WCAP-17137-NP
Revision 0

October 2010

Westinghouse Stability Methodology for the ABWR

Westinghouse

WESTINGHOUSE NON-PROPRIETARY CLASS 3

WCAP-17137-NP
Revision 0

Westinghouse Stability Methodology for the ABWR

Author's Names

C. Rotander*
Transient Analysis

J. Blaisdell*
LOCA Analysis & Methods

M. Azuma*
LOCA Analysis & Methods

October 2010

Reviewer: Thomas Lindqvist*
U.S. BWR & Criticality

Approved: Håkan Svensson*
Transient Analysis

*Electronically approved records are authenticated in the electronic document management system.

Westinghouse Electric Company LLC
1000 Westinghouse Drive
Cranberry Township, PA 16066

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ABA	Amplitude Based Algorithm
ABWR	Advanced BWR
APRM	Average Power Range Monitor
BSP	Backup Stability Protection
BWR	Boiling Water Reactor
BWROG	BWR Owners' Group
CGS	Columbia Generating Station
CPR	Critical Power Ratio
CRD	Control Rod Drive
DIVOM	Delta CPR Over Initial CPR Versus Oscillation Magnitude
DR	Decay Ratio
f_c	Cutoff Frequency
FRAD	Fraction Radial (radial peaking factor)
GDC	General Design Criteria
GR	Growth Rate
GRA	Growth Rate Algorithm
HCOM	Hot Channel Oscillation Magnitude
ICPR	Initial CPR
k	Normalized Change in MCPR Following the Trip of 3 RIPs
KKL	Kernkraftwerk Leibstadt
LPRM	Local Power Range Monitor
LTR	Licensing Topical Report
MCPR	Minimum CPR
N_p	PBDA Successive Confirmation Count
OLMCPR	Operating Limit MCPR
OPRM	Oscillation Power Range Monitor
P_A, P_B	Power (%-rated) Corresponding to BSP Line Intersection with Maximum Rodline (A) and Natural Circulation Line (B)
PBDA	Period Based Detection Algorithm
P_C, P_G, P_R	Core Power (%-rated) Corresponding to the Channel, Global, Regional Stability Thresholds
PPF	Power Peaking Factor (nodal peaking factor)
RIP	Reactor Internal Pump
RPS	Reactor Protection System
SCRRI	Selected Control Rods Run In
S_D	Slope of the DIVOM Curve
SLMCPR	Safety Limit MCPR
S_p	PBDA Amplitude Setpoint
S(t)	OPRM Cell Signal
t_e	PBDA Period Tolerance

LIST OF ACRONYMS (continued)

T_{max}	PBDA Maximum Expected Oscillation Period
T_{min}	PBDA Minimum Expected Oscillation Period
W_A, W_B	Core Flow (%-rated) Corresponding to BSP Line Intersection with Maximum Rod Line (A) and Natural Circulation Line (B)
δC, δR	Channel, Regional Mode Correction Factors
3D	Three Dimensional

1 INTRODUCTION

The current Westinghouse boiling water reactor (BWR) stability methodology is described in References 1 and 2. This methodology has been used to implement the BWR Owners' Group (BWROG) Long Term Stability Solution Option III in BWR reload analyses using the approach developed by the BWROG, which is described in References 3, 4 and 5, using the cycle-specific guidance that is provided by the utility.

The Advanced BWR (ABWR) differs from the BWR most significantly in the recirculation system where the ABWR uses 10 reactor internal pumps (RIPs) in place of 2 external recirculation loops feeding 20 internal jet pumps. This difference requires a departure from the Option III methodology for BWRs.

The purpose of this licensing topical report (LTR) is to request NRC approval for the methodology Westinghouse uses to implement the Option III stability solution for the ABWR and to provide a basis for the setpoints used in the oscillation power range monitor (OPRM), which is used to implement Option III.

2 SUMMARY

In the Westinghouse reload safety analysis process, thermal-hydraulic stability analyses are performed as required by plant-specific stability licensing bases. In general, stability performance is evaluated for each reload application or plant modification with the potential to change the core nuclear or thermal-hydraulic performance characteristics. This LTR presents the Westinghouse stability methodology that would be used in support of an ABWR that has implemented the Option III long term stability solution as defined in References 3, 4 and 5.

The Option III solution involves establishing setpoints for the OPRM and developing backup stability protection (BSP) measures that rely on exclusion regions on the power / flow map in the event the OPRM becomes inoperable. The OPRM relies on local power range monitor (LPRM) detector signals that are grouped into signals that are indicative of local power fluctuations and are therefore able to detect regional mode power instabilities.

The OPRM is comprised of two algorithms. The first is an algorithm that analyzes the OPRM cell signals and will issue a plant trip signal based on the growth rate or the amplitude of the OPRM cell signals. This algorithm is actually two algorithms that share common logic and it is referred to as the amplitude based and the growth rate based algorithm (ABA / GRA). The ABA / GRA is considered defense-in-depth and is intended to protect the plant from unexpected instabilities. The second algorithm is the period based detection algorithm (PBDA), which is intended to protect the plant from expected thermal-hydraulic instabilities. The PBDA has two setpoints that are confirmed each reload – the successive confirmation count (Np) setpoint and the amplitude setpoint (Sp). The successive confirmation count is the number of successive peaks and valleys of power oscillations within a specified frequency band that must occur before a trip signal can be generated. The amplitude setpoint is the amplitude of the cell signal at which a trip signal must be generated in order to prevent the power oscillation from reaching the safety limit minimum critical power ratio (SLMCPR).

The amplitude setpoint must take into account the relationship between channel power oscillations and the corresponding CPR fluctuations within the channel, the relationship between channel power and the OPRM cell signals as well as the various delays associated with processing the raw LPRM signals, processing the trip signal, inserting the control rods sufficiently to suppress the instability, etc.

The first of these relationships is referred to as the ΔCPR over initial CPR (ICPR) versus oscillation magnitude (DIVOM) relationship. This relationship is determined analytically as described in Section 6.2. It consists of comparing the normalized ΔCPR during an oscillation to the corresponding normalized hot channel oscillation magnitude (HCOM). The result is a series of points for several hot channels on a plot of ΔCPR normalized by the ICPR versus HCOM. This plot is referred to as the DIVOM curve. The slope of the resulting curve is used to determine the value of HCOM that will result in the CPR reaching the SLMCPR.

The second of these relationships is the relationship between the OPRM amplitude setpoint (Sp) and the limiting value of HCOM. The development of this relationship is described in Section 5.2.1. The relationship is determined using the results of transient three-dimensional (3D) simulations that provide channel power and LPRM detector signals. The simulated LPRM detector signals are processed offline to create OPRM signals in the same way as they are by the OPRM hardware in the plant. These signals are then processed by the PBDA logic to determine a relationship between the signal amplitude and the calculated HCOM. Then the various time delays are factored in to develop the value of HCOM at which the trip signal must be initiated to ensure the plant is tripped before reaching the value of HCOM corresponding to the safety limit.

The BSP analysis methodology is described in Section 6.3. The plant model used for this analysis is generated and applied in a manner that is consistent with the validation of the methodology. This is necessary to ensure the acceptance criterion established for the methodology can be applied to the plant being analyzed. The plant analysis consists of performing decay ratio (DR) calculations to confirm that the prescribed exclusion regions on the power / flow map are conservative at the limiting exposure using limiting plant conditions. The boundaries of the exclusion regions consist of a scram line and an exit line. If an event were to occur that results in plant conditions within the scram region, the plant operators are instructed to immediately scram the reactor. If an event were to result in plant conditions between the scram and exit regions, the operators are instructed to exit the region immediately.

The acceptance criterion for the analyses used to verify the scram line is defined in terms of a decay ratio (DR) that provides margin to the stability threshold (DR = 1.0). This margin accounts for uncertainty in the application of the methodology and uncertainties in the measurements used to benchmark the methodology. The exit line provides a buffer to the scram line providing the operators sufficient warning that they are approaching a region of instability, enabling them to exit the region without having to scram the plant. The BSP acceptance criteria are described in Section 6.3.2.

The BSP analysis is comprised of the following 7 parts, which are described in more detail in Section 6.3.3.

1. Establish conservative initial conditions,
2. Search for the limiting exposure (global mode),
3. Global mode analysis (at the limiting exposure),
4. Regional mode analysis,
5. Channel stability analysis,
6. Cycle-specific bounding mode scram and exit regions,
7. Compare cycle-specific results to existing BSP region boundaries.

3 THERMAL-HYDRAULIC STABILITY BACKGROUND

Power and flow fluctuations, which occur normally, do not grow in magnitude during normal operation. However, there are conditions at low core flow and high core power where such fluctuations can grow in amplitude. These fluctuations are the result of density waves passing through the core coupled with void reactivity feedback on the nuclear power generation and changes in the heat removal characteristics of the fuel rods. If allowed to proceed, these growing oscillations might create sufficient channel voiding that the fuel cladding safety limit could be challenged. Three recognized modes of density-wave instability are (1) global (when the power and flow of all the core channels oscillate in phase), (2) regional (when the power and flow of half the core channels oscillate out-of-phase with the other half), and (3) single-channel flow instability (when the flow in a single channel oscillates accompanied by small power oscillations).

Early design and testing in operating BWRs led to a detect-and-suppress stability solution based on high APRM flux scram as the safety protection for the fuel. After observed instability events at several operating BWRs, the most well-known of which was the LaSalle event in March 1988, it was recognized that the protection systems in place at the time might not be sufficient to insure meeting General Design Criteria (GDC) 10 and 12 (see Section 6.2.2). As a result of these events at operating BWRs, the BWROG developed several options for BWRs to meet GDC 10 and 12 (References 3 through 5). The ABWR has adopted a multi-layered defense-in-depth strategy for protecting its fuel, based primarily on the BWROG Options I-A and III. Option I is based on having an operating exclusion region, outside of which instabilities are very unlikely to occur. Immediate automatic protective actions are taken in Option I-A, either by scram or select rod insert, if the plant enters the exclusion region. The ABWR has chosen the Selected Control Rods Run-In (SCRRI) system to implement Option I-A.

Option III is a LPRM-based detect and suppress approach that looks at local power variations via algorithms that are designed to detect increasing periodic oscillations typical of limit-cycle instability behavior, and provides scram protective actions before the Safety Limit Minimum Critical Power Ratio (SLMCPR) can be reached. The ABWR has also installed the Option III solution based on an Oscillation Power Range Monitor (OPRM) system.

4 DESCRIPTION OF THE ABWR

Figure 4-1 shows a schematic of the ABWR reactor vessel. The internals are similar to typical U.S. BWR designs except that there are no jet pumps and no external recirculation loops. Instead, there are 10 RIPs that provide forced circulation of reactor coolant from the reactor vessel annulus to the reactor core. The core flow rate and core thermal power can be regulated by changing the pump speed. The RIPs are powered from 2 separate non-safety electrical load groups, each load group supplying 5 RIPs. Although an electrical fault in one of the load groups will lead to a loss of power to 5 RIPs, the electrical fault will result in a trip of the generator, which will lead to a turbine trip and a reactor trip. Within each load group, the RIP power supplies are further divided between 2 13.8 kV buses. At most 3 RIPs can trip due to a single electrical fault and result in continued operation at reduced core flow. A single electrical fault that affects more than 3 RIPs will also result in a reactor trip. As a result, the limiting loss of flow event for stability considerations is a single electrical failure resulting in the loss of power to 3 RIPs while operating at the minimum pump speed with 9 RIPs operating. This event will result in the plant operating on the maximum rod line with 6 RIPs operating at minimum speed.

