statistical analysis is performed to calculate a conservative value of the hot bundle oscillation magnitude. An upper bound (one-sided tolerance limit) at the 95% probability with a 95% confidence level is selected. This methodology is conceptually identical to the methodology described in Section 6 of Reference 1. The statistical process used to determine the conservative value of $\Delta_h$ is described below.

## 4.3.2 STATISTICAL MODEL

### 4.3.2.1 Nomenclature

The following symbols are used in the discussions presented in this section:

| | |
|---|---|
| $F_l(t)$, $F_o(t)$, $F_h(t)$ | Oscillation signal for an LPRM, an OPRM cell, and the hot bundle, respectively. The signals (F(t)) are normalized to their respective averages (A). |
| $A_l$, $A_o$, $A_h$ | Oscillation signal average for an LPRM, an OPRM cell, and the hot bundle, respectively. |
| $P_l$, $P_o$, $P_h$ | Oscillation signal peak for an LPRM, an OPRM cell, and the hot bundle, respectively. |
| $M_l$, $M_o$, $M_h$ | Oscillation signal minimum for an LPRM, an OPRM cell, and the hot bundle, respectively. |
| $\Delta_l$, $\Delta_o$, $\Delta_h$ | Oscillation magnitude (defined as peak minus minimum divided by the average) of an LPRM, an OPRM cell, and the hot bundle, respectively: $(P_x - M_x)/A_x \equiv \Delta_x$. |
| $S_p$ | PBDA amplitude trip setpoint |
| $\delta$ | Setpoint overshoot |
| $\varphi_l$, $\varphi_h$ | Phase angle of an individual LPRM and of the hot bundle, respectively |
| $G_r$ | Oscillation growth rate |
| T | Oscillation period |

#### 4.3.2.2 Definitions

Important parameters used in the statistical model are described below. Several of these parameters are defined in Reference 1. However, clarification was considered desirable to assist in the description of the current statistical model.

**Hot Bundle**: The "hot bundle" is defined as the bundle that attains the highest normalized oscillation magnitude, (P-M)/A. For a side-by-side oscillation, there are two such "hot bundles", one located on each side of the oscillation symmetry line. The average power ($A_h$) of these "hot bundles" thus does not necessarily correspond to the highest radial peaking factor bundle. However, these bundles exhibit the largest oscillations during the event. The "hot bundle" oscillation magnitude is denoted by $\Delta_h$.

**Setpoint ($S_p$)**: The trip setpoint, denoted by $S_p$, is the relative power level (peak over average) at which the OPRM cell will generate a trip signal after the required number of confirmations has been reached.

**Growth Rate ($G_r$):** The growth rate, $G_r$, is the relative change in the peak of two consecutive oscillation cycles, i and i+1:

$G_r = \{(P_{i+1} / A) - 1\} / \{(P_i / A) - 1\}$, where:

$P_i$ and $P_{i+1}$ are the peak signals for their respective cycles.

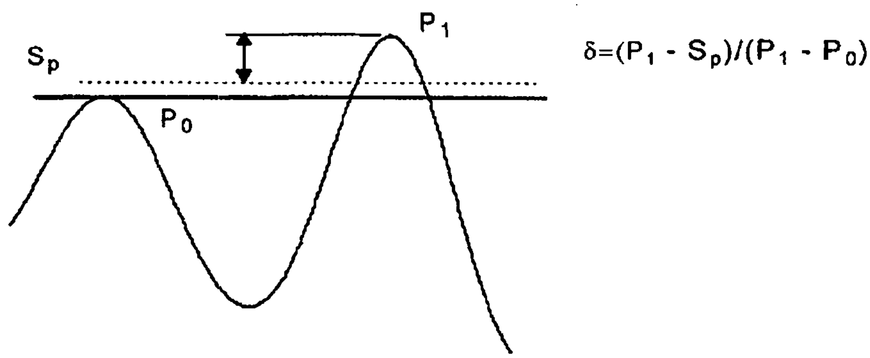
The growth rate is applied to the statistical model using two assumptions:
(a) the growth rate remains constant during the portion of the oscillation which generates the trip signal; and (b) all signals (LPRMs, OPRMs, and hot bundles) experience the same growth rate.

**Overshoot ($\delta$)**: When an OPRM signal exceeds the trip setpoint, the overshoot ($\delta$) is the fraction of the difference between successive peaks which lies above the trip setpoint. The parameter $\delta$ is defined in terms of two cycle peaks: one just prior to the setpoint ($P_0$) and one just after the trip setpoint ($P_1$).

$$\delta = ( P_1 - S_p ) / ( P_1 - P_0 ), \text{ where } P_0 < S_p < P_1.$$

This is schematically shown in Figure 4-1.

**Figure 4-1: Overshoot Illustration**




**Oscillation Contour**: The oscillation contour primarily represents the relative power distribution among LPRMs in the core. The oscillation contours used were calculated by the GE 3D BWR Simulator. The use of oscillation contours in the statistical model is discussed in Section 4.3.2.4. Each contour contains the following information:

(a) <u>LPRM normalized average</u>: The LPRM average, $A_l$, of each LPRM; these values are calculated from the core radial and axial bundle power distribution. The GE 3D BWR Simulator calculates the fundamental mode power distribution at axial locations of each bundle. The powers at various LPRM locations are then obtained by averaging the powers of the surrounding bundle nodes. The $A_l$ value in a contour is normalized such that $\Sigma A_l=1$. The LPRM average signals are assumed to remain constant during the oscillation.

(b) <u>LPRM oscillation magnitude</u>: The oscillation magnitude for a specific LPRM is defined as $\Delta_l = (P_l - M_l) / A_l$. The values of $\Delta_l$ are calculated from the first-order harmonic mode (side-by-side) power distribution obtained from the 3D BWR simulation. Each LPRM has its own value of $\Delta_l$ which is contained in the contour information as a value normalized to the hot bundle oscillation magnitude (i.e., $\Delta_l / \Delta_h$). The oscillation magnitudes of the hot bundle and of each LPRM increase as the oscillation grows, but the ratio $\Delta_l/\Delta_h$ is assumed constant during an oscillation.

(c) <u>LPRM signal phase information</u>: The relative phase shift among LPRM signals is included in the contour. The axial phase shifts of the B, C and D level LPRMs are measured relative to the bottom LPRM level (level A). The axial phase differences are $\varphi_{B-A}$=23°, $\varphi_{C-A}$=59°, $\varphi_{D-A}$=82°, and are assumed constant (Reference 1) . For a core-wide oscillation mode, a zero phase angle is assigned to all A level LPRMs. In a side-by-side regional oscillation, a zero phase angle is assigned to A level LPRMs in one-half of the core, and a 180° angle assigned to the other half across the oscillation symmetry line. The symmetry line is determined by the 3D BWR Simulator.

**LPRM Assignment**: The LPRM assignment refers to the combination of two or more LPRMs into OPRM cells. The redundancy of the OPRM trip system is described in detail in Reference 1. Several more LPRM assignment options are introduced in this report covering 2, 3, 4, and 8 LPRMs per OPRM cell. The effects of various LPRM assignments are presented in Section 4.3.5.1.

**Most Responsive Channel Failure**: The most responsive channel failure is defined as the failure of the trip channel containing the "most responsive" OPRM cell (i.e., the cell that would generate the first half-trip signal).

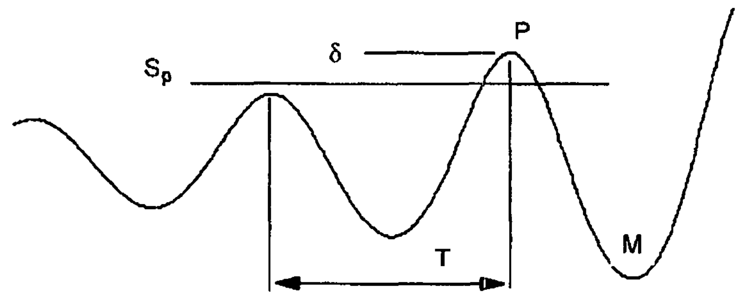
**95/95 Value of Hot Bundle Oscillation Magnitude**: The 95/95 value of the hot bundle oscillation magnitude, $\Delta_{h(95/95)}$, is produced by the Monte Carlo analysis. With 95% confidence, at least 95% of the true hot bundle oscillation magnitudes would be less than the calculated value of $\Delta_{h(95/95)}$, at the time of oscillation suppression.

### 4.3.2.3 Oscillation Model

At the core of the statistical model is the simulation of individual LPRM oscillation signals. The empirical time-dependent model of an LPRM signal is described in Reference 1 and is denoted here as $F_l(t;T,G_r,\Delta_l,A_l,\varphi_l,\delta)$. The oscillation period (T) and growth rate ($G_r$) are independent, statistically selected input parameters. The LPRM signal average ($A_l$), oscillation magnitude ($\Delta_l$), and phase information ($\varphi_l$), are obtained from the oscillation contour, which is itself statistically selected.

Ideally, an initial condition (oscillation start time and initial magnitude) would be necessary to completely model an oscillation. This information can be treated as essentially random for any given oscillation. Therefore, the simulation is focused only in the time segment of interest when the OPRM signal crosses the trip setpoint. For this reason, the setpoint overshoot $\delta$ is an additional, randomly selected parameter in the OPRM model which is used in lieu of the initial condition. An example of an OPRM oscillation signal is shown in Figure 4-2.

**Figure 4-2: Simulated OPRM Oscillation Signal**




The time dependent LPRM signals are averaged in accordance with the LPRM-to-OPRM assignment. The averaging of LPRM signals in an OPRM cell ignores any failed LPRMs. The failure of the most responsive OPRM channel is applied before the trip signal time is determined.

The application of the trip logic in the model is described below. The trip system consists of four OPRM channels divided into two separate divisions: Division A (Channels A1 and A2) and Division B (Channels B1 and B2). Trip signals from two separate OPRM channels are required to cause a reactor scram. The first OPRM cell signal that exceeds the trip setpoint (most responsive OPRM cell) constitutes the first half-trip. The OPRM channel to which this cell belongs is also designated as the most responsive channel. In a one-out-of-two-taken-twice trip logic, a full-trip is complete only when a signal from an OPRM cell in each division exceeds the trip setpoint. For example, if the most responsive OPRM channel is A2, the full-trip is complete when an OPRM cell signal from either Channel B1 or B2 reaches the setpoint. In the application of the model to licensing analysis, the most responsive channel is assumed to fail. The model also allows the selection of a two-out-of-four logic in which the channel division is ignored, and any two channel trip signals will constitute a full-trip.

Once the reactor trip time is determined, a fixed time increment is added to account for the time delay before the oscillation is successfully suppressed. This time delay consists of four components:

1. Response time of the OPRM hardware
2. RPS response time (from trip signal to de-energization of scram pilot solenoid valve)
3. Delay time prior to start of scram rod motion (from de-energization of scram pilot solenoid valve)
4. Time for the control rod insertion to prevent further growth of the oscillation (referred to as the time of oscillation suppression)

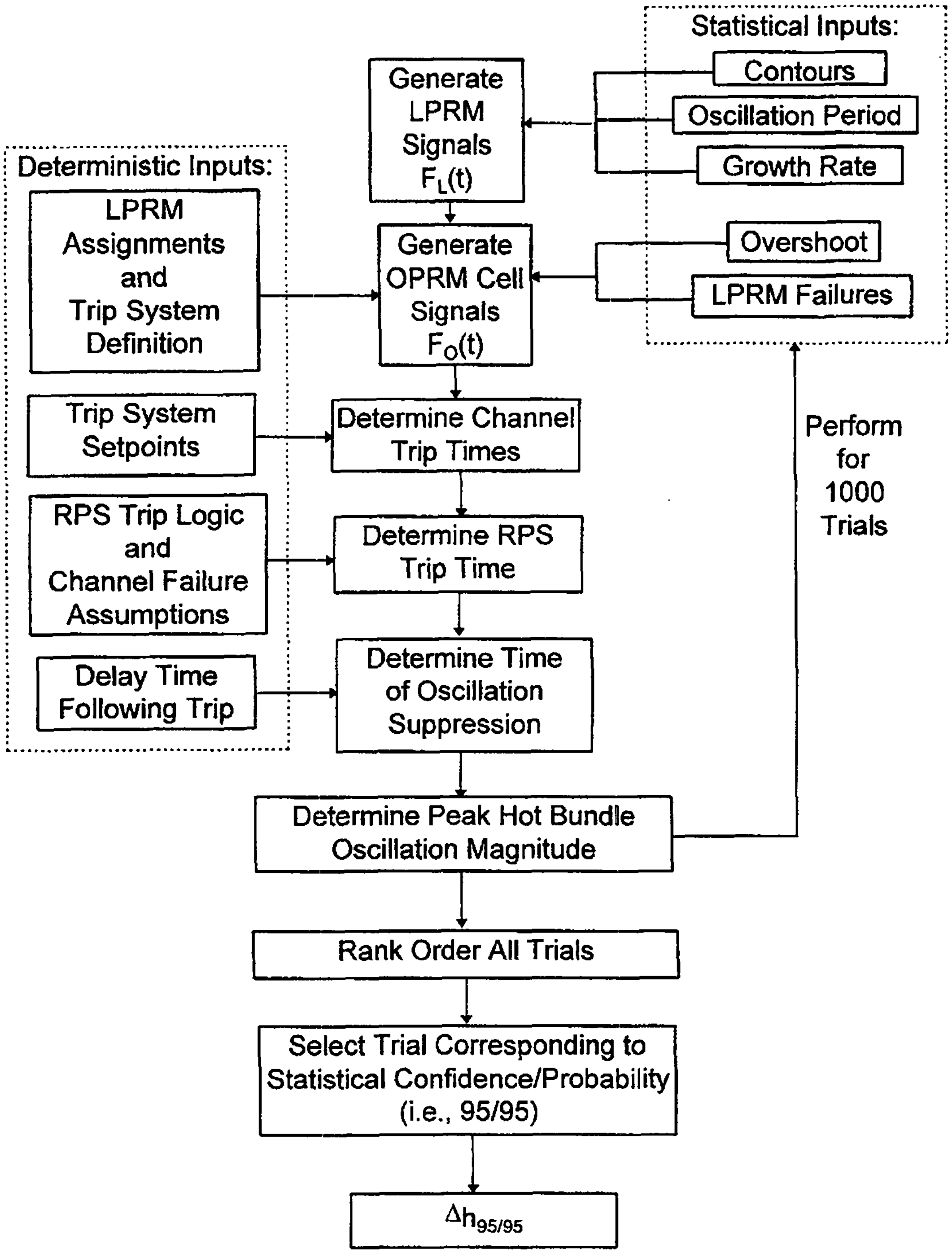
The sum of the above four components determines the time when the oscillation is suppressed, $t_f$. For example, the total delay time is about 1300 msec for a typical BWR-4. The total delay time is a plant-specific input to the statistical model.

In addition to simulating the LPRM and OPRM signals, the statistical model also simulates the oscillation of the hot bundles using the same empirical model. For a regional mode oscillation, there are two hot bundles (bundles with the highest oscillation magnitudes), one on each side of the oscillation symmetry line. Since they are 180° out of phase with each other, their peaks alternately occur every half cycle at a constant growth rate. The calculated maximum hot bundle oscillation magnitude at time of oscillation suppression is that corresponding to the higher peak of the two hot bundles.

Each application of the oscillation model uses one value for each of the following inputs: oscillation period, growth rate, trip setpoint overshoot, and LPRM failure percentage (demonstration calculations provided in Section 4.3.5.2 show that it is conservative to assume there are no LPRM failures for Option III application). These values are randomly selected from input probability distributions that represent anticipated oscillations. The input distributions for these parameters (based on observed test data and actual instability events) are described in subsequent sections. Each calculation using a set of randomly selected inputs constitutes one "trial" in the Monte Carlo analysis. The peak hot bundle oscillation magnitudes resulting from all trials produce an output probability distribution of hot bundle oscillation magnitude, $\Delta_h$. The 95/95 value of the hot bundle oscillation magnitude is determined from this distribution once sufficient samples are obtained.

Tests with various numbers of trials indicate that 1000 trials are sufficient to construct a $\Delta_h$ distribution. The current statistical model applies a non-parametric tolerance limit (Reference 5) to the hot bundle oscillation magnitude distribution to determine the 95/95 value. Figure 4-3 presents a schematic diagram of the statistical process.

**Figure 4-3: Statistical Model Outline**

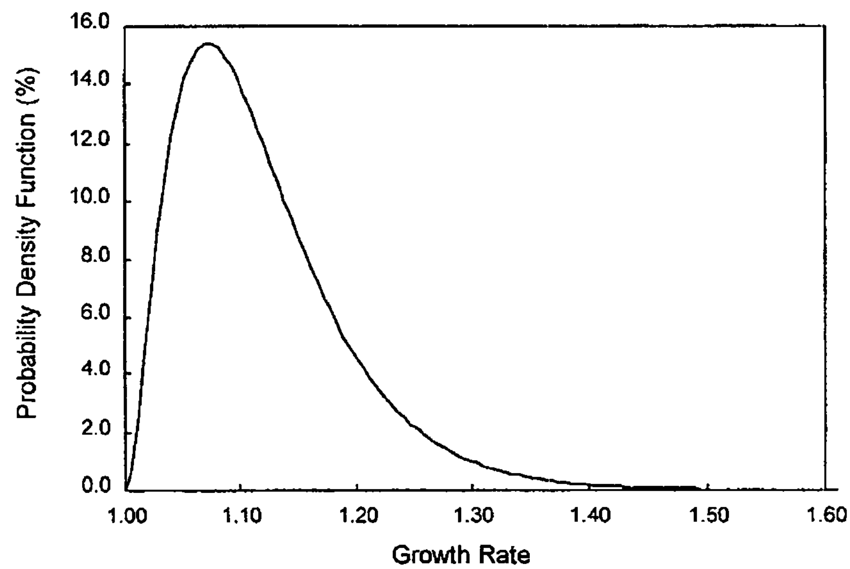


#### 4.3.2.4 Statistical Inputs

The statistical inputs to the Monte Carlo analysis, including the assumed distributions and the bases for those distributions, are discussed in this section.

**Growth Rate:** A review of actual instability events indicates that most BWR oscillations would be expected to have a growth rate only slightly above 1.00. For the statistical model, a growth rate is randomly selected from the probability density function with a $\chi^2$ distribution shown in Figure 4-4. Using this distribution, the probability of having an oscillation growth rate greater than 1.10 is approximately 50% which is conservative relative to actual experience.

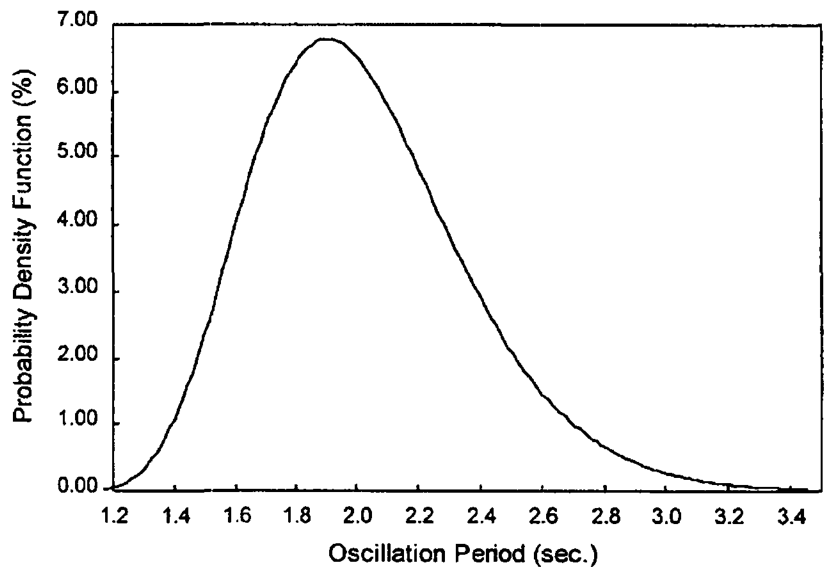
**Figure 4-4: Growth Rate Distribution**




**Overshoot:** The trip setpoint overshoot is a measure of how much an oscillation exceeds the trip setpoint. As defined in Section 4.3.2.1, the overshoot is the fraction of the peak-to-peak difference between two consecutive cycles which is above the setpoint, when a trip occurs. Thus, $0.0 \leq \delta \leq 1.0$; and the value of $\delta$ can be considered to be essentially random. Therefore, a uniform distribution is selected for the random overshoot in the statistical methodology.

**Oscillation Period:** It is indicated in Reference 1 that the statistical methodology will consider a range of oscillation periods. Studies of actual instability events indicate that the expected value for the period is approximately 1.8 to 2.0 seconds. However, it is desirable to consider an oscillation frequency range between 0.7 Hz and 0.3 Hz (Reference 1). This corresponds to a desired period range of 1.4 sec $\leq$ T $\leq$ 3.3 sec. For the statistical model, an oscillation period is randomly selected from the probability density function with a $\chi^2$ distribution shown in Figure 4-5. The distribution has a mean period of approximately 2.0 seconds, and there is greater than 97% probability of having an oscillation period inside of the desired period range.

**Figure 4-5: Oscillation Period Distribution**




**LPRM Failures:** No LPRM failures are assumed in the Monte Carlo analysis. Sensitivity studies presented in Section 4.3.5.2 show that random LPRM failures reduce the peak hot bundle oscillation magnitude. Thus, it is conservative to assume there are no failures for Option III licensing analyses.

**Oscillation Contours:** The contour is used as a plant-specific input to the statistical methodology. This input is plant type specific due to the impact of different core sizes. However, previous studies (Reference 1) have indicated that the contour shape does not change appreciably for different cycles or exposures. Nevertheless, for each plant type, the 3D BWR Simulator is used to generate a representative set of oscillation contours at different exposures for a typical cycle. These contours are representative of the plant being analyzed and are not regenerated on a cycle-specific basis. At each exposure, an orthogonal pair of first-order side-by-side regional harmonics is calculated by the 3D Simulator. In a plant-specific calculation, six (6) contours are typically used. For each "trial" in a Monte Carlo statistical analysis, one of the plant-specific contours is randomly selected.

#### 4.3.2.5 Deterministic Inputs

The deterministic inputs to the Monte Carlo analysis are discussed in this section. The bases for these inputs are also discussed.

**LPRM Assignments and Trip System Definition:** The LPRM assignments and trip system definition identify which LPRMs are assigned to which OPRM cell. The LPRM assignment has a significant effect on the calculated hot bundle oscillation magnitude. Essentially, the number and location of the LPRMs assigned to each OPRM cell strongly affects the response of the OPRM to an oscillation. Fewer LPRMs per cell generally results in a greater response of that cell to an oscillation. Thus, choice of LPRM assignments represents a compromise between a system that is too sensitive and one that is not sensitive enough. For example, one LPRM per OPRM cell may increase the probability of spurious trips, whereas a cell with greater than 8 LPRMs may not be responsive enough to a growing oscillation. Furthermore, the assignment of LPRMs is restricted by the plant-specific hardware configuration. Thus, the LPRM assignment is a plant-specific input in the statistical methodology.

**Trip Setpoint:** The normalized (peak/average) oscillation magnitude setpoint, $S_p$, at which the trip will occur is input to the statistical calculation. For anticipated oscillations, the Option III Period Based Detection Algorithm (PBDA) reaches the required number of period confirmations prior to reaching $S_p$.

**RPS Trip Logic:** The plant-specific trip logic is input to the statistical model. It is either a one-out-of-two, taken twice, or a two-out-of-four trip logic. The trip system has two divisions, A and B, and two channels within each division, [A1, A2] and [B1, B2]. For a one-out-of-two, taken twice trip logic, at least one channel from [A1, A2] and at least one channel from [B1, B2] must reach $S_p$ for the trip signal to be generated. For a two-out-of-four trip logic, any two channels from [A1, A2, B1, and B2] must reach $S_p$ for the trip signal to be generated.

**OPRM Channel Failure:** The failure of one of the four OPRM channels (A1, A2, B1, and B2) is considered. The model provides several options: no OPRM channel failure, failure of a specific channel, failure of a channel at random, and failure of the most responsive channel. For conservatism, only the "most responsive channel" failure is considered. The "most responsive channel" is defined as the channel containing the most responsive OPRM cell.

**Delay Time:** The delay time for control rod insertion to terminate oscillation growth is input to the model. The time at which the reactor trip criterion is reached plus the delay time sets the time window in which the peak hot bundle oscillation magnitude can occur. The delay time is a plant-specific input which includes the Option III hardware processing time, the RPS processing time, the control rod drive delay time before rod motion begins, and the time for control rods to insert two (2) feet into the core assuming control rods insert at the minimum scram speed allowed by the plant Technical Specifications. Even though control rod insertion two feet into the core will not shut the reactor down, it is judged to be adequate to prevent further growth of the hot bundle oscillation.

### 4.3.3 SAMPLE SINGLE TRIAL CALCULATIONS

This section presents several sample calculations to demonstrate the application of the oscillation model. Each case represents one "trial" in the Monte Carlo statistical calculation. Unless otherwise indicated, the following parameters were used in all cases:

| | |
|---|---|
| Plant: | BWR-4, 764 assembly |
| LPRM assignment: | 4-LPRMs per OPRM cell |
| Oscillation period: | T=2.0 seconds |
| Growth rate: | $G_r$=1.16 |
| First-peak overshoot: | $\delta$=0.3 |
| Total delay time: | 1.300 seconds |
| APRM channel failure: | none |
| Trip logic: | one-out-of-two, taken twice. |

The total delay time for the sample trial calculations is composed of (1) 0.400 second Option III hardware processing time, (2) 0.050 second RPS processing time, (3) 0.200 second delay time before the start of control rod motion, and (4) 0.615 second for control rod insertion to 2 feet at a speed of 3.25 ft/sec. The total delay time is rounded up to 1.300 seconds.

