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Enhanced Option III Long Term Stability Solution

Presentation to the Nuclear Regulatory Commission

March 14, 2006

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Agenda

- > Option III Detect & Suppress Solutions
  - Need for enhancement to widen the range of applicability
- > The Enhanced Option III Solution
  - Physical basis
  - Licensing basis
- > Conclusions

Introduction to D&S

> Elements of Option III Detect & Suppress

- **Hardware:**
  - Several OPRM cells (closely spaced LPRMs)
- **Algorithms:**
  - OPRM cell signals are conditioned and filtered for oscillation detection
  - Oscillation recognition using a Period-Based Detection Algorithm (PBDA)
- **Setpoints:**
  - Number of PBDA confirmation counts (N_P)
  - Amplitude setpoint (S_P)

Introduction to D&S

> Elements of Option III Detect & Suppress

- Calculated Relationships:
  - Plant-Specific relationship between S_P and Hot Channel Oscillation Magnitude (HCOM) – Monte Carlo Analysis
    - Probability distributions for oscillation period and growth ratio
    - Oscillation Contours
    - Scram Delay
    - OPRM cell design (LPRM grouping)
    - Trip Logic
  - Relationship between relative HCOM and relative CPR response – Time Domain System Codes
    - Originally generic DIVOM curve
    - Currently cycle-specific

> Option III Detect and Suppress Application

- Initial MCPR at 2 state points
  - Steady State OLMCPR at 45% flow and highest rod line
  - Initial MCPR following a two pump trip transient along the highest rod line. Pre-trip at 100% power and OLMCPR.
- Hot Channel Oscillation Magnitude (HCOM) for a given S_p
- Use HCOM value and DIVOM curve to get relative CPR response
- Final MCPR is initial MCPR minus the CPR change
- Repeat for different S_p until Final MCPR > SLMCPR

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Issues with Option III

- Part 21 Report: Generic DIVOM curve nonconservative
- Probability of Spurious Scram
  - PBDA is sensitive to noise level which is higher at low flow
  - High DIVOM slope requires low S_P
  - Low S_P Requires low N_P
  - Low setpoints may result in false oscillation identification
  - Example: Peach Bottom Unit 3 (Feb. 11, 2005)
    - Trip signal received, but OPRM system not yet armed
    - No other indication of oscillations
    - Attributed to overly conservative OPRM setpoints
  - Counter examples of where the OPRM system worked as designed
    - Perry (Dec. 23, 2004)
    - Nine Mile Point Unit 2 (July 24, 2003)
- Not licensed for extended flow window operating domain such as MELLLA+

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Resolving Option III Issues

> **Current Practice:**
- Figure Of Merit (FOM) DIVOM slope multiplier (GE)
  - FOM Correlated with hot channel Power/Flow ratio
  - Produces high DIVOM slope and consequently low S_P setpoint
- Cycle-Specific DIVOM calculation
  - Elevated DIVOM slopes less likely for current cycle designs

> **New Solutions:**
- Applicable to all operating domains including MELLLA+
- Proposed solutions:
  - DSS-CD by GE
  - Enhanced Option III by Framatome ANP presented today

MELLLA+ Stability Issues

> Stability issues identified for MELLLA+ operation

- Limiting conditions following a two pump trip transient
- All issues originate from deeper penetration of the instability domain

I. High growth ratios (GR)

a. Questionable reliability of oscillation detection
b. Questionable timely suppression of oscillation which continues to grow fast during the scram delay

II. Pathological DIVOM Curve

- Multiple instability mode excitations become possible
  - Limiting case Regional + single (few) hydraulic channels
- Resulting DIVOM problems
  - Elevated slope
    - Physical explanation of the GE Part 21 in 2001 identifying elevated DIVOM slopes at high power/flow ratios
  - Sensitivity to initial perturbations
  - Irregular shape
  - Breakdown of the detected/protected phenomena relationship

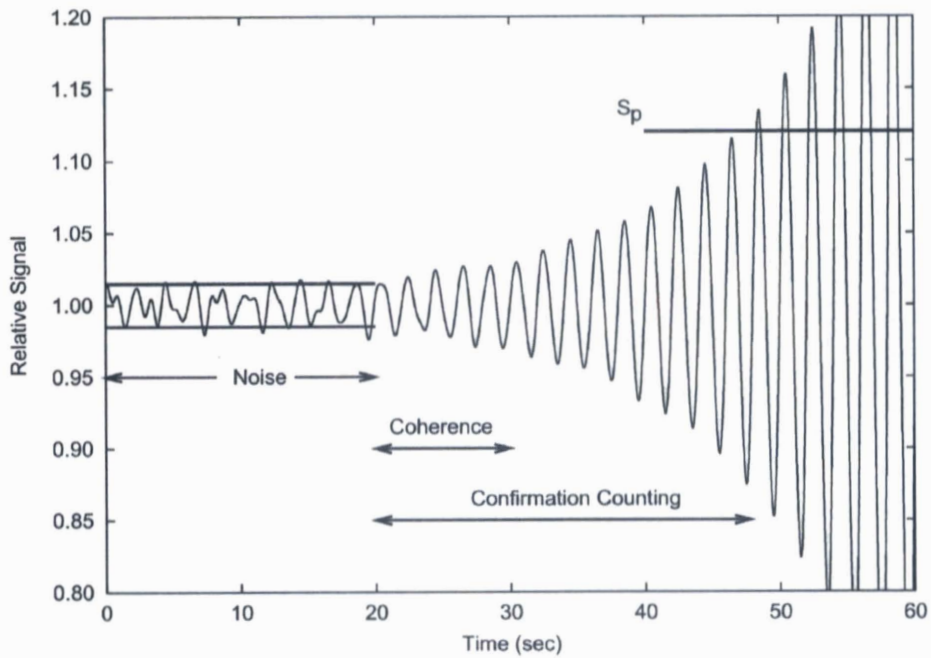
> Resolution of these issues → Enhanced Option III

MELLLA+ Stability Issues

I. **High growth ratios (GR)**

a. **Questionable reliability of oscillation detection**

– **Requires a minimum number of counts (N_P) be reached prior to the amplitude setpoint (S_P) being reached**



MELLLA+ Stability Issues

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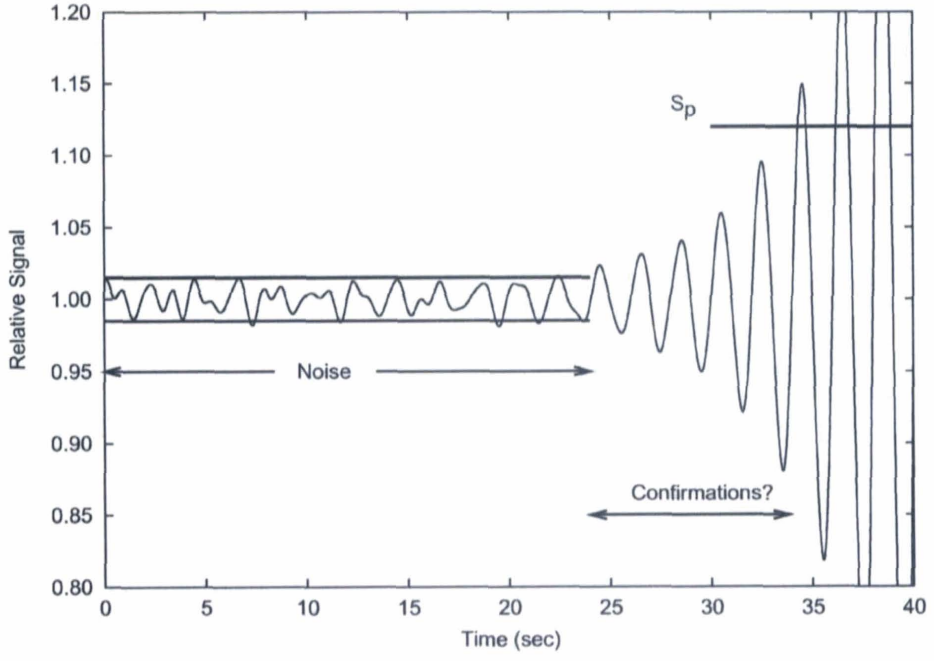

MELLLA+ Stability Issues

I. High growth ratios (GR)

a. Questionable reliability of oscillation detection

- Requires a minimum number of counts (N_P) be reached prior to the amplitude setpoint (S_P) being reached

- Work for the resolution of Issue I-a:
  - [
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Resolution of Issue I-a

> Two Pump Trip Transient [
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- Limiting transient leading to high power/flow ratio and instability
  - Transient begins with fast reduction in flow
  - Power recovers as core inlet subcooling increases
  - Brings the reactor into the instability region
- Starting the 2PT from the MELLLA+ line leads to least stable state
- Full scale simulation with RAMONA5-FA
- Idealized simulation using a Reduced Order Model