Figure 4-2 shows a typical power / flow map for the ABWR. Operation to the left of the minimum pump speed line is not permitted. The minimum pump speed line is established to protect the RIP anti-rotation device from excessive wear and to ensure operation in a stable operating domain. Stability is typically the limiting factor in establishing the minimum pump speed for the condition of 9 RIPs operating.

The region in 4-2 denoted by 'SCRRI' (Selected Control Rods Run In) is the high-power / low-flow region that is susceptible to thermal/hydraulic instabilities. In the event of a trip of 2 or more RIPs, this system initiates automatically if core flow is less than 36% of rated flow and core power is greater than 30% of rated thermal power. The system automatically inserts pre-selected control rods and thereby prevents operation in the region that is susceptible to power oscillations. The SCRRI system is not safety grade and is considered defense-in-depth in the ABWR.

The region in 4-2 denoted by 'Rod Block' is a system that limits the likelihood of entering the unstable region during power ascension. Automatic withdrawal of control rods is blocked whenever power is greater than 25% and flow is less than 36% in the event that 2 or more RIPs trip. Figure 4-3 shows the protection logic for SCRRI and the rod block.

The ABWR has also implemented the OPRM that checks for the existence of local power oscillations with prescribed characteristics. The system initiates an automatic reactor scram when its setpoints are exceeded. This stability solution is referred to as the Option III long term stability solution.

This LTR is primarily concerned with the Option III solution, which also requires a BSP procedure that is used whenever the OPRM is out of service. The BSP solution identifies regions on the power / flow map that are susceptible to thermal-hydraulic instabilities. The regions are identified based upon calculated decay ratio criteria.

In summary, there are 5 types of protective measures that limit the likelihood of stability events in the ABWR and to suppress them should they occur:

1. The 9-pump minimum speed line, which administratively prevents intentional operation in a region where core instabilities are a possibility;
2. the SCRRI system, which automatically inserts selected control rods if an event puts the plant unintentionally into a region on the power / flow map where core instabilities are a possibility;

3. the rod block to prevent automatic control rod withdrawal under prescribed conditions during power ascension;

4. the OPRM system, which automatically detects oscillations and initiates reactor scram if setpoints of any of the detection algorithms are exceeded while operating in the OPRM armed region; and

5. BSP exclusion regions, which administratively require the operator to exit the region or to scram the reactor if an event puts the plant unintentionally into a region on the power / flow map where core instabilities are a possibility.