### 4.3.3.1 Trial 1- No LPRM Failures

This is the base case in which all LPRMs are operable and all OPRM channels are operable. The calculation simulates the oscillation periods near the time of reactor trip. Listed in Table 4-1 is the information pertaining to the first four OPRM cell signals that exceed the trip setpoint. The overshoot times are measured from the start of the simulation. In this case, cell OPRM B2-9 is the most responsive cell, generating the first half-trip signal at t = 4.1756 sec. The next two cells that exceed the setpoint are disregarded because they belong to the same trip division. A full-trip is complete only when cell A2-23 (Division A) crosses the setpoint at t = 5.1160 sec.

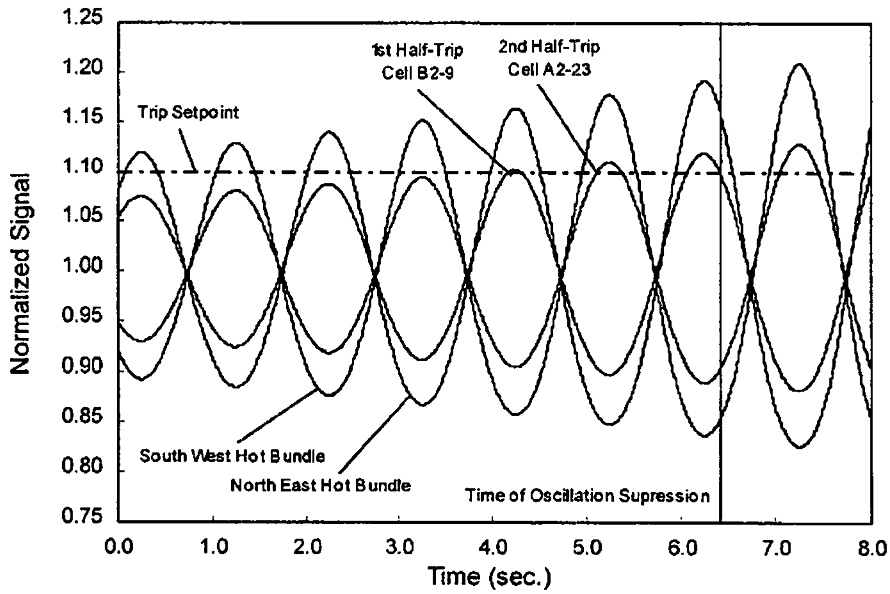
Figure 4-6 plots the oscillation signals from two of the above four OPRM cells: the cell that generates the first half-trip (B2-9) and the cell that generates the second half-trip (A2-23). Plots of the two hot bundle oscillation signals, which are 180° out of phase with each other, are also presented. The vertical line represents the time at which the oscillation is effectively suppressed, $t_f$ = 6.4160 sec, taking into account the delay time of 1.300 sec. Oscillation peaks which occur later than this time are ignored, since the scram would have suppressed the oscillation. The maximum calculated $\Delta_h$ for this case is 0.356 from the North-East hot bundle.

If a two-out-of-four trip logic is applied to this case, the OPRM channel Divisions A and B are disregarded. The first half-trip and full-trip signals can be from any two of the four channels. Under this condition, the full-trip signal would be generated by channel B1 (Table 4.3.2) at t = 4.1798 sec. and the suppression time is $t_f$ = 5.4798 sec. The maximum $\Delta_h$ would be only 0.330 from the South-West hot bundle.

**Table 4-1: Trial 1 - Trip Time Without LPRM Failures**

| Division | OPRM Channel | OPRM Cell | Assigned LPRMs | Operable LPRMs | Overshoot Time (sec) |
|---|---|---|---|---|---|
| B | B2 | OPRM B2-9 | 33, 35, 62, 64 | 33, 35, 62, 64 | 4.1756 |
| B | B1 | OPRM B1-9 | 34, 36, 61, 63 | 34, 36, 61, 63 | 4.1798 |
| B | B2 | OPRM B2-15 | 62, 64, 93, 95 | 62, 64, 93, 95 | 4.2096 |
| A | A2 | OPRM A2-23 | 98, 100, 129, 131 | 98, 100, 129, 131 | 5.1160 |

**Figure 4-6: Trial 1 - OPRM System Trip Without Failures**




### 4.3.3.2 Trial 2 - Most Responsive OPRM Channel Failure

Trial 2 is identical to Trial 1 except for a failure of the most responsive OPRM channel. In this particular example, the results are unchanged from Trial 1. This is shown in Table 4-2. When the most responsive Channel, B2, fails, the first half-trip signal is generated by Channel B1, which contains the next most responsive OPRM cell (B1-9). Since both B2 and B1 are in the same trip division, the full-trip signal is still generated by Channel A2 at t = 5.1160 sec. The resulting maximum $\Delta_h$ at time of suppression thus remains the same as in Trial 1. This identical result is not always the case, although the redundancy of the Option III solution (i.e., many overlapping OPRM cells) will cause the system to be relatively insensitive to an OPRM channel failure.

**Table 4-2: Trial 2 - Trip Time With Most Responsive Channel Failure**

| Division | OPRM Channel | OPRM Cell | Assigned LPRMs | Operable LPRMs | Overshoot Time (sec) |
|---|---|---|---|---|---|
| B | B2 (fail) | OPRM B2-9 | 33, 35, 62, 64 | 33, 35, 62, 64 | 4.1756 |
| B | B1 | OPRM B1-9 | 34, 36, 61, 63 | 34, 36, 61, 63 | 4.1798 |
| B | B2 (fail) | OPRM B2-15 | 62, 64, 93, 95 | 62, 64, 93, 95 | 4.2096 |
| A | A2 | OPRM A2-23 | 98, 100, 129, 131 | 98, 100, 129, 131 | 5.1160 |

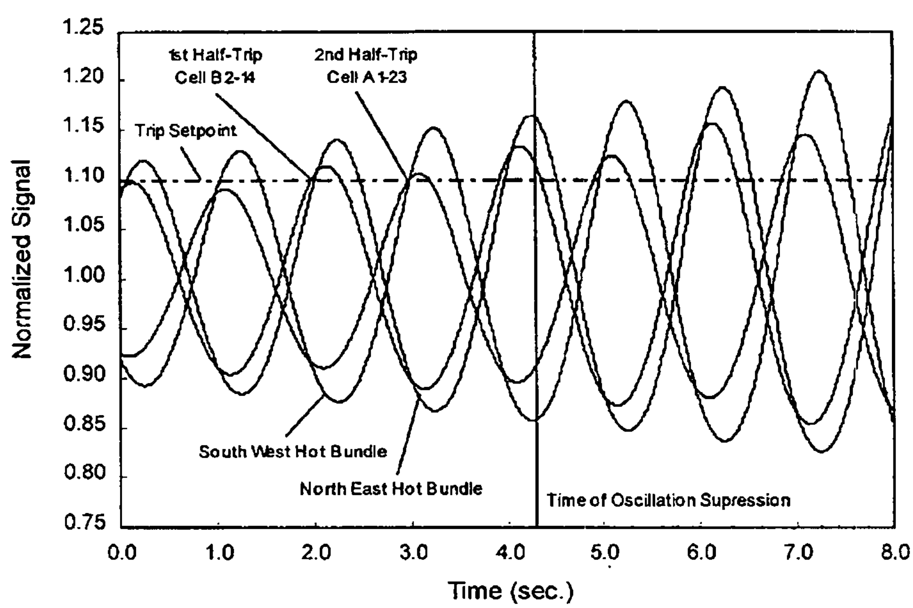
### 4.3.3.3 Trial 3 - LPRM Failures

In Trial 3, selected LPRMs are failed to study the effect on trip time and calculated $\Delta_h$. Table 4-3 shows that, as LPRMs 33, 35, 64, 85, and 87 fail, OPRM cells B2-9 and B2-14 become single-LPRM cells. Since single LPRM cells tend to be more sensitive than four LPRM cells, the LPRM failures make cells B2-9 and B2-14 more sensitive than their original 4-LPRM cells. Thus, the first half-trip is generated earlier than in Trial 1. Similarly, an earlier second half-trip is generated by a 2-LPRM cell (A1-23) at t = 2.9922 sec. Compared to the base case, the time of oscillation suppression occurs approximately one cycle earlier ($t_f$ = 4.2922 sec.). The corresponding maximum hot bundle oscillation magnitude is $\Delta_h$=0.306. System responses for Trial 3 are illustrated in Figure 4-7.

**Table 4-3: Trial 3 - Trip Time With LPRM Failures**

| Division | OPRM Channel | OPRM Cell | Assigned LPRMs | Operable LPRMs | Overshoot Time (sec) |
|---|---|---|---|---|---|
| B | B2 | OPRM B2-14 | 85, 87, 62, 64 | 62 | 1.9849 |
| B | B2 | OPRM B2-9 | 33, 35, 62, 64 | 62 | 1.9849 |
| A | A1 | OPRM A1-23 | 97, 99, 130, 132 | 97, 130 | 2.9922 |

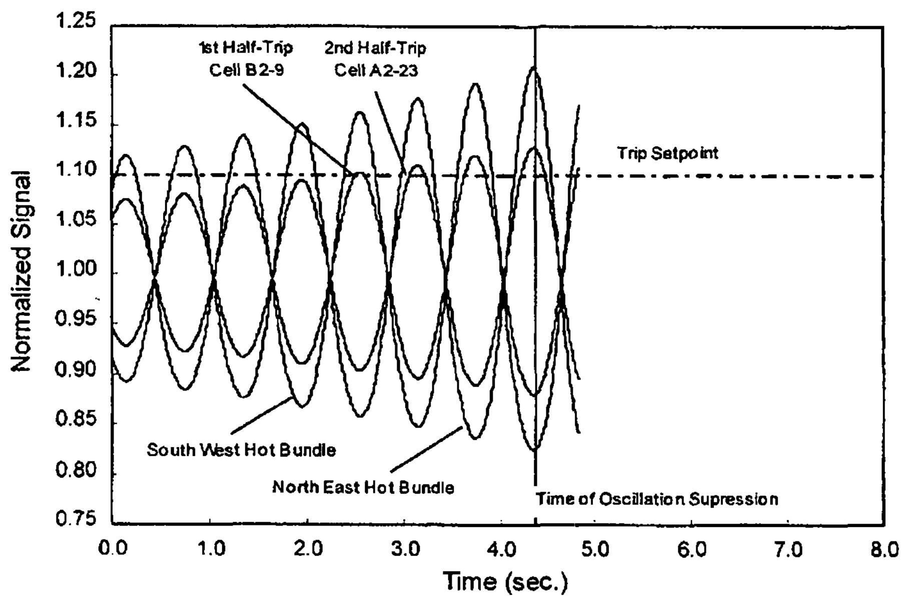
**Figure 4-7: Trial 3 - OPRM System Trip With LPRM Failures**



### 4.3.3.4: Trial 4 - Short Oscillation Period Without LPRM Failures

Trial 4 examines the effect of oscillation period. As the period is shortened from 2.0 sec to 1.2 sec, the OPRM cell trip times exhibit the same chronological order as the base case. However, the total delay time remains constant at 1.300 sec. Thus, the oscillation can go through more cycles prior to oscillation suppression. The result is a higher hot bundle oscillation magnitude, $\Delta_h$ = 0.383, at time of oscillation suppression. This is shown in Figure 4-8.

**Figure 4-8: Trial 4 - OPRM System Trip With Short Period**




### 4.3.4 STATISTICAL MODEL SAMPLE CALCULATIONS

The sample calculations in the previous section represent individual trials using single value inputs for period, growth rate, overshoot, and contour. The two examples presented below are full, 1000 trial statistical calculations to construct a distribution for the hot bundle oscillation magnitude, $\Delta_h$.

In both examples, no LPRM or APRM failures are considered, and the most responsive OPRM channel is assumed to fail for every trial. One thousand trials are used in each example. The results from these trials are listed in ascending order of $\Delta_h$ and the 39$^{th}$ highest value corresponds to the 95/95 value (Reference 5).

Example 1 models a 764-bundle BWR-4 with appropriate contours, a 4-LPRM per cell assignment, and one-out-of-two, taken-twice logic. Table 4-4 lists the key inputs. Table 4-5 gives the 50 highest calculated values of $\Delta_h$ and the 95/95 value (= 0.365).

Example 2 models a 560-bundle BWR-4 with appropriate contours, a 3-LPRM per cell assignment, and two-out-of-four logic. Table 4-6 lists the key inputs. Table 4-7 gives the 50 highest calculated values of $\Delta_h$ and the 95/95 value (= 0.310).

The two examples demonstrate that, for a given LPRM assignment, the hot bundle oscillation magnitude at time of oscillation suppression generally correlates to the growth rate (i.e., a higher growth rate tends to produce a higher $\Delta_h$). The oscillation period and trip overshoot have lesser effects on $\Delta_h$.

**Table 4-4: Example 1 Inputs for Sample Hot Bundle Oscillation Magnitude Calculation**

| | |
|---|---|
| BWR-4, 764-bundle core | |
| Trip System: | OPRM / 4 LPRMs per OPRM cell |
| Trip Logic: | ONE-OUT-OF-TWO, TAKEN TWICE |
| Oscillation Mode: | REGIONAL |
| APRM Channel Failure: | NONE |
| OPRM Channel Failure: | Most Responsive OPRM channel (applied to all trials) |
| LPRM Failures: | NONE |
| Period T: | RANDOM (Chi-Square Distribution, see Figure 4-5) |
| Growth Rate, Gr: | RANDOM (Chi-Square Distribution, see Figure 4-4) |
| Overshoot, $\delta$: | RANDOM (Uniform Distribution) |
| Trip setpoint: | Sp = 1.10 |
| Total Delay Time : | 1300 msec. (measured from time of full trip) |
| Total Number of LPRMs: | 172 |
| Oscillation Contour Selection: | RANDOM; Contour names: KR1BEQAH1, KR1BEQAH2, KR1MEQAH1, KR1MEQAH2, KR1EEQAH1, KR1EEQAH2 |

## Table 4-5: Example 1 Output for Sample Hot Bundle Oscillation Magnitude Calculation (*)

| TRIAL | CONTOUR | T (sec) | GR | OVRSHT | RNDM LPRM FAIL | APRM CHNL FAIL | TOTAL LPRM FAIL | % LPRM FAIL | OPRM CHNL FAIL | HOT (P-M)/A |
|---|---|---|---|---|---|---|---|---|---|---|
| 313 | KR1MEQAH2 | 1.84 | 1.19 | 0.29 | 0 | - | 0 | 0 | B2 | 0.358 |
| 694 | KR1EEQAH2 | 1.75 | 1.16 | 0.87 | 0 | - | 0 | 0 | A2 | 0.358 |
| 656 | KR1BEQAH1 | 1.90 | 1.21 | 0.74 | 0 | - | 0 | 0 | A1 | 0.360 |
| 228 | KR1MEQAH1 | 1.30 | 1.22 | 0.54 | 0 | - | 0 | 0 | B1 | 0.360 |
| 501 | KR1EEQAH2 | 2.20 | 1.19 | 0.74 | 0 | - | 0 | 0 | B1 | 0.361 |
| 986 | KR1EEQAH2 | 1.43 | 1.20 | 0.23 | 0 | - | 0 | 0 | B2 | 0.363 |
| 617 | KR1EEQAH2 | 1.60 | 1.19 | 0.30 | 0 | - | 0 | 0 | B2 | 0.363 |
| 742 | KR1MEQAH1 | 1.73 | 1.17 | 0.73 | 0 | - | 0 | 0 | B2 | 0.363 |
| 727 | KR1MEQAH1 | 1.93 | 1.20 | 0.14 | 0 | - | 0 | 0 | B2 | 0.364 |
| 648 | KR1EEQAH2 | 1.71 | 1.17 | 0.93 | 0 | - | 0 | 0 | A2 | 0.364 |
| 420 | KR1EEQAH2 | 2.11 | 1.21 | 0.24 | 0 | - | 0 | 0 | B2 | 0.365 |
| 368 | KR1BEQAH2 | 1.59 | 1.30 | 0.27 | 0 | - | 0 | 0 | A2 | 0.365 |
| | HOT BUNDLE (P-M)/A AT 95/95 LEVEL = 0.365 | | | | | | | | | |
| 925 | KR1EEQAH2 | 1.52 | 1.18 | 0.86 | 0 | - | 0 | 0 | A2 | 0.365 |
| 186 | KR1EEQAH2 | 2.17 | 1.16 | 0.52 | 0 | - | 0 | 0 | B2 | 0.366 |
| 385 | KR1MEQAH2 | 1.86 | 1.17 | 0.53 | 0 | - | 0 | 0 | B2 | 0.366 |
| 177 | KR1EEQAH2 | 1.83 | 1.15 | 0.60 | 0 | - | 0 | 0 | B1 | 0.367 |
| 819 | KR1MEQAH2 | 1.91 | 1.22 | 0.80 | 0 | - | 0 | 0 | B1 | 0.367 |
| 478 | KR1MEQAH2 | 1.98 | 1.17 | 0.56 | 0 | - | 0 | 0 | B2 | 0.367 |
| 605 | KR1EEQAH2 | 2.40 | 1.24 | 0.68 | 0 | - | 0 | 0 | B1 | 0.367 |
| 25 | KR1EEQAH2 | 1.96 | 1.19 | 0.86 | 0 | - | 0 | 0 | A2 | 0.368 |
| 849 | KR1MEQAH1 | 1.59 | 1.21 | 0.17 | 0 | - | 0 | 0 | B2 | 0.368 |
| 606 | KR1EEQAH2 | 2.22 | 1.17 | 0.46 | 0 | - | 0 | 0 | B2 | 0.368 |
| 614 | KR1MEQAH2 | 2.19 | 1.20 | 0.40 | 0 | - | 0 | 0 | B2 | 0.369 |
| 756 | KR1MEQAH1 | 2.22 | 1.25 | 0.07 | 0 | - | 0 | 0 | B2 | 0.369 |
| 13 | KR1MEQAH2 | 2.01 | 1.20 | 0.40 | 0 | - | 0 | 0 | B2 | 0.369 |
| 782 | KR1MEQAH1 | 2.13 | 1.22 | 0.18 | 0 | - | 0 | 0 | B2 | 0.372 |
| 200 | KR1MEQAH1 | 1.91 | 1.18 | 0.83 | 0 | - | 0 | 0 | B2 | 0.372 |
| 839 | KR1BEQAH2 | 2.21 | 1.31 | 0.31 | 0 | - | 0 | 0 | A1 | 0.372 |
| 373 | KR1MEQAH2 | 1.32 | 1.25 | 0.28 | 0 | - | 0 | 0 | B2 | 0.372 |
| 864 | KR1MEQAH2 | 2.20 | 1.27 | 0.73 | 0 | - | 0 | 0 | B2 | 0.373 |
| 862 | KR1EEQAH2 | 1.59 | 1.19 | 0.48 | 0 | - | 0 | 0 | B2 | 0.374 |
| 748 | KR1EEQAH1 | 1.91 | 1.27 | 0.90 | 0 | - | 0 | 0 | B1 | 0.375 |

*** Note that these are the 50 trials having the largest calculated values of hot bundle (P-M)/A. The remaining 950 trials had smaller values of hot bundle (P-M)/A.**

## Table 4-5 (Continued)

| TRIAL | CONTOUR | T (sec) | GR | OVRSHT | RNDM LPRM FAIL | APRM CHNL FAIL | TOTAL LPRM FAIL | % LPRM FAIL | OPRM CHNL FAIL | HOT (P-M)/A |
|---|---|---|---|---|---|---|---|---|---|---|
| 768 | KR1MEQAH2 | 1.75 | 1.19 | 0.57 | 0 | - | 0 | 0 | B2 | 0.375 |
| 973 | KR1EEQAH2 | 1.75 | 1.20 | 0.48 | 0 | - | 0 | 0 | B2 | 0.377 |
| 256 | KR1BEQAH1 | 2.08 | 1.29 | 0.73 | 0 | - | 0 | 0 | A1 | 0.379 |
| 773 | KR1EEQAH2 | 1.88 | 1.22 | 0.89 | 0 | - | 0 | 0 | A2 | 0.379 |
| 741 | KR1EEQAH2 | 1.98 | 1.19 | 0.55 | 0 | - | 0 | 0 | B2 | 0.379 |
| 73 | KR1EEQAH2 | 2.06 | 1.21 | 0.45 | 0 | - | 0 | 0 | B2 | 0.380 |
| 413 | KR1EEQAH2 | 2.06 | 1.18 | 0.61 | 0 | - | 0 | 0 | B1 | 0.381 |
| 191 | KR1EEQAH2 | 1.92 | 1.23 | 0.42 | 0 | - | 0 | 0 | B2 | 0.384 |
| 440 | KR1BEQAH1 | 2.00 | 1.30 | 0.75 | 0 | - | 0 | 0 | A1 | 0.384 |
| 439 | KR1EEQAH2 | 2.19 | 1.23 | 0.48 | 0 | - | 0 | 0 | B2 | 0.388 |
| 267 | KR1MEQAH2 | 1.89 | 1.23 | 0.61 | 0 | - | 0 | 0 | B2 | 0.396 |
| 311 | KR1MEQAH1 | 1.68 | 1.32 | 0.22 | 0 | - | 0 | 0 | B2 | 0.398 |
| 68 | KR1EEQAH2 | 2.08 | 1.44 | 0.62 | 0 | - | 0 | 0 | B1 | 0.402 |
| 568 | KR1EEQAH2 | 1.33 | 1.39 | 0.21 | 0 | - | 0 | 0 | A2 | 0.406 |
| 681 | KR1BEQAH2 | 1.47 | 1.37 | 0.46 | 0 | - | 0 | 0 | A1 | 0.407 |
| 45 | KR1MEQAH2 | 1.97 | 1.39 | 0.35 | 0 | - | 0 | 0 | B1 | 0.418 |
| 551 | KR1BEQAH1 | 1.91 | 1.41 | 0.80 | 0 | - | 0 | 0 | A1 | 0.420 |
| 936 | KR1MEQAH1 | 1.69 | 1.36 | 0.88 | 0 | - | 0 | 0 | B1 | 0.431 |
| | MINIMUM | 1.27 | 1.00 | 0.00 | 0 | | 0 | 0.0 | | 0.289 |
| | MAXIMUM | 3.67 | 1.44 | 1.00 | 0 | | 0 | 0.0 | | 0.431 |
| | AVERAGE | 2.04 | 1.10 | 0.49 | 0 | | 0 | 0.0 | | 0.320 |

**Table 4-6: Example 2 Inputs for Sample Hot Bundle Oscillation Magnitude Calculation**

| | |
|---|---|
| BWR-4, 560-bundle core | |
| Trip System: | OPRM / 3 LPRMs per OPRM cell |
| Trip Logic: | TWO-OUT-OF-FOUR |
| Oscillation Mode: | REGIONAL |
| APRM Channel Failure: | NONE |
| OPRM Channel Failure: | Most Responsive OPRM channel (applied to all trials) |
| LPRM Failures: | NONE |
| Period T: | RANDOM (Chi-Square Distribution, see Figure 4-5) |
| Growth Rate, Gr: | RANDOM (Chi-Square Distribution, see Figure 4-4) |
| Overshoot, $\delta$: | RANDOM (Uniform Distribution) |
| Trip setpoint: | Sp = 1.10 |
| Total Delay Time : | 1300 msec. (measured from time of full trip) |
| Total Number of LPRMs: | 124 |
| Oscillation Contour Selection: | RANDOM; Contour names: HT1H12AH1, HT1H12AH2, HT1B12AH1, HT1B12AH2, HT2M09AH1, HT2M09AH2 |