Reduced Order Model

- Extension of earlier models
  - March-Leuba 1984
  - Muñoz-Cobo et al. 1996
- Basic Features
  - Modal Kinetics
    - Single energy group and delayed neutron precursor
    - Fundamental flux mode
    - First azimuthal flux mode
  - Channel hydraulics
    - Harmonic oscillator model
    - Recirculation loop correction
  - First order heat conduction in fuel pins
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Resolution of Issue I-a

Reduced Order Model

Resolution of Issue I-a

> Idealized Simulation of 2PT with Reduced Order Model

- **Observations:**
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Resolution of Issue I-a

> **Full-Scale Simulation of 2PT with RAMONA-FA**

- **Performed using limiting regional decay ratio exposures for a Susquehanna equilibrium EPU core**
  - **Initial state at 100% EPU power, 80% flow**
- **[**
  -
  - **]**

Resolution of Issue I-a

[ ]

Resolution of Issue I-a

> **Oscillation Detection with MELLLA+**

- **MELLLA+ results in less stable final state following 2PT compared with MELLLA**
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Resolution of Issue I-a

> Relationship between Amplitude Setpoint and Period-Based Algorithm Confirmation Count

- **Original Option III provides the condition for the number of confirmation count setpoint:**

$$N_p \pounds \text{ int}\left[\frac{2 \times \log\left(\frac{S_p}{e} - 1\right)}{\log(G)} - 1\right]$$

where:

G = Constant oscillation growth ratio

ε = Minimum amplitude at the onset of oscillation, noise level

Resolution of Issue I-a

> Relationship between Amplitude Setpoint and Period-Based Algorithm Confirmation Count

- [

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MELLLA+ Stability Issues

I. **High growth ratios (GR)**

a. **Questionable reliability of oscillation detection**

– Requires a minimum number of counts (N_P) be reached prior to the amplitude setpoint (S_P) being reached

- **Resolution of Issue I-a:**
  - [
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] the number of available confirmation counts remains adequate for reliable detection

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MELLLA+ Stability Issues

I. **High growth ratios (GR)**

b. **Questionable timely suppression of oscillation which continues to grow fast during the scram delay**

– Once the amplitude setpoint S_P is reached, high GR may not allow timely suppression to avoid SLMCPR violation

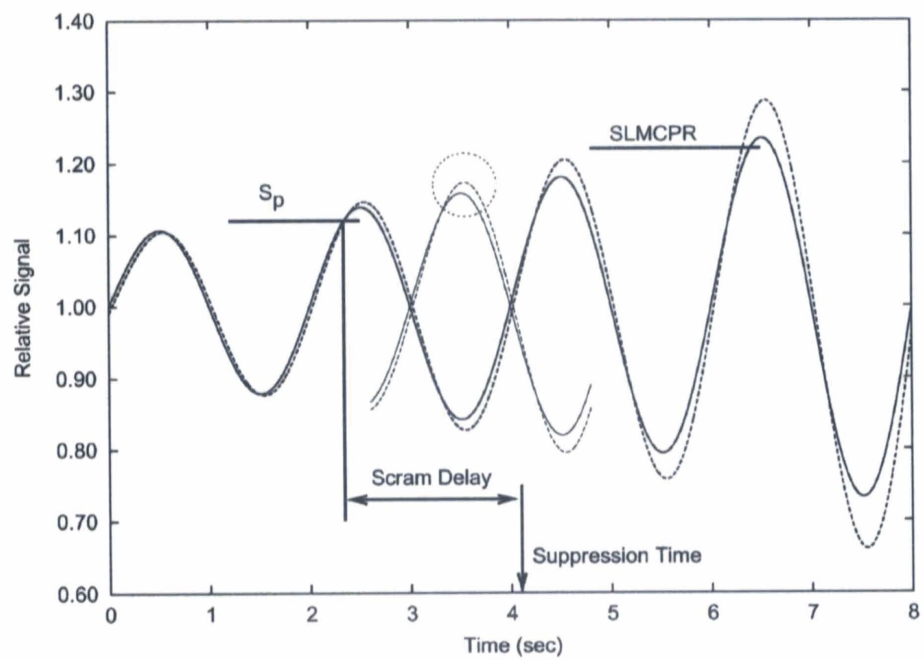
- **Work for the resolution of Issue I-b:**
  - Perform relative HCOM statistical analysis to quantify the effects of reduced stability

Resolution of Issue I-b

I. **High growth ratios (GR)**

b. **Questionable timely suppression of oscillation which continues to grow fast during the scram delay**

– Once the amplitude setpoint S_P is reached, high GR may not allow timely suppression to avoid SLMCPR violation