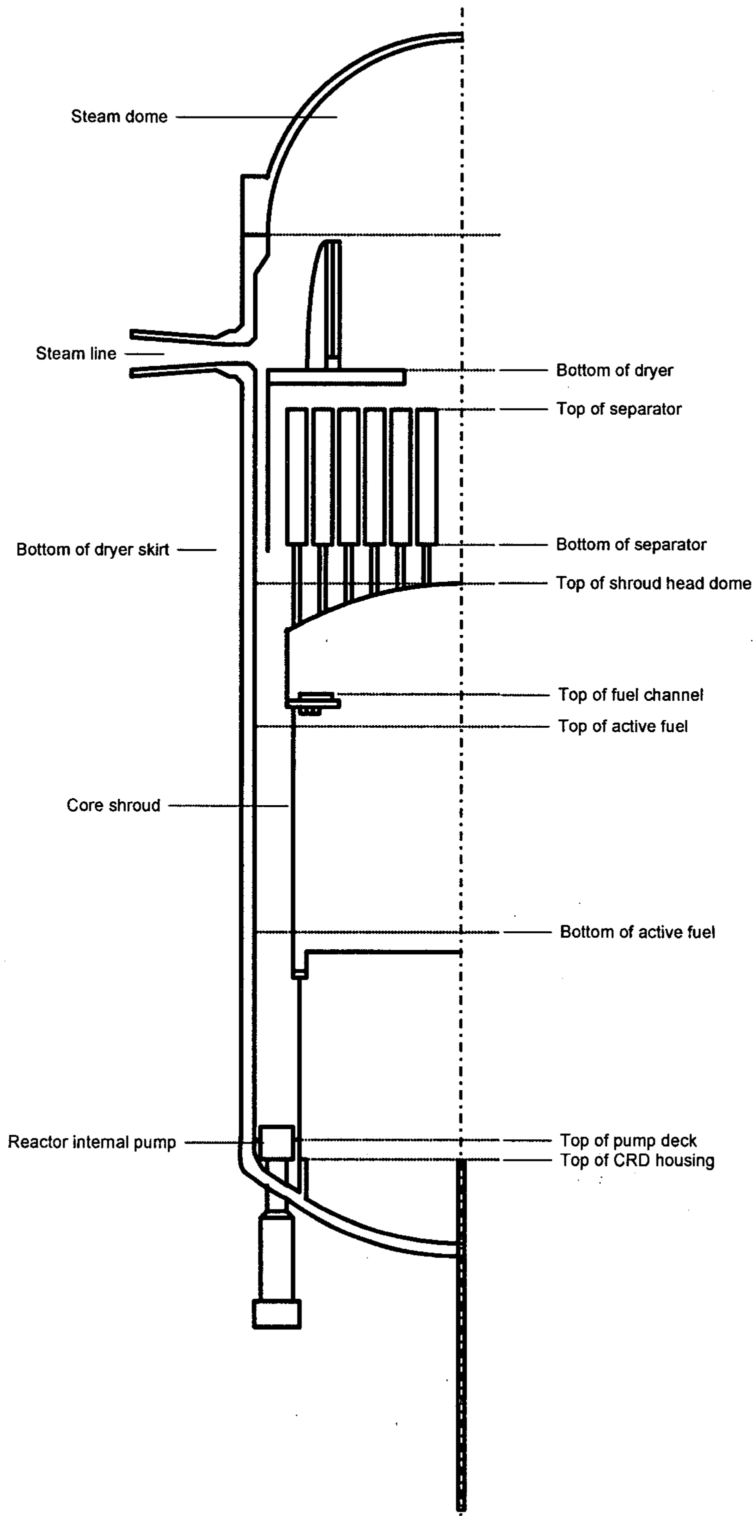

Figure 4-1 Schematic of the ABWR Reactor Vessel

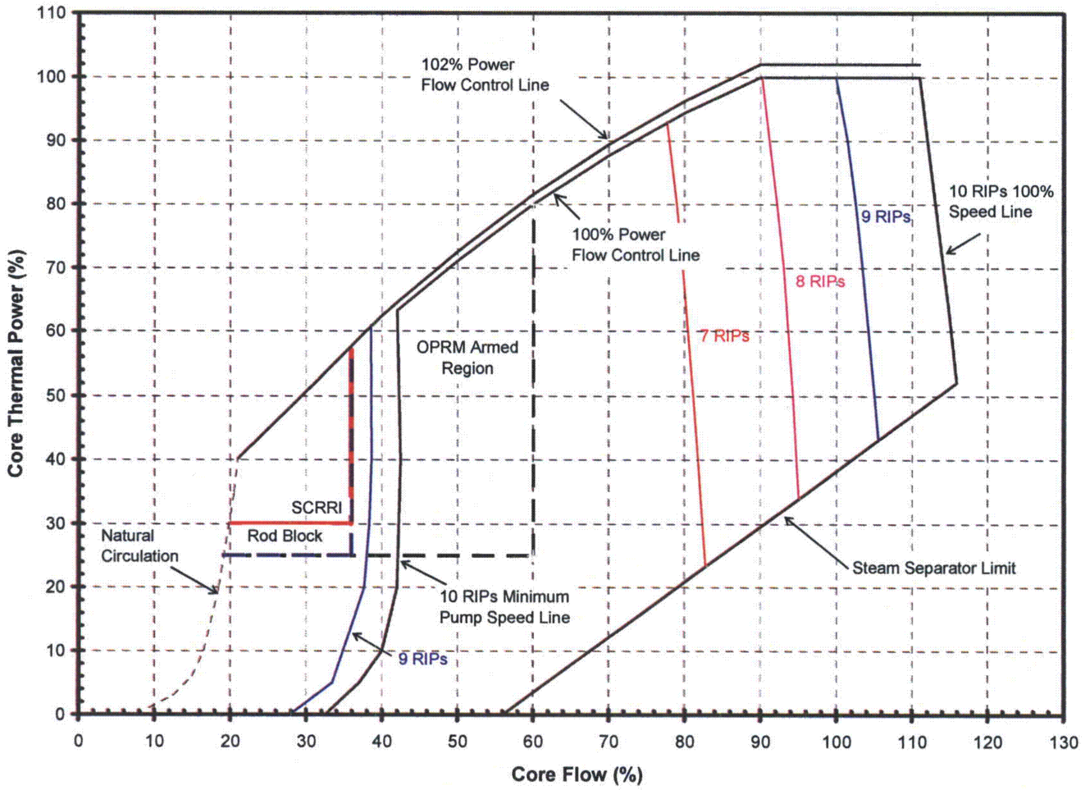

Figure 4-2 Typical ABWR Power/Flow Map

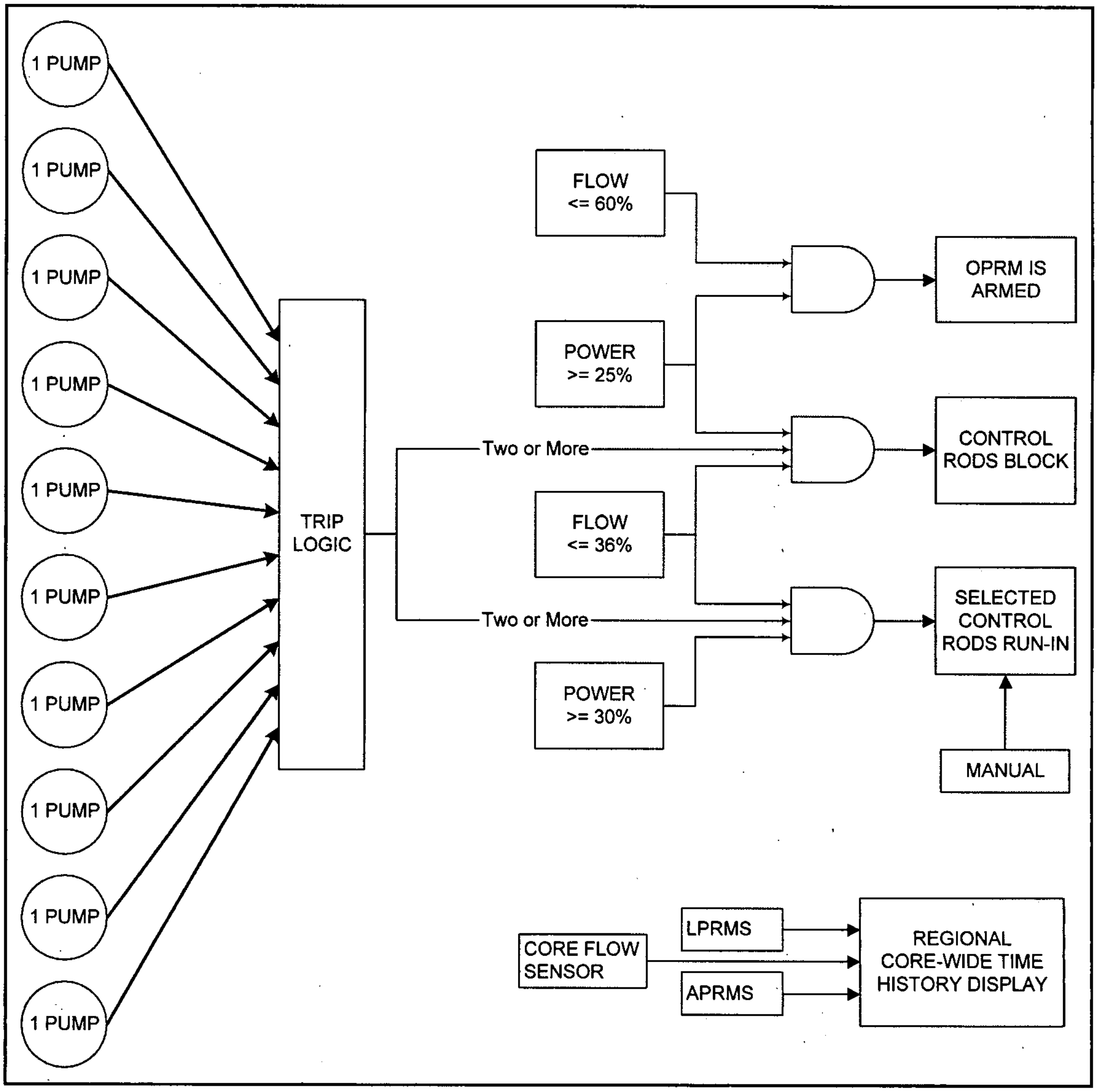

Figure 4-3 Stability Protection Logic and Control Room Displays

5 DESCRIPTION OF THE OSCILLATION POWER RANGE MONTIOR DESIGN

The Option III long term stability solution is implemented in the ABWR by including the OPRM trip logic function within the APRM system. The OPRM trip logic is intended to detect increasing periodic oscillations typical of limit-cycle behavior, and provide scram protective actions before the SLMCPR can be reached. When armed, the OPRM receives input signals from LPRM detectors within the core. An OPRM reactor trip signal is generated if oscillatory changes in neutron flux are detected that satisfy the OPRM trip criteria.

The OPRM is comprised of many cells. As shown in Figure 5-1, the OPRM cells are distributed radially across the core and each cell provides a measure of the neutron flux oscillations in that radial region. Each LPRM string is comprised of neutron flux detectors distributed axially at four different elevations (A, B, C, D). As shown, each OPRM cell takes inputs from detectors at different elevations from its neighboring LPRM strings. By taking advantage of different combinations of detectors, each OPRM cell has four channels. Figure 5-1 shows a configuration for one channel. As shown, OPRM cells in the interior of the core make use of four LPRM strings, while OPRM cells near the core periphery make use of three LPRM strings.

The signals from each LPRM detector in an OPRM cell channel are processed by a second order Butterworth conditioning filter to remove noise components with frequencies above the range of interest. Typically, the signal is conditioned by a filter with a corner frequency of from 1.0 to 2.5 Hz to "clean up" the signal such that it can be analyzed for lower frequency thermal-hydraulic oscillations. If the cutoff frequency (f_c) of the filter is too high, the resulting signal may be too noisy, which can cause erroneous resetting of the successive confirmation counts. If the cutoff frequency is too low, the filter may take out oscillations that are in the expected frequency range of a thermal-hydraulic instability. The lower range of the cutoff frequency range is recommended (i.e., 1.0 Hz), which is the upper frequency range of expected thermal-hydraulic instabilities. Figure 5-2 shows a simulated signal that was used to test the conditioning and averaging filters. The LPRM detector signal was simulated using a second order autoregressive model. The autoregressive model generates a signal based on past values of the signal.

Figure 5-3 shows the effect of filtering on the frequency content of a simulated LPRM detector signal using a second order Butterworth filter with a cutoff frequency of 1.0 Hz. As shown, the filter is reasonably effective at removing high frequency content. The dashed line in Figure 5-3 shows the conditioned LPRM detector signal.[1]

The four conditioned LPRM detector signals that make up an OPRM cell channel are then combined into a single averaged signal. This signal passes through an averaging filter that approximates the mean of the oscillating signal and is used to generate a normalized signal that has an average close to 1.0. The variations in the normalized signal are representative of the fractional change in local fission power relative to the average value. The averaging filter is a second order Butterworth filter with a cutoff frequency between 0.1 to 0.2 Hz. Figure 5-4 shows the resulting 'mean' of the oscillating signal. As shown, the averaging filter does not remove all oscillations. However, the lowest cutoff frequency has the smallest amplitude, although it will respond more slowly to changes in the average of the signal.

1 10 CFR Part 21 report 2003-025 identified an event wherein the cutoff frequency was set at 3.0 Hz, which resulted in too many successive confirmation count resets. The recommended cutoff frequency was 1.0 Hz, which resulted in the expected OPRM response.

Figure 5-5 shows the resulting normalized signal using three cutoff frequencies. As shown, the cutoff frequencies of 0.1 Hz and 0.167 Hz provide an adequately normalized signal although the signal is somewhat amplified by the higher cutoff frequency. Since the higher cutoff frequency (0.167 Hz) will be more responsive to changes in the average power and is conservative, it is considered the best alternative.

The normalized signal is then processed by the detection algorithms to look for evidence of local power oscillations in the expected frequency range. If sufficient evidence exists, the OPRM cell channel generates a reactor trip signal to the reactor protection system (RPS). Trip signals from any two of the four OPRM cell channels will initiate a reactor scram.

There are two detection algorithms built into each OPRM cell channel. The period based detection algorithm (PBDA) is credited in the licensing analysis. This algorithm provides protection for anticipated power oscillations. The amplitude based and the growth rate algorithm (ABA / GRA) provide defense-in-depth against unanticipated power oscillations. The latter algorithm is actually two algorithms that share common logic. These algorithms are described in the following sections.