## Table 4-7: Example 2 Output for Sample Hot Bundle Oscillation Magnitude Calculation (*)

| TRIAL | CONTOUR | T (sec) | GR | OVRSHT | RNDM LPRM FAIL | APRM CHNL FAIL | TOTAL LPRM FAIL | % LPRM FAIL | OPRM CHNL FAIL | HOT (P-M)/A |
|---|---|---|---|---|---|---|---|---|---|---|
| 543 | HT2M09AH2 | 2.35 | 1.16 | 0.28 | 0 | - | 0 | 0 | A1 | 0.306 |
| 306 | HT1H12AH2 | 2.07 | 1.15 | 0.97 | 0 | - | 0 | 0 | B2 | 0.306 |
| 313 | HT1B12AH2 | 1.84 | 1.19 | 0.29 | 0 | - | 0 | 0 | A1 | 0.306 |
| 278 | HT2M09AH2 | 2.37 | 1.16 | 0.27 | 0 | - | 0 | 0 | A1 | 0.307 |
| 798 | HT2M09AH1 | 1.48 | 1.22 | 0.61 | 0 | - | 0 | 0 | A2 | 0.308 |
| 542 | HT1H12AH2 | 1.67 | 1.20 | 0.67 | 0 | - | 0 | 0 | A1 | 0.308 |
| 698 | HT2M09AH1 | 1.49 | 1.16 | 0.84 | 0 | - | 0 | 0 | A2 | 0.308 |
| 605 | HT2M09AH2 | 2.40 | 1.24 | 0.68 | 0 | - | 0 | 0 | B1 | 0.309 |
| 555 | HT1H12AH2 | 2.08 | 1.20 | 0.17 | 0 | - | 0 | 0 | B2 | 0.309 |
| 986 | HT2M09AH2 | 1.43 | 1.20 | 0.23 | 0 | - | 0 | 0 | A1 | 0.309 |
| 501 | HT2M09AH2 | 2.20 | 1.19 | 0.74 | 0 | - | 0 | 0 | B2 | 0.310 |
| 457 | HT1H12AH2 | 1.72 | 1.17 | 0.91 | 0 | - | 0 | 0 | B2 | 0.310 |
| | HOT BUNDLE (P-M)/A AT 95/95 LEVEL = 0.310 | | | | | | | | | |
| 420 | HT2M09AH2 | 2.11 | 1.21 | 0.24 | 0 | - | 0 | 0 | A1 | 0.311 |
| 839 | HT1H12AH2 | 2.21 | 1.31 | 0.31 | 0 | - | 0 | 0 | B2 | 0.311 |
| 617 | HT2M09AH2 | 1.60 | 1.19 | 0.30 | 0 | - | 0 | 0 | A1 | 0.311 |
| 1000 | HT1H12AH2 | 2.15 | 1.23 | 0.07 | 0 | - | 0 | 0 | B2 | 0.312 |
| 957 | HT2M09AH1 | 2.08 | 1.22 | 0.18 | 0 | - | 0 | 0 | B1 | 0.312 |
| 742 | HT1B12AH1 | 1.73 | 1.17 | 0.73 | 0 | - | 0 | 0 | B1 | 0.312 |
| 538 | HT1H12AH2 | 1.68 | 1.17 | 0.93 | 0 | - | 0 | 0 | B2 | 0.312 |
| 116 | HT2M09AH1 | 1.97 | 1.26 | 0.60 | 0 | - | 0 | 0 | A2 | 0.313 |
| 356 | HT2M09AH1 | 1.45 | 1.16 | 0.91 | 0 | - | 0 | 0 | B2 | 0.314 |
| 242 | HT2M09AH1 | 2.15 | 1.17 | 0.91 | 0 | - | 0 | 0 | B2 | 0.314 |
| 440 | HT1H12AH1 | 2.00 | 1.30 | 0.75 | 0 | - | 0 | 0 | A2 | 0.314 |
| 819 | HT1B12AH2 | 1.91 | 1.22 | 0.80 | 0 | - | 0 | 0 | B2 | 0.314 |
| 311 | HT1B12AH1 | 1.68 | 1.32 | 0.22 | 0 | - | 0 | 0 | B1 | 0.315 |
| 13 | HT1B12AH2 | 2.01 | 1.20 | 0.40 | 0 | - | 0 | 0 | B1 | 0.316 |
| 733 | HT2M09AH1 | 1.94 | 1.22 | 0.72 | 0 | - | 0 | 0 | A2 | 0.316 |
| 618 | HT2M09AH1 | 1.47 | 1.24 | 0.67 | 0 | - | 0 | 0 | A2 | 0.316 |
| 256 | HT2M09AH2 | 2.08 | 1.29 | 0.73 | 0 | - | 0 | 0 | B1 | 0.316 |
| 228 | HT1B12AH1 | 1.30 | 1.22 | 0.54 | 0 | - | 0 | 0 | B1 | 0.316 |
| 373 | HT1B12AH2 | 1.32 | 1.25 | 0.28 | 0 | - | 0 | 0 | A1 | 0.318 |
| 398 | HT2M09AH1 | 2.03 | 1.21 | 0.79 | 0 | - | 0 | 0 | A2 | 0.318 |

*** Note that these are the 50 trials having the largest calculated values of hot bundle (P-M)/A. The remaining 950 trials had smaller values of hot bundle (P-M)/A.**

## Table 4-7 (Continued)

| TRIAL | CONTOUR | T (sec) | GR | OVRSHT | RNDM LPRM FAIL | APRM CHNL FAIL | TOTAL LPRM FAIL | % LPRM FAIL | OPRM CHNL FAIL | HOT (P-M)/A |
|---|---|---|---|---|---|---|---|---|---|---|
| 864 | HT1B12AH2 | 2.20 | 1.27 | 0.73 | 0 | - | 0 | 0 | A1 | 0.319 |
| 978 | HT1H12AH2 | 1.50 | 1.21 | 0.82 | 0 | - | 0 | 0 | A1 | 0.320 |
| 768 | HT1B12AH2 | 1.75 | 1.19 | 0.57 | 0 | - | 0 | 0 | B1 | 0.321 |
| 773 | HT2M09AH2 | 1.88 | 1.22 | 0.89 | 0 | - | 0 | 0 | B2 | 0.322 |
| 745 | HT2M09AH1 | 2.22 | 1.28 | 0.15 | 0 | - | 0 | 0 | B1 | 0.323 |
| 973 | HT2M09AH2 | 1.75 | 1.20 | 0.48 | 0 | - | 0 | 0 | B1 | 0.323 |
| 73 | HT2M09AH2 | 2.06 | 1.21 | 0.45 | 0 | - | 0 | 0 | A1 | 0.323 |
| 191 | HT2M09AH2 | 1.92 | 1.23 | 0.42 | 0 | - | 0 | 0 | A1 | 0.324 |
| 439 | HT2M09AH2 | 2.19 | 1.23 | 0.48 | 0 | - | 0 | 0 | A1 | 0.328 |
| 447 | HT1H12AH1 | 1.92 | 1.28 | 0.49 | 0 | - | 0 | 0 | A1 | 0.330 |
| 267 | HT1B12AH2 | 1.89 | 1.23 | 0.61 | 0 | - | 0 | 0 | B1 | 0.338 |
| 748 | HT2M09AH1 | 1.91 | 1.27 | 0.90 | 0 | - | 0 | 0 | A2 | 0.340 |
| 936 | HT1B12AH1 | 1.69 | 1.36 | 0.88 | 0 | - | 0 | 0 | A2 | 0.341 |
| 681 | HT1H12AH2 | 1.47 | 1.37 | 0.46 | 0 | - | 0 | 0 | A1 | 0.343 |
| 551 | HT1H12AH1 | 1.91 | 1.41 | 0.80 | 0 | - | 0 | 0 | A2 | 0.348 |
| 45 | HT1B12AH2 | 1.97 | 1.39 | 0.35 | 0 | - | 0 | 0 | A1 | 0.350 |
| 68 | HT2M09AH2 | 2.08 | 1.44 | 0.62 | 0 | - | 0 | 0 | A1 | 0.384 |
| 568 | HT2M09AH2 | 1.33 | 1.39 | 0.21 | 0 | - | 0 | 0 | B2 | 0.386 |
| | MINIMUM | 1.27 | 1.00 | 0.00 | 0 | | 0 | 0.0 | | 0.250 |
| | MAXIMUM | 3.67 | 1.44 | 1.00 | 0 | | 0 | 0.0 | | 0.386 |
| | AVERAGE | 2.04 | 1.10 | 0.49 | 0 | | 0 | 0.0 | | 0.277 |

### 4.3.5 SENSITIVITY STUDIES

Several studies were conducted to establish the sensitivity of the 95/95 value of hot bundle oscillation magnitude to key input parameters: LPRM assignment, LPRM failure, and trip logic. For the purpose of these studies, the two examples discussed in Section 4.3.4 are used as the base cases.

#### 4.3.5.1 Effect of LPRM Assignments

The LPRM-to-OPRM assignment has a large impact on the hot bundle oscillation magnitude. Table 4-8 shows the change in the $\Delta_{h(95/95)}$ among seven different trip configurations using the 560 bundle, BWR-4 contours. The LPRM assignment for each of these configurations is shown in Appendix D. A higher $\Delta_{h(95/95)}$ value indicates a less sensitive system response. As expected, the trip system sensitivity decreases if a large number of LPRM signals are averaged to make one OPRM cell.

The number of LPRMs per cell, however, is not solely responsible for the change in the system response. The 4W configuration which combines 4 LPRMs (one at each level) in a diamond shape is the least sensitive among the 4-LPRM cell designs. On the other hand, the 4P design is more responsive because it combines LPRMs that are closer together. Thus, both the number and location of the LPRMs that are grouped to form an OPRM cell affect the calculated $\Delta_{h(95/95)}$.

To demonstrate that the sensitivity to number of LPRMs per cell is not plant dependent, the 4BL and 2BL designs were evaluated for the 764 bundle BWR-4. Results, shown in Table 4-9, show the same sensitivity.

**Table 4-8: Effect of LPRM Assignment on Hot Bundle Oscillation Magnitude, 560-Bundle Core**

| LPRM Assignment | 8W | 4W | 4BL | 4P | 3M | 2W | 2BL |
|---|---|---|---|---|---|---|---|
| $\Delta_{h(95/95)}$ | 0.447 | 0.401 | 0.351 | 0.319 | 0.310 | 0.323 | 0.314 |

**Table 4-9: Effect of LPRM Assignment on Hot Bundle Oscillation Magnitude, 764-Bundle Core**

| LPRM Assignment | 4BL | 2BL |
|---|---|---|
| $\Delta_{h(95/95)}$ | 0.365 | 0.331 |

#### 4.3.5.2 Effect of LPRM Failures

The Monte Carlo methodology conservatively assumes that there are no LPRM failures. The conservatism of no LPRM failures is demonstrated through four statistical analyses, each with a different assumed LPRM failure percentage. The results of the LPRM failure sensitivity studies are reported in Tables 4-10 and 4-11.

The first case assumes no LPRM failures. The second case randomly selects the LPRM failure percentage from the probability density function with a $\chi^2$-distribution shown in Figure 4-9. This distribution has a mean failure rate of approximately 9% and is representative of plant data on LPRM failure rates as described in Reference 1. The third case applies a fixed 20% LPRMs failure percentage, and the fourth case applies a fixed 50% LPRM failure percentage. For each case which has LPRM failures, the selection of which specific LPRMs are failed is random for each trial.

**Figure 4-9: Representative LPRM Failure Distribution**

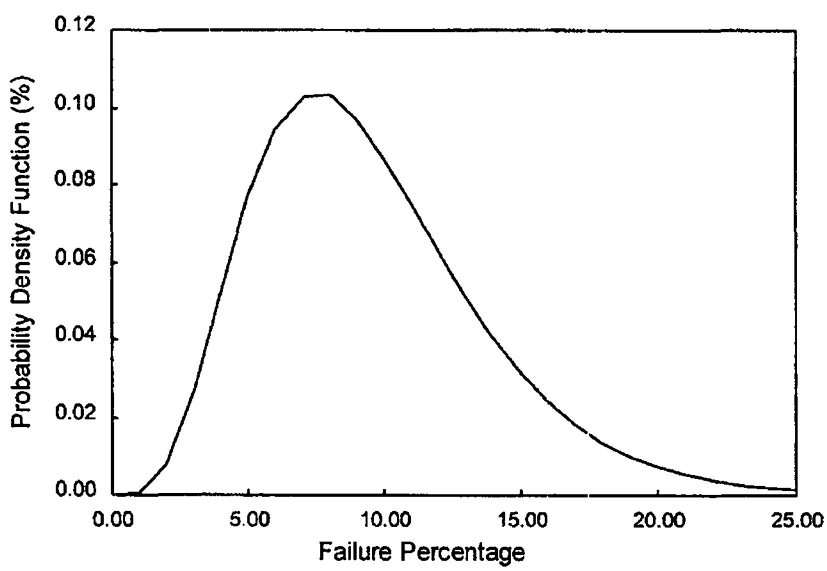


**Table 4-10: Effect of LPRM Failure on Hot Bundle Oscillation Magnitude, 560-Bundle Core, 3M LPRM Assignment**

| LPRM Failure Percentage | 0% | Variable mean=9% | 20% | 50% |
|---|---|---|---|---|
| $\Delta_{h(95/95)}$ | 0.310 | 0.307 | 0.307 | 0.290 |

**Table 4-11: Effect of LPRM Failure on Hot Bundle Oscillation Magnitude, 764-Bundle Core, 4BL LPRM Assignment**

| LPRM Failure Percentage | 0% | Variable mean=9% | 20% | 50% |
|---|---|---|---|---|
| $\Delta_{h(95/95)}$ | 0.365 | 0.360 | 0.350 | 0.328 |

The statistical results concur with results for sample Trial 1 (Section 4.3.3.3), in that the system becomes more sensitive as more OPRM cells are reduced to 2- or 1-LPRMs per cell. In a purely random selection of failed LPRMs, some cells will become less sensitive while many will become more sensitive, since fewer LPRMs per cell is inherently more sensitive. However, the trip is always triggered by the *most responsive, or most sensitive* cell. Therefore, the $\Delta_{h(95/95)}$ decreases as the number of LPRM failures increases.

This conclusion, of course, is true only within a reasonable failure rate. Nevertheless, the results show that even at a 50% failure rate, the calculated value of $\Delta_{h(95/95)}$ is less than the value assuming no LPRM failures. For conservatism, all Option III licensing analyses will be conducted assuming no LPRM failures.

#### 4.3.5.3 Effect of APRM Channel Failure

The Option III solution incorporated into the GE Power Range Neutron Monitor has a one-to-one correspondence between the APRM and OPRM channels. Since the most responsive OPRM channel is assumed to fail, this also covers the failure of an APRM channel.

In the ABB Option III solution, there is not a one-to-one correspondence between the APRM and OPRM channels. Failure of an APRM channel affects different LPRMs in more than one OPRM channel, similar to the random failure of selected LPRMs. A sample analysis of the random failure of an APRM channel showed that there is a negligible effect on the calculated value of $\Delta h_{(95/95)}$.

#### 4.3.5.4 Effect of Trip Logic

The effect of trip logic (one-out-of-two-taken-twice versus two-out-of-four) is shown in Tables 4-12 and 4-13. The sample trial (Section 4.3.3.1) shows that the two-out-of-four logic can produce an earlier scram signal, hence a lower maximum hot bundle oscillation magnitude. This result is also confirmed at the 95/95 level. However, the difference at the 95/95 level is not very significant. Thus, both trip logics provide approximately the same level of protection.

**Table 4-12: Effect of Trip Logic on Hot Bundle Oscillation Magnitude, 560-Bundle Core**

| Trip Logic | 1 out of 2 taken twice | 2 out of 4 |
|---|---|---|
| $\Delta_{h(95/95)}$ | 0.311 | 0.310 |

**Table 4-13: Effect of Trip Logic on Hot Bundle Oscillation Magnitude, 764-Bundle Core**

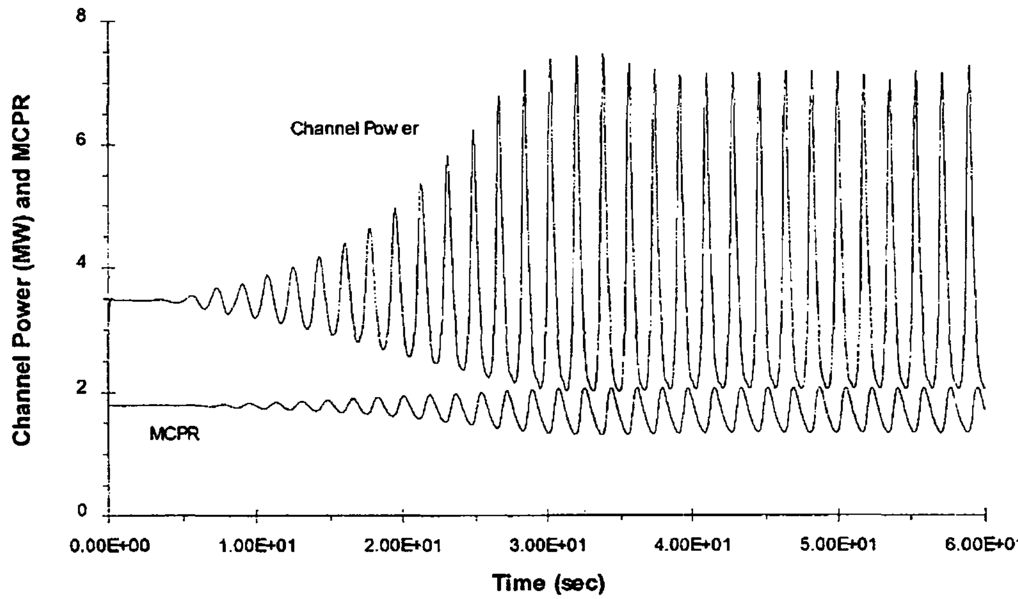
| Trip Logic | 1 out of 2 taken twice | 2 out of 4 |
|---|---|---|
| $\Delta_{h(95/95)}$ | 0.365 | 0.355 |

## 4.4 MCPR PERFORMANCE

### 4.4.1 OVERVIEW

The Option III solution methodology employs the results of 3-D TRACG calculations to determine the relative change in hot bundle CPR as a function of hot bundle oscillation magnitude. TRACG was used to perform these calculations, since it has an axially varying model of both neutronic and thermal hydraulic conditions in a reactor core, and performs a minimum CPR calculation. TRACG also has the capability to model multiple channels. The channels may be grouped according to their power distribution and the core harmonic response distribution. This allows for the calculation of a hot bundle power and flow oscillation and the corresponding CPR response. A typical response is shown in Figure 4-10.

**Figure 4-10: Typical Instability Channel Power and CPR Oscillations**




As shown in Figure 4-10, there is a MCPR decrease corresponding to each power increase. The relationship between the normalized oscillation magnitude [(P-M)/A] and the fractional change in MCPR (ΔCPR/Initial MCPR) is referred to as the DIVOM (Delta CPR Over Initial MCPR Versus Oscillation Magnitude) curve. The hot bundle DIVOM curve is used in conjunction with the other two portions of the methodology which determine the maximum hot bundle oscillation magnitude and the initial hot bundle MCPR. Significant conservatism exists in the other two portions of the methodology (Sections 4.2 and 4.3). As discussed in Section 2.1, the use of the MCPR SL is extremely conservative for protecting the fuel. These conservatisms allow for the selection of a reasonably conservative (but not necessarily bounding in all cases) hot bundle DIVOM curve to be used on a generic basis.

TRACG analyses were performed for both core wide and regional mode oscillations. Regional mode oscillations have a more limiting ΔCPR/Initial MCPR response for a given oscillation magnitude and are the basis for the generic DIVOM curve which is applied to Option III licensing analysis. The generic DIVOM curve for core wide mode oscillations is discussed in Section 7.4.2.

The generic DIVOM curve for regional mode oscillations is drawn as a linear slope with an intercept of zero ΔCPR/Initial MCPR at zero hot bundle oscillation magnitude (i.e., there is no fractional CPR change for a steady power condition). The generic DIVOM curve is intended for use in the licensing methodology for reload evaluations.

The analyses reported in this LTR are representative of all current, commercially available BWR fuel types for fractional changes in CPR versus hot bundle oscillation magnitude.

### 4.4.2 RELATION OF DIVOM TO LICENSING METHODOLOGY

An inherent conservatism has been produced by the restructuring of the NRC approved licensing methodology described in References 1 and 2. This conservatism derives from a basic, statistical fact: if values of two independent parameters, each having the same probability and confidence level, are multiplied together, the product will have a probability/confidence level higher than that of the individual parameters.

In the context of the restructured Option III methodology, the slope of the generic DIVOM curve and the hot bundle oscillation magnitude ($\Delta_{h(95/95)}$) are multiplied together to produce the limiting value of $\Delta$CPR/IMCPR. The NRC SER (Reference 3) approved use of a statistical methodology for establishing the final value of MCPR (FMCPR). The statistical evaluation of $\Delta_{h(95/95)}$ in the restructured methodology (described in this report) selects a value of hot bundle oscillation magnitude at the 95% probability with a 95% confidence level (95/95 value). Thus, use of a bounding value for the slope of the generic DIVOM curve is not necessary to produce a 95/95 value for the final MCPR. Rather, use of a reasonable value for the slope of the generic DIVOM curve would produce a FMCPR at approximately the 95/95 level, which is consistent with the NRC approved approach.

Due to the large number of factors which influence DIVOM, generation of a statistical distribution of the hot bundle DIVOM slope is not practical. However, a large number of cases were analyzed to evaluate different fuel configurations and different operating conditions. The TRACG analyses were used to produce a generic DIVOM curve having a conservative, but not necessarily bounding slope. This maintains the 95/95 level for the FMCPR calculated by the licensing methodology.

### 4.4.3 CONTRAST OF INSTABILITY EVENTS WITH TRADITIONAL LICENSING TRANSIENTS

As described in the FSAR, fuel cladding damage will be avoided during an AOO if the MCPR SL is not violated. The Generator Load Rejection without Bypass (GLRWOB) is characterized by a large fuel rod power rise of relatively short duration. The large, rapid power rise causes the GLRWOB event to approach boiling transition. Another AOO, the Rod Withdrawal Error (RWE), is characterized by a moderate fuel rod power rise that can last for several minutes before being terminated by operator action. The RWE approach to boiling transition is characterized by the long duration. Although they are quite different, both events use the MCPR SL as a basis for protecting fuel cladding integrity.

In contrast to these events, the power rise of a stability related oscillation prior to termination by the Option III hardware is very small compared to the GLRWOB and of short duration compared to the RWE.

Also, the power transient for an instability event is cyclic in nature with a frequency shorter than the fuel rod thermal time constant. Due to the responsiveness of the PBDA and Option III hardware, the hot bundle will only experience a few oscillations with a relative power higher than the setpoint prior to scram. If a rod actually experienced boiling transition, the cyclic nature of the event would result in clad rewet within a fraction of the oscillation period. A few oscillations in which the clad experienced boiling transition and then rapidly rewets would result in a nearly negligible cladding temperature transient. Therefore, use of the MCPR SL is extremely conservative in protecting the fuel for an instability event.

Another aspect relating to the conservatism of using the MCPR SL for Option III licensing compliance is that the PBDA can be less responsive to a regional mode oscillation than to a core wide mode oscillation. This fact is due to the more highly peaked harmonic power distribution of the regional mode oscillation, which results in a higher value of $\Delta_{h(95/95)}$ than for a core wide oscillation. However, the regional mode oscillation only causes a few bundles to approach the MCPR SL (peak power bundles near the peak of the oscillation). Thus, relatively few pins approach dryout conditions.

### 4.4.4 GENERIC MCPR PERFORMANCE (DIVOM) CURVE

GE's 3-D TRACG code was used to develop a generic DIVOM curve for regional mode oscillations. A generic DIVOM curve for core wide mode oscillations for application to Option I-D is provided in Section 7. Details of the TRACG methodology are given in References 1 and 2. Further discussion of the TRACG analyses used to generate the generic DIVOM curves and a description of sensitivity studies are given in Appendix B.

In TRACG, fuel bundles are grouped into "channel types" according to their oscillation magnitude (i.e., first order harmonic power distribution) and fuel type. Generally, a number of single, limiting fuel bundles (channels) are included in the model. An event is then simulated (e.g., a flow coastdown) that results in a growing reactor oscillation. The TRACG calculated bundle transient thermal hydraulic conditions are input to a bundle CPR evaluation. Thus, time dependent power and CPR responses are produced as shown in Figure 4-10. The TRACG output is processed to correlate each minimum of the time-varying CPR with the preceding channel power maximum. For each power oscillation peak, the normalized oscillation magnitude [(P-M)/A] and associated fractional change in CPR (ΔCPR/IMCPR) are determined. Thus, each TRACG analysis produces a set of points that can be used to produce bundle specific DIVOM curves.

The TRACG analyses have demonstrated that the relationship between hot bundle oscillation magnitude and fractional change in CPR is fairly linear (i.e., $\Delta$CPR/IMCPR increases with increasing (P-M)/A). The slope of the DIVOM curve represents the thermal-hydraulic responsiveness of the fuel to a given oscillation magnitude. Thus, a steeper slope is more adverse than a flatter slope.

The DIVOM curve is primarily determined by the bundle flow response. In other words, two channels which oscillate with the same normalized oscillation magnitude may have different fractional CPR changes if there is a large difference in the flow response between the two channels. As such, there is a large difference between the DIVOM curves for core-wide mode and regional mode oscillations. For core wide mode oscillations, the channel flow response is coupled to the global core flow response with only a moderate channel-to-channel redistribution of the flow and, thus, the fractional CPR change for all channels is similar. This results in a small difference between the channel specific DIVOM curves for a core wide mode oscillation. For example, even a channel which is very stable hydraulically will experience a flow oscillation and will have a corresponding non-zero DIVOM response.

For regional mode oscillations, the core boundary conditions are essentially constant and there is very little global core flow response. This decoupling of individual channels from the global response allows for a much greater channel-to-channel redistribution of flow and a correspondingly greater variation in fractional CPR change. For example, a channel which is very stable hydraulically would have a very limited flow oscillation and, therefore, produce a very flat DIVOM curve. However, less stable regions of the core can oscillate with a large magnitude flow response and produce a correspondingly steep DIVOM curve. Thus, there is a much greater difference between the channel specific DIVOM curves for regional mode oscillations than for core wide mode oscillations.

To address the relation between the slope of the DIVOM curve and fuel type, TRACG cases were performed for 8x8, 9x9, and 10x10 fuel designs. A mixed core case (9x9 and 10x10) was also analyzed. The most limiting bundles (steepest DIVOM slope) were selected from the TRACG cases analyzed as the basis for the generic DIVOM curve. Since the regional mode oscillation produces the most limiting DIVOM curves, more regional mode oscillations were studied. Various post-flow runback power and flow conditions, and different core inlet subcooling conditions were evaluated. Sample calculations have shown that the $\Delta h_{95/95} < 0.4$ for expected LPRM assignments and trip system setpoints. The hot bundle DIVOM results for the regional mode oscillation cases evaluated are shown up to an oscillation magnitude of 0.4 in Figure 4-11. The hot bundle DIVOM results for the core wide mode oscillation cases evaluated are shown up to an oscillation magnitude of 0.4 in Figure 4-12. A line with an intercept at the origin and a slope of 0.45 as shown in Figure 4-13 is specified as the generic DIVOM curve for regional mode oscillations.