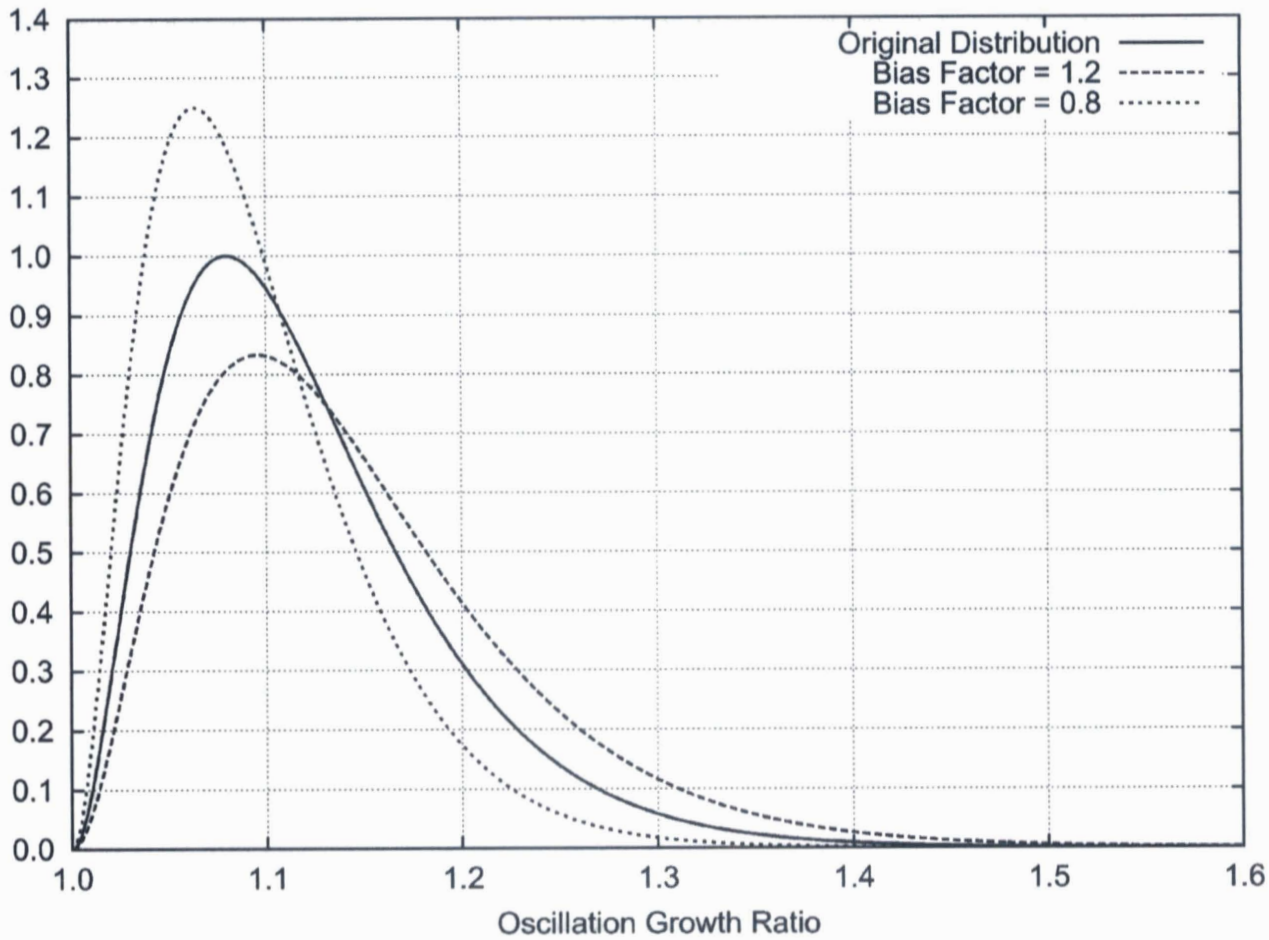


Resolution of Issue I-b

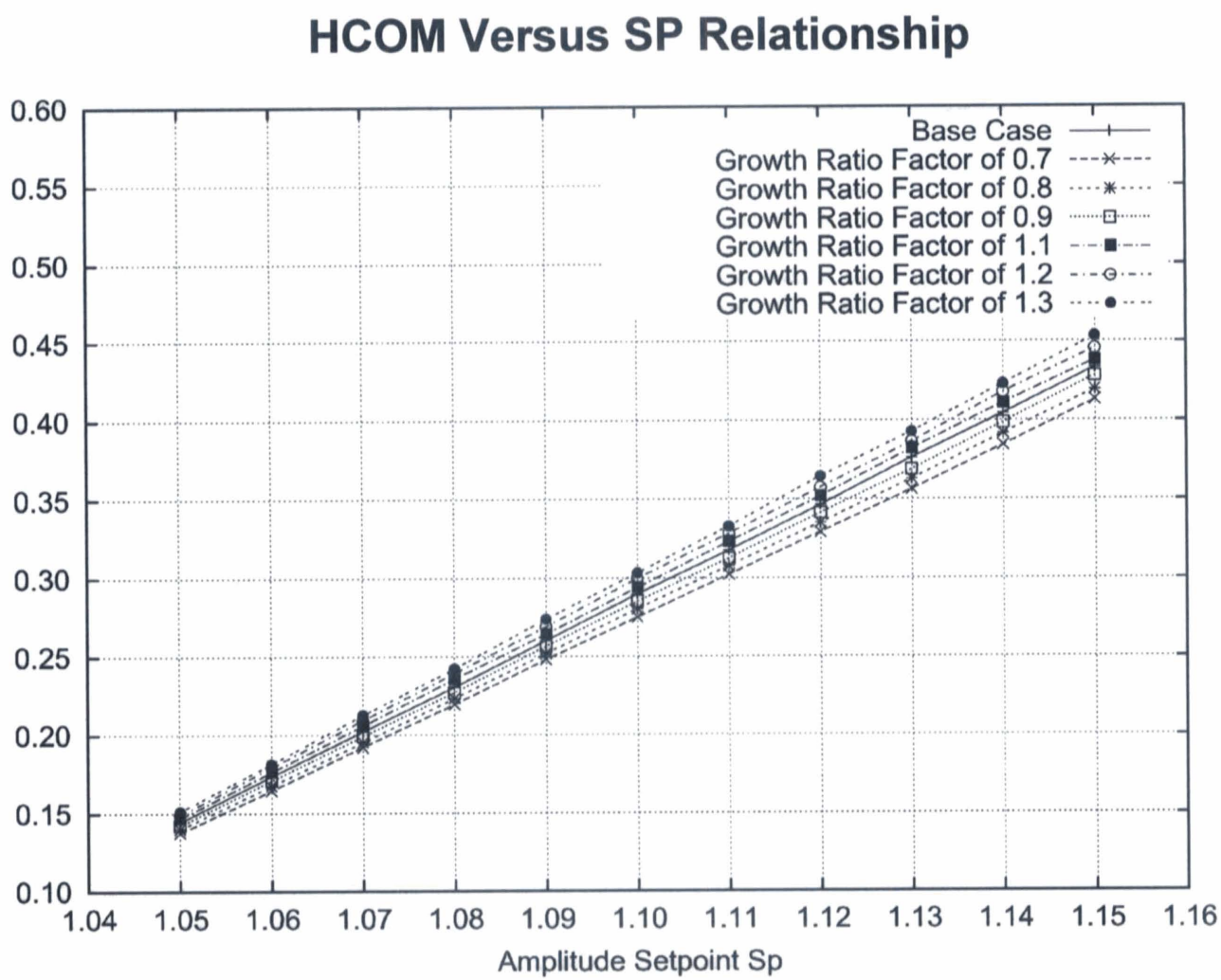
- Perform Relative HCOM Analysis
  - Not plant specific
  - Can parametrically study the effect of
    - Probability distribution biased to higher decay ratios
    - Sensitivity to oscillation frequency biasing
- Observations:
  - Oscillation frequency has a negligible impact on HCOM
    - Higher frequency increases the effect of scram delay and increases HCOM very slightly. However, it also lowers CPR response and DIVOM slope which is an implied conservatism
    - Lower frequency reduces the effect of scram delay and lowers HCOM
  - Higher growth ratios have a minor effect on HCOM
    - HCOM Penalty estimated < 5%
    - Equivalent S_p Adjustment of approximately – 0.005

Relative HCOM Sensitivity Analysis
Effect of Growth Ratio

Probability Distributions for Growth Ratio



Relative HCOM Sensitivity Analysis
Effect of Growth Ratio



Relative HCOM Sensitivity Analysis
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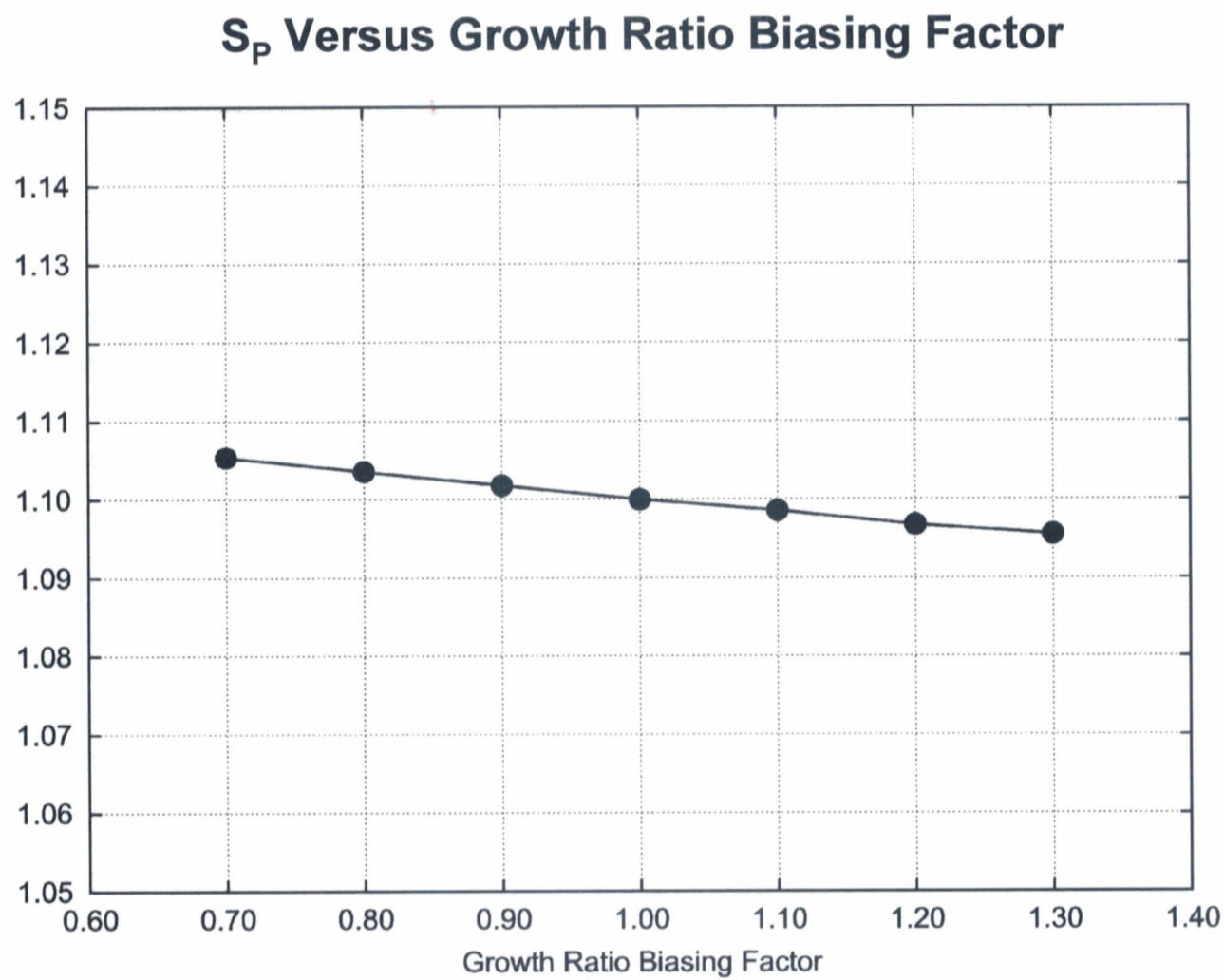

MELLLA+ Stability Issues

I. **High growth ratios (GR)**

b. **Questionable timely suppression of oscillation which continues to grow fast during the scram delay**

– Once the amplitude setpoint S_P is reached, high GR may not allow timely suppression to avoid SLMCPR violation

- **Resolution of Issue I-b:**
  - Impose a 5% penalty on HCOM to conservatively account for anticipated increase in oscillation growth ratio