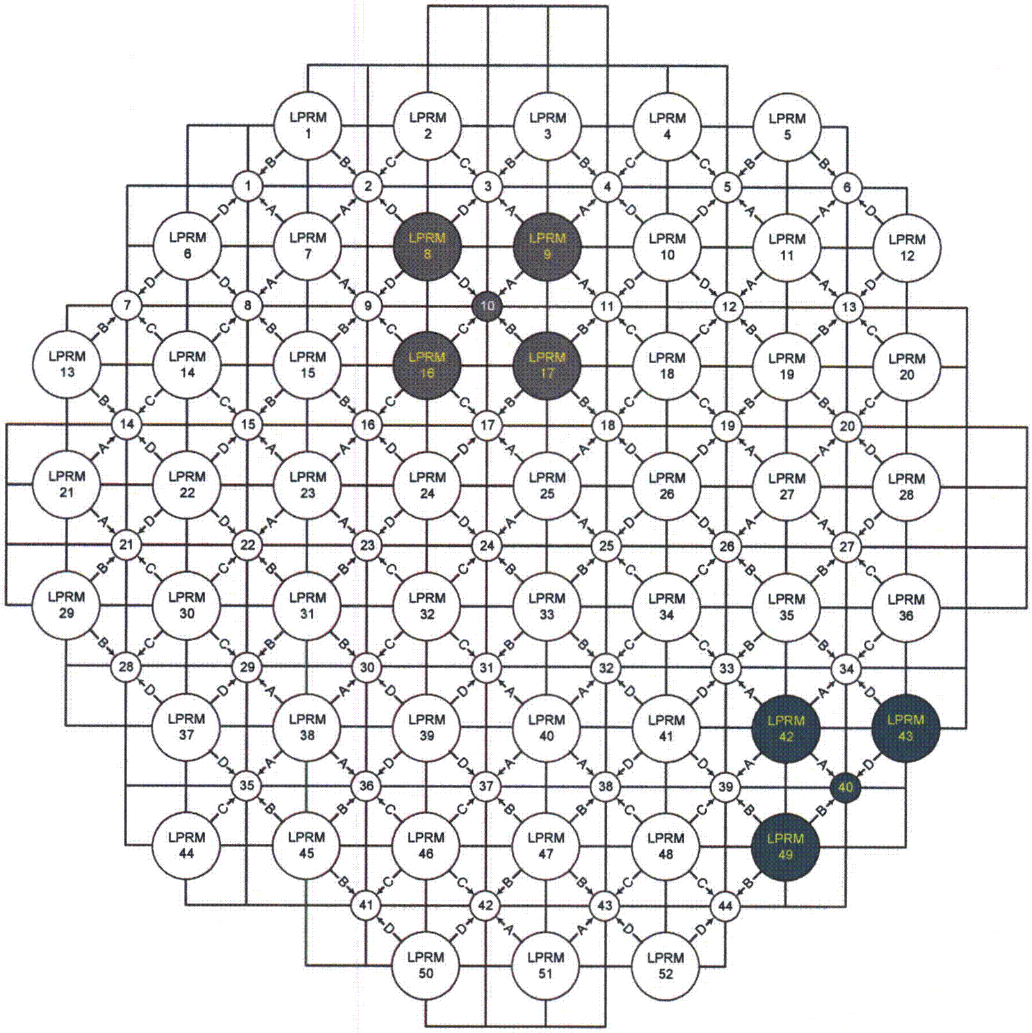

Figure 5-1 Typical Radial Arrangement of OPRM Cells

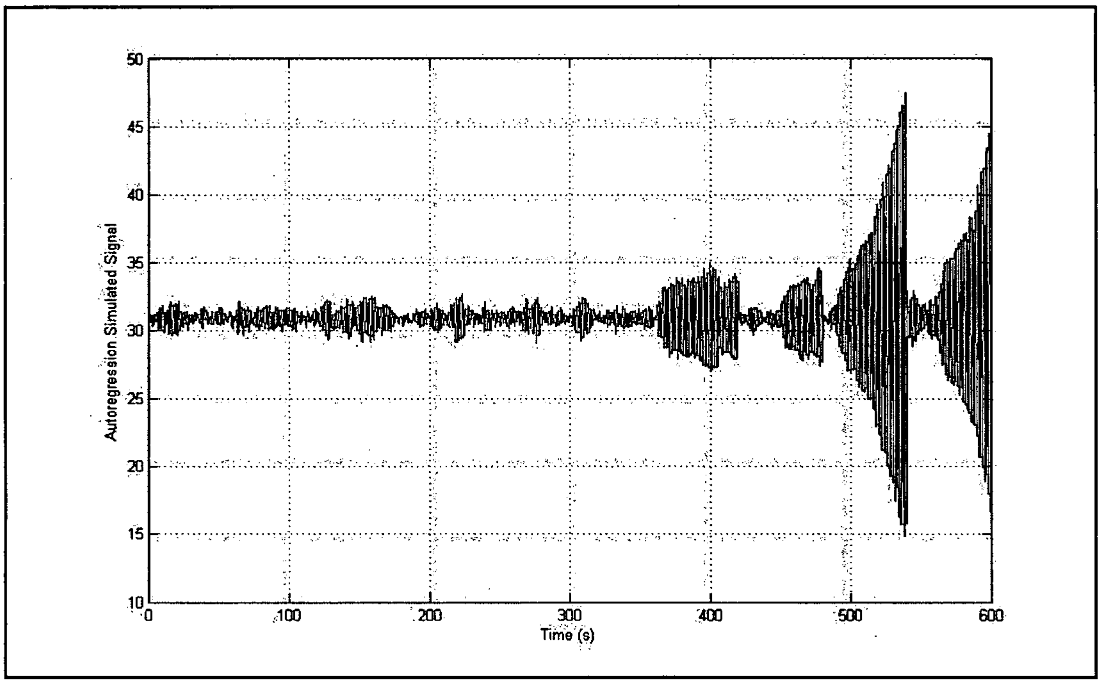

Figure 5-2 Unfiltered Simulated LPRM Signal

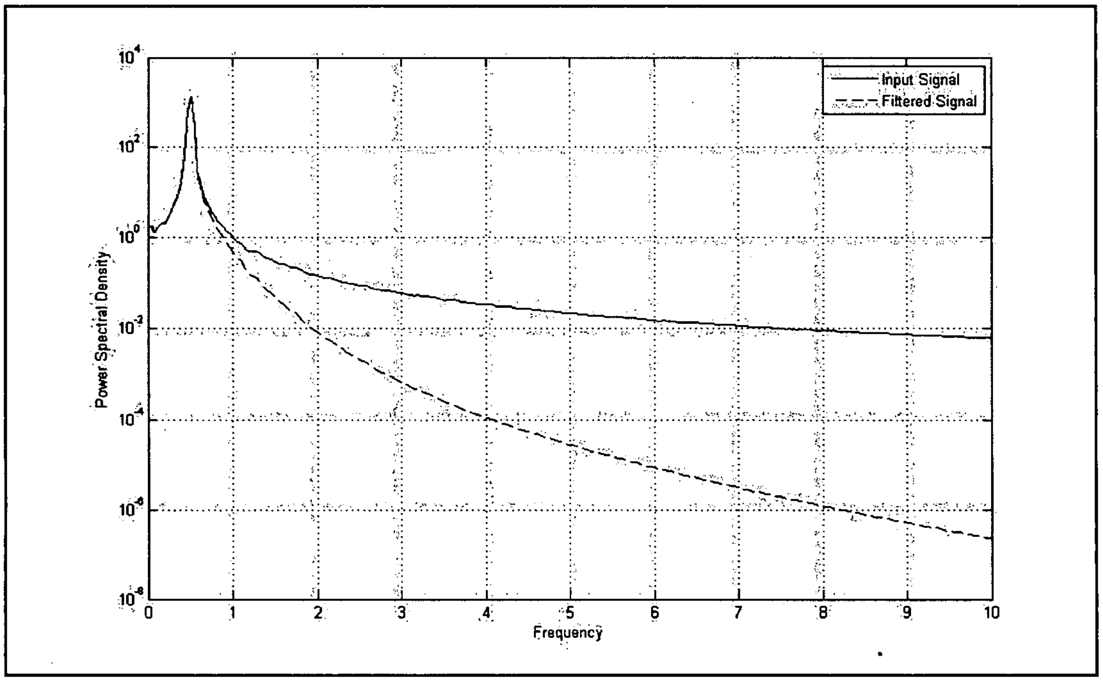

Figure 5-3 Effect of Filtering LPRM Signal (1 Hz)

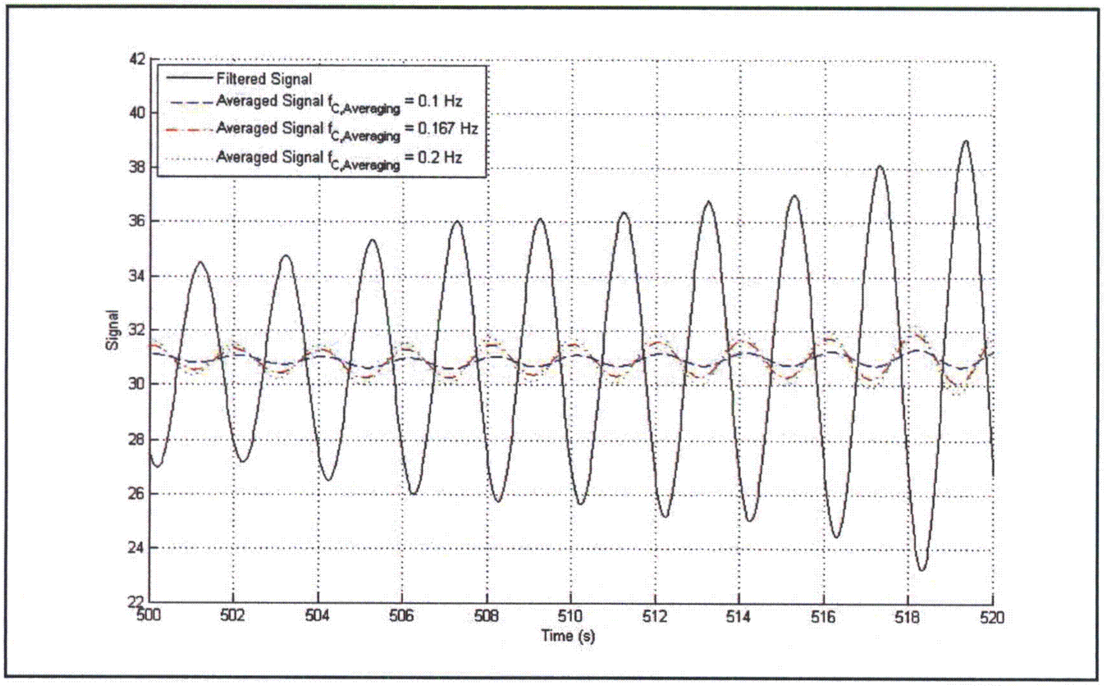

Figure 5-4 Effect of Averaging Filter Cutoff Frequency

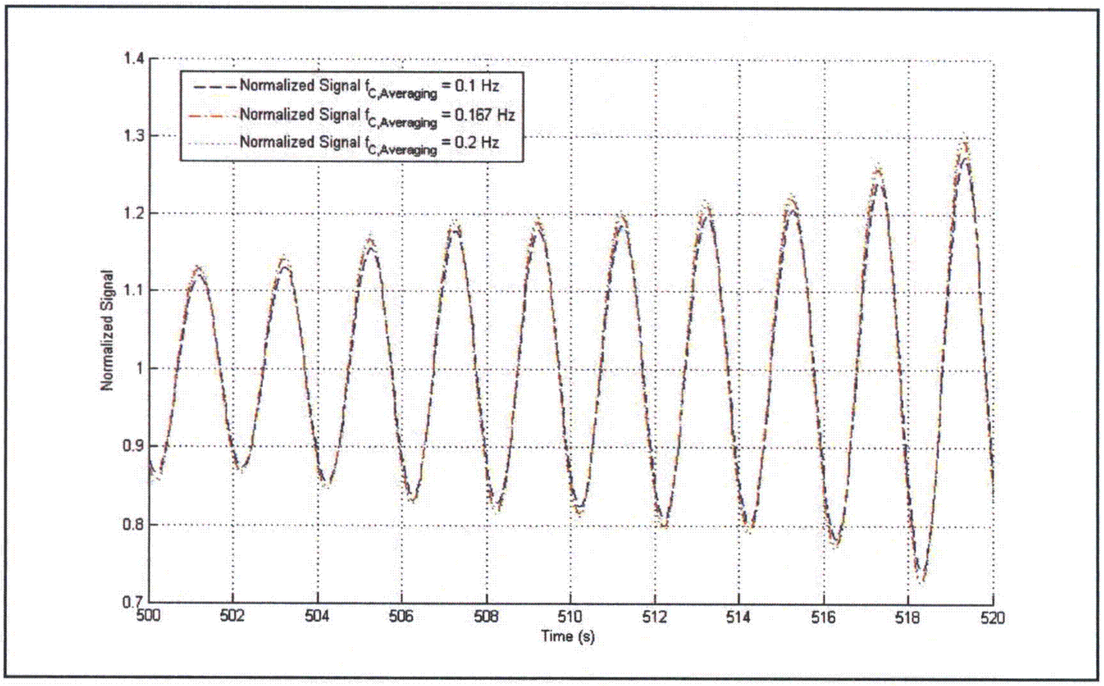

Figure 5-5 Effect of Averaging Filter on Normalized OPRM Cell Signal

5.1 AMPLITUDE / GROWTH RATE ALGORITHM

The ABA portion of the algorithm initiates a reactor trip signal when the relative signal amplitude exceeds a specified value. The relative OPRM signal value is compared continuously to a threshold setpoint to determine if the signal is greater than the expected noise level. If the amplitude threshold is exceeded, the ABA / GRA begins to look for oscillatory behavior that is within the range of expected frequencies. If the range of frequencies is satisfied and the signal exceeds the amplitude setpoint, an ABA trip is generated.

The GRA portion of the algorithm initiates a reactor trip signal when the amplitude growth rate (GR) exceeds a specified value. The GRA portion of the detection algorithm follows the same logic as the ABA portion, except that a trip is initiated if the calculated growth rate between successive peaks exceeds the algorithm setpoint.

The ABA / GRA is considered defense-in-depth and is not credited in the reload analysis.

5.2 PERIOD BASED DETECTION ALGORITHM

The PBDA is based on the observation that thermal-hydraulic instabilities result in neutron flux oscillations that have a known frequency range. The PBDA makes use of the number of successive oscillation cycles within that frequency range and the oscillation amplitude to determine if a reactor trip signal should be generated. The oscillation amplitude is selected to protect the SLMCPR. The trip logic of the PBDA is presented in Figure 5-7.

Since the PBDA is intended to protect the SLMCPR, a relationship must be derived between the oscillating signals from the OPRM cells and the resulting change in MCPR of the limiting fuel channels. This relationship is comprised of two parts. The first part is developed from an analysis of the reactor core to determine the relationship between channel power variations and the resulting variations in CPR. This analysis is described in Section 6.2. The second part is the relationship between the amplitude of the channel power oscillations (HCOM) and the amplitude of the OPRM cell oscillations (Sp). This relationship is developed in Section 5.2.1. The bases for the other PBDA setpoints are provided below.

Period interval (T_{min} – T_{max}) – The oscillation period is a strong function of core flow as shown in Figure 5-8. The predicted range of oscillation period for the ABWR is between 1.5 and 2.5 seconds. The recommended values for T_{min} and T_{max} are 1.0 and 3.5 seconds respectively to allow for uncertainty in the prediction of oscillation period.[2]

Period tolerance (t_e) – The PBDA algorithm is based on the concept that a thermal-hydraulic instability will have a period that will be within the range of T_{min} and T_{max}, and, for a given event, will be maintained at a relatively constant value. If a disturbance is detected wherein the period changes significantly, it is not considered to be a confirmed thermal-hydraulic instability and the counting of oscillations is restarted. If the period tolerance is made too small, there is the possibility of restarting the count of an actual instability due to errors due to the sampling frequency of the neutron flux. At the other extreme, if the period tolerance is made too large, the system might generate spurious scrams. A period tolerance between 0.1 and 0.3[3] seconds is recommended.

Successive confirmation count trip setpoint (Np) – The two setpoints that are determined from the cycle-specific DIVOM analysis are the successive confirmation count and the amplitude setpoint. The two setpoints are related as described in this paragraph. The peaks and valleys of an oscillation will start to be counted when the peaks and valleys have a period within a certain range ($T_{min} \leq T \leq T_{max}$) and that period does not change significantly ($\delta T \leq t_e$) as shown in Figure 5-7. If the oscillations have a particular GR, as shown in Figure 5-6, there is a relationship between the number of successive peaks and valleys (N_p) that have occurred and the amplitude (S_p) of the oscillation.