In addition, to address the range of fuel design parameters representative of all current fuel types, a number of TRACG sensitivity cases were run. In these runs, several key fuel design parameters were varied over relatively wide ranges. The sensitivity studies are provided in Appendix B. The parameters varied were: fuel thermal time constant, core void coefficient, and two-phase to single-phase pressure drop ratio. Conservatisms in other portions of the methodology support selection of a reasonably limiting generic DIVOM curve. This generic curve can be used to conservatively represent all current fuel types (all vendors, 8x8, 9x9, 10x10) for regional mode oscillations.

The CPR correlation used in the TRACG analyses provides a conservative prediction of boiling transition during reactor instability. The correlation has been validated in actual tests under various cyclic power and flow conditions. It must be stressed that the CPR correlation is used in this study to predict the *fractional* change in CPR, rather than the absolute value of MCPR. The demonstrated ability of the correlation to predict boiling transition for various steady state and oscillatory conditions provides confidence that the TRACG analyses provide an adequate prediction of fractional change in CPR ($\Delta$CPR/ Initial CPR) for other CPR correlations.

The generic DIVOM curve can be used to represent all current fuel types (ABB, GE, and SPC; 8x8, 9x9, and 10x10) for use in Option III licensing analyses. If significantly different fuel types are introduced in the future (e.g., 11x11), the vendor will either assure that the generic DIVOM curves are applicable to the new fuel design, or new DIVOM curves must be generated.

The use of generic DIVOM curves to cover all existing fuel designs is an important factor in the practical application of this methodology. Calculation of CPR response during an oscillation requires treatment of very complex neutronic/thermal-hydraulic phenomena. Explicit calculation of cycle-specific CPR response would, therefore, require sophisticated 3-D analysis techniques and entail extensive reload analyses. The conservatism present in the methodology as a whole justifies use of the generic DIVOM curves for all current fuel types based on the results detailed in this report.

## Figure 4-11: Regional Mode Hot Bundle DIVOM Data

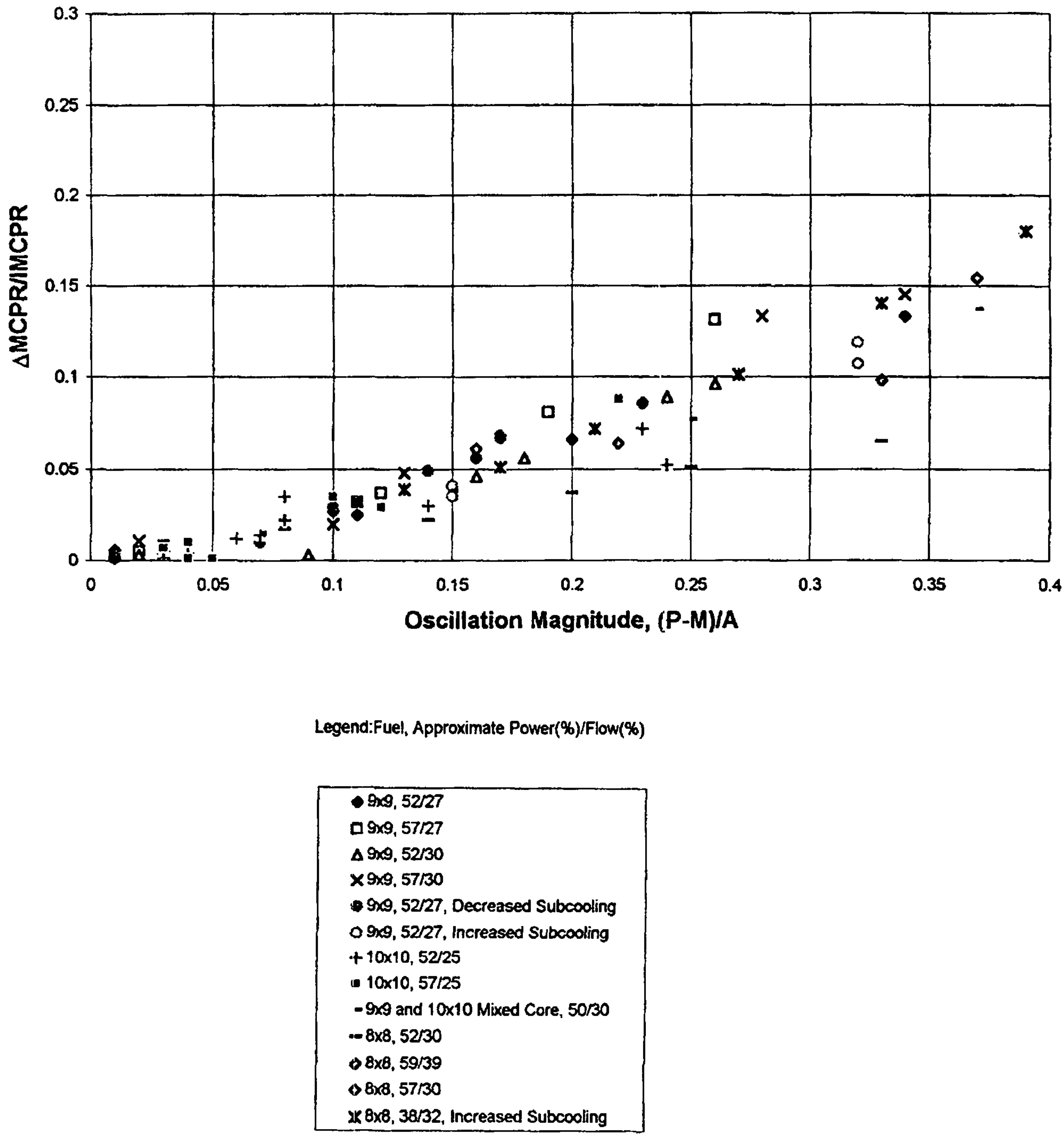


**Figure 4-12: Core Wide Mode Hot Bundle DIVOM Data**

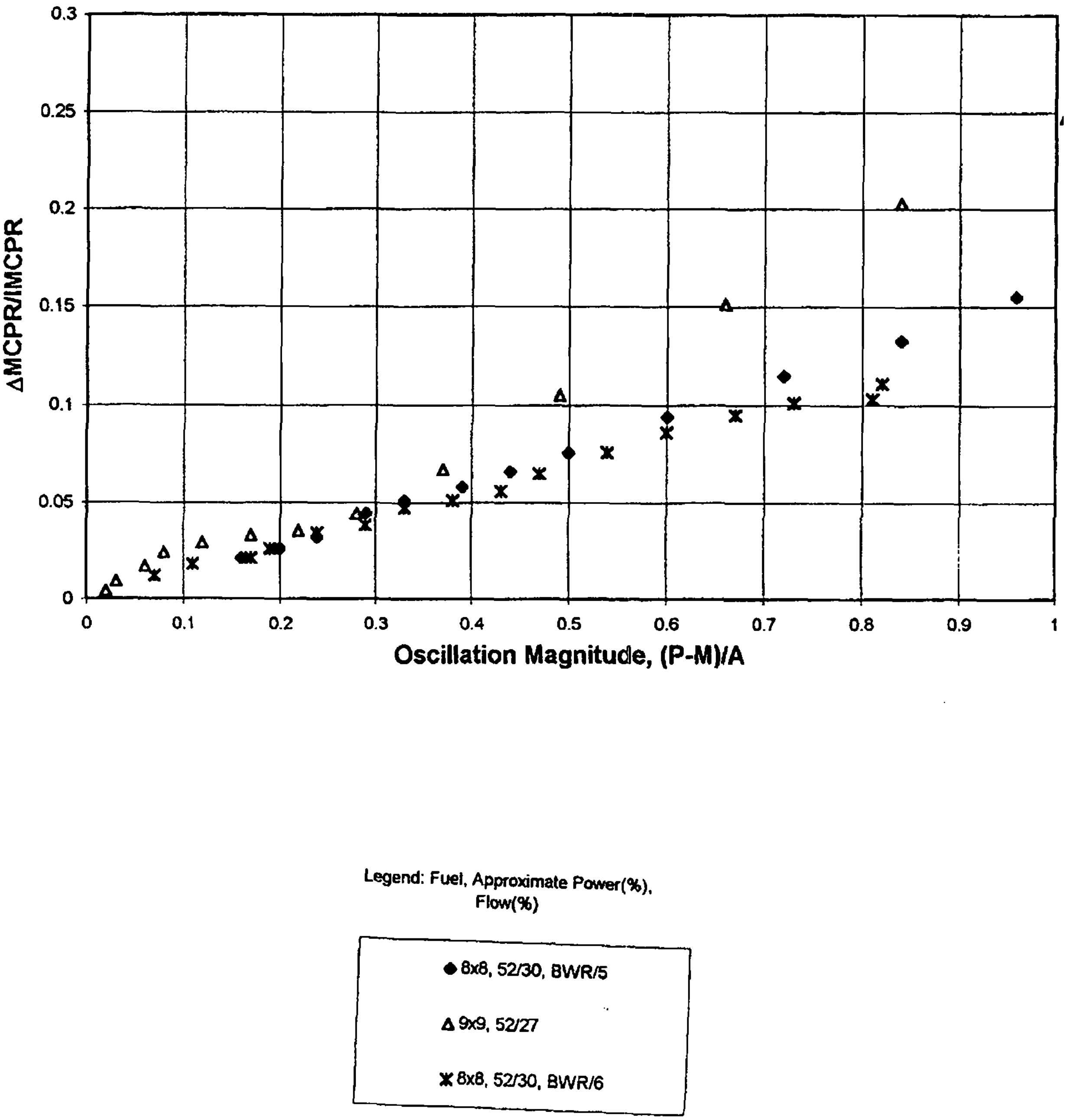
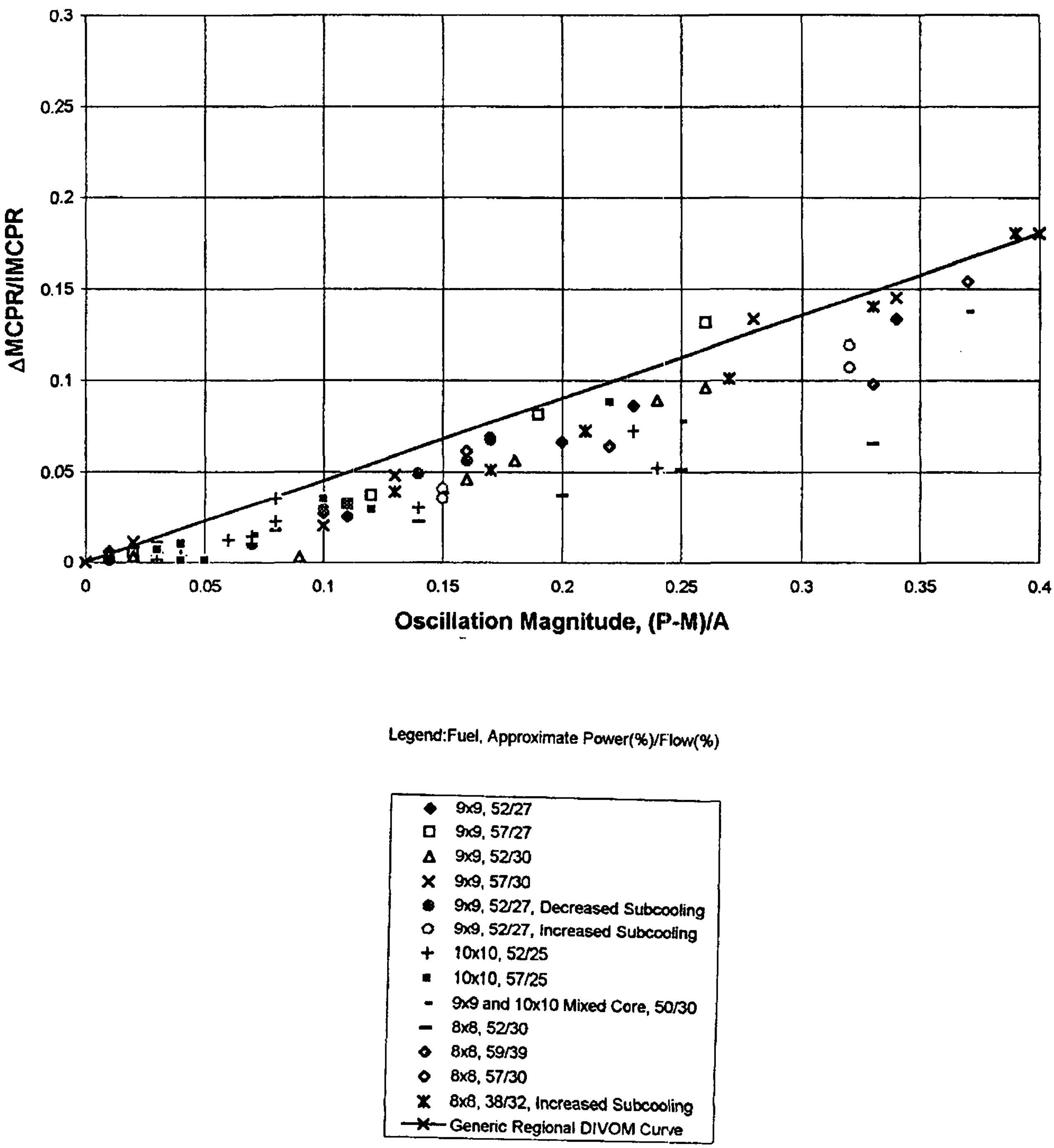


**Figure 4-13: Generic DIVOM Curve for Regional Mode Oscillations**



## 4.5 SUMMARY

### 4.5.1 FINAL MCPR CALCULATION

The process described in Sections 4.1 to 4.4 allows the calculation of a conservative final MCPR value for an anticipated stability related oscillation. First, the Initial MCPR (IMCPR) is determined by a cycle-specific evaluation. Next, the hot bundle oscillation magnitude (at a 95% probability with a 95% confidence level) is calculated using the Monte Carlo methodology. Finally, the ΔCPR/IMCPR corresponding to the 95/95 value of the hot bundle oscillation magnitude is determined from the DIVOM curve. From these elements, the final MCPR (FMCPR) can be determined:

$$FMCPR = IMCPR - IMCPR * \{\Delta CPR/IMCPR\}$$

where:

$\{\Delta CPR/IMCPR\}$ = determined from generic DIVOM curve at the specified $(P\text{-}M)/A_{95/95}$ oscillation magnitude.

The licensing criterion is met when the FMCPR is greater than the MCPR SL.

### 4.5.2 METHODOLOGY CONSERVATISMS

The Option III licensing methodology described in Sections 4.1 to 4.4, taken as a whole, is a conservative means of demonstrating with a high probability and confidence that the MCPR SL will not be violated for anticipated oscillations. The statistical portion of the methodology does not consider the propensity of the reactor to oscillate; it assumes that the reactor power oscillations occur for every statistical trial. No probabilistic credit is taken for the fact that the reactor may not oscillate. Conservatisms inherent in the methodology include:

1. The use of the MCPR SL to provide protection against possible fuel damage is exceedingly conservative, as discussed in Sections 2.1 and 4.4.3.

2. The reactor is assumed to be at the MCPR Operating Limit prior to the event. Realistically, reactors normally operate well above the MCPR Operating Limit.

3. For Option III analyses, the regional oscillation mode is always assumed. TRACG analyses have demonstrated that the DIVOM curve for regional mode oscillations is much more conservative than the DIVOM curve for a core wide oscillation. Also, the regional mode is worse for determining the hot bundle oscillation magnitude because the oscillation is more peaked than

a core wide oscillation. This allows for a larger difference between the hot bundle power oscillation and the OPRM cell response, producing a larger hot bundle oscillation magnitude.

4. The statistical analysis selects a 95% probability with a 95% confidence level value of (P-M)/A. In addition, other conservative assumptions are made in the statistical methodology (Section 4.3).

5. Maximum allowed Technical Specification scram times and response times are used for the analysis. The scram and delay times affect the trip setpoint overshoot calculation in the Monte Carlo analysis of hot bundle oscillation magnitude.

6. Using the minimum available IMCPR from either the two pump RPT from full power or operation at 45% core flow is also quite conservative with respect to reality. This is due to the fact that a reasonable percentage of instability events can be expected to occur at low flows. Due to the increase in MCPR OL at lower flows, oscillations initiated at low flows would have significantly higher values of IMCPR than is assumed in the analysis.

Thus, the Option III licensing methodology is a conservative means of demonstrating that the MCPR SL will not be violated for anticipated oscillations.

# 5.0 INITIAL APPLICATION

This section describes the process for a plant-specific first application of the Option III licensing method described in Section 4. A number of analyses and evaluations are performed for a first application which normally would not change from reload to reload. The result of the first application is a plant-specific trip system definition (LPRM assignments, etc.) and a set of system setpoints.

## 5.1 OVERVIEW

Essentially, the first application may involve an iterative process on the part of the individual utility. In this process, setpoints and LPRM-to-OPRM cell assignments are adjusted to produce acceptable results (i.e., MCPR SL is not violated). Once done, this will establish the trip system definition. It is expected that acceptable system performance can be demonstrated with this trip system definition for future reloads.

The first application process follows the three major steps in the licensing methodology described in Section 4. The utility selects an LPRM-to-OPRM cell assignment configuration. Example LPRM-to-OPRM cell assignment configurations are supplied in Appendix D. Essentially, the utility chooses the number (expected to be from 2 to 4) and specific LPRM for each OPRM cell and the assignment of OPRM cells to RPS trip channels. Next, the trip setpoints relating to the PBDA (primarily $S_p$ described in Section 3.3.3) are chosen. At this point, a statistical calculation to determine the conservative hot bundle oscillation magnitude [$(P\text{-}M)/A_{95/95}$] is performed using plant-specific inputs and the method described in Section 4.3. The generic DIVOM curve is confirmed to be valid for the fuel types considered under the initial application. Then, the generic DIVOM curve is used with the calculated hot bundle oscillation 95/95 value to determine the fractional CPR change, $\Delta$CPR/IMCPR.

Next, expected plant/cycle-specific values for the initial MCPR (IMCPR) are evaluated as described in Section 4.2. Finally, the final MCPR (FMCPR) is calculated as described in Section 4.5.1.

If the FMCPR from this evaluation is greater than the MCPR SL, the trip setpoints and LPRM assignments represent an acceptable trip system definition. If the FMCPR is below the MCPR SL (or if the utility desires more margin between the MCPR SL and the FMCPR to account for possible cycle-specific differences), then the LPRM assignments and/or the setpoints can be modified. The process is repeated using the modified trip system definition until acceptable results are achieved. The result is a trip system definition that is not expected to change for subsequent cycles. In other words, the LPRM assignments and setpoints are expected to remain constant from cycle to cycle. Thus, the $(P\text{-}M)/A_{95/95}$ will also remain fixed for reload evaluations.

## 5.2 SAMPLE PLANT CALCULATIONS

Two sample calculations are provided to illustrate the process described in Section 5.1. The first sample is for a 560-bundle BWR-4, with 3 LPRMs grouped closely together per OPRM cell. The second sample is for a 764-bundle BWR-4 with 4 LPRMs grouped somewhat farther apart in each OPRM cell. It should be noted that the IMCPR values used are sample values, and the results are only provided for the purpose of illustrating the process.

### 5.2.1 BWR-4, 560-BUNDLE PLANT

A sample Monte Carlo analysis for a 560-bundle BWR-4 plant is reported in Table 4-7. An LPRM arrangement using 3 LPRMs per cell was assumed (LPRM Assignment 3M). The PBDA setpoint was assumed to be 1.10. The hot bundle oscillation magnitude 95/95 value from the Monte Carlo statistical analysis is:

$$(P\text{-}M)/A_{95/95} = 0.310$$

Using the generic DIVOM curve (Figure 4-13) and the calculated $(P\text{-}M)/A_{95/95}$, the $\Delta$CPR/IMCPR is determined to be 0.140. The initial MCPR prior to the onset of the oscillation is assumed to be 1.30, and the MCPR SL is assumed to be 1.06. Thus, the final MCPR is:

$$\begin{aligned} \text{FMCPR} &= \text{IMCPR} - \text{IMCPR} * \{\Delta\text{CPR/IMCPR}\} \\ &= 1.30 - 1.30 * (0.140) \\ &= 1.12 \end{aligned}$$

Since the final MCPR is greater than the MCPR SL, the setpoints and trip system definition would be acceptable.

### 5.2.2 BWR-4, 764-BUNDLE PLANT

A sample Monte Carlo analysis for a 764-bundle BWR-4 plant is reported in Table 4-5. An LPRM arrangement using 4 LPRMs per cell was assumed (LPRM Assignment 4BL). The PBDA setpoint was assumed to be 1.10. The hot bundle oscillation magnitude 95/95 value from the Monte Carlo statistical analysis is:

$$(P\text{-}M)/A_{95/95} = 0.365$$

Using the generic DIVOM curve (Figure 4-13) and the calculated $(P\text{-}M)/A_{95/95}$, the $\Delta$CPR/IMCPR is determined to be 0.164. The initial MCPR prior to the onset of the oscillation is assumed to be 1.40, and the MCPR SL is assumed to be 1.08. Thus, the final MCPR is:

$$\begin{aligned} \text{FMCPR} &= \text{IMCPR} - \text{IMCPR} * \{\Delta\text{CPR/IMCPR}\}, \text{ where} \\ &= 1.40 - 1.40 * (0.164) \\ &= 1.17 \end{aligned}$$

Since the final MCPR is greater than the MCPR SL, the setpoints and trip system definition would be acceptable.

# 6.0 RELOAD REVIEW

## 6.1 OVERVIEW

The purpose of the reload review procedure is to confirm that the combination of trip setpoints and IMCPR provides a high confidence that the MCPR SL will not be violated for anticipated stability related oscillations. The reload review procedure is a simplified version of the first application procedure described in Section 5. It consists of the cycle-specific calculation of IMCPR along with confirmations that the DIVOM curve applicability, trip system definition, and trip system setpoints have not changed. Figure 6-1 illustrates the Option III reload review process.

## 6.2 MAXIMUM HOT BUNDLE OSCILLATION MAGNITUDE

The plant-specific statistical calculation that generated the value of $\Delta_{h(95/95)}$ for the first application used certain key assumptions. Each of these assumptions must be checked to assure that they have not been changed for the reload cycle under evaluation. The two principal items to be examined are the value of the setpoint ($S_p$) and the LPRM assignments. In general, it is not expected that these will be changed from cycle to cycle. If changes in these parameters do not support the previous calculation of $\Delta_{h(95/95)}$, a new evaluation would be required.

## 6.3 INITIAL MCPR CALCULATION

The value of Initial MCPR (IMCPR) is calculated as described in Section 4.2. This calculation produces the cycle-specific IMCPR used to calculate the final MCPR.

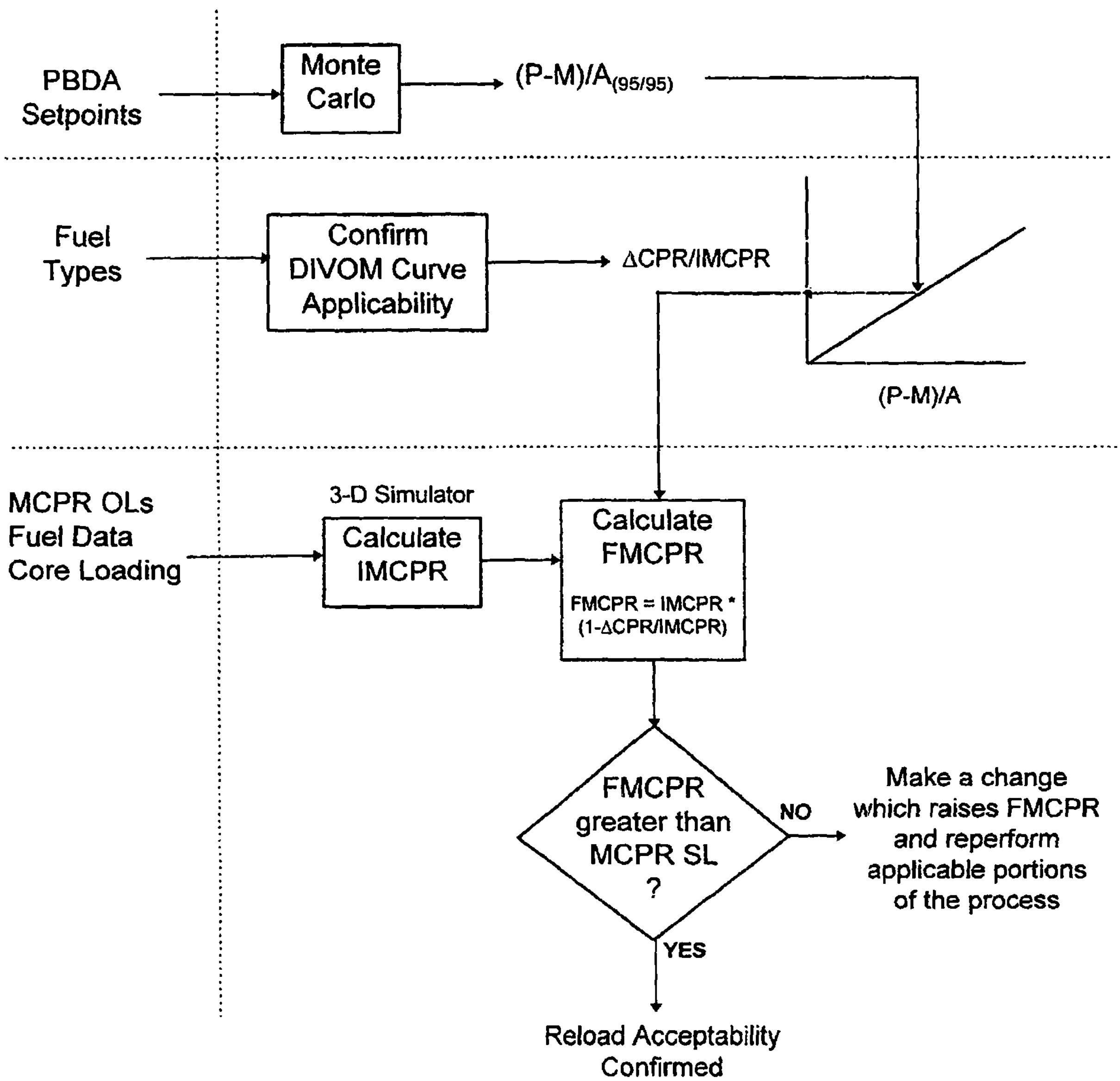
## 6.4 MCPR PERFORMANCE CURVE

The DIVOM curve used for the previous plant calculation must be determined to be applicable to the fuel types that exist in the reload core. If a fuel type significantly different from the ones previously considered is being introduced (except for LUAs), a new DIVOM curve may need to be determined.