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Resolution of Issue II

II. Pathological DIVOM Curve

- Multiple instability mode excitations become possible
  - Limiting case Regional + single (few) hydraulic channels
- Resulting DIVOM problems
  - Elevated slope
  - Sensitivity to initial perturbations
  - Irregular shape
  - Breakdown of the detected/protected phenomena relationship

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Review of DIVOM Issues

- DIVOM curve is fairly linear and well-bounded under
  - Conditions:
    - Power, flow, fuel types, loading and control rod patterns…
    - Initial perturbation
  - Modeling methods:
    - CPR correlation, steady state simulator, transient code
  - Exception: Mixed mode oscillations
- Irregular DIVOM curves with elevated slopes observed when single channel decay ratios exceed unity
  - Demonstrated with Reduced Order Model
  - Demonstrated using RAMONA5-FA

Demonstration of Irregular DIVOM Theoretical: Reduced Order Model

> Use the reduced order model:

- Studied the effects of hot channel Decay Ratio on DIVOM
- Verified that DIVOM is not sensitive to hydraulic nonlinearity with stable single channels
  - System transient codes differ in their ability to simulate nonlinear effects making the reduced order model exercise particularly valuable
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Demonstration of Irregular DIVOM Theoretical: Reduced Order Model

> **Basic Features**

- **Modal Kinetics**
  - Single energy group and delayed neutron precursor
  - Fundamental flux mode
  - First azimuthal flux mode
- **Multi-Channel hydraulics**
  - Harmonic oscillator with optional nonlinear damping
  - Recirculation loop correction
- **First order heat conduction in fuel pins**

Demonstration of Irregular DIVOM Theoretical: Reduced Order Model

> **Analytical & Numerical Model Predictions**
  - Oscillation characteristics consistent with test data and system code results

> **Cases Fitted to STAIF for quantitative analysis**
  - Based on STAIF simulation (38 hydraulic channels) of an actual regional oscillation stability test
  - Same channel power and modal reactivity weighting as STAIF
  - Replicate Linear Decay Ratios

> **Analysis:**
  - Nonlinear hydraulic term varied parametrically
  - Regional and Hot Channel decay ratios varied parametrically
  - Process output for relative effect on DIVOM slope

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Demonstration of Irregular DIVOM Theoretical: Reduced Order Model

> Observations from relative DIVOM calculations

- DIVOM is well-behaved with stable single channels regardless of nonlinear modeling and decay ratios
- DIVOM curve deviates from linear shape as hot channels become unstable, and its slope diverges
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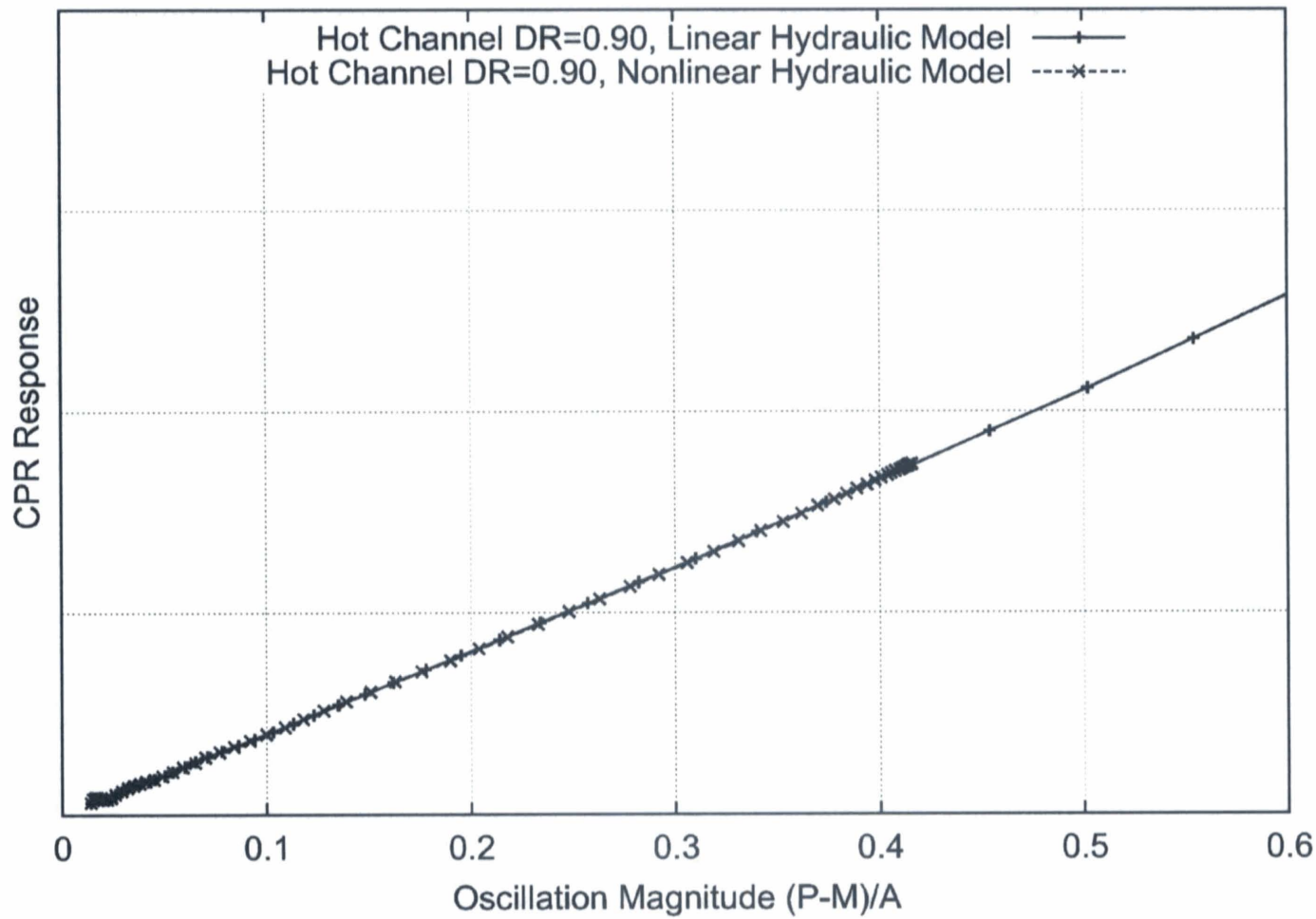
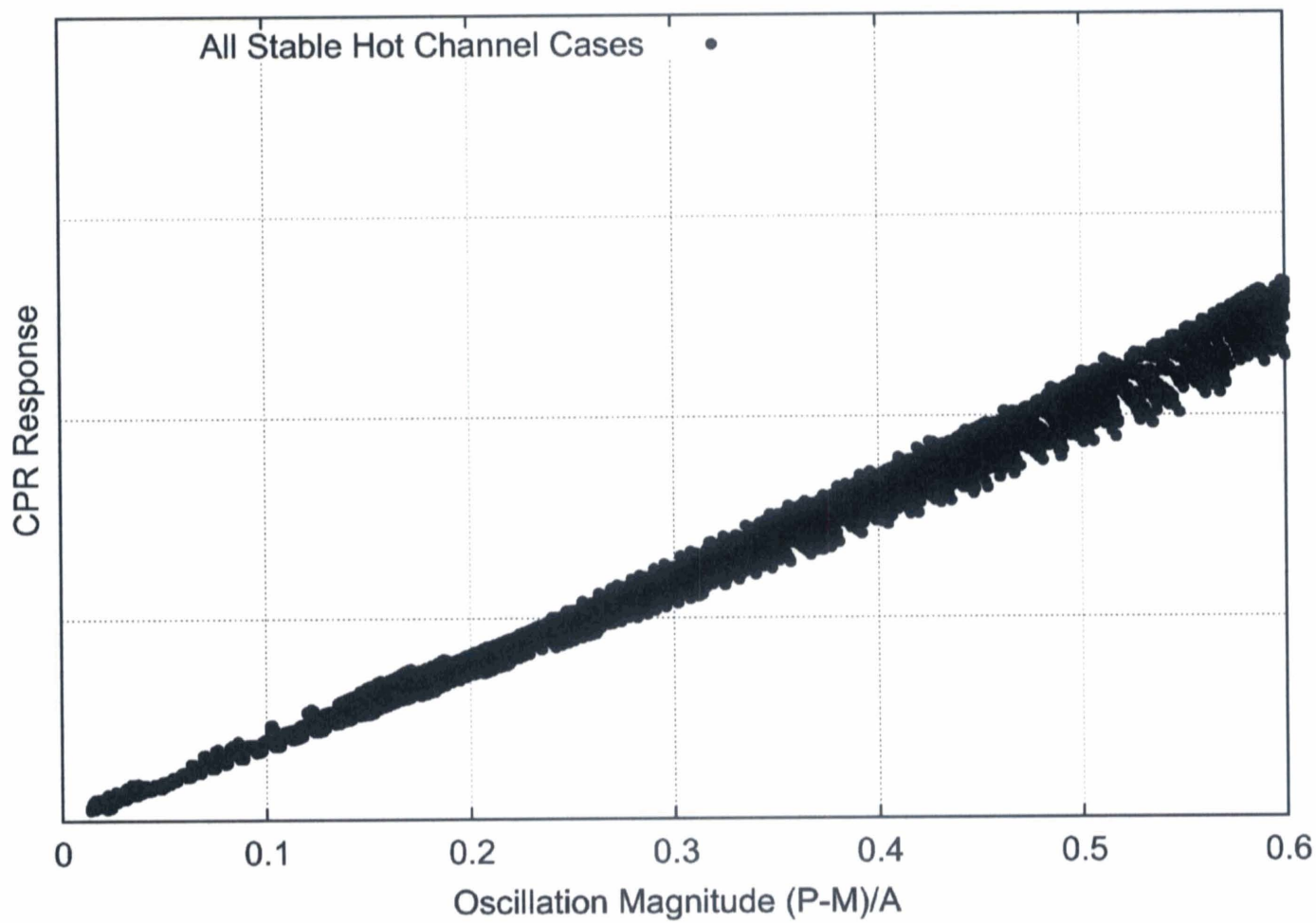
Reduced Order Model