2 10 CFR Part 21 report 2002-31 identified an issue regarding the range of values recommended for T_{min} (i.e., 1.0 s < T_{min} < 1.4 s). BWR calculations indicated that T_{min} could be lower than 1.4 s. Although calculations for the ABWR indicate that the original range is adequate, the recommended value for T_{min} for the ABWR is 1.0 s to allow for uncertainty in the analytical value.

3 10 CFR Part 21 report 2002-27 identified an issue where changes in the oscillation period could cause the successive confirmation count to reset if the period tolerance was set too small. 10 CFR Part 21 report 2003-025 identified an issue during an actual event where there were too many successive confirmation count resets because the period tolerance was set too small. The resolution of the issue was to increase the period tolerance to $t_e \geq 0.1$ s.

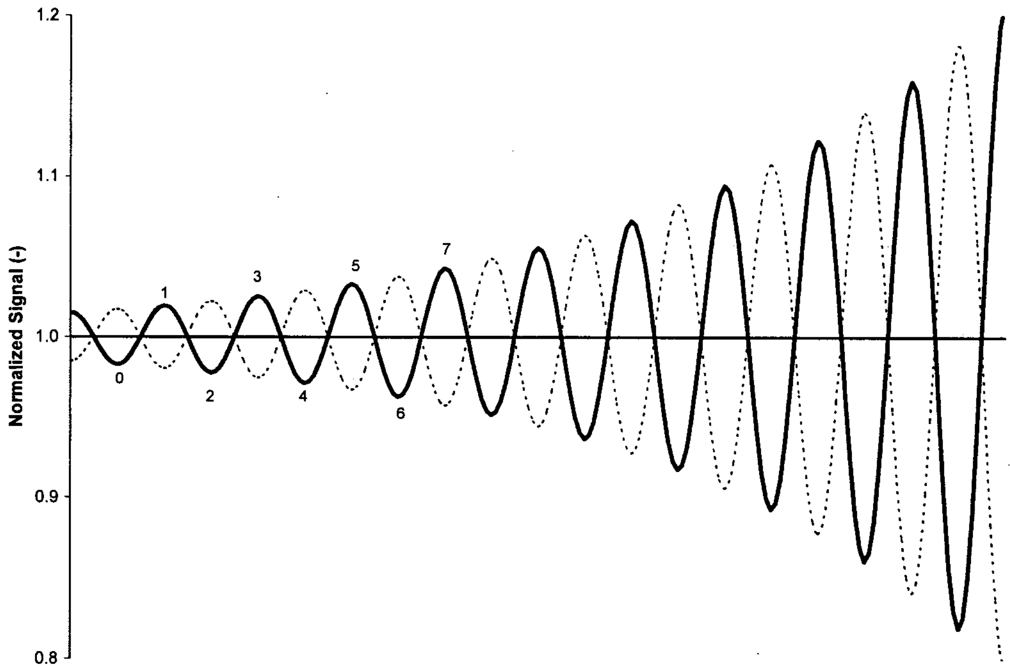

Figure 5-6 Successive Confirmation Counts vs. OPRM Amplitude Setpoint

The relationship can be shown to be:

$$|S_p - 1| = |S_p^o - 1| \times GR^{\frac{N_p+1}{2}}$$

where $|S_p\text{-}1|$ is the amplitude, N_p is the number of counts, GR is the growth rate and $|S_p^o\text{-}1|$ is the amplitude of the first detected peak or valley. The values used in the DIVOM analysis assume a conservative growth rate of 1.30 and a threshold setpoint (S_1) of 1.015. Table 5-1 shows the resulting values. The table should be interpreted such that, if the amplitude setpoint falls between values in the table, the lower successive confirmation count number should be used. To use the higher successive confirmation count might result in the oscillation exceeding the setpoint before a scram signal is issued.

Table 5-1 Amplitude vs. Confirmation Count

Confirmation Count (N_p)	Amplitude (S_p)
8	≥ 1.05
9	≥ 1.06
10	≥ 1.07
11	≥ 1.08
12	≥ 1.09
13	≥ 1.10
14	≥ 1.11
14	≥ 1.12
15	≥ 1.13
16	≥ 1.14
16	≥ 1.15
17	≥ 1.16
17	≥ 1.17
18	≥ 1.18
18	≥ 1.19
18	≥ 1.20

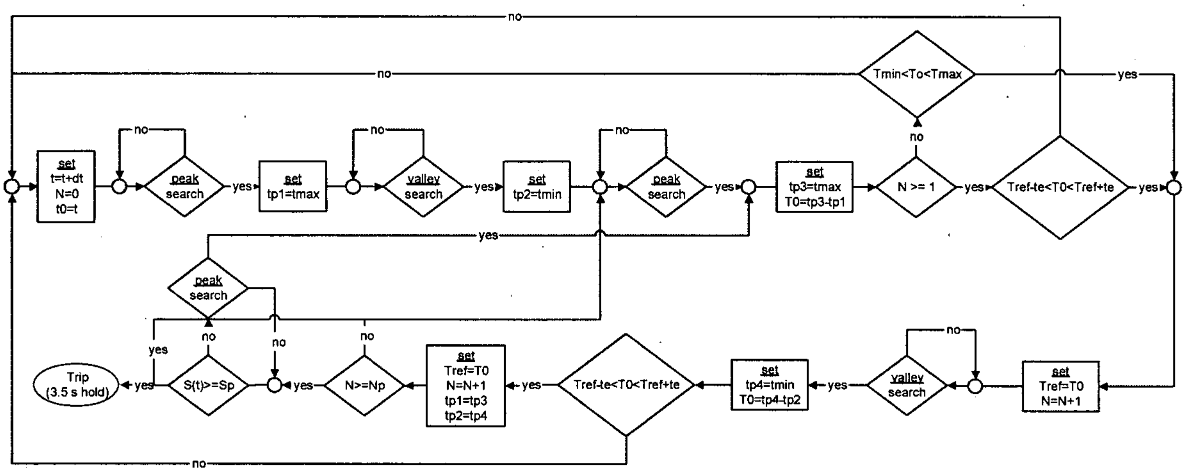

Figure 5-7 PBDA Trip Logic

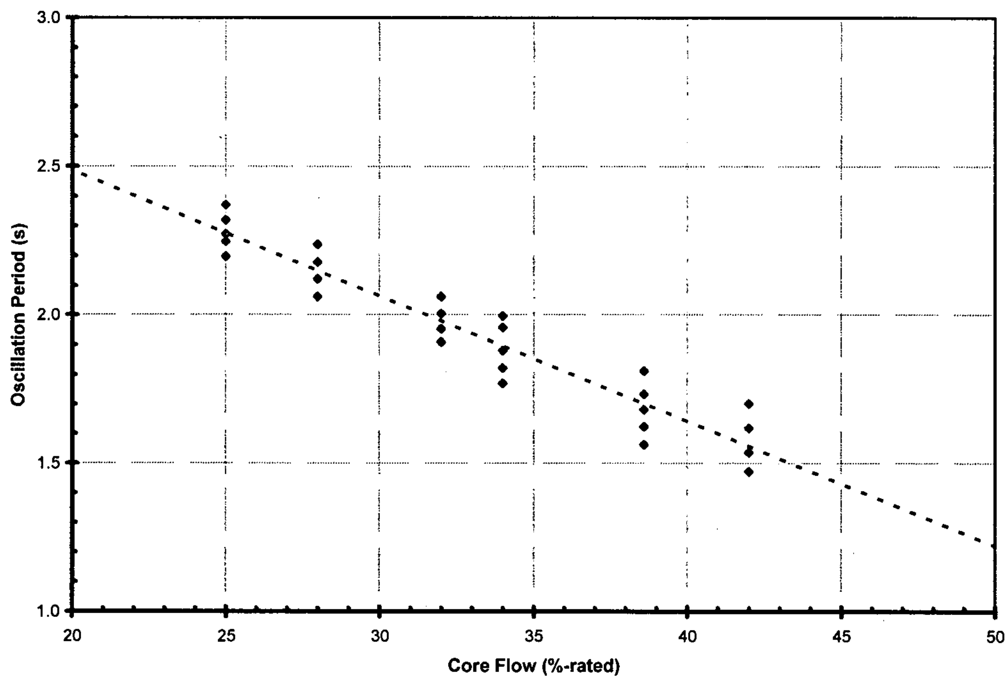

Figure 5-8 PBDA Variation of Oscillation Period with Core Flow

5.2.1 Sp vs. HCOM

The hot channel oscillation magnitude is defined as:

$$HCOM = \frac{P_{\max} - P_{\min}}{A}, \text{ where}$$

P_{max} = peak hot channel power for a given oscillation cycle before the MCPR,
P_{min} = minimum hot channel power for a given oscillation cycle before the MCPR,
A = average value of hot channel power during the oscillation

At the time of MCPR for each oscillation cycle, HCOM is calculated using the previous maximum (P_{max}) and previous minimum power (P_{min}) and the integrated average power (A). As shown in Figure 5-9, there is typically a lag of ~180° between the time of peak channel power and the corresponding MCPR.