## 6.5 SUMMARY

Using the IMCPR, $\Delta_{h(95/95)}$, and the appropriate DIVOM curve, the final MCPR is calculated as described in Section 4.5.1. If the FMCPR is greater than or equal to the MCPR SL, then the trip setpoints and LPRM assignments are acceptable for that cycle (i.e., the MCPR SL is not violated for anticipated oscillations). If the FMCPR is less than the MCPR SL, then a change must be made and the evaluation redone until the FMCPR is greater than the MCPR OL. Changes which would raise the FMCPR include selecting a lower amplitude trip setpoint, using a more responsive LPRM assignment scheme, and increasing the MCPR OLs.

**Figure 6-1: Option III Reload Review Process**



# 7.0 APPLICATION TO OPTION 1-D

## 7.1 BACKGROUND

The Option 1-D Long-Term Solution was previously described in BWROG Licensing Topical Report NEDO-31960 and NEDO-31960, Supplement 1 (References 1 and 2). The solution takes credit for unique plant characteristics which make regional mode oscillations very unlikely in conjunction with a demonstration that the existing plant instrumentation provides a sufficient automatic detect and suppress function for core wide mode oscillations. The NRC requested additional information on Option 1-D in the SER (Reference 3) on NEDO-31960 and NEDO-31960, Supplement 1. The requested information was to be evaluated for the lead Option 1-D plant before approving Option 1-D. Vermont Yankee (the lead plant) submittals have been reviewed by the NRC, and an SER was issued accepting Option 1-D for application to Vermont Yankee (Reference 8).

This section documents the application methodology for the detect and suppress portion of the Option 1-D solution licensing bases. This methodology is essentially the same as Option III except that it is applied for core wide mode oscillations and the Average Power Range Monitor (APRM) flow-biased scram is used instead of the OPRM scram previously described.

## 7.2 LICENSING COMPLIANCE

The general licensing approach for Option 1-D is to assure compliance with GDC 10 and 12 by preventing the occurrence of reactor instability related oscillations that could result in a violation of the MCPR safety limit (SL). This is primarily accomplished through monitoring and preventing operation in the region of potential instabilities. However, if that region is unintentionally entered as a result of an unplanned operational event, this solution provides automatic detection and suppression of reactor instability through the APRM flow-biased scram input to the RPS. The detect and suppress methodology for application to Option 1-D is designed to determine MCPR SL protection provided by that trip system for anticipated core wide mode oscillations. The licensing methodology described in this report is consistent with that described in References 1 and 2.

The licensing basis for Option 1-D application demonstrates that regional mode oscillations are not likely to occur. This is demonstrated on a plant-specific basis by the core and channel decay ratio calculations performed for generation of the plant-specific exclusion region and maintained by the associated administrative controls implemented by the utilities using Option 1-D. Even though regional mode oscillations are not probable, the NRC requested (Reference 3) an evaluation of the protection against out-of-phase instabilities provided by the APRM flow-biased scram as part of the lead

Option 1-D plant submittal. Determination of protection lines at both high statistical confidence and nominal statistical confidence was requested. In addition, the NRC requested that the margin to occurrence of regional mode instability be demonstrated at the nominal statistical confidence protection line.

Calculations for four Option 1-D plants (Fitzpatrick, Vermont Yankee, Duane Arnold, and Monticello) were performed and presented to the NRC (Reference 9). They showed that the location of the protection lines were primarily a function of the APRM flow-biased scram setpoints. For lower setpoints, protection was provided at lower rodlines. However, all the plants demonstrated significant margin to the occurrence of regional mode instability at the nominal statistical confidence protection line. Therefore, it is only required that application of the detect and suppress methodology for Option 1-D determine the protection line for core wide mode reactor instability.

The protection line for core wide mode oscillations is determined with a high statistical confidence.

## 7.3 METHODOLOGY APPLICATION

### 7.3.1 APPLICATION OVERVIEW

Other analyses (including plant-specific exclusion region calculations) have demonstrated that the likelihood of an occurrence of a regional mode oscillation is low for plants qualifying for Option 1-D. The unique Option I-D plant characteristic is a combination of tight inlet orificing and small core size which make a core wide reactor instability the predominate oscillation mode. The methodology will be used for plant-specific applications to determine MCPR SL protection provided by the APRM flow-biased scram for core wide mode oscillations. The stability related design basis of the flow-biased scram is to generate a trip signal to provide high confidence that the MCPR SL will not be violated for an anticipated core wide mode oscillation.

As with Option III, the Option 1-D licensing analysis methodology consists of three major components:

a. Calculation of the Pre-Oscillation MCPR: A plant and cycle-specific determination of the MCPR on the protection line prior to the onset of the oscillation captures the margin to the MCPR SL prior to the oscillation. This is known as the initial MCPR (IMCPR).

b. Statistical Calculation of Peak Oscillation Magnitude: A statistical evaluation of the peak oscillation magnitude due to an oscillation initiating on the protection line captures the effect of plant characteristics, trip system definition, and setpoint values on the peak fuel bundle power oscillation magnitude. The statistical methodology considers power distributions, oscillation contours, oscillation growth rates, frequencies, trip overshoot, and LPRM failures. The result of the statistical evaluation is a conservative value of the peak hot bundle oscillation magnitude for anticipated oscillations.

c. MCPR Performance of the Hot Bundle: A relationship between the fractional change in CPR and the hot bundle oscillation magnitude for core wide mode oscillations captures the effect of fuel design. This relationship is derived from 3-D TRACG analyses performed over a range of conditions selected to represent all current fuel designs.

As stated previously, the purpose of the Option 1-D licensing detect and suppress methodology is to determine, with a high statistical confidence, the protection line (i.e., the rod line) which results in suppression of anticipated core wide mode oscillations without violating the MCPR SL. Therefore, the IMCPR and oscillation magnitude calculations are both evaluated at the same rod line. The NRC approved methodology given in References 1 and 2 was in part restructured to simplify the first application process and reload review process. The methodology is conceptually identical to that approved by the NRC. Additional conservatisms have been added to streamline the reload review process. An evaluation will be performed for each cycle to assure with a high confidence that the RPS and trip setpoints continue to provide protection of the MCPR SL for anticipated reactor instability.

As stated above, the statistical methodology of References 1 and 2 has been divided into three distinct parts. It is reviewed here as applied to Option 1-D.

### 7.3.2 PRE-OSCILLATION MCPR

The initial (pre-oscillation) MCPR is the more limiting (lower) of two scenarios on the flow control line selected for evaluation as the protection line (e.g., the 100% rod line). The two scenarios considered are (1) a two recirculation pump trip, and (2) steady-state operation at 45% core flow. The determinination of the IMCPR for the two scenarios is identical to that described for Option III in Section 4.2, except that the evaluation is performed at the selected flow control line.

### 7.3.3 STATISTICAL CALCULATION OF HOT BUNDLE OSCILLATION MAGNITUDE

The statistical methodology for application to Option III is described in Section 4.3. There are some differences for application to Option 1-D which are described below.

The hot bundle oscillation magnitude, $\Delta_h$, is dependent on plant-specific factors. A statistical analysis is performed to calculate a conservative value of the hot bundle oscillation magnitude. An upper bound at the 95% probability with a 95% confidence level is selected.

#### 7.3.3.1 Oscillation Model

The basic LPRM oscillation model is the same as for Option III. For Option 1-D, LPRM signals are combined into an APRM signal instead of an OPRM signal. An example of an LPRM oscillation signal was previously shown in Figure 4-2.

Differences from Option III are the result of the Option 1-D evaluation of core wide mode oscillations and use of the APRM trip system. The Option III application calculates a normalized oscillation response (peak/average) and uses a normalized trip setpoint ($S_p$). The Option 1-D application calculates an APRM signal response (% rated power) and uses a core power value as the trip setpoint (from the APRM flow-biased trip). Therefore, the LPRM and hot bundle signals, $F_l(t)$ and $F_h(T)$, are calculated as % power instead of normalized signals. In addition, Option III application uses countours representative of regional mode oscillations. Option 1-D application uses countours representative of core wide mode oscillations. The core wide contours specify that all the LPRMs have the same relative oscillation magnitude. Therefore, the hot bundle radial peaking factor is an additional parameter used in the oscillation model for core wide mode oscillations to determine the hot bundle response.

The oscillation simulation is focused only in the time segment of interest when the APRM signal crosses the trip setpoint. An APRM trip system is generally less responsive than an OPRM trip system, so the time segment of interest for an Option 1-D statistical trial will typically have a larger hot bundle oscillation magnitude than for a typical Option III statistical trial.

Like Option III, the peak hot bundle oscillation magnitudes resulting from all trials produce an output probability distribution of hot bundle oscillation magnitude, $\Delta_h$. Option 1-D also applies a one-sided nonparametric tolerance limit to determine the limiting hot bundle oscillation magnitude, $\Delta_{h(95/95)}$, with 95% probability at a 95% confidence level.

### 7.3.3.2 Statistical Inputs

**Growth Rate**: The growth rate distribution used for Option 1-D is the same as discussed in Section 4.3.2.4 for Option III.

**Trip Setpoint Overshoot**: The trip setpoint overshoot distribution used for Option 1-D is the same as discussed in Section 4.3.2.4 for Option III.

**Oscillation Period**: The oscillation period distribution used for Option 1-D is the same as discussed in Section 4.3.2.4 for Option III.

**LPRM Failures:** The statistical model provides options for considering an input LPRM failure probability distribution, a fixed failure percentage, or no LPRM failures in the calculation of hot bundle oscillation magnitude. Option 1-D uses random LPRM failures from a distribution which is representative of plant data on LPRM failure rates. Plant data (Reference 1) indicates that the number of LPRM failures does not vary significantly among different cycles or exposure points in a cycle. Reference 1 also shows that a histogram of the LPRM failure frequency, expressed as a percentage of the total LPRMs, follows a skewed $\chi^2$ distribution. This distribution, which provides a mean failure rate of approximately 9%, was shown in Figure 4-9. Each trial selects a failure percentage from the specified distribution, and randomly selects which LPRMs are failed.

**Oscillation Contours**: A set of contours is used as plant-specific input to the statistical methodology. Option 1-D uses the same methodology for contour development and application as Option III, except that the contours are developed for core wide mode oscillations. For a core wide oscillation, the oscillation contour is constant for all LPRMs. The same axial phase lags are used as for Option III. All A-level LPRMs have a zero phase angle for a core wide mode contour.

### 7.3.3.3 Deterministic Inputs

**LPRM Assignments**: Option 1-D relies on the APRM flow-biased trip. LPRMs are assigned to their respective APRM channels according to the plant configuration. All non-failed LPRM signals in an APRM are used to produce an averaged power signal for comparison to the trip setpoint.

**Trip Setpoint**: The APRM trip setpoint is input as a percentage of rated power.

**Radial Peaking Factor**: Since only the fundamental mode from the 3-D BWR simulator is used to calculate the relative LPRM signal averages, $A_l$, there is only one hot bundle in the core wide mode oscillation. This bundle is also the "true" hot bundle with the highest radial peaking factor. Its oscillation magnitude ,$\Delta_h$, is the same as any other location in the core.

**RPS Trip Logic**: All Option 1-D plants have a one-out-of-two, taken twice trip logic. Therefore, at least one channel from Division A ***and*** at least one channel from Division B must reach the APRM trip setpoint for the trip signal to be generated.

**APRM Channel Failure**: In addition to the failure of individual LPRMs, the failure of one APRM channel is considered. The model provides several options: no APRM channel failure, failure of a specified channel, failure of a randomly selected channel, and failure of the most responsive channel. For conservatism, the failure of the most responsive channel (i.e., the first channel to reach the trip setpoint) is used for Option 1-D analysis.

**Delay Time**: The delay time is determined in the same way as described in Section 4.3.2.5 for Option III.

### 7.3.4 SAMPLE SINGLE TRIAL CALCULATION

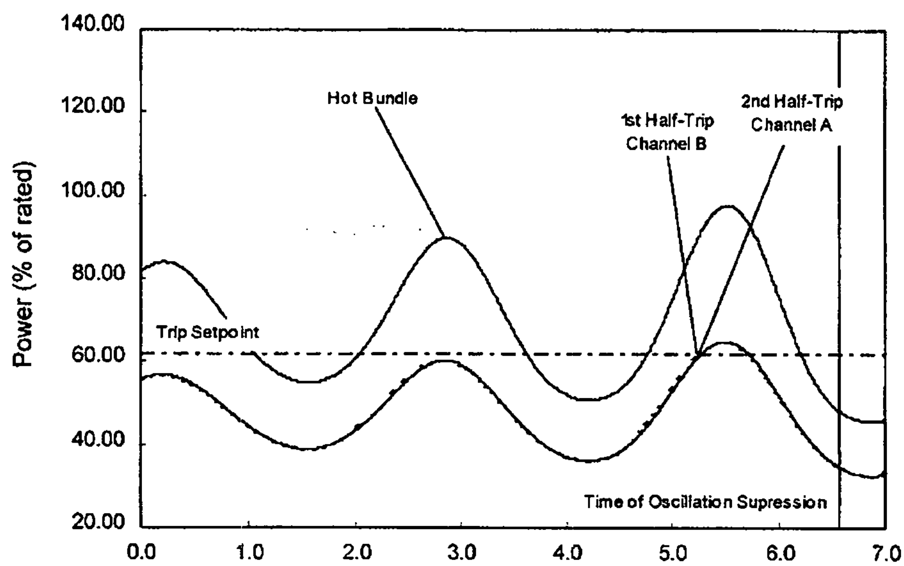
An Option 1-D sample single Monte Carlo trial calculation is presented for a BWR/4, with a 368-bundle core. The input parameters for the single trial are provided below. The resulting APRM channel trip times are listed in Table 7-1. Note that Division A consists of Channels A, C, and E while Division B consists of Channels B, D, and F. Figure 7-1 illustrates the hot bundle and system responses. The maximum calculated hot bundle oscillation magnitude is 0.712.

| | |
|---|---|
| Plant: | BWR/4, 368-bundle core |
| Oscillation period: | T = 2.65 seconds |
| Growth rate: | $G_r = 1.33$ |
| First-peak overshoot: | $\delta = 0.47$ |
| Total delay time: | 1.300 seconds |
| Contour: | Core-wide mode |
| LPRM failure: | 18 LPRMs (22.5%) |
| APRM channel failure: | Most responsive channel |
| Average reactor power: | 48% rated power (100% rod line, natural circulation) |
| Radial peaking factor: | 1.44 |
| Trip setpoint: | 62% rated power (at natural circulation) |
| Trip logic: | One-out-of-two, taken twice. |

**Table 7-1: Flow-Biased APRM Trip Time With Most Responsive Channel Failure**

| Division | APRM Channel | Overshoot Time (sec) |
|---|---|---|
| B | F (Failed) | 5.2581 |
| B | B | 5.2722 |
| A | A | 5.2722 |

**Figure 7-1: Sample Trial - APRM System Trip with Most Responsive Channel Failure**




### 7.3.5 SAMPLE STATISTICAL MODEL CALCULATION

To illustrate the complete statistical process, a full 1000-trial statistical analysis is presented for the same sample plant. Table 7-2 lists the key inputs. Table 7-3 provides the highest 50 calculated values of $\Delta_h$ and the 95/95 value (= 0.701). Compared to Option III, the $\Delta h_{95/95}$ for this case is substantially higher because the trip setpoint is at 62% of rated power with an average power of 48% power. This is equivalent to a peak/average trip setpoint of 1.29, compared to Option III peak/average trip setpoints which are typically near 1.10.

**Table 7-2: Example Option I-D Inputs for Sample Hot Bundle Oscillation Magnitude Calculation**

BWR/4, 368-bundle core

| | |
|---|---|
| Trip System: | APRM |
| Trip Logic: | ONE-OUT-OF-TWO, TAKEN TWICE |
| Oscillation Mode: | CORE WIDE |
| APRM Channel Failure: | Most Responsive APRM Channel (applied to 100.0% of all trials) |
| LPRM Failures: | RANDOM (Chi-Square Distribution, see Figure 4-9) |
| Period T: | RANDOM (Chi-Square Distribution, see Figure 4-5) |
| Growth Rate, Gr: | RANDOM (Chi-Square Distribution, see Figure 4-4) |
| Overshoot, $\delta$: | RANDOM (Uniform Distribution) |
| Reactor Power: | 48.0 (% of rated) (100% rod line at natural circulation) |
| Radial Peaking Factor: | 1.440 |
| Trip Level: | 62.0 (% of rated) (at natural circulation) |
| Total Delay Time: | 1300 msec. (measured from time of full trip) |
| Total Number of LPRMs: | 80 |

Oscillation Contour Selection: RANDOM; Contours names: KE1B10AH1, KE1B10AH3, KE1M10AH1, KE1M10AH3, KE1E10AH1, KE1E10AH3, KE1H10AH1, KE1H10AH3

## Table 7-3: Example Option I-D Output for Sample Hot Bundle Oscillation Magnitude Calculation (*)

| TRIAL | CONTOUR | T (sec) | GR | OVRSHT | RNDM LPRM FAIL | INOP APRM CHAN | APRM CHAN FAIL | TOT LPRM FAIL | %LPR FAIL | OPRM CHNL FAIL | HOT (P-M)/A | HT BNDL PEAK (% of rated) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 270 | KE1H10AH3 | 1.57 | 1.14 | 0.84 | 4 | 0 | B | 4 | 5.0 | N/A | 0.698 | 96.98 |
| 171 | KE1H10AH3 | 1.66 | 1.14 | 0.80 | 6 | 0 | F | 6 | 7.5 | N/A | 0.698 | 96.99 |
| 815 | KE1H10AH1 | 1.53 | 1.14 | 0.83 | 8 | 0 | F | 8 | 10.0 | N/A | 0.698 | 96.99 |
| 690 | KE1E10AH1 | 1.70 | 1.17 | 0.71 | 3 | 0 | F | 3 | 3.8 | N/A | 0.698 | 97.02 |
| 317 | KE1E10AH1 | 2.45 | 1.15 | 0.82 | 9 | 0 | B | 9 | 11.3 | N/A | 0.699 | 97.04 |
| 956 | KE1E10AH3 | 2.06 | 1.18 | 0.67 | 8 | 0 | F | 8 | 10.0 | N/A | 0.699 | 97.05 |
| 567 | KE1H10AH1 | 2.83 | 1.16 | 0.76 | 15 | 0 | F | 15 | 18.8 | N/A | 0.700 | 97.09 |
| 579 | KE1M10AH3 | 2.09 | 1.13 | 0.89 | 5 | 0 | B | 5 | 6.3 | N/A | 0.701 | 97.11 |
| 694 | KE1M10AH3 | 1.75 | 1.16 | 0.87 | 4 | 0 | F | 4 | 5.0 | N/A | 0.701 | 97.12 |
| 287 | KE1E10AH3 | 2.04 | 1.15 | 0.84 | 5 | 0 | F | 5 | 6.3 | N/A | 0.701 | 97.13 |
| 365 | KE1E10AH3 | 1.73 | 1.12 | 0.00 | 5 | 0 | B | 5 | 6.3 | N/A | 0.701 | 97.14 |
| 45 | KE1E10AH1 | 1.97 | 1.39 | 0.35 | 6 | 0 | F | 6 | 7.5 | N/A | 0.702 | 97.11 |
| | HOT BUNDLE (P-M)/A AT 95/95 LEVEL = 0.702 | | | | | | | | | | | |
| 961 | KE1H10AH1 | 2.10 | 1.21 | 0.61 | 7 | 0 | F | 7 | 8.8 | N/A | 0.702 | 97.16 |
| 269 | KE1E10AH1 | 2.10 | 1.15 | 0.83 | 5 | 0 | F | 5 | 6.3 | N/A | 0.702 | 97.17 |
| 370 | KE1E10AH1 | 2.31 | 1.16 | 0.79 | 8 | 0 | F | 8 | 10.0 | N/A | 0.703 | 97.20 |
| 656 | KE1B10AH3 | 1.90 | 1.21 | 0.74 | 4 | 0 | F | 4 | 5.0 | N/A | 0.703 | 97.22 |
| 742 | KE1E10AH3 | 1.73 | 1.17 | 0.73 | 3 | 0 | F | 3 | 3.8 | N/A | 0.705 | 97.29 |
| 812 | KE1M10AH3 | 2.49 | 1.22 | 0.64 | 7 | 0 | F | 7 | 8.8 | N/A | 0.705 | 97.28 |
| 179 | KE1E10AH1 | 2.00 | 1.14 | 0.89 | 10 | 0 | B | 10 | 12.5 | N/A | 0.706 | 97.35 |
| 733 | KE1B10AH1 | 1.94 | 1.22 | 0.72 | 2 | 0 | F | 2 | 2.5 | N/A | 0.708 | 97.43 |
| 698 | KE1H10AH3 | 1.49 | 1.16 | 0.84 | 5 | 0 | F | 5 | 6.3 | N/A | 0.708 | 97.46 |
| 618 | KE1B10AH3 | 1.47 | 1.24 | 0.67 | 6 | 0 | F | 6 | 7.5 | N/A | 0.709 | 97.48 |
| 624 | KE1H10AH3 | 2.68 | 1.17 | 0.78 | 7 | 0 | F | 7 | 8.8 | N/A | 0.710 | 97.54 |
| 200 | KE1M10AH3 | 1.91 | 1.18 | 0.83 | 3 | 0 | F | 3 | 3.8 | N/A | 0.711 | 97.57 |
| 25 | KE1B10AH1 | 1.96 | 1.19 | 0.86 | 4 | 0 | F | 4 | 5.0 | N/A | 0.711 | 97.58 |
| 678 | KE1H10AH3 | 2.65 | 1.33 | 0.47 | 18 | 0 | F | 18 | 22.5 | N/A | 0.712 | 97.63 |
| 978 | KE1B10AH1 | 1.50 | 1.21 | 0.82 | 10 | 0 | F | 10 | 12.5 | N/A | 0.714 | 97.72 |
| 501 | KE1E10AH3 | 2.20 | 1.19 | 0.74 | 2 | 0 | F | 2 | 2.5 | N/A | 0.715 | 97.77 |
| 105 | KE1M10AH1 | 2.02 | 1.19 | 0.85 | 9 | 2 | B | 9 | 11.3 | N/A | 0.716 | 97.77 |
| 116 | KE1H10AH1 | 1.97 | 1.26 | 0.60 | 6 | 0 | F | 6 | 7.5 | N/A | 0.719 | 97.95 |
| 983 | KE1B10AH3 | 2.34 | 1.22 | 0.83 | 8 | 0 | F | 8 | 10.0 | N/A | 0.720 | 97.96 |
| 482 | KE1E10AH1 | 2.13 | 1.16 | 0.92 | 6 | 0 | F | 6 | 7.5 | N/A | 0.721 | 98.02 |
| 242 | KE1E10AH1 | 2.15 | 1.17 | 0.91 | 7 | 1 | D | 7 | 8.8 | N/A | 0.722 | 98.05 |

*** Note that these are the 50 trials having the largest calculated values of hot bundle (P-M)/A. The remaining 950 trials had smaller values of hot bundle (P-M)/A.**

# Table 7-3 (Continued)

| TRIAL | CONTOUR | T (sec) | GR | OVRSHT | RNDM LPRM FAIL | INOP APRM CHAN | APRM CHAN FAIL | TOT LPRM FAIL | %LPR FAIL | OPRM CHNL FAIL | HOT (P-M)/A | HT BNDL PEAK (% of rated) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 925 | KE1E10AH1 | 1.52 | 1.18 | 0.86 | 9 | 0 | B | 9 | 11.3 | N/A | 0.725 | 98.17 |
| 681 | KE1H10AH3 | 1.47 | 1.37 | 0.46 | 6 | 0 | F | 6 | 7.5 | N/A | 0.725 | 98.18 |
| 605 | KE1E10AH1 | 2.40 | 1.24 | 0.68 | 4 | 0 | F | 4 | 5.0 | N/A | 0.729 | 98.37 |
| 398 | KE1H10AH1 | 2.03 | 1.21 | 0.79 | 8 | 0 | F | 8 | 10.0 | N/A | 0.731 | 98.47 |
| 785 | KE1H10AH3 | 3.50 | 1.21 | 0.81 | 8 | 0 | F | 8 | 10.0 | N/A | 0.731 | 98.49 |
| 819 | KE1H10AH1 | 1.91 | 1.22 | 0.80 | 14 | 0 | B | 14 | 17.5 | N/A | 0.736 | 98.71 |
| 256 | KE1B10AH1 | 2.08 | 1.29 | 0.73 | 3 | 0 | F | 3 | 3.8 | N/A | 0.737 | 98.75 |
| 892 | KE1E10AH3 | 1.36 | 1.19 | 0.94 | 3 | 0 | B | 3 | 3.8 | N/A | 0.738 | 98.80 |
| 864 | KE1M10AH1 | 2.20 | 1.27 | 0.73 | 10 | 0 | F | 10 | 12.5 | N/A | 0.739 | 98.82 |
| 773 | KE1E10AH1 | 1.88 | 1.22 | 0.89 | 14 | 0 | D | 14 | 17.5 | N/A | 0.752 | 99.42 |
| 262 | KE1E10AH3 | 2.45 | 1.21 | 0.96 | 7 | 0 | B | 7 | 8.8 | N/A | 0.754 | 99.53 |
| 748 | KE1B10AH3 | 1.91 | 1.27 | 0.90 | 8 | 0 | B | 8 | 10.0 | N/A | 0.762 | 99.85 |
| 440 | KE1H10AH1 | 2.00 | 1.30 | 0.75 | 3 | 0 | F | 3 | 3.8 | N/A | 0.764 | 99.95 |
| 68 | KE1H10AH1 | 2.08 | 1.44 | 0.62 | 14 | 0 | F | 14 | 17.5 | N/A | 0.789 | 101.1 |
| 402 | KE1H10AH3 | 2.35 | 1.29 | 0.96 | 8 | 0 | B | 8 | 10.0 | N/A | 0.806 | 101.9 |
| 936 | KE1H10AH3 | 1.69 | 1.36 | 0.88 | 8 | 0 | F | 8 | 10.0 | N/A | 0.829 | 102.9 |
| 551 | KE1E10AH1 | 1.91 | 1.41 | 0.80 | 3 | 0 | F | 3 | 3.8 | N/A | 0.833 | 103.1 |
| | MINIMUM | 1.27 | 1.00 | 0.00 | 1 | | | 0 | 1.3 | | 0.599 | 92.62 |
| | MAXIMUM | 3.67 | 1.44 | 1.00 | 22 | | | 0 | 27.5 | | 0.833 | 103.1 |
| | AVERAGE | 2.04 | 1.10 | 0.49 | 7 | | | 0 | 8.4 | | 0.643 | 94.56 |

## 7.4 MCPR PERFORMANCE

The Option 1-D solution methodology also employs the results of 3-D TRACG calculations to determine the relative change in hot bundle CPR as a function of hot bundle oscillation magnitude. The analyses reported in this LTR are representative of all current BWR fuel types. This section describes the generic DIVOM curve for core wide mode oscillations which is intended for use in reload licensing evaluations.