DIVOM Slope is not affected by hydraulic model nonlinearity



Reduced Order Model
DIVOM curve is regular and bounded for stable channels



Reduced Order Model
DIVOM deviation with unstable hot channel

Reduced Order Model
DIVOM deviation increases with hot channel decay ratio

Reduced Order Model
DIVOM deviation increases with hot channel decay ratio

Reduced Order Model
DIVOM deviation increases with hot channel decay ratio

Reduced Order Model
DIVOM deviation increases with hot channel decay ratio

Reduced Order Model
Elevated DIVOM slope for channel decay ratio > 1
Consistent with Part 21 Report

Reduced Order Model
Elevated DIVOM slope for channel decay ratio > 1
Consistent with Part 21 Report

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Resolving Issue II

> Reduced Order Model Conclusions

- Observations are consistent with the Part 21 report on DIVOM calculations
- Elevated DIVOM slopes correspond to high channel decay ratios
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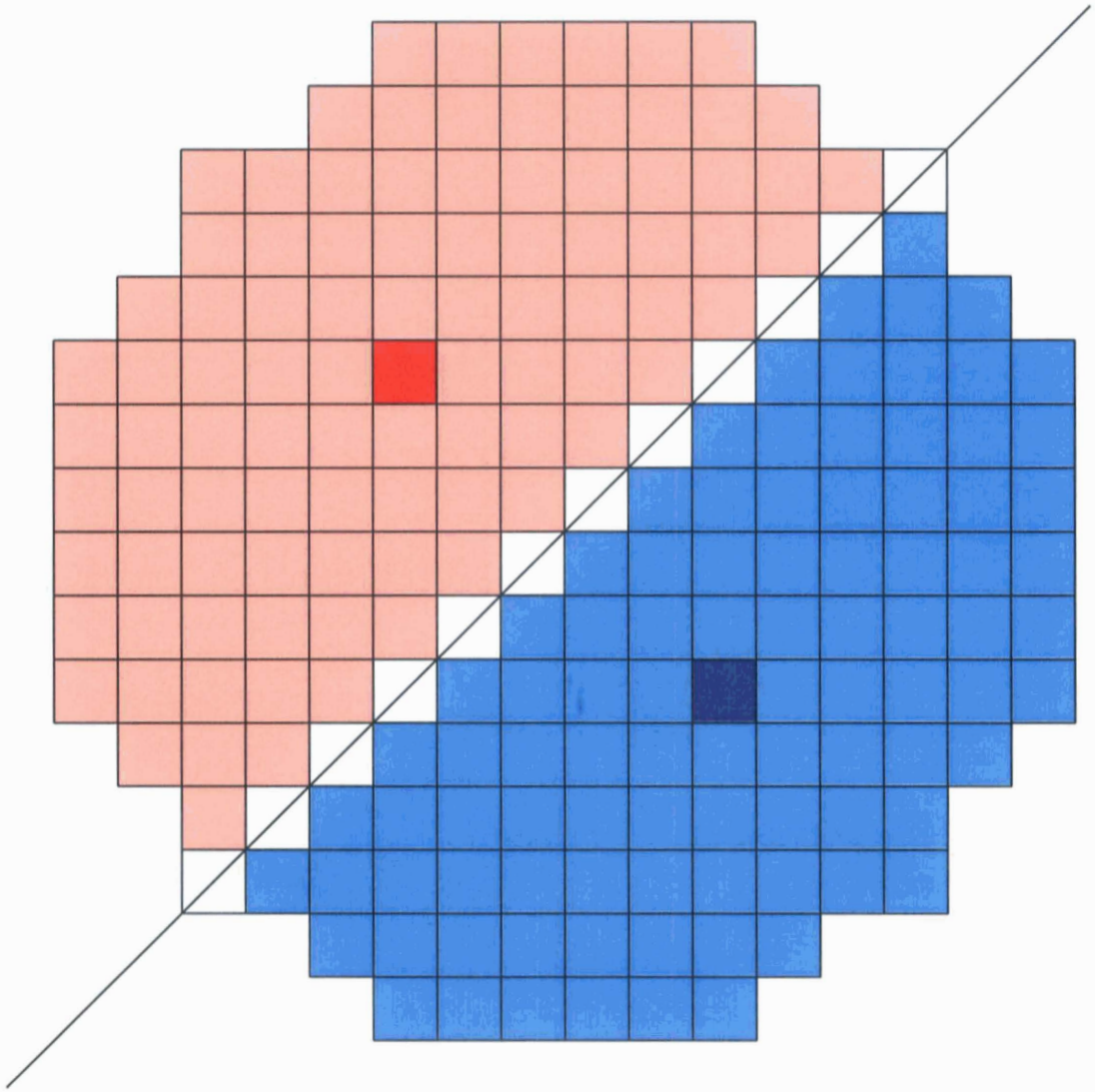
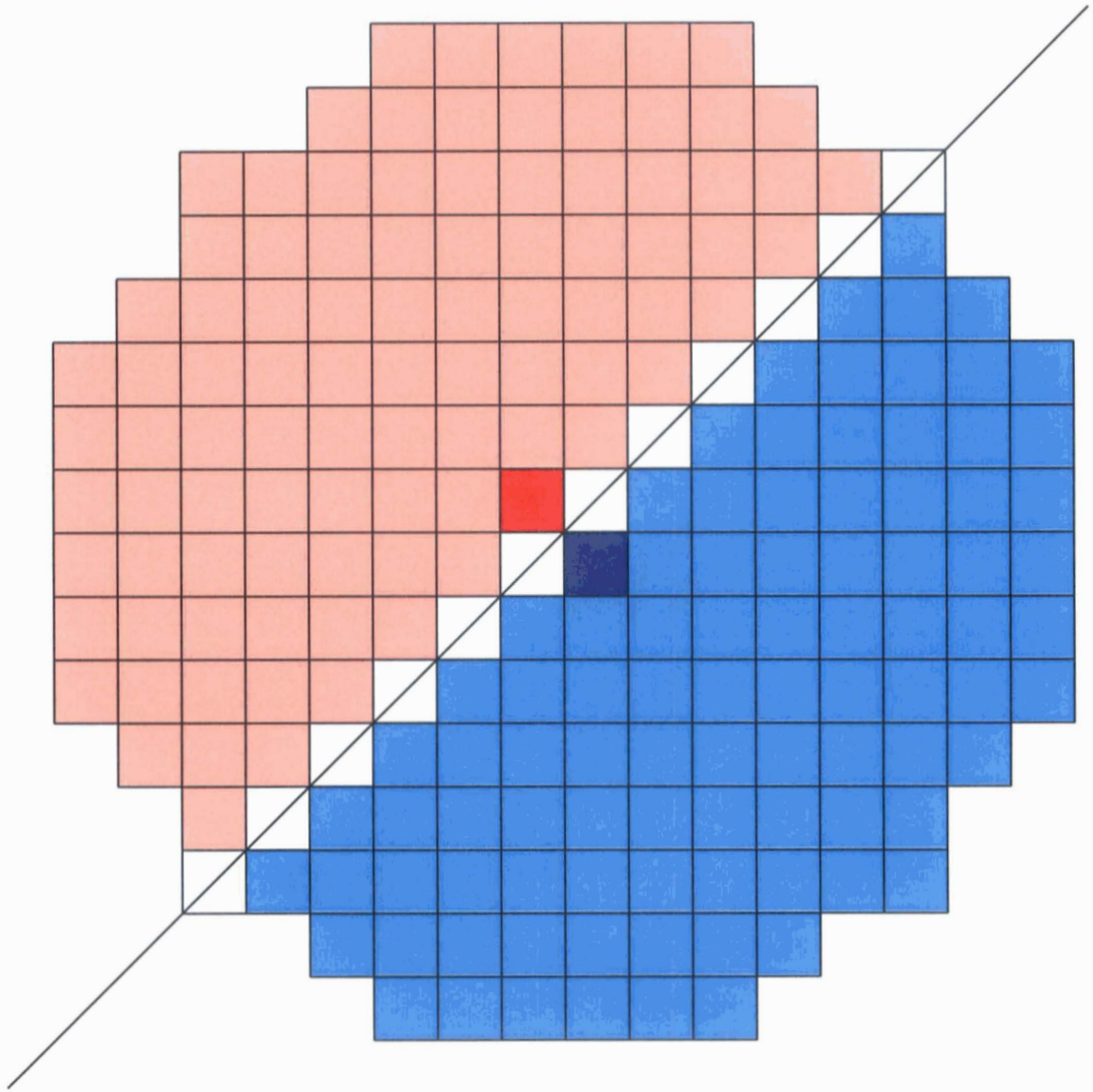
Demonstration of Irregular DIVOM Numerical: RAMONA5-FA