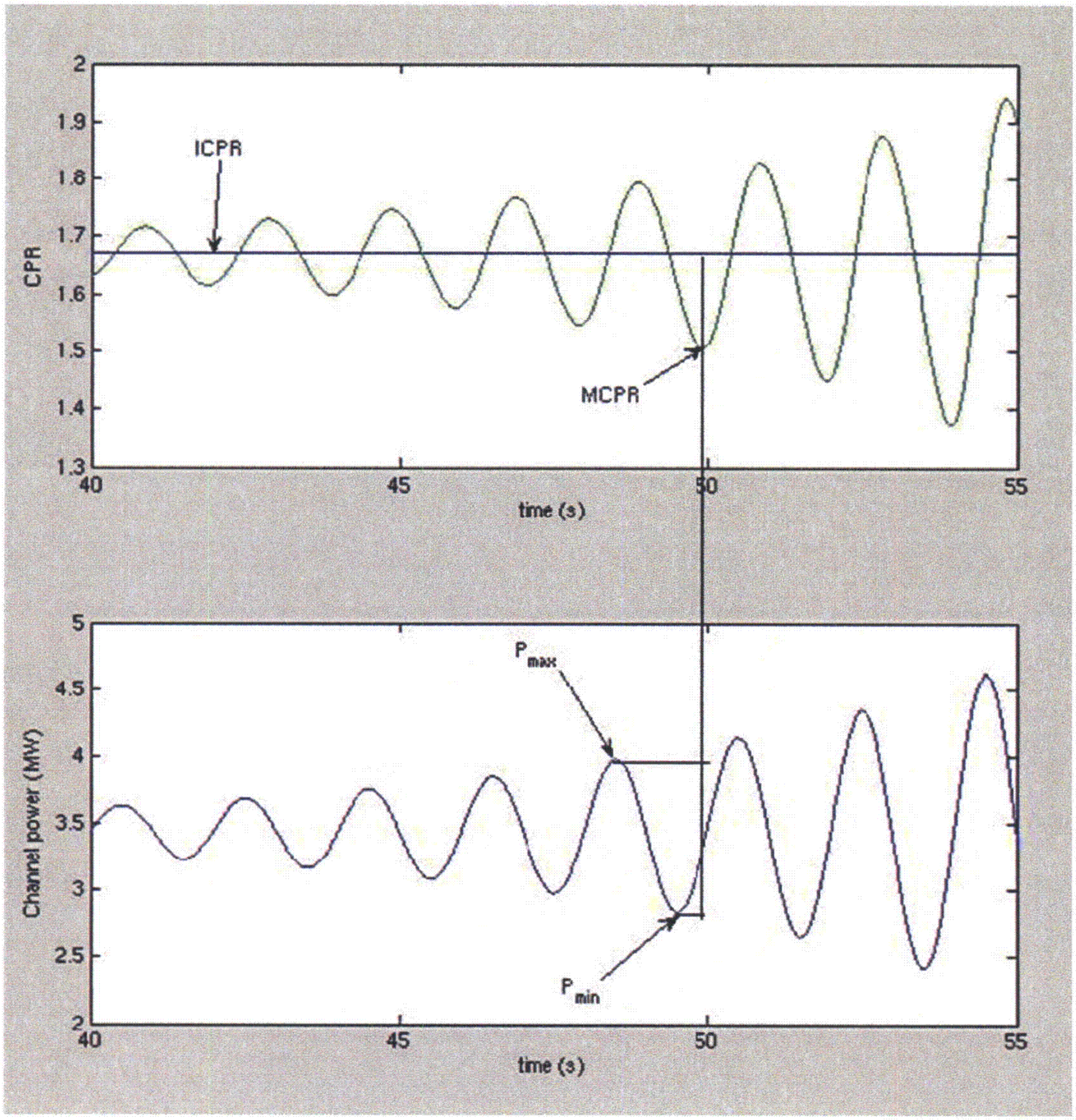

Figure 5-9 Definition of HCOM in Relation to Oscillating CPR

The relationship between HCOM and the OPRM cell amplitude is determined by a [

]a,c

[

]a,c

[

]a,c

In some cases the HCOM values are the same for consecutive setpoints. This is due to that the same maximum satisfying consecutive Sp/Np values, see for example Figure 5-11, where both Sp = 1.09 and Sp = 1.10 have the same trip time.

Table 5-2 Sp vs. HCOM (without time delays)

a,c

[

]

[ ]a,c

Figure 5-10 Sp vs. HCOM (without time delays)

5.2.2 OPRM Cell Processing

[ ]a,c

a,c

Figure 5-11 Time Delays in OPRM Cell Processing

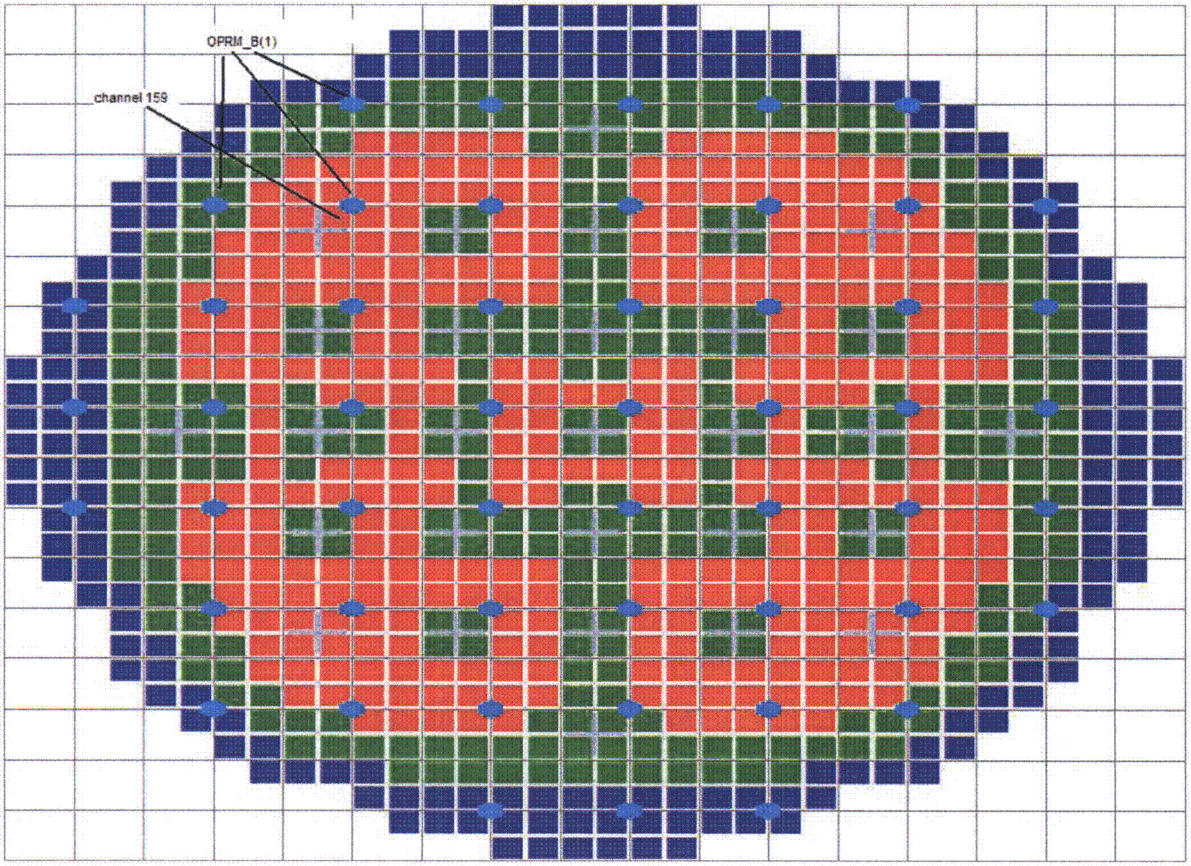

Figure 5-12 Limiting Channel and OPRM Cell Giving the Trip

5.2.3 Trip Overshoot

This delay element may occur if the OPRM amplitude setpoint (Sp) is above the oscillating cell signal S(t) such that the next oscillation exceeds the setpoint.

The scram time is determined by comparing oscillation maxima to the amplitude setpoint. However, the actual maximum could be higher than the Sp value, see Figure 5-13 below. That is, the setpoint could have been passed before the amplitude maximum is detected. [

]a,c

[

]a,c

[

]a,c

Taking this into account, the Sp vs. HCOM values shown in Table 5-2 above are modified as shown in Table 5-4.

a,c

Figure 5-13 Maximum Trip Overshot

Table 5-3 Maximum Trip Overshot for Different Growth Rates and Resonance Frequencies

[ ] a,c

Table 5-4 Sp vs. HCOM (with trip overshoot delay)

[ ] a,c

5.2.4 OPRM Trip Delay

The OPRM hardware must initiate a reactor trip signal and the rods must insert sufficiently to suppress the reactor power sufficiently before the safety limit can be reached. The response times for the OPRM hardware to initiate a reactor trip signal and insert control rods to suppress oscillations are shown in Table 5-5. The Sp vs. HCOM relationship is modified to include these delays as shown in Table 5-6 and Figure

5-14. The final Sp vs. HCOM relationship that is used to generate the OPRM trip setpoint is the bounding line shown in Figure 5-14.

Table 5-5 Response Times for OPRM Hardware

Item	Response Time
OPRM Unit (From detector to the OPRM trip)	400 ms
Reactor protection system delay (From OPRM trip to time of de-energizing of scram solenoids)	50 ms
Control Rod Insertion (From time of deenergizing of scram solenoids to start of control rod insertion)	200 ms
2 feet insertion of control rods	550 ms
Total response time	1200 ms

Table 5-6 Sp vs. HCOM (with time delays)

a,c

[ ]a,c

Figure 5-14 Sp vs. HCOM (with time delays)

5.2.5 HCOM vs. MCPR

This delay element occurs because of the [

]a,c

6 DESCRIPTION OF THE METHODOLOGY

6.1 COMPUTER CODES

Westinghouse uses NRC-approved computer codes for performing stability analyses. Currently there are two computer codes that have been reviewed and approved by the NRC for stability analysis applications – RAMONA-3 (References 2 and 6) and POLCA-T (Reference 7).

RAMONA-3 is a transient, coupled neutronic and thermal-hydraulic code with the 3D core physics described by the PRESTO nodal methods, which have been extended for kinetics. RAMONA-3 has been benchmarked against separate effects tests in the FRIGG loop facility in Västerås Sweden and against BWR stability events / tests at the Columbia Generating Station (CGS), Oskarshamn 3, Ringhals 1, Forsmark 3 and Kernkraftwerk Leibstadt (KKL) power plants.

POLCA-T is an advanced dynamic system analysis code with the 3D core physics described by the nodal code POLCA. It can be used as a general tool for advanced simulation of single- and two-phase flows. POLCA-T has been benchmarked against stability tests at the Forsmark 2, Ringhals 1, and KKL reactors, as well as against separate effects tests in the FRIGG loop.

As noted above, both computer codes have been benchmarked against stability events / tests in jet pump plants (CGS, KKL), an external pump plant (Ringhals 1) and internal pump plants (Oskarshamn 3, Forsmark 2 and Forsmark 3) with several different fuel designs. The methodology described below is applicable to both computer codes.

6.2 DIVOM METHODOLOGY

6.2.1 Background

The OPRM trip logic provides protection against violating the SLMCPR in the event of thermal-hydraulic power oscillations. The OPRM monitors for local power oscillations by interrogating many OPRM cells, which are comprised of regionally grouped LPRM detectors. A trip signal is generated if oscillatory changes in neutron flux are detected by these cells while the OPRM is armed. The OPRM armed region of the power / flow map is defined as the operating region where thermal-hydraulic oscillations might occur – typically below 60% of rated core flow and above 25% of rated power. Each OPRM cell is comprised of a small number of LPRM detectors in the same area of the core so that the presence of regional power oscillations can be detected.

The setpoints of the OPRM are developed or confirmed each operating cycle using conservative methodology to ensure that the trip setpoints will detect the presence of instabilities and suppress them before the SLMCPR is reached. The initial operating conditions for the DIVOM analysis are selected in a way that the stability analysis does not set the operating limit MCPR (OLMCPR). The cycle-specific setpoint analysis determines a relationship between the HCOM and the corresponding oscillating changes in CPR (i.e., the DIVOM curve).

6.2.2 Acceptance Criteria

The overriding acceptance criteria are General Design Criteria (GDC) 10 and 12 of 10 CFR 50 Appendix A, which require:

- 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 operational occurrences.

- 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 setpoints of the PBDA of the OPRM ensure that the reactor will be tripped before oscillations from expected instability transients can grow to such an extent that the SLMCPR can be reached. Therefore, implementation of the OPRM (hardware, software and system setpoints) assures that the GDCs are met by automatic detection and suppression of power oscillations.

6.2.3 Methodology

The OPRM is designed to protect the fuel from reaching the safety limit during expected transients that result in thermal-hydraulic instability. The region of the operating domain that is most susceptible to such instabilities is to the left of the minimum pump speed line along the 100% flow control line. Since operation in this region of the power / flow map is not allowed, an operational transient, such as a trip of one or more RIPs, must occur. As discussed in Section 4, a single failure in the power supply feeding the RIPs will trip, at most, three RIPs without resulting in a trip of the reactor. Therefore, the design transient for establishing the OPRM setpoints is assumed to be a trip of 3 RIPs while operating at steady state on the maximum rod line with 9 RIPs at minimum speed. The pre-trip MCPR corresponds to the OLMCPR with 9 RIPs running at minimum speed. There will be an increase in CPR following the trip of 3 RIPs, which will be the initial CPR prior to the onset of oscillations.