### 7.4.1 RELATION OF DIVOM TO LICENSING METHODOLOGY

In the restructured Option 1-D methodology, the DIVOM curve is used with the hot bundle oscillation magnitude ($\Delta h_{95/95}$) to produce the limiting value of $\Delta$CPR/IMCPR.

The NRC SER (Reference 3) approved use of a statistical methodology for establishing the final value of MCPR (FMCPR). The statistical evaluation of $\Delta h_{95/95}$ in the restructured methodology (described in this report) selects the value of hot bundle oscillation magnitude at a 95% probability with a 95% confidence level. Like Option III, using a DIVOM curve with a conservative slope maintains the 95/95 level for the FMCPR calculated by the licensing methodology.

The generic DIVOM curve for core wide mode oscillations is selected to be the same as specified in the plant-specific Option 1-D application licensing topical reports (Reference 6). This DIVOM curve has a conservative slope when compared to the TRACG calculated core wide mode DIVOM data.

### 7.4.2 GENERIC MCPR PERFORMANCE (DIVOM) CURVE

Section 4.4.4 describes the TRACG analyses which were performed and provides DIVOM data for both core wide and regional mode oscillations. To justify generic DIVOM curves, a large number of studies were performed for different fuel designs. More studies were performed for regional oscillations than for core wide oscillations since regional oscillations produce more limiting DIVOM results. The reasons for this have been described in Section 4.4.4. However, core wide and regional mode cases were analyzed for both 8x8 and 9x9 fuel designs. The studies are consistent in that 9x9 has more limiting DIVOM data than 8x8 for both core wide and regional oscillations. Since these results were consistent, and 9x9 is the limiting fuel design for regional mode oscillations, no further base case or sensitivity studies were performed for core wide mode oscillations.

A fixed DIVOM curve was previously specified for Option 1-D application in Reference 6. The equation of the fixed curve is [$\Delta CPR/IMCPR = 0.175 * \Delta_h + 0.05$]. The specified fixed curve is shown in Figure 7-2 with a comparison to the core wide

CPR performance data in Figure A-16 of Reference 1, as previously reported in Reference 6. The recently completed TRACG analyses generally show margin to the previously specified fixed DIVOM curve. Therefore, this fixed DIVOM curve is selected as the generic DIVOM curve for core wide mode oscillations. The generic DIVOM curve for core wide oscillations is shown in Figure 7-3 with the recently completed TRACG CPR performance data. The core wide oscillation hot bundle DIVOM results are shown up to an oscillation magnitude of 1.0 in Figure 7-3. This range is adequate for the expected maximum Option 1-D hot bundle oscillation magnitude.

The generic DIVOM curve for core wide oscillations is reasonably conservative (but not necessarily bounding in all cases) when compared to the TRACG CPR performance data. As discussed in Section 4.4.2, using a reasonable value for the slope of the generic DIVOM curve in the licensing methodology would produce a FMCPR at approximately the 95/95 level.

Based on the specification of a regional mode generic DIVOM curve which represents all current fuel types, the generic DIVOM curve for core wide oscillations also conservatively represents all current fuel types (all vendors, 8x8, 9x9, 10x10) for the following reasons:

1. A wide range of the fuel design attributes were considered in the regional mode base cases and sensitivity studies (fuel thermal time constant, core void coefficient, and two-phase to single-phase pressure drop ratio).

2. There is relatively close spacing of the extensive 9x9 regional mode oscillation base case DIVOM data for a wide range of conditions.

3. The spread between the hot bundle and core average DIVOM data is less for core wide mode oscillations than it is for regional mode oscillations.

Therefore, the impact of fuel design differences shown for regional mode oscillations will be compressed for core wide mode oscillations. In other words, it is not expected that there would be any fuel designs which would show a large offset from the core wide mode DIVOM data available. The offset of the generic DIVOM curve for core wide oscillations at a zero oscillation magnitude is an additional conservatism in specification of the generic DIVOM curve for core wide mode oscillations. For these reasons, it is concluded that the specified generic DIVOM curve for core wide oscillations conservatively represents all current fuel types (all vendors, 8x8, 9x9, 10x10).

**Figure 7-2: Previously Specified Fixed DIVOM Curve for Core Wide Mode Oscillations**

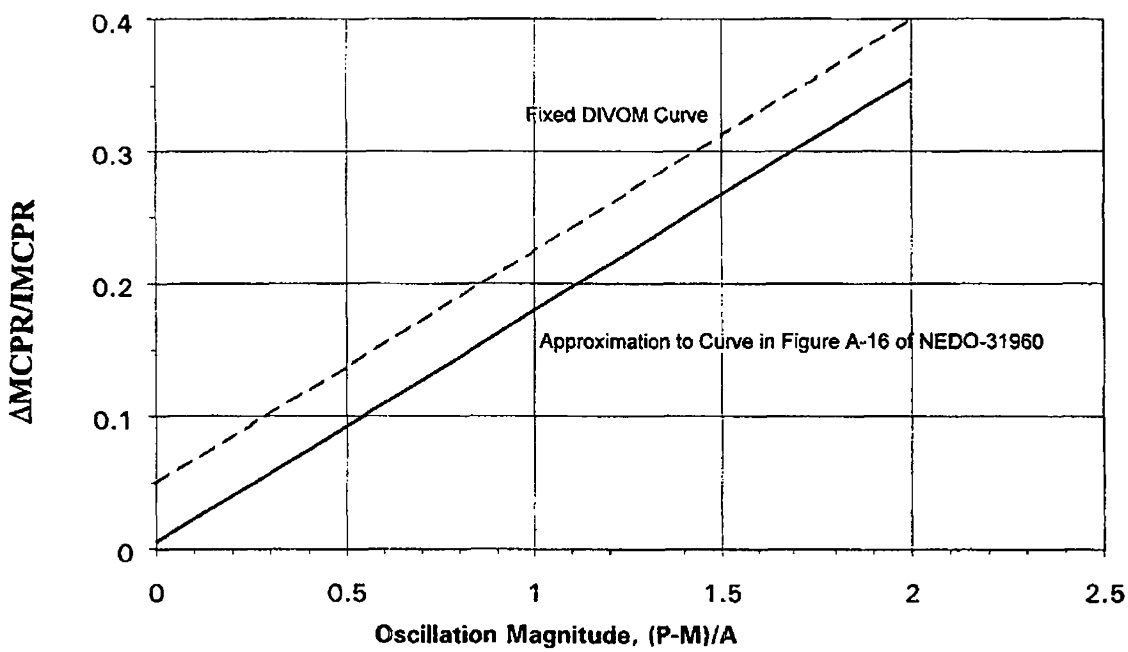
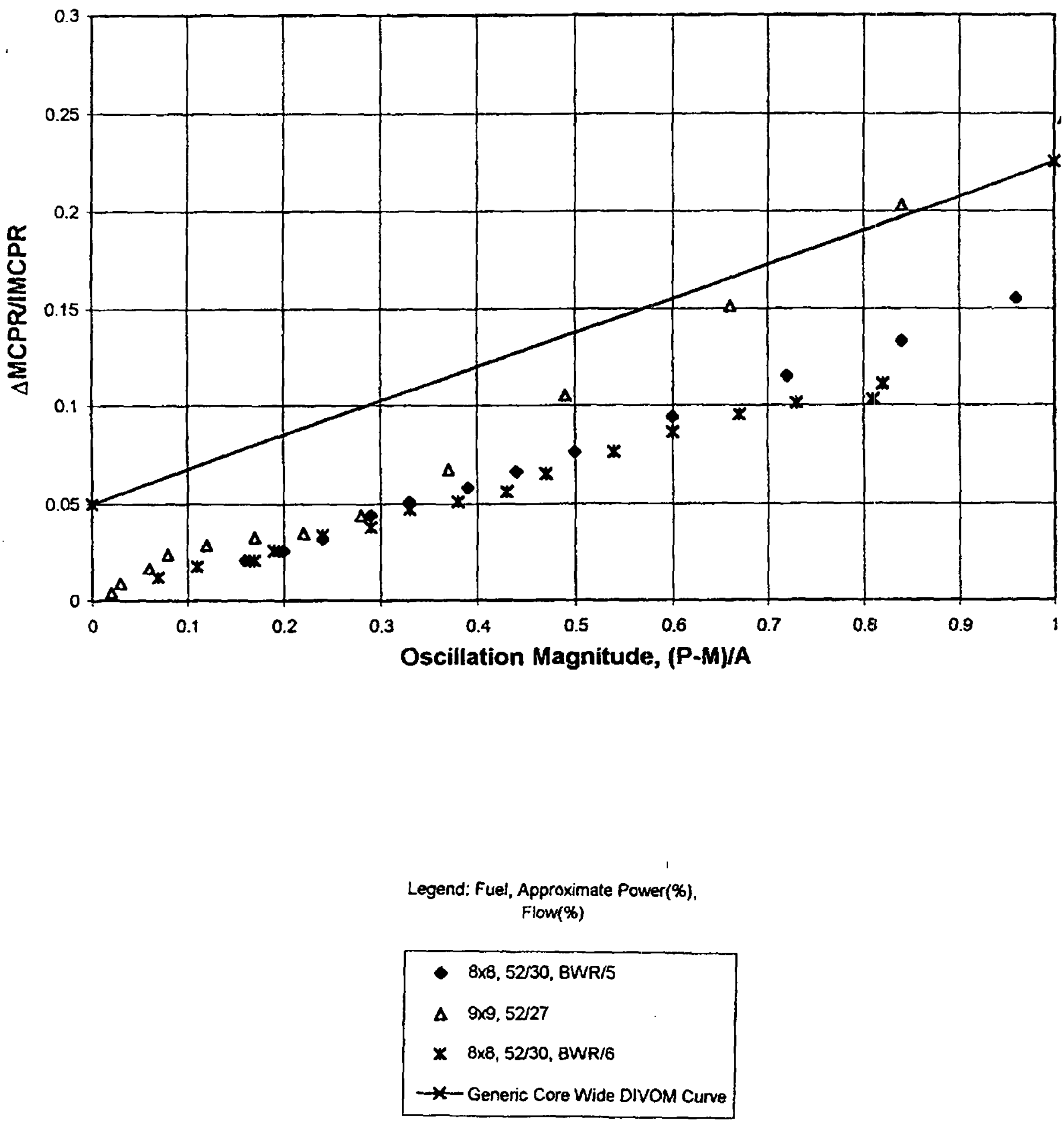


**Figure 7-3: Generic DIVOM Curve for Core Wide Mode Oscillations**



## 7.5 SUMMARY

### 7.5.1 FINAL MCPR CALCULATION

The three-part process described in Sections 7.3 and 7.4 allows the calculation of a conservative value of the minimum MCPR for an anticipated stability-related oscillation. First, the initial MCPR (IMCPR) is determined by a cycle-specific evaluation at the selected rod line. Next, the hot bundle oscillation magnitude (at a 95% probability/95% confidence level) is calculated at the selected rod line. Finally, the MCPR performance corresponding to the 95/95 value of the hot bundle oscillation magnitude is determined. From these three elements, the final MCPR (FMCPR) can be determined:

$$\text{FMCPR} = \text{IMCPR} - \text{IMCPR} * \{\Delta\text{CPR/IMCPR}\}$$

where:

$\{\Delta\text{CPR/IMCPR}\}$ = determined from generic DIVOM curve at the specified $(\text{P-M})/\text{A}_{95/95}$ oscillation magnitude.

The licensing criterion is met when the FMCPR is greater than the MCPR SL.

### 7.5.2 METHODOLOGY CONSERVATISMS

The detect and suppress portion of the Option 1-D licensing methodology, which is conceptually identical to Option III taken as a whole, is a conservative means of demonstrating that the MCPR SL will not be violated for anticipated oscillations. The statistical portion of the methodology does not consider the propensity of the reactor to oscillate; it assumes that the reactor power oscillations occur for every statistical trial. No probabilistic credit is taken for the fact that the reactor may not oscillate. A number of these conservatisms, inherent in the methodology, are listed below:

1. The use of the MCPR SL to provide protection against possible fuel damage is exceedingly conservative, as discussed in Section 2.1.

2. The reactor is assumed to be at the MCPR Operating Limit prior to the event. Realistically, reactors normally operate well above the MCPR Operating Limit.

3. The statistical analysis selects a 95% probability with a 95% confidence level value of (P-M)/A. In addition, other conservative assumptions are made in the statistical methodology (Section 7.3).

4. Maximum allowed Technical Specification scram times and response times are used for the analysis. The scram and delay times affect the trip

overshoot calculation in the Monte Carlo analysis of hot bundle oscillation magnitude.

5. Using the minimum available IMCPR on the selected rod line from either the two recirculation pump trip (RPT) from full power or operation at 45% core flow is also quite conservative with respect to reality. This is due to the fact that plants do not normally operate on limits, and a reasonable percentage of instability events can be expected to occur at low flows. Due to the increase in MCPR OL at lower flows, oscillations initiated at low flows would have significantly higher values of IMCPR than is assumed in the analysis.

## 7.6 INITIAL APPLICATION

This section describes the process for a plant-specific first application of the Option 1-D detect and suppress licensing methodology. In the first application, analyses are performed that may not need repetition in future fuel cycles. For an Option 1-D plant, this initial application is intended to demonstrate that the existing APRM flow-biased scram setpoint is adequate to protect the MCPR SL for anticipated oscillations.

### 7.6.1 OVERVIEW

The first application process follows the three major steps in the licensing methodology. First, a rod line is selected to specify the basis for the IMCPR calculation, the average core power, and the trip setpoint. A statistical calculation is performed for natural circulation on the selected rod line to determine the conservative hot bundle oscillation magnitude [$(P\text{-}M)/A_{95/95}$] using the method described in Section 7.3. Second, the generic DIVOM curve for core wide mode oscillations is used, along with the calculated $(P\text{-}M)/A_{95/95}$ value, to determine the fractional CPR change, $\Delta$CPR/IMCPR. It must be confirmed that the generic DIVOM curve for core wide oscillations is valid for application to the current fuel types. Third, the expected plant/cycle-specific values for the initial MCPR (IMCPR) are determined as described in Section 7.3.2. Then, the final MCPR is calculated as described in Section 7.5.1. If the FMCPR is greater than the MCPR SL, then it has been demonstrated with high confidence that the flow-biased APRM trip system provides protection for the MCPR SL at the analyzed rod line.

### 7.6.2 SAMPLE PLANT CALCULATIONS

A sample Monte Carlo analysis for a BWR/4, with a 368-bundle core is reported in Table 7-3 for a core average power of 48% of rated (on the 100% rod line), at natural circulation, with a 62% power APRM flow-biased trip setpoint. The hot bundle oscillation magnitude 95/95 value resulting from the Monte Carlo statistical analysis is:

$$(P\text{-}M)/A_{95/95} = 0.702$$

Using the generic DIVOM curve for core wide mode oscillations (Figure 7-2) and the calculated $(P\text{-}M)/A_{95/95}$, the $\Delta$CPR/IMCPR is determined to be 0.173. The initial MCPR prior to the onset of the oscillation is assumed to be 1.45, and the MCPR SL is assumed to be 1.07. Thus, the FMCPR is:

$$\begin{aligned} \text{FMCPR} &= \text{IMCPR} - \text{IMCPR} * \{\Delta\text{CPR/IMCPR}\} \\ &= 1.45 - 1.45 * (.173) \\ &= 1.20 \end{aligned}$$

Since the FMCPR is greater than the MCPR SL, the APRM flow-biased trip system shows protection for core wide mode oscillations at the analyzed rod line.

## 7.7 RELOAD REVIEW

### 7.7.1 OVERVIEW

The purpose of the reload review procedure is to confirm that the combination of APRM trip setpoints and IMCPR provides a high confidence that the MCPR SL will not be violated for anticipated stability related oscillations. The reload review procedure is a simplified version of the first application procedure described in Section 7.6. It consists of the cycle-specific calculation of IMCPR along with confirmations that the DIVOM curve remains applicable and the hot bundle oscillation magnitude ($\Delta_{h(95/95)}$) has not changed.

### 7.7.2 MAXIMUM HOT BUNDLE OSCILLATION MAGNITUDE

The plant-specific statistical calculation that generated the value of $\Delta_{h(95/95)}$ for the first application used certain key assumptions. Each of these assumptions must be checked to assure that they have not been changed for the reload cycle under evaluation. The principal item to be examined is the value of the APRM setpoint ($S_p$). In general, it is not expected that inputs to the statistical calculation will be changed from cycle to cycle. If changes in these parameters do not support the previous calculation of $\Delta_{h(95/95)}$, a new evaluation would be required.

### 7.7.3 INITIAL MCPR CALCULATION

The value of initial MCPR (IMCPR) is calculated as described previously. This calculation produces the cycle-specific IMCPR used to calculate the final MCPR. If the MCPR OL has changed for the new reload, it is likely that the IMCPR will also change.

### 7.7.4 MCPR PERFORMANCE (DIVOM) CURVE

The generic DIVOM curve for core wide mode oscillations (Figure 7-2) must be determined to be applicable to the fuel types that exist in the reload core. If a fuel type significantly different from the ones previously considered is being introduced (except for LUAs), a new DIVOM curve may need to be determined.

### 7.7.5 SUMMARY

Using the IMCPR, $\Delta_{h(95/95)}$, and DIVOM curve established for the reload, the final MCPR is calculated as described in Section 7.5.1. If the FMCPR is greater than or equal to the MCPR SL, then the APRM flow-biased trip setpoints are acceptable for that cycle (i.e., the MCPR SL is not violated for anticipated oscillations). If the FMCPR is less than the MCPR SL, the setpoints or the MCPR OLs need to be changed and the evaluation redone.

# 8.0 REFERENCES


1. NEDO-31960, *BWR Owners' Group Long-Term Stability Solutions Licensing Methodology*, June 1991.

2. NEDO-31960, Supplement 1, *BWR Owners' Group Long-Term Stability Solutions Licensing Methodology.*

3. NRC Letter to L. A. England (Chairman BWR Owners' Group), "Acceptance for Referencing of Topical Reports NEDO-31960 and NEDO-31960 Supplement 1, "BWR Owners' Group Long-Term Stability Solutions licensing Methodology", July 12 1993.

4. NEDO-32047, *ATWS Rule Issues Related to BWR Core Thermal-Hydraulic Stability.*

5. Somerville, Paul N., "Tables For Obtaining Non-Parametric Tolerance Limits," Ana. of Math. Statistics, Vol. 29, 1958, pp. 599-601.

6. GENE-637-018-0793, *Application of the 'Regional Exclusion with Flow-Biased APRM Neutron Flux Scram' Stability Solution (Option 1-D) to the Vermont Yankee Nuclear Power Plant*, July 1993.

7. NEDE-32177P, Revision 1, *TRACG Qualification*, June 1993.

8. NRC letter to Donald A. Reid (VYNPC), "Thermal Hydraulic Stability - Vermont Yankee Nuclear Power Station (TAC No. M87091)," NVY 95-43, March 30, 1995.

9. Letter from D.W. Newkirk (GE) to Utilities Participating in Stability Long-Term Solution Option I-D, "Conference Report: December 16, 1993 Meeting With The NRC (Washington, D.C)," SIE94-06, January 14, 1994.

# APPENDIX A: AMPLITUDE AND GROWTH RATE ALGORITHMS

## A.1 INTRODUCTION

As described in References 1 and 2, the Option III solution includes three separate algorithms for detecting stability related oscillations: the Period Based Detection Algorithm (PBDA), the Growth Rate Algorithm (GRA), and the Amplitude Based Algorithm (ABA). All three algorithms perform calculations on each OPRM cell signals to determine if a trip is required. The OPRM cell parameter examined by the algorithms is defined as the peak of the oscillation divided by the average value (P/A). Each algorithm examines a different aspect of an oscillation.

The growth rate and amplitude based components of the detection algorithm are not needed to ensure compliance with the MCPR SL; therefore, they are not part of the licensing basis for the Option III solution. This function is accomplished solely by the PBDA described in Section 3. The growth rate and amplitude algorithms offer defense-in-depth by providing protection for oscillation characteristics which have not been observed and are not expected to occur. Regardless of their low probability, it was considered prudent to provide some form of protection for these "unanticipated oscillations".

The design objective for the growth rate and amplitude algorithms was to provide automatic action to limit the size of these unanticipated oscillations, thereby preventing fuel cladding damage. As demonstrated in Reference 4, power oscillations up to 200% of rated power produce a temperature transient such that no cladding failure would be expected. The defense-in-depth, provided by the amplitude and growth rate algorithms described in References 1 and 2, offers a high degree of assurance that fuel failure will not occur as a consequence of stability related oscillations.

Table A-1 contains a set of typical growth rate and amplitude algorithm setpoints. These setpoints would reasonably limit the size of a stability related power oscillation. Although less restrictive values of the setpoints could be demonstrated to be acceptable, these setpoints are considered to be reasonable, based on engineering judgment. The typical growth rate setpoint given in Table A-1 (i.e., 1.30) is less than the upper bound of the growth rate distribution used in the Monte Carlo determination of hot bundle oscillation magnitude. Thus, there is a measure of "overlap" between the growth rates considered for the PBDA and growth rate algorithms. Also, an evaluation demonstrated that the setpoints given in Table A-1 would have resulted in termination of the LaSalle 2 instability (both amplitude and growth rate trips) prior to the time that the reactor scram occurred. Thus, the amplitude and growth rate trips with the specified setpoints provide backup protection greater than that provided by the APRM high flux scram. No further analyses will be performed to justify these setpoints.

## A.2 ALGORITHM DESCRIPTION

### A.2.1 AMPLITUDE BASED ALGORITHM

The Amplitude Based Algorithm is described in Section B.1 of Reference 1 and Section 6.1 of Reference 2. The value of the OPRM cell relative signal (P/A) is compared at each hardware time step to a threshold setpoint, $S_1$ (greater than 1.0). If the relative signal exceeds $S_1$, then the algorithm checks to determine if the relative signal decreases to a second setpoint, $S_2$ (less than 1.0), within a time period typical of an instability oscillation. If the signal goes below $S_2$ in the expected time widow ($T_1$), then the algorithm looks for the next peak in the relative signal. Then, if the relative signal exceeds the trip setpoint, $S_{max}$, in the expected time window ($T_2$), a trip is generated for that OPRM cell (and hence for that RPS channel). Typical values for $S_1$, $S_2$, $S_{max}$, $T_1$, and $T_2$ are given in Table A-1.

### A.2.2 GROWTH RATE BASED ALGORITHM

The Growth Rate Based Algorithm (described in Section 6.1 of Reference 2) examines OPRM cell signals for rapidly growing oscillations. This algorithm basically follows the same logic as the Amplitude Based Algorithm. After exceeding $S_1$ and decreasing below $S_2$ in the expected time window, a trip is generated if a setpoint $S_3$ is exceeded in the expected time window. $S_3$ is a setpoint calculated from the peak of the previous cycle ($P_1$) and the desired maximum allowable growth rate ($GR_3$):

$$S_3 = GR_3 * (P_1 - 1.0) + 1.0$$

If the signal goes above $S_1$, then below $S_2$ in the expected time window, and then exceeds $S_3$ within the expected time window, a trip is generated for that OPRM cell (and hence for that RPS channel). The Growth Rate Based Algorithm uses the same values for $S_1$, $S_2$, $T_1$, and $T_2$ as the Amplitude Based Algorithm. Typical values for $S_1$, $S_2$, $GR_3$, $T_1$ and $T_2$ are given in Table A-1.