- Elevated DIVOM slopes are evident in full three dimensional simulations when channel decay ratios exceed unity
- Two Limiting Cases:
  - Hot channel in the eye of regional oscillation contour
  - Hot channel near the neutral line
- Modified control rod patterns to increase the hot channel radial power factor and ensure a channel instability
- Imposed combination of varying amplitudes of mixed regional and global power initial perturbations

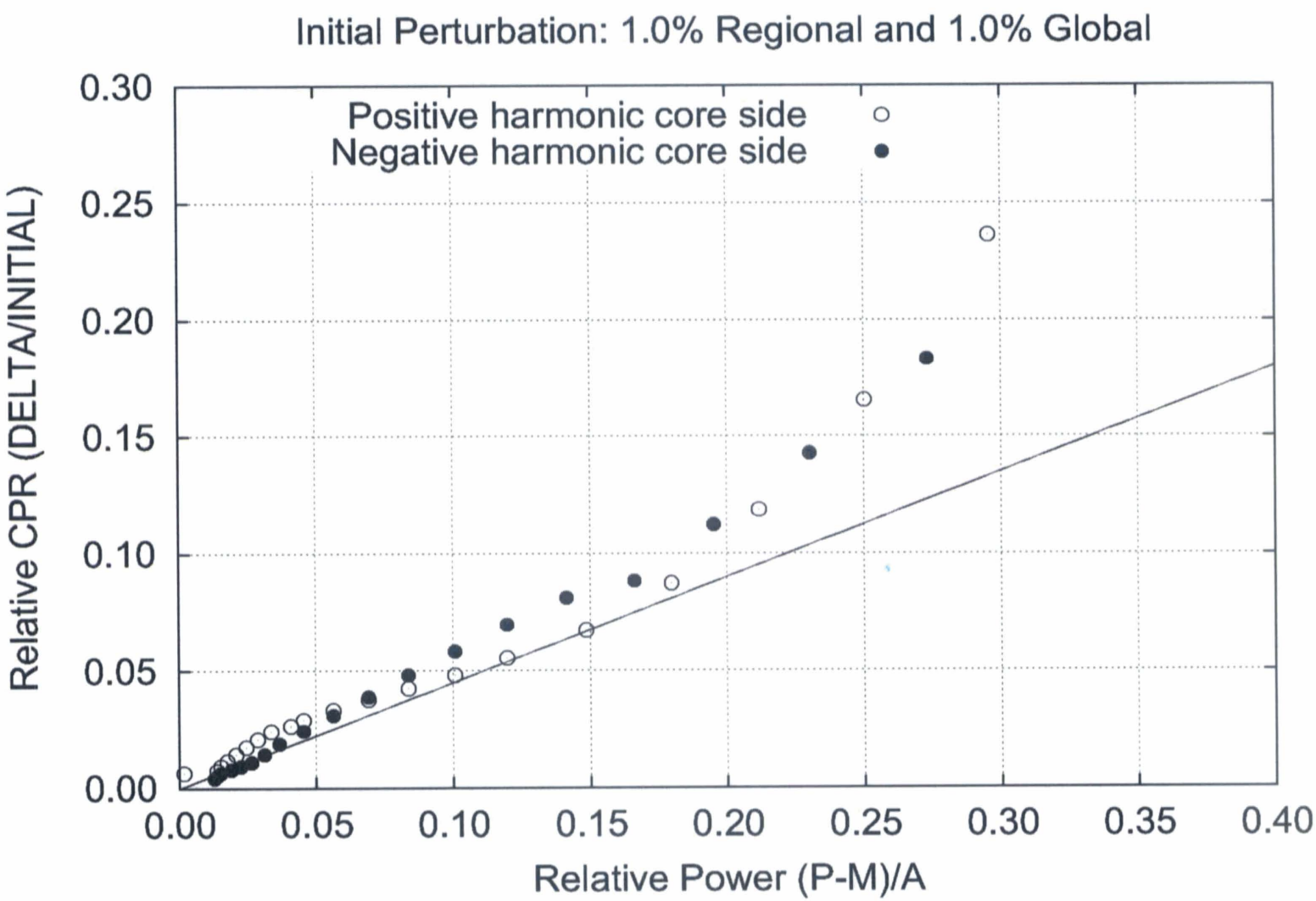
Unstable Channel in the Eye of the Regional Oscillation