The following steps are taken for the cycle-specific[4] DIVOM calculation:

1. **Cycle Exposure**: The stability of the core is exposure dependent. 3D simulation data are generated to determine which exposure yields the DIVOM data with the steepest slope. As a minimum, the following [

]^{a,c}

4. **ΔCPR Calculations**: An approved CPR correlation for the fuel type being analyzed is used to determine the time varying CPR for each of the selected hot assemblies based on the predicted channel boundary conditions.

5. **Data Processing**: The time varying data for channel power and CPR are tabulated for each of the selected assemblies. These data are processed to capture the peaks and valleys of the oscillations and their corresponding times. Since the time varying channel power and CPR are not in phase, the change in CPR relative to the pre-oscillation CPR for a particular oscillation is associated with the previous power oscillation. Since the power oscillations are growing in magnitude, this process ensures a conservative ΔCPR with a minimum change in channel power.

6. **DIVOM Slope Determination**: Plot the $\frac{ICPR - MCPR(i)}{ICPR}$, $HCOM(i)$ pairs for each of the selected hot assemblies, where ICPR is the CPR prior to the start of oscillations, MCPR(i) is the minimum CPR during oscillation cycle (i). This term is referred to as the ΔCPR over ICPR (ΔCPR/ICPR). HCOM(i) is the hot channel oscillation magnitude, which is defined in Section 5.2.1. The resulting points form the basis for the DIVOM curve, which is a straight line bounding the data points at high values of HCOM where the SLMCPR might be reached.

4 10 CFR Part 21 report 2001-23 identified an issue regarding use of a generic DIVOM curve for establishing OPRM setpoints. This issue is resolved by requiring the use of cycle-specific DIVOM curves.

7. **Setpoint Determination**: The slope of the DIVOM curve (S_D) provides a conservative connection between the oscillation magnitude and the ΔCPR. Knowing the OLMCPR and the initial change in CPR (δCPR) due to the pump trip transient enables the determination of the $HCOM_{MAX}$ that will challenge the safety limit (SLMCPR). That relationship can be shown to be:

$$HCOM_{MAX} = \frac{1}{S_D} \times \left(1 - \frac{SLMCPR}{(1+k) \times OLMCPR}\right), \text{ where } k = \frac{\delta CPR}{OLMCPR}$$

The methodology for developing the relationship between the HCOM and the OPRM amplitude setpoint (S_p) is provided in Section 5.2.1. The OPRM setpoints can be determined using the S_p vs. HCOM relationship and the equation shown above.

6.3 BSP METHODOLOGY

6.3.1 Background

The backup stability protection (BSP) requirements are implemented in accordance with technical specifications if the OPRM trip function becomes inoperable. This section describes the BSP analysis methodology and acceptance criteria.

The BSP consists of exclusion regions on the power / flow operating map that identify regions where power / flow oscillations due to thermal-hydraulic instability might occur. There are two region boundaries – one is the scram boundary, the other is the exit boundary. If a transient were to take the reactor to the left of the scram boundary, the operators are expected to immediately scram the reactor. If a transient were to take the reactor to a point between the two boundaries, the operators are expected to change power / flow such that the reactor will operate to the right of the exit boundary. The operators are not expected to operate purposely between the two boundaries.

BSP exclusion boundaries are developed prior to plant operation and are implemented by plant procedures. The BSP boundaries are confirmed each reload cycle by performing cycle-specific BSP analyses.

The OPRM trip-enabled region must bound regions of operation that are susceptible to thermal-hydraulic instabilities. Therefore, the OPRM trip-enabled region should encompass the BSP exclusion boundaries.

6.3.2 Acceptance Criteria

As discussed above, there are two regions defined by the BSP analysis – the scram region and the exit region. The acceptance criterion for the boundary of each region is described as follows:

Scram Region – The reactor is scrammed manually if the scram region is entered. The region boundary can be calculated using an approved 3D transient code as the locus of state points that result in a decay ratio (DR) of [

]^{a,c}

Exit Region – The exit region provides the operator with the capability to take actions to exit the region before having to scram the plant. The exit region boundary is calculated in a similar manner as the scram region boundary as the locus of state points that result in [ ]^{a,c}

6.3.3 Methodology

An approved system transient code with 3D core physics capability is used for predicting the dynamic response of the ABWR to perturbations in core power and/or core flow. References 2 and 7 describe the currently approved codes that can be used currently for this analysis. The following steps are performed to identify / confirm the BSP exclusion boundaries:

1. **Establish conservative initial conditions** – Since system pressure may vary as reactor power is changed, the stability analysis must be done at a conservative system pressure. Sensitivity studies have shown that a low system pressure will result in a higher decay ratio at a given power / flow state point. The nominal system pressure with respect to reactor power is obtained from the utility along with the variation of pressure with respect to the nominal value. The BSP stability analyses are performed at the lower bound system pressure.

2. **Search for limiting cycle exposure**. A series of [

]^{a,c}

3. **Global mode analysis**: A series of global mode stability analyses are performed at the limiting exposure for several state points covering the low flow / high power region. The feedwater temperature for each case is assumed to be the nominal feedwater temperature corresponding to the core power state point being analyzed. State points are chosen that result in global mode decay ratios spanning unity and the acceptance criterion for the exit region boundary.

   a) **Feedwater temperature sensitivity**. For a given core flow rate, feedwater temperature has an impact on the boiling length and the void distribution. There can be competing effects due to the changes to the single phase pressure drop and the void reactivity feedback. The influence of each effect depends on the flow rate and core power. A feedwater temperature sensitivity study is performed for a series of state points covering the range of core flow rates of interest. State points are chosen that have DRs closest to the scram line acceptance criterion. Several cases are run for each state point by varying the feedwater temperature over a specified range. The results are used to generate [

   ]^{a,c} Typically there are two feedwater heating conditions that are analyzed – one for nominal feedwater heating and one for reduced feedwater heating. Each condition allows for a variation of feedwater temperature over a specified range.

   b) **Global mode BSP exclusion boundaries**. The [

   ]^{a,c}

4. **Regional mode analysis**. The regional mode consists of power / flow oscillations that are out of phase across the core. A series of regional mode calculations are performed at the state points corresponding to the [ ]^{a,c}

[

]^{a,c}

6. **Cycle-specific bounding-mode scram and exit region boundaries.** The reactor power levels that define the global mode BSP regions I and II ($P^{I}_{i,G}$ *and* $P^{II}_{i,G}$) derived in step 3.b) above are [

]^{a,c}

Table 6-1 Example of Adjusted Cycle-Specific BSP Regions

a,c

7. **Compare cycle-specific results to existing BSP regions.** The BSP region boundaries are described by functions that bound the cycle-specific BSP state points for the limiting mode as shown in the above example. The bounding function is described by a state point along the 100% flow control line (P_A, W_A) and the natural circulation line (P_B, W_B) as follows:

$$P = P_B \times \left[\frac{P_A}{P_B} \right]^{\frac{W-W_B}{W_A-W_B}}$$

where:

P = percent rated power

P_A = percent rated power at point A on the 100% flow control line

P_B = percent rated power at point B on the natural circulation line

W = percent rated core flow

W_A = percent rated core flow at point A

W_B = percent rated core flow at point B

The cycle-specific scram and exit region boundaries are compared to the existing BSP regions to ensure the BSP regions remain bounding.

7 APPLICATION OF THE METHODOLOGY

7.1 BSP ANALYSIS

The BSP demonstration analysis was performed for an equilibrium core of a typical ABWR using the POLCA-T code.

An off-rated heat balance calculation was used to determine the variation in steam dome pressure with reactor power. For a typical plant application, this relationship would be compared to plant data to determine the variation in measured steam dome pressure with the analytical result. The stability analysis would then use the nominal relationship minus an allowance that bounds the measured pressure. Sensitivity studies have shown that core stability improves with increasing vessel pressure. Since this information was not available for this demonstration analysis, the nominal relationship for steam dome pressure was used.

The off-rated heat balance calculation was used to determine the variation in feedwater temperature with reactor power. For a typical plant application, this nominal calculation would be compared to plant data to determine the variation in feedwater temperature for nominal feedwater heating and for reduced feedwater heating. The BSP analysis would cover the range of feedwater temperatures for both conditions. Since this information was not available for this sample application, the nominal feedwater temperature relationship was used. The stability calculations are performed assuming equilibrium feedwater temperature.

The following summarizes the results of those analyses.

7.1.1 Searching for Limiting Exposure

A series of global mode stability analyses are performed to determine the cycle exposure that is most unstable. In this example, the search was performed for several state points along the maximum rod line in decreasing flow rates until the stability threshold (global DR = 1.0) was exceeded. As shown in Figure 7-1, the entire range of cycle exposure was included in this search. In this example, the exposure with the highest global DR was approximately [

]a,c

a,c

Figure 7-1 Global Decay Ratio vs. Cycle Exposure

7.1.2 Global Mode Analysis

A series of global mode analyses were performed at the limiting exposure that was determined in the previous step to determine the DR at various state points within the low flow / high power region. These cases are performed at the nominal feedwater temperature and at a conservative system pressure corresponding to the thermal power being analyzed.

The objective of this analysis is to determine conditions that result in DRs that span the DRs of unity and the acceptance criterion for the exit region boundary. These results are subsequently used to interpolate to find the locus of state points that correspond to the scram line, exit line acceptance criteria and the global mode stability threshold. The results of this demonstration analysis are presented in Table 7-1 and Figure 7-2.

Table 7-1 Global Mode Results

[ ] a,c

[ ] a,c

Figure 7-2 Global Mode Stability Results[6]

6 [ ]a,c

7.1.2.1 Feedwater Temperature Sensitivity Study

The feedwater temperature used in the stability analysis was assumed to be the equilibrium value corresponding to the state point being evaluated. Typically, the equilibrium feedwater temperature is a function of core power. However, there may be a range of feedwater temperature at a particular core power, depending on the operation of the feedwater heaters. This variation in feedwater temperature is normally accounted for in a typical reload analysis. However, this information was not available for this demonstration analysis. As a result, the analysis presented in this report assumes the plant would operate at the nominal equilibrium feedwater temperature.

Figure 7-3 shows the result of a sensitivity study assuming the feedwater temperature could vary from 10 F above the nominal condition to -100 F below the nominal condition. As shown, the sensitivity is [ ]a,c For [

]a,c

a,c

Figure 7-3 Effect of Feedwater Temperature on Decay Ratio

7.1.3 Regional Mode Analysis

The purpose of the regional mode analysis is to determine if it is more limiting than the global mode. The analysis is performed at limiting state points to determine if diverging regional mode oscillations will occur at the global mode stability threshold. If diverging regional mode oscillations occur at the global mode stability threshold, these results are used to find the regional mode stability threshold. The more limiting stability mode is determined by comparing the regional and global mode stability threshold state points.

The regional mode was excited by introducing an asymmetric control rod perturbation from a steady-state condition. Since the symmetry line for the regional mode oscillation is not known a priori, the selection of control rods to initiate the disturbance is an iterative process.