**Table A-1: Example Amplitude and Growth Rate Algorithm Setpoints**

| Setpoint | Typical Value |
|---|---|
| $S_1$ | 1.10 |
| $S_2$ | 0.92 |
| $S_{max}$ | 1.30 |
| $GR_3$ | 1.30 |
| $T_1$ (time window) | 0.3 to 2.5 seconds |
| $T_2$ (time window) | 0.3 to 2.5 seconds |

# APPENDIX B:
# FULLY COUPLED TRACG RESULTS

## B.1 INTRODUCTION

The goal of the MCPR performance analysis, using the TRACG Code, was to develop generic DIVOM curves. Generation of generic curves which are applicable to all current 8x8, 9x9, and 10x10 fuel designs greatly simplifies the initial application and reload review processes.

TRACG is an appropriate code to use for this fully coupled neutronic/thermal hydraulic analysis as documented in References 1 and 2. TRACG provides a multi-dimensional two-fluid model for reactor thermal hydraulics and a three-dimensional neutronic kinetics model. TRACG qualification for reactor instability time dependent response calculations has been documented in Reference 7. A BWR-5 with 764 bundles was chosen for the analysis documented herein. One additional BWR-6 case was performed to confirm that BWR type does not significantly affect the DIVOM curve.

The MCPR performance curves, known as the DIVOM curves, are a fractional change in CPR (CPR change due to an oscillation divided by the initial CPR) versus oscillation magnitude. The CPR correlation used in the TRACG analysis provides a conservative prediction of approach to boiling transition during reactor instability. The CPR correlation testing and validation, including under various cyclical power and flow conditions, ensures that there is an accurate prediction of the fractional change in CPR. The demonstrated ability of the correlation to predict boiling transition for various steady state and oscillatory conditions provides confidence that the TRACG calculation adequately predicts the fractional CPR change for other CPR correlations.

## B.2 BASE CASES

The TRACG base cases reported in Section 4.4.4 calculated DIVOM data for 8x8, 9x9, 10x10, and mixed core fuel loading at similar operating state conditions. The 8x8 and 9x9 fuel designs were evaluated for both core wide and regional mode oscillations. The CPR performance was similar for all fuel designs, though the 9x9 fuel design evaluated generally had the most limiting DIVOM data.

The base case operating conditions are identified in Tables B-1 and B-2. They evaluated the impact of power, flow rate, and core inlet subcooling. These cases are representative of plant conditions at which anticipated oscillations could occur. The cases included a range of powers from 52% to 57% which represent rated rod line to extended rod line operating conditions. Higher powers tend to make the core less stable and produce a steeper DIVOM curve. For the 9x9 cases, nominal core inlet subcooling was 56 Btu/lbm. Feedwater temperature was varied to produce an increased core inlet subcooling of 75 Btu/lbm and a reduced core inlet subcooling of 28 Btu/lbm. Increasing core inlet subcooling increased the oscillation growth rate and maximum oscillation magnitude, but had very little effect on the slope of the DIVOM curve. Similarly, decreasing core inlet subcooling decreased the oscillation growth rate and maximum oscillation magnitude and also had little effect on the slope of the DIVOM curve. Core flow rates from natural circulation (25% to 30% core flow) to low forced flow (30% to 39% core flow) were also studied. Increasing the core flow rate made the core somewhat more stable and reduced the oscillation growth rate and maximum oscillation magnitude, but also had very little effect on the slope of the DIVOM curve.

**Table B-1: Regional Mode Base Case Evaluation Conditions**

| Fuel Type | Power | Flow | Subcooling |
|---|---|---|---|
| 8x8 | 52% | 30% | Nominal |
| 8x8 | 59% | 39% | Nominal |
| 8x8 | 57% | 30% | Nominal |
| 8x8 | 38% | 32% | Increased |
| 9x9 | 52% | 27% | Nominal |
| 9x9 | 57% | 27% | Nominal |
| 9x9 | 52% | 30% | Nominal |
| 9x9 | 57% | 30% | Nominal |
| 9x9 | 52% | 27% | Decreased |
| 9x9 | 52% | 27% | Increased |
| 10x10 | 52% | 25% | Nominal |
| 10x10 | 57% | 25% | Nominal |
| Mixed Core 9x9 and 10x10 | 50% | 30% | Nominal |

**Table B-2: Core Wide Mode Base Case Evaluation Conditions**

| Fuel Type | Power | Flow | Subcooling |
|---|---|---|---|
| 8x8 (BWR-5) | 52% | 30% | Nominal |
| 8x8 (BWR-6) | 52% | 30% | Nominal |
| 9x9 | 52% | 27% | Nominal |

The base case fuel design parameters are shown in Table B-3. The values for core void coefficient, fuel thermal time constant, and two-phase to single-phase pressure drop are provided. The two-phase to single-phase pressure drop ratios shown in Table B-3 include the core inlet orifice pressure drop. Sensitivity studies on these fuel design parameters are described in Section B.3.

**Table B-3: Base Case Fuel Design Parameters**

| Parameter | 8x8 | 9x9 | 10x10 |
|---|---|---|---|
| **Core Void Coefficient** | -0.26 ($/%Δvoids) | -0.18 ($/%Δvoids) | -0.21 ($/%Δvoids) |
| **Fuel Thermal Time Constant** | 5.0 sec | 4.6 sec | 3.6 sec |
| **Two-phase to Single-phase pressure drop ratio** | 2.4 | 2.9 | 2.4 |

## B.3 SENSITIVITY STUDY PARAMETERS

Sensitivity studies were performed to provide a perspective on the selection of the generic DIVOM curves for all fuel types. The base cases evaluated a wide range of fuel designs and core conditions. The variation of individual fuel design paramenters is useful to show how changing one specific parameter would affect the fractional CPR response as a function of oscillation magnitude. None of the sensitivity study cases represents a real fuel design, since actual fuel designs do not vary single parameters independently.

The base cases provided in Figures 4-11 and 4-12 showed that the 9x9 fuel design cases generally had a somewhat more limiting (steeper) DIVOM curve than the 8x8 or 10x10 fuel design cases. The base cases clearly showed that regional mode oscillations have more limiting DIVOM data than core wide mode oscillations. Therefore, the 9x9 fuel design with a regional mode oscillation was selected as the base case for the sensitivity studies.

Core void coefficient, fuel thermal time constant, and two-phase to single-phase pressure drop ratio were selected as the fuel design parameters to vary for the sensitivity studies. These are the fuel design parameters which can significantly affect core stability. The parameter ranges used in the sensitivity studies are shown in Table B-4. The impact of these parameters on the propensity to oscillate is generally known. For example, a more negative core void coefficient produces a greater power change for a change in void content which is a less stable condition. However, the impact of these parameters on DIVOM data is not generally known. Specifically, an increased propensity to oscillate does not necessarily translate into a steeper DIVOM curve. The sensitivity studies independently the fuel design parameters to provide insights into the effect of these design parameters on the DIVOM data.

**Table B-4: MCPR Performance Sensitivity Study Parameter Ranges**

| Parameter | Base Value | Range |
|---|---|---|
| **Core Void Coefficient** | -0.18 ($/%Δvoids) | -0.13 to -0.23 ($/%Δvoids) |
| **Fuel Thermal Time Constant** | 4.6 seconds | 2.9 to 4.6 seconds |
| **Two-phase to Single-phase pressure drop ratio** | 2.9 | 3.8 to 2.9 |

## B.4 SENSITIVITY STUDY RESULTS

All the sensitivity studies were performed with a 9x9 fuel design, for a regional mode oscillation, at 52% power and natural circulation (27% core flow). The base case parameters for the sensitivity studies are shown in Table B-4. CPR performance results from the sensitivity studies are provided in Figure B-1.

The core void coefficient was varied using a void coefficient factor which is built into the TRACG Code. As shown in the legend of Figure B-1, a VC Factor of 0.7 means that the case had a factor of 0.7 applied to the base case core void coefficient (i.e., 0.7 * -0.18 ($/% Δvoids) = -0.13 ($/% Δvoids)). The results show that a less negative void coefficient produces a steeper DIVOM curve. This trend is compensated somewhat by the fact that actual fuel and core designs with a less negative void coefficient have a much lower propensity to oscillate (i.e., they are inherently more stable). As shown in Table B-3, the 9x9 fuel design case has the least negative void coefficient of the base case fuel designs analyzed. This is probably the main reason that the 9x9 cases produced the steepest DIVOM results. One sensitivity study used a more negative core void coefficient (VC Factor of 1.3). While this case has a greater propensity to oscillate, it produces less limiting DIVOM results. The relationship between void coefficient and DIVOM slope is expected given that the CPR change is primarily a flow driven response. If a flow change produces a smaller power change (as it would for a less negative void coefficient), then the slope of the DIVOM curve would be steeper.

The fuel thermal time constant (Tau in the legend of Figure B-1) was reduced to a value of 2.9 seconds. In general, reducing fuel thermal time constant makes the core less stable and produces a small increase in the DIVOM data.

The two-phase to single-phase pressure drop ratio (2P/1P in the legend of Figure B-1) was increased to a value of 3.8. In general, while increasing the two-phase to single-phase pressure drop ratio makes the core less stable, there is relatively little impact on the resulting DIVOM data.

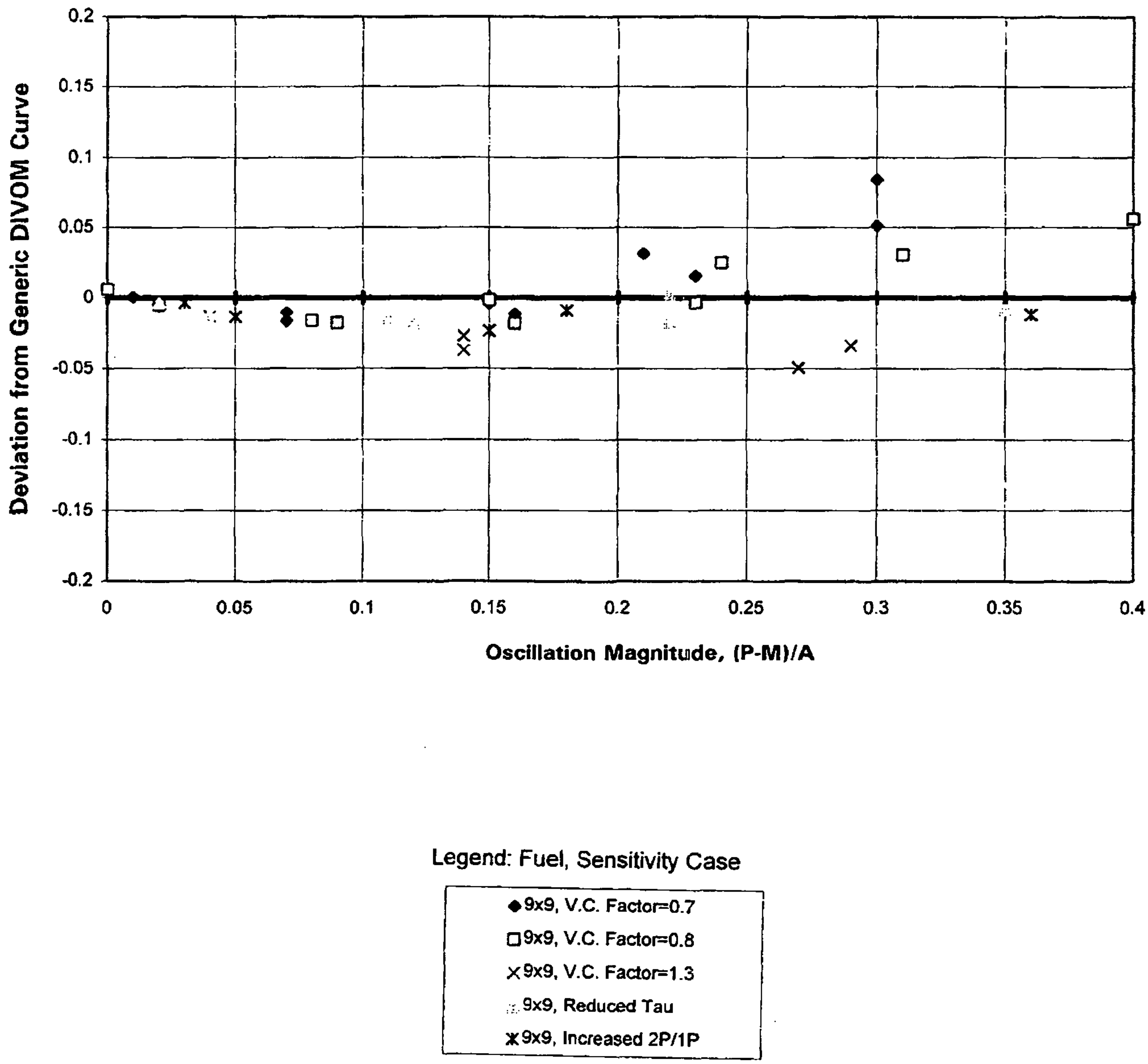
The only sensitivity studies which showed DIVOM data more limiting than the base cases were the studies with the significantly less negative core void coefficient. The study with the significantly less negative core void coefficient has a reduced hot bundle power oscillation magnitude, but very nearly the same hot bundle CPR response. Although taken alone, this produces a steeper DIVOM curve, the core is less likely to oscillate and would have a lower oscillation growth rate if reactor instability were to occur. A lower growth rate produces a lower value of hot bundle oscillation magnitude which would mitigate the DIVOM behavior in a FMCPR calculation.

The overall impact on stability and DIVOM for each of the sensitivity studies is shown in Table B-5. The results provide a perspective of the impact of fuel design changes on the DIVOM data. It should be noted, however, that these parameters are not varied independently in the creation of new fuel designs. Therefore, the sensitivity study results support the conclusion that the generic DIVOM curves reasonably represent all current fuel types with respect to the application to the detect and suppress licensing methodology.

**Table B-5: MCPR Performance Sensitivity Study Results**

| Parameter | Effect on Reactor Stability | Effect on DIVOM Slope |
|---|---|---|
| **Less Negative Core Void Coefficient** | More stable | Increase |
| **More Negative Core Void Coefficient** | Less stable | Decrease |
| **Decrease Fuel Thermal Time Constant** | Less stable | Small increase |
| **Increase Two-phase to Single-phase pressure drop ratio** | Less stable | No change |

**Figure B-1: Sensitivity Study DIVOM Data**



# APPENDIX C: RESOLUTION OF SER COMMENTS ON OPTIONS III AND III-A

**Reference:** Letter Ashok C. Thadani (NRC) to L.A. England (BWROG Chairman), "Acceptance for Referencing of Topical Reports NEDO-31960 and NEDO-31960 Supplement 1, 'BWR Owners' Group Long-Term Stability Solutions Licensing Methodology' (TAC No. M75928)", July 12, 1993

This appendix identifies the closure of each comment in the NRC Safety Evaluation Report on Stability Long-Term Solution Options III and III-A. All comments have been resolved with the completion of this licensing methodology.

**Comments:**

1. "The exclusion region calculation methodology described in NEDO-31960 and its Supplement 1 is acceptable for defining ... the Options III and III-A exclusion boundaries outside of which the detect and suppress action may be deactivated." (SER page 5)

   Response: The exclusion region methodology would define a curved region on the power/flow operating map cutting across the corner of the map near the intersection of the natural circulation line and the highest flow control line. The proximity of the line to the corner would depend upon plant-specific stability characteristics. To ease implementation of the solution, squared off boundaries at [≤60%] rated core flow and [≥30%] rated power will be used. This does not prevent a licensee from using the exclusion region methodology to define the boundaries of the region if they are so inclined.

2. "The overall treatment of uncertainties is acceptable for the selection of initial conditions and for the selection of oscillation contours and the treatment of failed LPRM sensors for Options III and III-A."

   Response: The overall treatment of uncertainties for detect and suppress solutions has not changed from that documented in NEDO-31960 and NEDO-31960 Supplement 1.

3. "All three algorithms described in NEDO-31960 and Supplement 1 should be used in Option III or III-A. These three algorithms are high LPRM oscillation amplitude, high-low detection algorithm, and period based algorithm." (SER page 8; also specified in TER page 5)

   "Automatic protection action must initiate if either of the algorithms detects oscillations." (TER page 7)

   **Response**: All three algorithms are included in the Option III design. Automatic protection is actuated if any of the three algorithms meet their trip conditions. Only the period based algorithm, however, is used to demonstrate protection of the MCPR Safety Limit for anticipated reactor instabilities. The other two algorithms are included as defense-in-depth features of the Option III design.

4. "The validity of scram setpoints selected should be demonstrated by analyses. These analyses ... should include an uncertainty treatment that accounts for the number of failed sensors permitted by the technical specifications." (SER page 8; also specified in TER page 7)

   **Response**: This licensing topical report defines the methodology by which the validity of Option III period based algorithm setpoints is demonstrated for plant specific applications. Accounting for failed sensors has been incorporated into the methodology. Portions of the methodology may also be used to demonstrate the ability of the flow-biased APRM trip to provide Safety Limit protection for Option 1-D plants. The setpoints for the other two Option III algorithms (i.e., amplitude based and growth rate algorithms) are generically specified based on engineering judgment to provide a level of defense-in-depth. The setpoints are selected to assure that a trip will occur for a reactor instability.

5. "Implementation of Option III or III-A will require that the selected bypass region outside of which the detect and suppress action is deactivated be defined in the technical specifications." (SER page 8)

   **Response**: The Technical Specifications will be addressed in licensing topical reports describing the specific Option III hardware designs.

6. "If an SRI is implemented with Option III or III-A, a backup full scram must take effect if the oscillations do not disappear ..." (SER page 9)

   <u>**Response**</u>: The methodology used to demonstrate protection of the Safety Limit includes a time delay from generation of the trip signal to rod insertion sufficient to suppress the reactor instability. This time delay is verified to be appropriate for each plant-specific application of the methodology. Thus, the methodology accommodates licensees which select SRI as the automatic safety function.

7. "The LPRM groupings defined in NEDO-31960 to provide input to Option III or III-A algorithms are acceptable ..." (SER page 9; also specified in TER page 8)

   <u>**Response**</u>: The basic philosophy of assigning LPRMs to overlapping OPRM cells and providing optimum core coverage has not changed. The acceptability of plant-specific LPRM assignments is demonstrated by analysis to show protection of the MCPR Safety Limit.

8. "Protection provided by Options III and III-A for single-channel instability is not highly reliable. When implementing the long term solution, a procedure to review the thermal hydraulic stability of lead use assemblies (LUA) in a core reload should be established." (SER page 9)

   <u>**Response**</u>: Generally, new fuel designs are not significantly less stable than previously approved fuel designs. In addition, the LUAs are customarily placed in non-limiting locations. Therefore, the fuel design and licensing process ensures that a single-channel oscillation is unlikely.

9. " ... implementation of this function must ... minimize the number of unnecessary actuations while maintaining a very high probability to perform the intended safety function." (TER page 1)

   <u>**Response**</u>: The period based algorithm is remarkably accurate in its ability to discern a true reactor instability from neutron flux noise (even at moderate to high decay ratios) with the algorithm parameters defined for Option III. Even if the algorithm were to indicate a sufficient number of period confirmations, the

peak/average amplitude setpoint must also be reached (on more than one channel) before a trip is initiated. Therefore, the algorithm will not trip unless a reactor instability occurs, and it will not trip unless the magnitude of the oscillation is large enough to reach the amplitude trip setpoint. For very slow growing oscillations (e.g., the Laguna Verde 1 event) this provides an opportunity for operator action to terminate oscillations prior to the initiation of a reactor trip. Thus, the design of Option III, in conjunction with the selected setpoints, minimizes unnecessary challenges to the Reactor Protection System.

10. "The main technical issue of significant relevance that still remains to be solved is the reload-dependent confirmatory analyses required to assert the applicability of the previous-cycle safety settings ..." (TER page 1)

    <u>Response</u>: The methodology used to confirm the cycle-specific applicability of the Option III system safety settings is documented in this report. The methodology has separated the analysis into three components: (1) Initial MCPR margin to the Safety Limit (IMCPR), (2) Normalized hot bundle oscillation magnitude at instability suppression ((P-M)/A), and (3) CPR performance versus oscillation magnitude (DIVOM). The separation allows for a logical grouping of the characteristics which could affect applicability of the system safety settings and simplifies the reload confirmation process.

11. "... will also contain a correlation to estimate the loss of critical-power-ratio margin as a function of as a function of the power oscillation amplitude." (TER page 2; also specified in TER page 5)

    "The applicability of the delta-CPR correlation ... to new fuels or fuels from different vendors is not clear." (TER page 6)

    <u>Response</u>: A correlation to estimate the loss of CPR margin as a function of the power oscillation amplitude is required for Option III and Option I-D solutions. Section 4.4 of this report discusses the procedure used to generate this correlation. The approach to develop this relationship for new fuel types and fuel types from different fuel vendors is also described.

12. "The good detection sensitivity of the period-based algorithm allows for fairly tight scram setpoints; therefore, this solution does not need to rely heavily on difficult calculations to show sufficient safety margin under a wide range of conditions and fuel types." (TER page 4)

<u>**Response**</u>: The good detection sensitivity of the PBA has allowed the use of conservative analysis assumptions. These conservatisms allow simplification of the reload calculation to demonstrate MCPR Safety Limit protection. The reload review methodology is described in Section 6 of this report.

13. "Reducing the number of false positives ... is crucial for the solution to work... we recommend (as proposed by the BWROG) that several diverse algorithms be implemented simultaneously for Solution III." (TER page 5)

<u>**Response**</u>: All three algorithms are included in the Option III design. The period based algorithm will provide a reactor trip for anticipated reactor instabilities and is the licensing basis by which Safety Limit protection is demonstrated. The other two algorithms are included as defense-in-depth features of the Option III design.

14. "The scram setpoints should be selected such that at least one of the algorithms has a large probability of detecting the oscillation and initiating protective action to prevent violation of any fuel safety criterion." (TER page 7)

<u>**Response**</u>: The validity of the scram setpoints for the PBDA is demonstrated by plant-specific calculations using the methodology defined in this report. These calculations provide a high statistical confidence that the plant-specific trip setpoints will prevent violation of the MCPR Safety Limit.