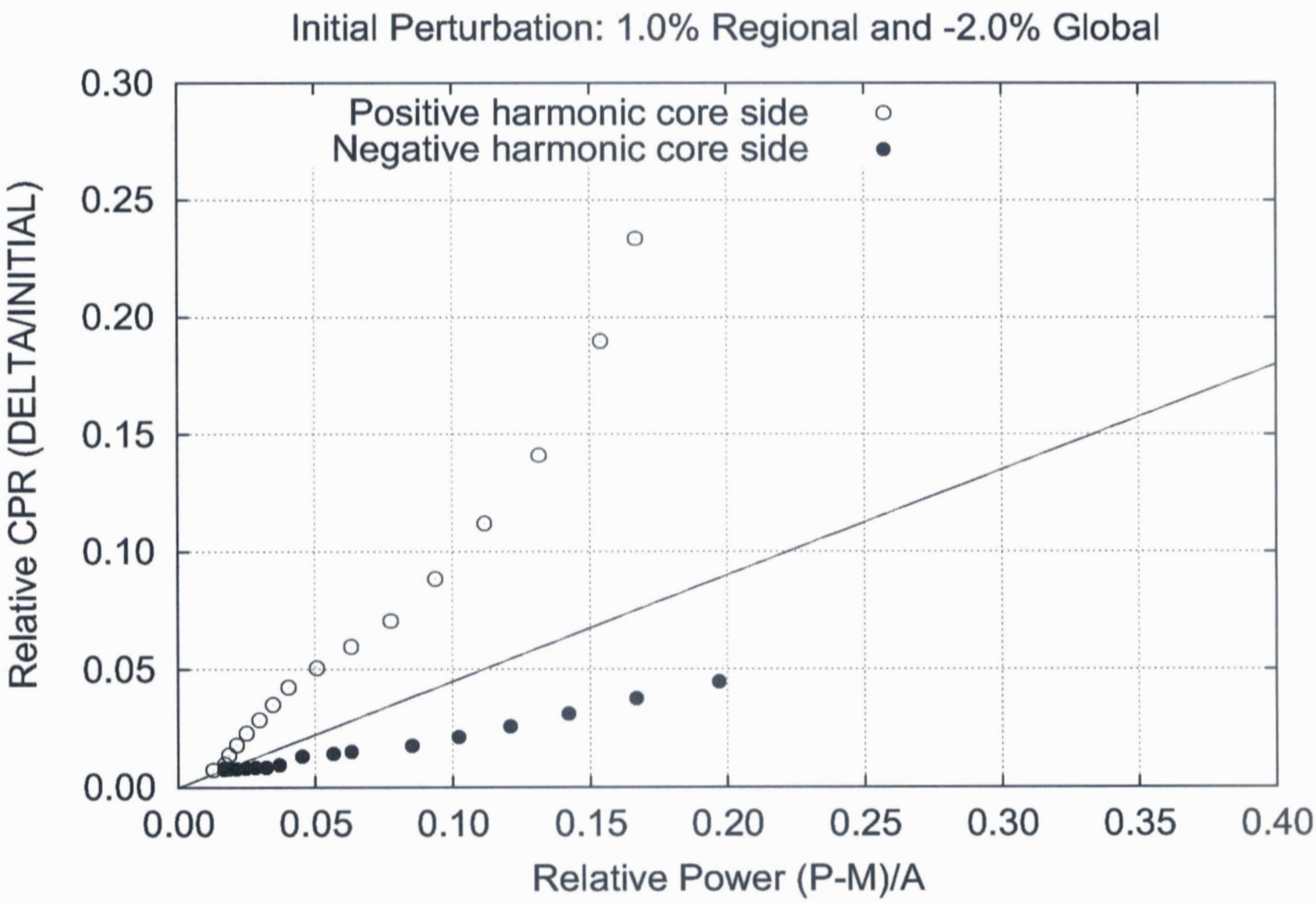
Unstable Channel Near the Neutral Line



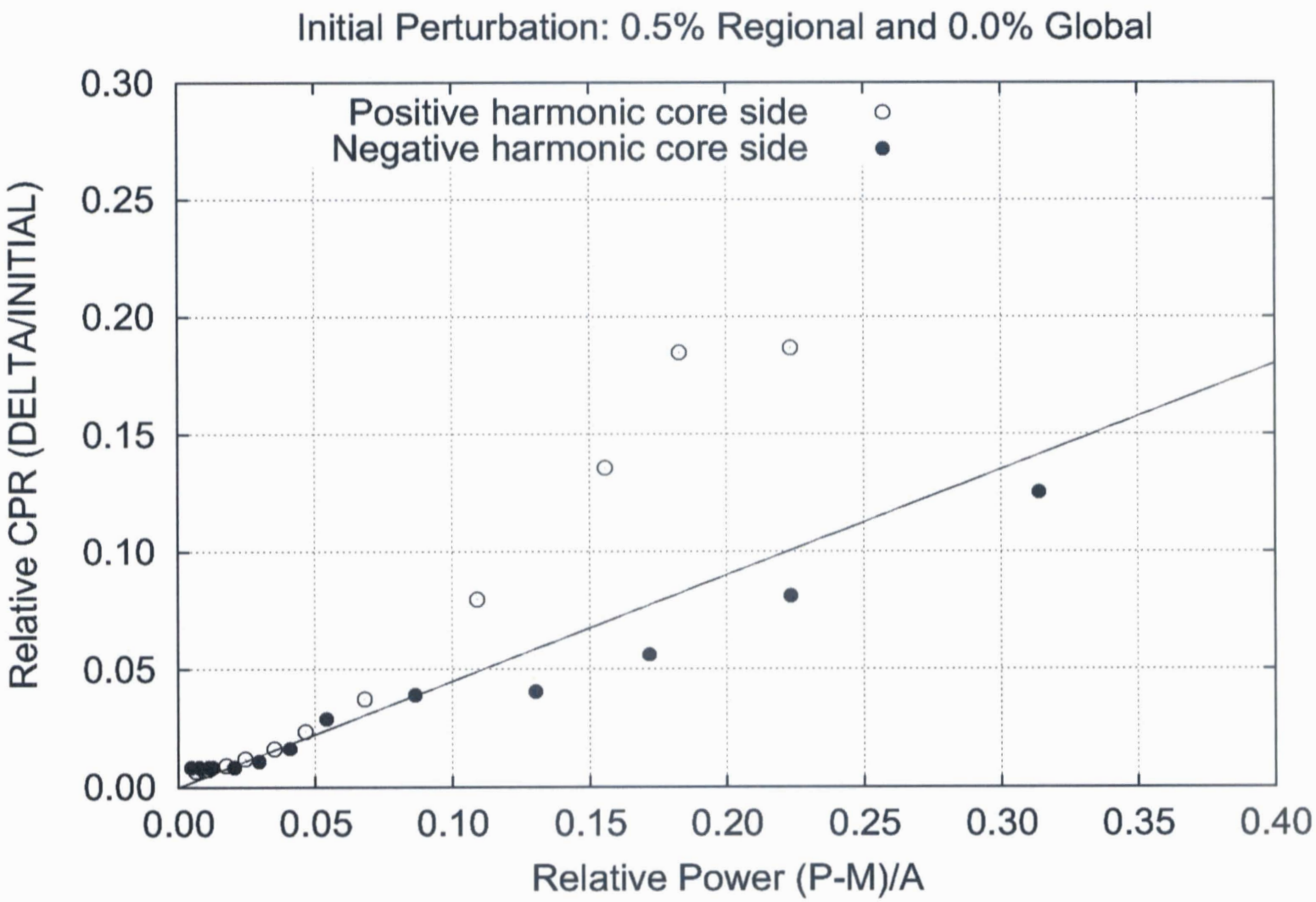
Unstable Channel in the Eye of the Regional Oscillation Contour



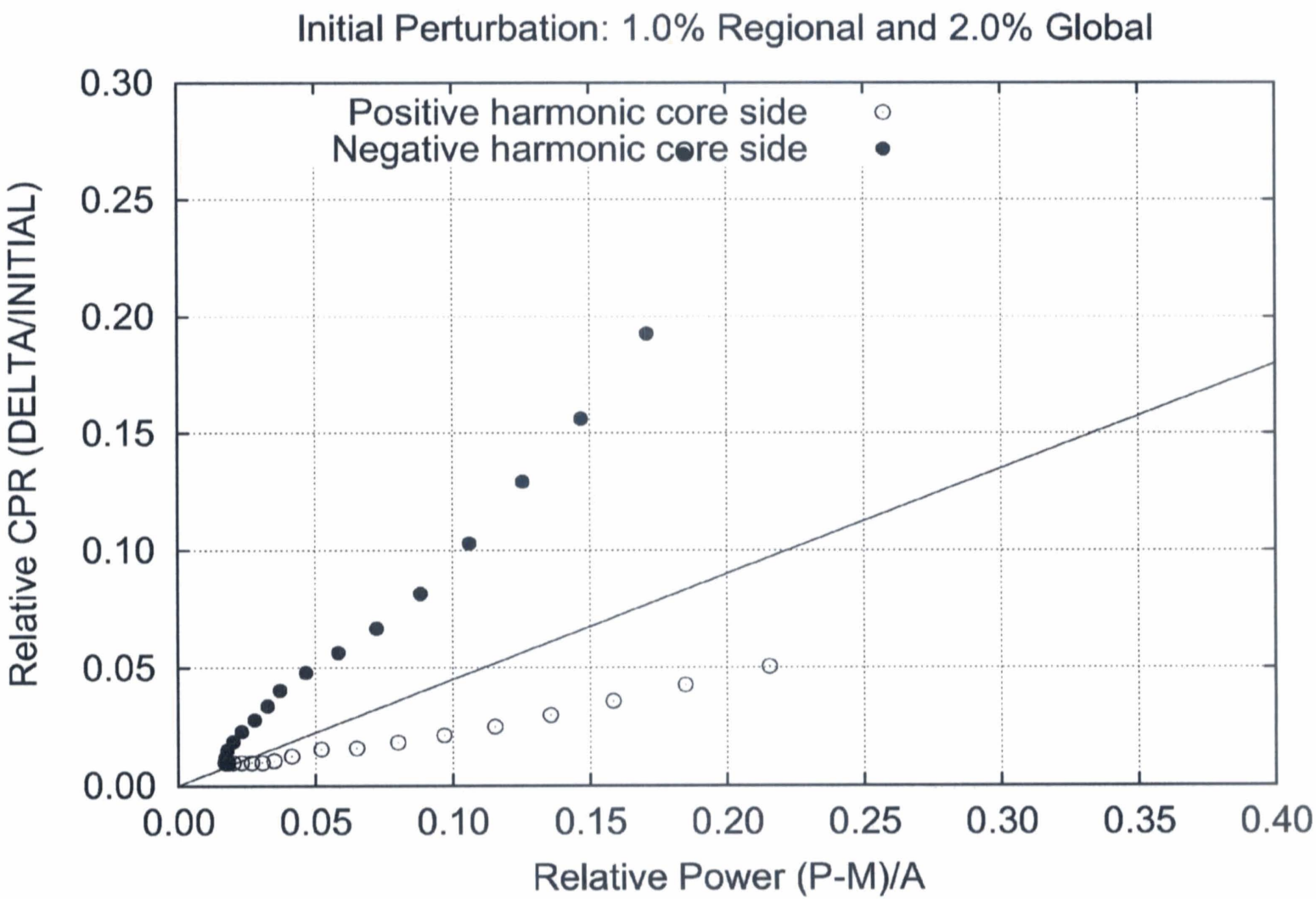
Unstable Channel in the Eye of the Regional Oscillation Contour