Three exposures were evaluated to determine the limiting exposure for regional oscillation – [

]a,c

Table 7-2 Regional Mode Threshold Analysis Results

[ ] a,c

7.1.4 Channel Mode Analysis

The channel mode was also evaluated at three cycle exposures to determine the limiting exposure for this mode. Three cycle exposures were evaluated to determine the limiting exposure for channel mode – [

]a,c

At each cycle exposure, the channel that had the highest assembly power was analyzed. This is accomplished by extracting channel conditions from the steady state condition corresponding to the global mode threshold power or higher. Then the channels are evaluated one by one by introducing a perturbation of [ ]a,c The response of the channel to the perturbation is obtained by monitoring the channel outlet flow. As shown in Table 7-3, the global mode was [

]a,c

Table 7-3 Channel Mode Threshold Analysis Results

[ ]a,c

7.1.5 BSP Exclusion Regions

As discussed in the previous sections, the [ ]a,c mode was determined to be the most limiting. Similar calculations are performed for each reload cycle to assess the adequacy of the BSP exclusion regions. The BSP regions are defined on the power / flow map by the function described in Section6.3.3. The function, shown below, is described in terms of the intersection of function with the maximum rod line and the natural circulation line. The end points are presented in Table 7-4 and shown in Figure 7-4. As shown, the BSP regions bound the calculated points of constant DR.

$$P = P_B \times \left[\frac{P_A}{P_B}\right]^{\frac{W-W_B}{W_A-W_B}}$$

Table 7-4 Option III BSP Regions

Power / Flow Point	% Flow	% Power	Comments
A1	38.6	60.9	BSP scram region – nominal feedwater temperature
B1	19.0	25.0	
A2	45.0	67.0	BSP exit region – nominal feedwater temperature
B2	19.0	25.0	

a,c

Figure 7-4 BSP Exclusion Regions (nominal feedwater temperature)

7.2 DIVOM ANALYSIS

The DIVOM analyses are performed to find the maximum acceptable HCOM during the cycle and to establish the OPRM setpoints. The design transient for establishing the OPRM setpoints is a trip of 3 RIPs while operating at steady state on the 102% Flow Control Line with 9 RIP at minimum pump speed. The final point is on the 102% Flow Control Line with 6 RIP at minimum speed as shown in Figure 7-5. Since the [

]^{a,c}

The DIVOM methodology assumes diverging regional oscillations begin at the end of the 3 RIP trip transient. As described in Section 6.2.3, an asymmetric control rod perturbation is used to excite regional mode oscillations. In the event that diverging regional mode oscillations fail to develop, as was the case in this example, an alternate approach is used. In the alternate approach, [

]^{a,c}

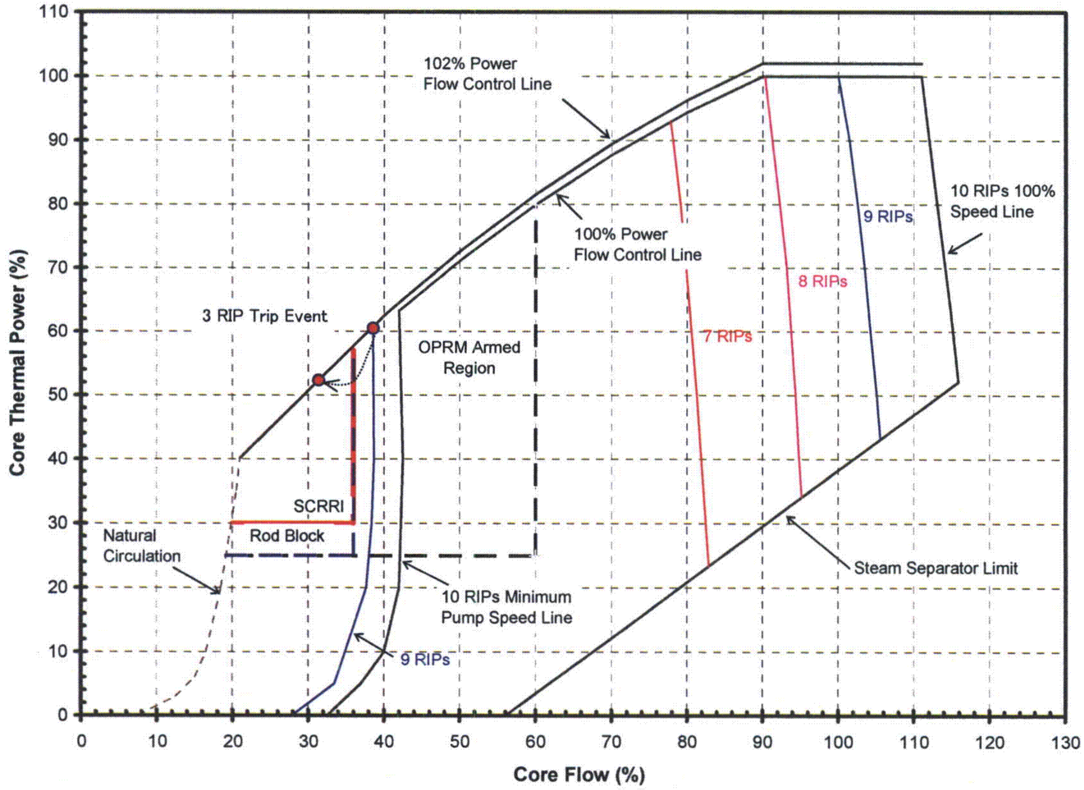

Figure 7-5 Three RIP Trip Transient for DIVOM Analysis

7.2.1 Search for Limiting Exposure

The DIVOM analyses are performed, at a minimum, at three cycle exposures – [

]^{a,c} The limiting exposure is the one that results in the DIVOM curve with the steepest slope.

The initial state point prior to the assumed trip of 3 RIPs is at an operating limit MCPR (OLMCPR) corresponding to operation at the 102% Power Flow Control Line with 9 RIPs at minimum pump speed. The loss of flow due to the trip of 3 RIPs, will also result in a decrease in core power and an increase in CPR. The final MCPR at steady state with 6 RIPs operating at the 102% Power Flow Control Line is the initial CPR that is assumed in the DIVOM calculation.

As discussed above, diverging regional mode oscillations failed to develop following the normal approach described in Section 6.2.3. The alternate calculation methodology is described by the following steps for each exposure:

1. Determine the state point for DIVOM calculations (the state point corresponds to the steady-state condition following a trip of 3 RIPs from steady-state conditions of 9 RIPs operating at minimum speed on the 102% Power Flow Control Line).

2. Perform global calculations at that state point. Extract the resonance frequency and boundary conditions for the channel calculations (inlet and outlet pressure, core flow, bypass flow and inlet temperature).

3. Perform channel calculations for 20 channels with the [

   ]a,c

4. Calculate the DIVOM slope for each channel.

The limiting DIVOM slope for all exposures and channels is used in the evaluation of the OPRM setpoint.

Table 7-5 provides an example for 5 of the channels chosen for the DIVOM analysis and their initial CPR prior to the onset of oscillations.

In this case, the limiting DIVOM slope occurs at the cycle exposure corresponding to the [

]a,c

Table 7-5 Fuel Channels Chosen for DIVOM Analysis

[

]a,c

a,c

Figure 7-6 Power Disturbance for DIVOM Analysis

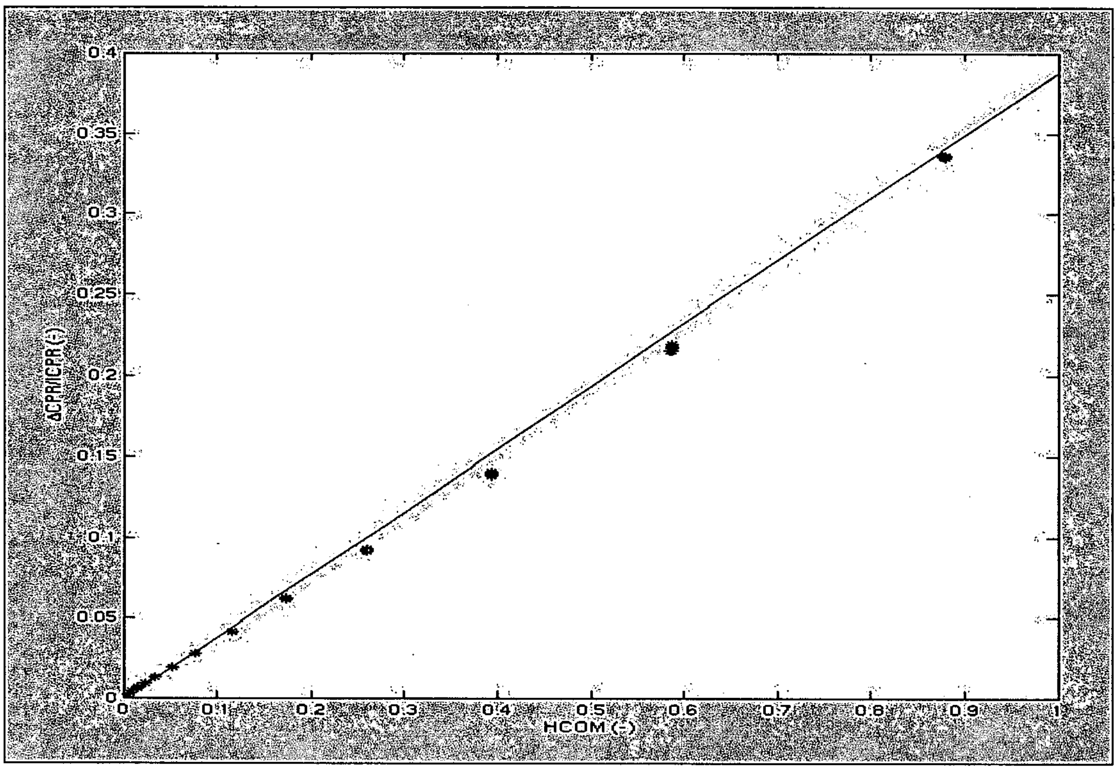

Figure 7-7 DIVOM Slope

7.2.2 Limiting HCOM and OPRM Setpoints

The limiting HCOM depends on the SLMCPR, the OLMCPR, the DIVOM slope and the change in CPR due to the trip of 3 RIPs while operating at steady state on the maximum rod line with 9 RIPs at minimum speed. The relationship between the limiting HCOM and these parameters is presented in Section 6.2.3

$$HCOM_{MAX} = \frac{1}{S_D} \times \left(1 - \frac{SLMCPR}{(1+k) \times OLMCPR}\right), \text{ where } k = \frac{\delta CPR}{OLMCPR}$$

Using this relationship and the relationship between the OPRM amplitude setpoint (S_p) and HCOM, the OPRM setpoint can be determined in terms of the OLMCPR as shown in Table 7-6.

Table 7-6 OLMCPR vs. OPRM Setpoint

a,c

8 REFERENCES

1. CENPD-300-P-A, "Reference Safety Report for Boiling Water Reactor Reload Fuel," July 1996.

2. CENPD-295-P-A, "Thermal-Hydraulic Stability Methodology for Boiling Water Reactors," July 1996.

3. NEDO-32465-A, "BWR Owners' Group Reactor Stability Detect and Suppress Solutions Licensing Basis Methodology for Reload Applications," August 1996.

4. NEDO-31960-A, "BWR Owners' Group Long Term Stability Solutions Licensing Methodology," June 1991.

5. NEDO-31960-A Supplement 1, "BWR Owners' Group Long Term Stability Solutions Licensing Methodology Supplement 1," March 1992.

6. CENPD-294-P-A, "Thermal-Hydraulic Stability Methods for Boiling Water Reactors," July 1996.

7. WCAP-16747-P, "POLCA-T: System Analysis Code with Three-Dimensional Core Model," March 2007 and Final Safety Evaluation for Westinghouse Electric Company Topical Report WCAP-16747-P, "POLCA-T: System Analysis Code With Three-Dimensional Core Model" (TAC No. MD5258), April 2010, Enclosure 2.