# APPENDIX D:
# EXAMPLE LPRM ASSIGNMENTS

This appendix provides several example LPRM-to-OPRM assignment schemes for two, three, and four LPRMs per OPRM cell. An example of 8 LPRMs per OPRM cell was shown in Reference 1. The examples are presented for one channel of a 560-bundle core, with 31 LPRM strings. The examples identify the LPRM level in the core (A to D, from bottom to top), the LPRM number using a consecutive numbering scheme for all the LPRMs in the core, and the OPRM cell number within the example channel. An isometirc of at least one OPRM cell is also provided to illustrate the configuration. The following figures are provided in this appendix:

Figure D-1. Two LPRMs per OPRM Cell - 2BL (Bockstanz-Lehmann) Design

Figure D-2. Two LPRMs per OPRM Cell - 2W (Watford) Design

Figure D-3. Three LPRMs per OPRM Cell - 3M (Mertz) Design

Figure D-4. Four LPRMs per OPRM Cell - 4BL (Bockstanz-Lehmann) Design

Figure D-5. Four LPRMs per OPRM Cell - 4W (Watford) Design

Figure D-6. Four LPRMs per OPRM Cell - 4P (Post) Design

**Figure D-1: Two LPRMS per OPRM Cell - 2BL (Bockstanz & Lehmann) Design**
**560-Bundle Core, OPRM Division A, Channel 1**

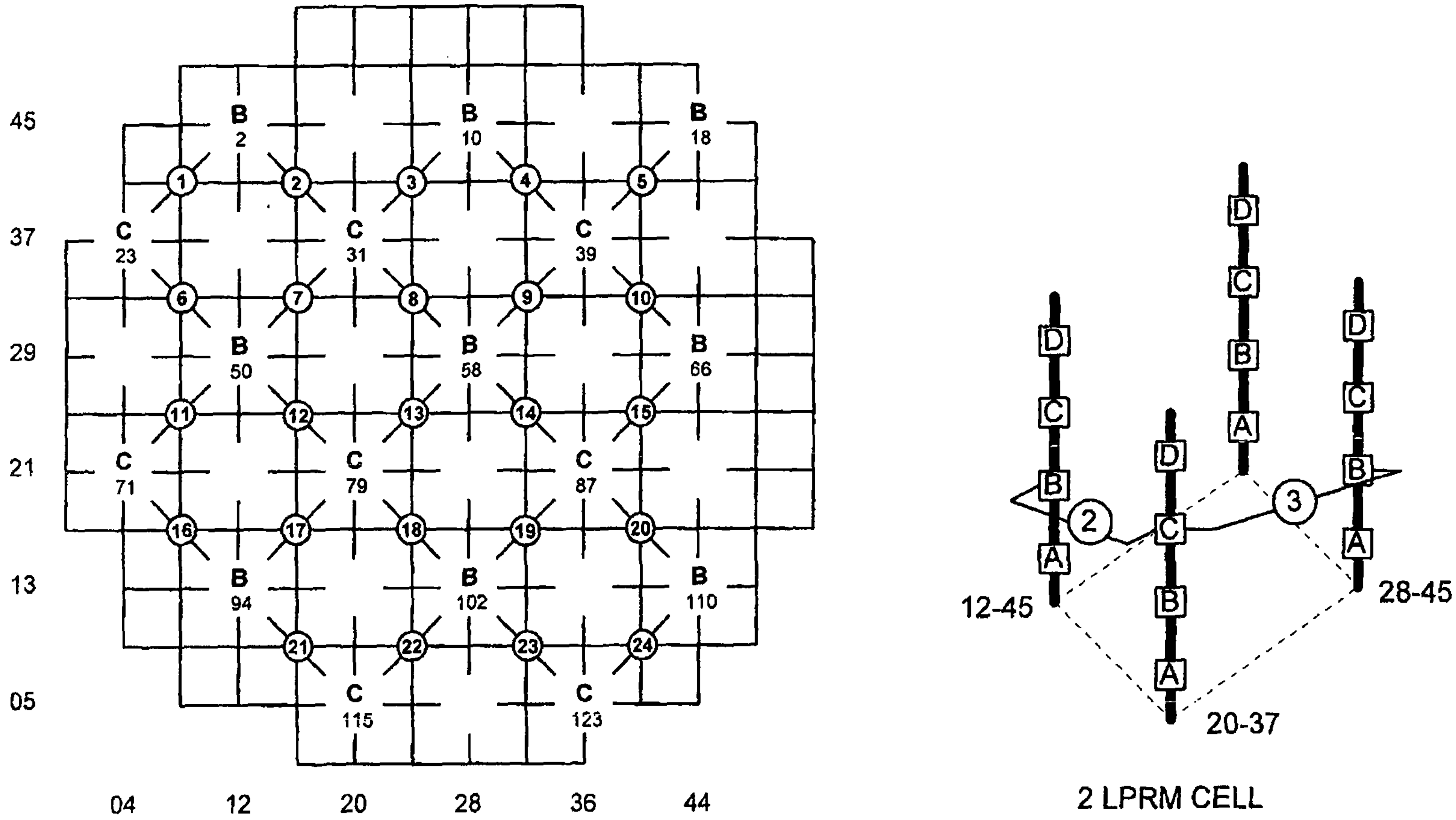


**Figure D-2: Two LPRMs per OPRM Cell - 2W (Watford) Design**
**560-Bundle Core, OPRM Division A, Channel 1**

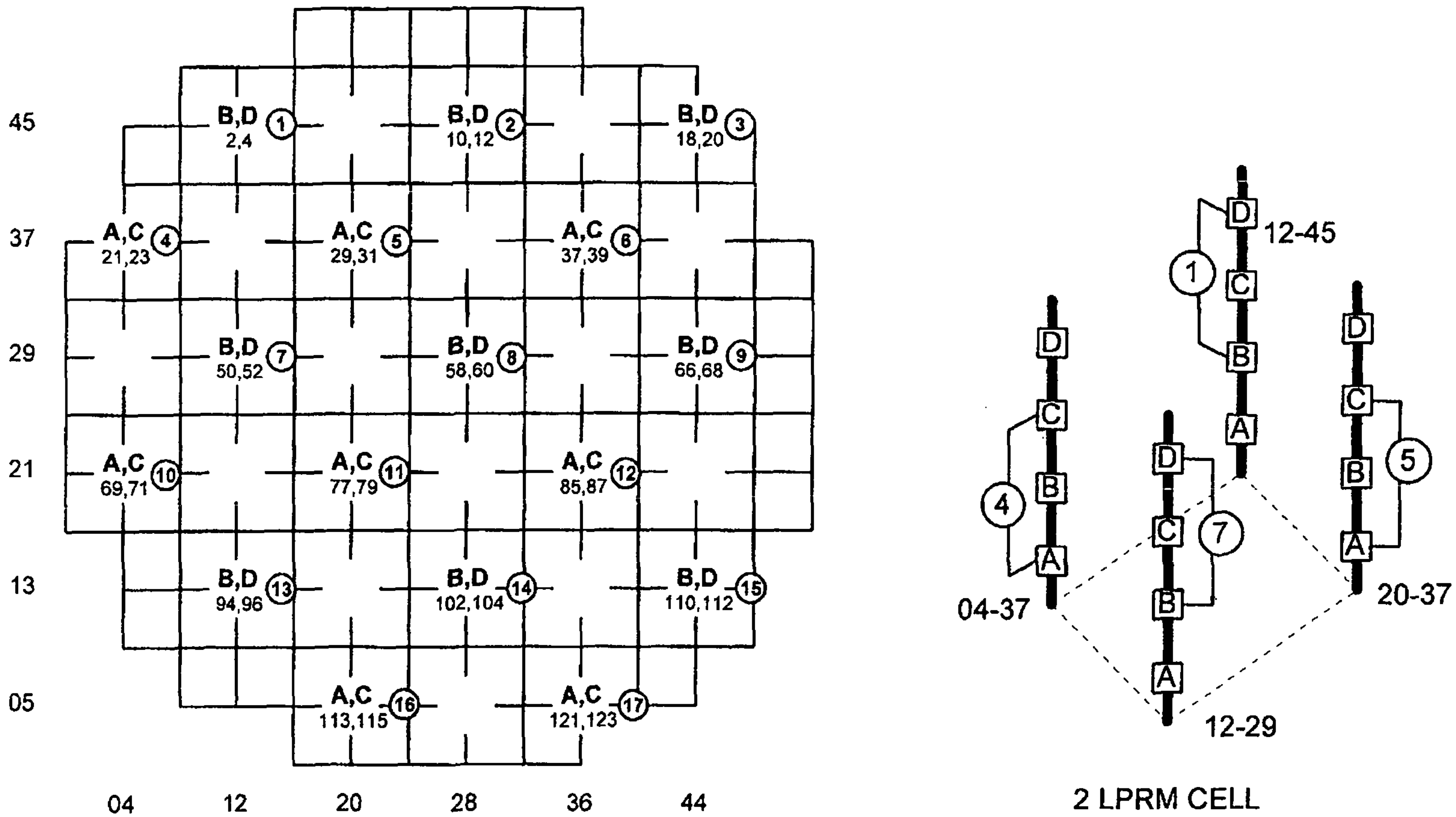


**Figure D-3: Three LPRMs per OPRM Cell - 3M (Mertz) Design**
**560-Bundle Core, OPRM Division A, Channel 1**

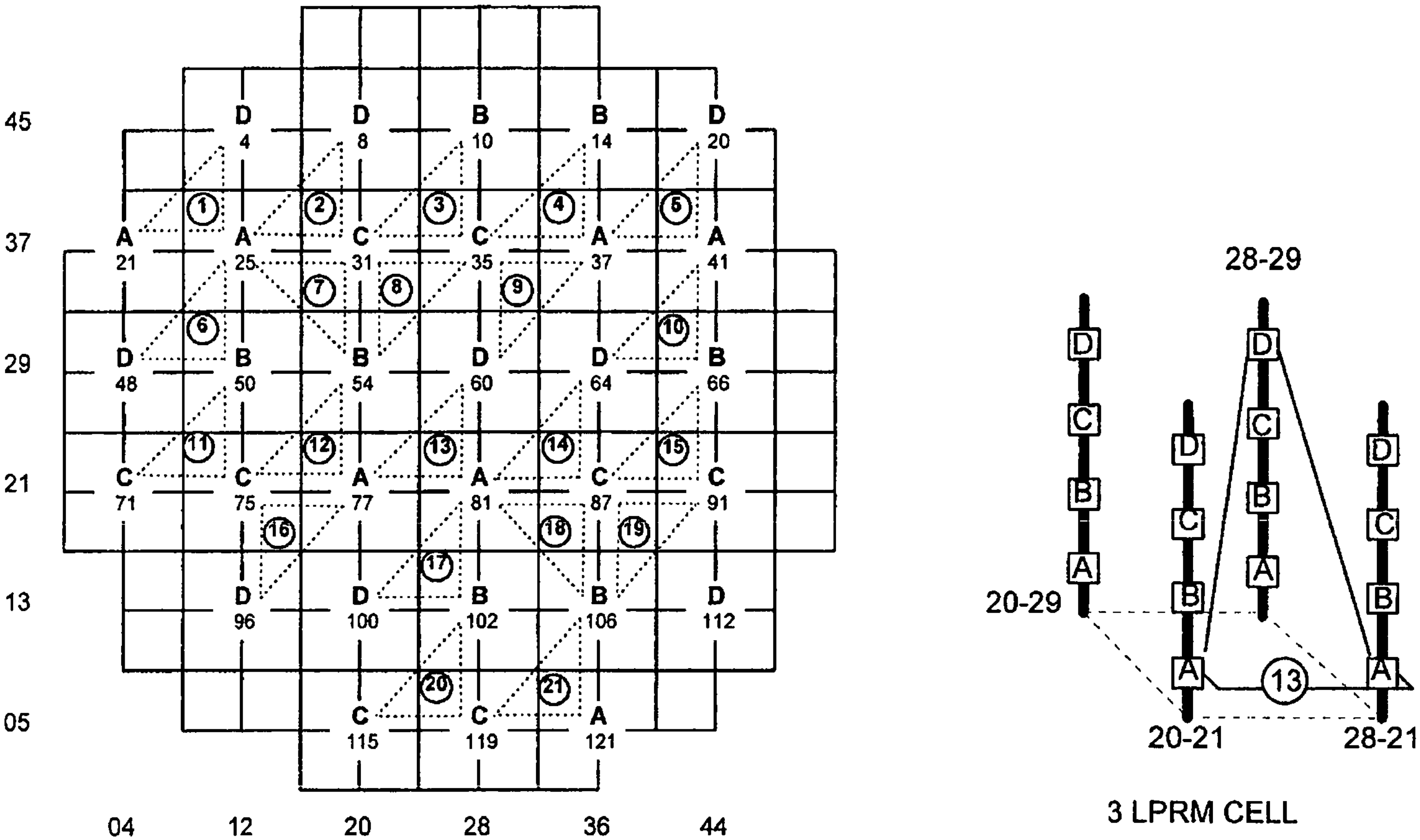


**Figure D-4: Four LPRMs per OPRM Cell - 4BL (Bockstanz & Lehmann) Design
560-Bundle Core, OPRM Division A, Channel 1**

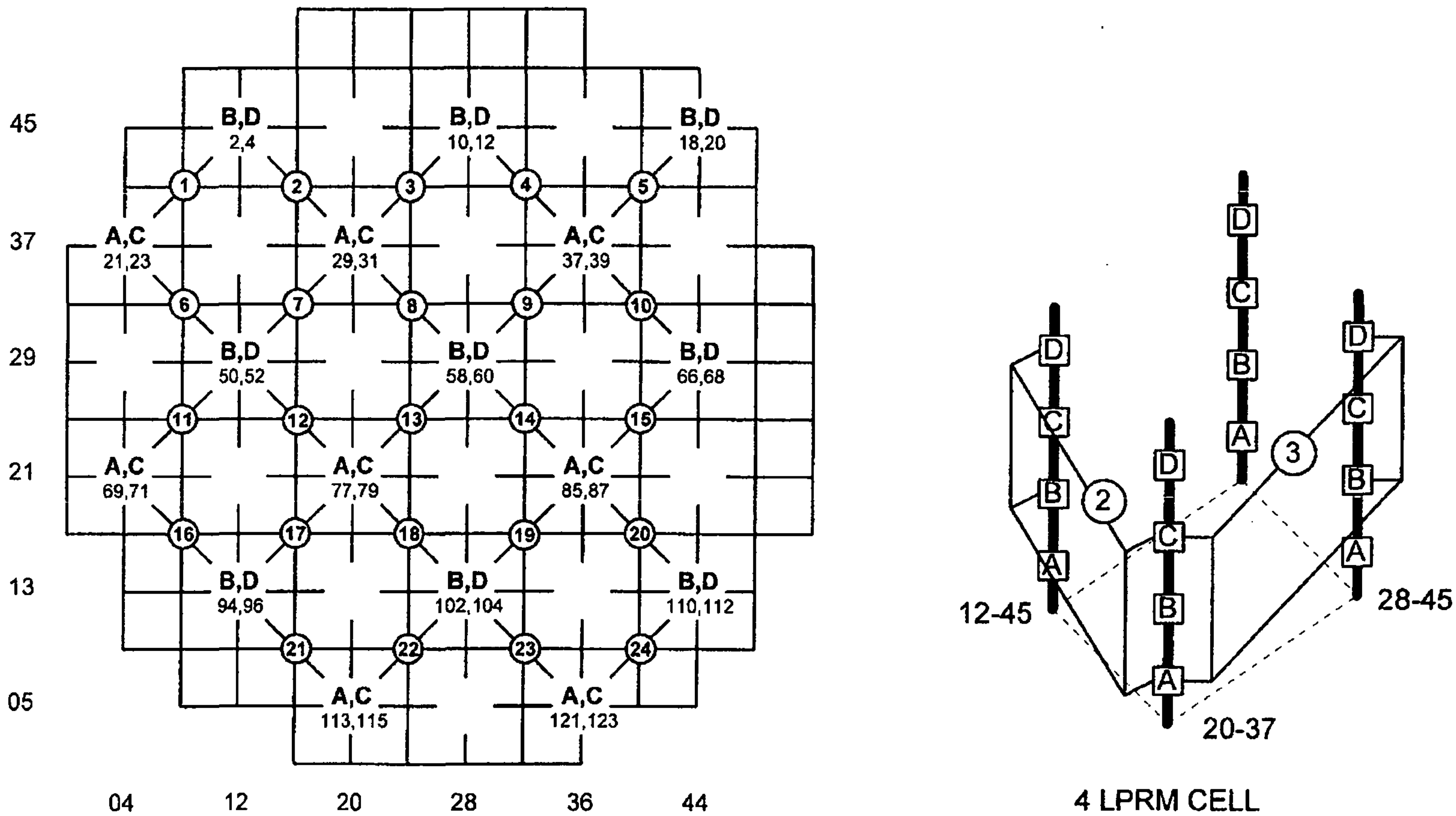


**Figure D-5: Four LPRMs per OPRM Cell - 4W (Watford) Design**
**560-Bundle Core, OPRM Division A, Channel 1**

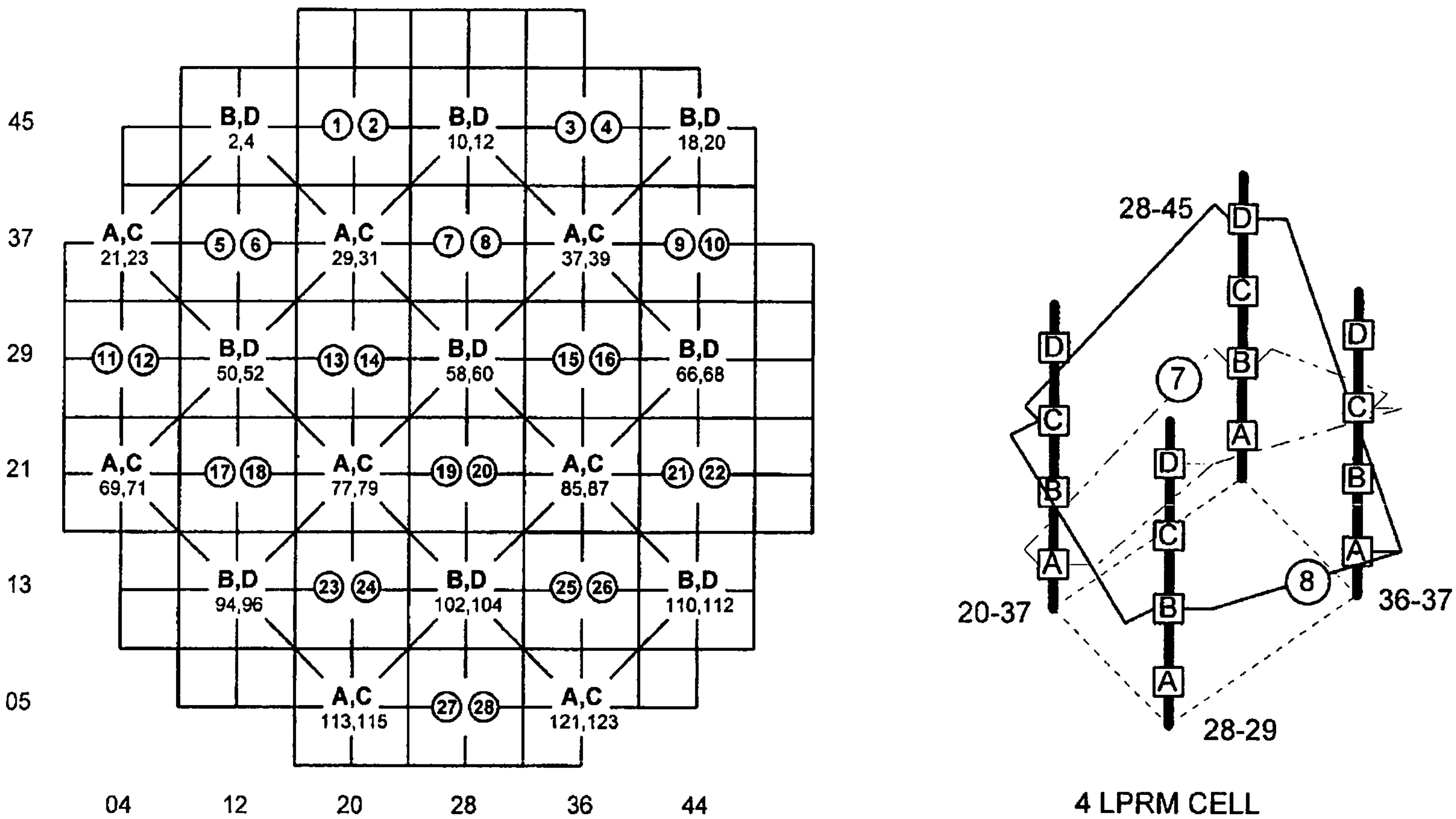
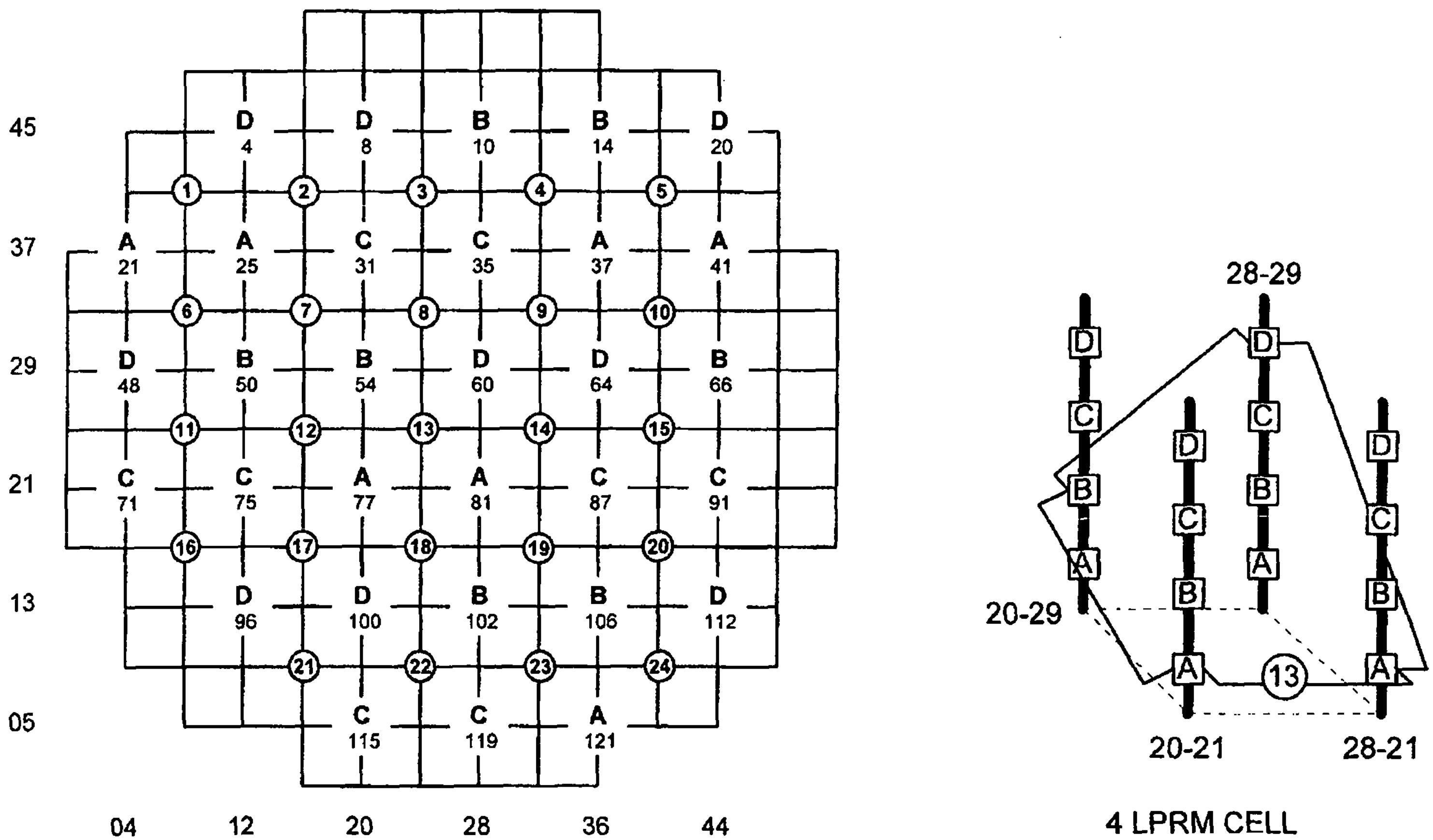


**Figure D-6: Four LPRMs per OPRM Cell - 4P (Post) Design**
**560-Bundle Core, OPRM Division A, Channel 1**



# APPENDIX E: Theoretical Model for Confirmation Count and Amplitude Trip Setpoints

This appendix provides a theoretical model to establish the relationship between the PBDA confirmation count setpoint, $N_P$, and the amplitude trip setpoint, $S_P$. Studies based on actual plant data indicate that many period confirmations are expected prior to a significant increase in amplitude. However, the theoretical model conservatively assumes ***no*** confirmations prior to reaching a specified amplitude. The theoretical model then uses the definition of growth rate for a normalized signal, as illustrated in Figure E-1, to define the relationship between confirmation count and amplitude.

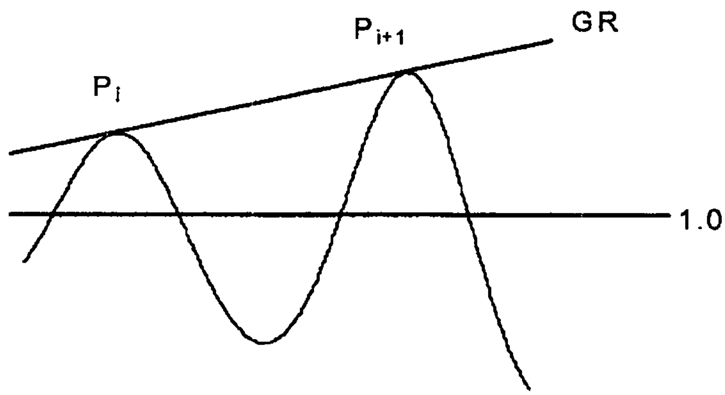



**Figure E-1: Illustration of Growth Rate**

In Figure E-1, $P_i$ and $P_{i+1}$ are successive peaks of the illustrated normalized oscillating signal. The growth rate (GR) from $P_i$ to $P_{i+1}$ is defined by the following equation.

$$GR = (P_{i+1} - 1)/(P_i - 1) \qquad \text{(E-1)}$$

The relationship between oscillation peak number (i) and the PBDA confirmation count (n) is illustrated in Figure E-2. It is assumed that the base period for the PBDA (n = 0) is established one-half cycle after the first oscillation peak (i = 0). Then the relationship between peak number (i) and confirmation count (n) is defined by the following equation.

$$i = n/2 + 0.5 \tag{E-2}$$

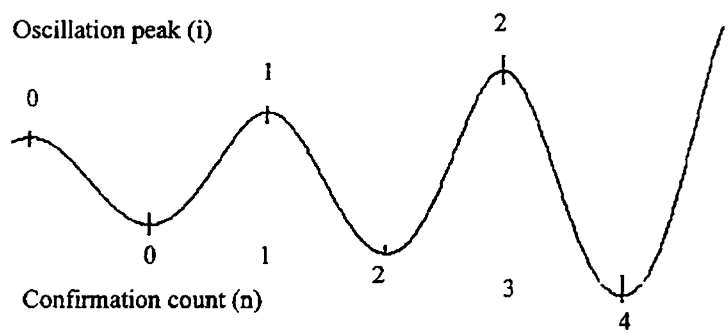



**Figure E-2: Illustration of Peak Number vs. Confirmation Count**

Using Equations E-1, the following equation is developed to calculate the peak amplitude for oscillation (i), depending upon growth rate and the magnitude of the initial oscillation detected ($P_0$).

$$P_i = 1 + GR^i (P_0 - 1) \tag{E-3}$$

Where $GR^i$ means GR raised to the power of i.

A conservative growth rate of 1.30 is assumed. This is at the high end of the growth rate distribution shown in Figure 4-4. The initial peak when the base period for the PBDA is established is assumed to be 1.015 (3% peak-to-peak). This is a conservative assumption based on the ability of the PBDA to detect reactor instability during the transition from stable to unstable conditions which was documented in Reference 2.

Using these values, a table of amplitude peak vs. confirmation count can be calculated as shown in Table E-1. The values shown in Table E-1 are used to specify the minimum allowable amplitude setpoint vs. confirmation count setpoint reported in Table 3-2. The values selected provide a reasonable progression of minimum amplitude vs. confirmation count and provide high confidence that the confirmation count will reach its setpoint before the amplitude reaches its setpoint for an anticipated reactor instability.

**Table E-1: Peak Amplitude vs. Confirmation Count**

| Confirmation Count Number n | Amplitude Peak $P_i$ |
|---|---|
| 6 | 1.038 |
| 7 | 1.043 |
| 8 | 1.049 |
| 9 | 1.056 |
| 10 | 1.064 |
| 11 | 1.072 |
| 12 | 1.083 |
| 14 | 1.107 |
| 16 | 1.140 |
| 18 | 1.181 |
| 20 | 1.236 |