Unstable Channel Near the Neutral Line



Unstable Channel Near the Neutral Line



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Resolution of Issue II

- Elevated DIVOM due to high channel decay ratios exist
- At the onset of core instability modes:
  - Channel mode is stable with decay ratio well below core (global or regional) decay ratio
  - However, channel decay ratio is increasing faster than the core decay ratio with increasing power
- For conditions following a two-pump trip
  - Operating conditions brought deep into the instability region
  - Channel decay ratios can become large
  - The diagnosis of a single (few) hydraulic channel oscillations superimposed on the regional mode oscillation is consistent with the observation leading to the Part 21 report

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Resolution of Issue II

II. Pathological DIVOM Curve

- Multiple instability mode excitations become possible
  - Limiting case Regional + single (few) hydraulic channels
- Resulting DIVOM problems
  - Elevated slope
  - Sensitivity to initial perturbations
  - Irregular shape
  - Breakdown of the detected/protected phenomena relationship

- **Resolution: Exclude single channel hydraulic mode excitation**

Enhanced Option III

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Elements of the Enhanced Option III Solution

- Define new boundary of applicability of the Option III Solution
  - Boundary defined to exclude conditions for unstable single channel interference
  - Imposing this restriction assures robust DIVOM curves
    - Fairly linear
    - Bounded slope
    - Invariant regardless of initial perturbation
- Protect the single channel instability exclusion region (immediate scram upon entry)
- Maintain all Detect & Suppress functions of Option III as licensed, outside the channel instability exclusion zone
- Define cycle-specific DIVOM curve for reactor states with all channels stable

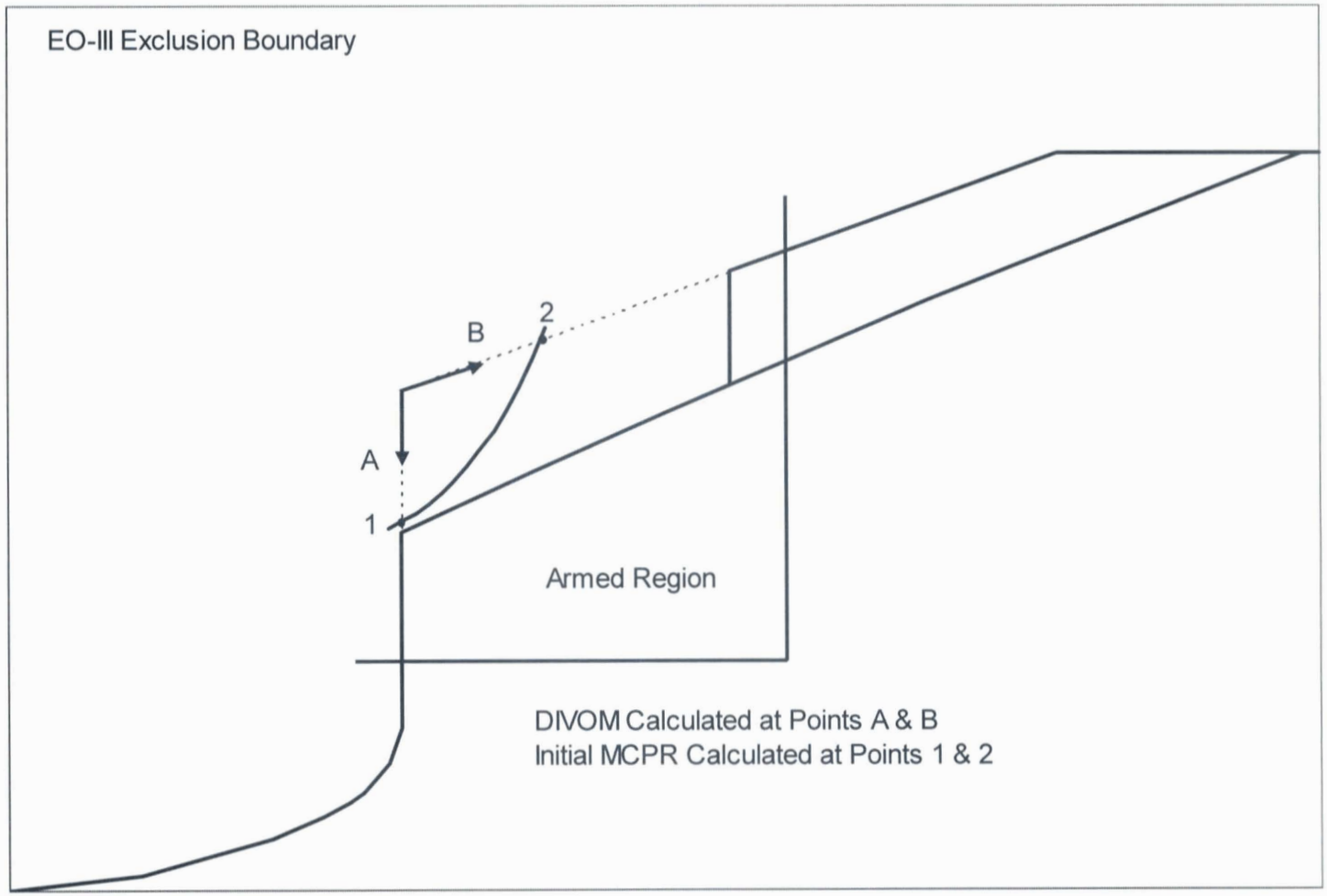
Enhanced Option III Solution Application Procedure

- Perform channel decay ratio calculations at several points on the power flow map to define channel decay ratio points
  - Determined by the applicable code channel decay ratio uncertainty criterion
  - For STAIF, a channel decay ratio of [ ] would be protected
  - Best estimate calculations performed at:
    - Constant xenon corresponding to rated conditions
    - Feedwater at equilibrium conditions at the specific power/flow point
    - Performed using the nominal target control rod step-through with allowances made to bound normal operational variations
    - If feedwater heater out-of-service is to be supported, then calculations need to be repeated
- Define the channel decay ratio exclusion boundary
  - STAIF calculation at several exposures
  - Bounds all STAIF calculated [ ] channel decay ratio points
  - Include allowances to bound normal operational variations
  - Verified on a cycle-specific basis

Enhanced Option III Solution Application Procedure

- Two limiting points inside exclusion region for DIVOM analysis
  - Point A: Natural circulation line
  - Point B: Highest rod line
  - Must be regionally unstable without single channel instability
- Initial MCPR at the two points defining exclusion region
  - Point 1: Intersection of exclusion boundary with Natural Circulation line
  - Point 2: Intersection of exclusion boundary with highest rod line
- Initial MCPR assuming steady state operation at 45% flow and highest rod line – Same as original Option III
- Amplitude Setpoint Analysis:
  - Apply 5% conservatism on the HCOM vs. Setpoint Relationship

Elements of the Enhanced Option III Solution



Conservatism in Enhanced Option III

- New exclusion region defined at STAIF DR_{CH} = [ ]
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- STAIF-based exclusion region is verified using RAMONA5-FA
  - DIVOM points (A and B) inside channel exclusion zone are free from channel instabilities
  - Provides independent validation of the exclusion zone boundary

STAIF Channel Decay Ratio

[ ]

RAMONA5-FA Channel Decay Ratio

[ ]

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Conservatism in Enhanced Option III

- 5% HCOM penalty applied to the originally conservative 95/95 analysis to account for anticipated increase in power oscillation growth ratios… although:
- Maximum core decay ratios are inherently limited by the existence of the channel exclusion region
  - Excessively high Global and/or Regional decay ratios are prevented by the immediate scram upon entering the channel exclusion region

Summary

> Summary of Enhanced Option III

- Channel exclusion
  - Defined by STAIF
  - Protected by immediate scram
- DIVOM calculation
  - Performed at 2 state points inside channel exclusion region
  - Ensures no single channel interference
- Setpoint Definition
  - Based on 3 state points instead of 2 points originally
  - Includes a conservative 5% HCOM penalty

Conclusions

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Conclusions
Advantages of Enhanced Option III

1. Maintains the basis of the original Option III solution with many years of operational experience
2. Clear physical basis for the proposed enhancements
3. Channel exclusion region based on approved frequency domain stability code (STAIF)
4. Small channel exclusion region should not interfere with normal operational flexibility
   - Much smaller than Backup Stability or E1A exclusion regions

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Conclusions
Advantages of Enhanced Option III

5. Amplitude trip setpoint will be not be restricted by single channel interference leading to elevated DIVOM slope
   - Reduces the probability of spurious scram due to the period-based algorithm response to LPRM noise
   - DIVOM curve will always be regular and bounded
6. The enhanced solution covers all operating domains including MELLLA+
7. Explicitly addresses single channel instabilities
8. Simple application procedure