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Licensing Topical Report

ODYSY Application for Stability Licensing Calculations Including Option I-D and II Long Term Solutions

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INFORMATION NOTICE

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DISCLAIMER

PREFACE

NEDE-33213P supercedes "ODYSY Application for Stability Licensing Calculations," NEDC-32992P-A, July 2001. Plants referencing NEDC-32992P-A may continue to do so as NEDE-33213P does not invalidate the previously approved report.

The sensitivity studies included herein support other Long Term Solutions that use the ODYSY methodology in the determination of various boundary regions. In the future, these other Long Term Solutions may reference this report as providing supporting studies.

In addition, this report documents an Exclusion Region boundary shape function called the Modified Shape Function, which is an alternative to the previously approved Generic Shape Function. The Modified Shape Function is a shared element that is also applied to the Option III solution.

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ABSTRACT

This report discusses the application of ODYSY (**O**ne-Dimensional **Dy**namic Code for **S**tabilit**y**), the General Electric (GE) proprietary best-estimate frequency domain stability code, to perform licensing basis stability calculations for Option I-D and II Stability Long Term Solutions (LTS). An appropriate procedure is defined for stability licensing calculation applications for boiling water reactors (BWRs).

ODYSY has been previously approved for Option I-D and Option II licensing stability calculations as well as new fuel licensing stability calculations [1]. ODYSY has also been approved for use in the Backup Stability Protection (BSP) evaluations in both the Option III and Detect and Suppress - Confirmation Density (DSS-CD) LTS solutions. The ODYSY procedure has been revised by removing the conservative 0.15 core decay ratio adder established in the earlier procedure [1] while maintaining a reasonably bounding stability solution that offers adequate thermal-hydraulic instability (THI) protection. This is supported by the conservatisms in the ODYSY application procedure observed in two recent THI events that utilized advanced fuel designs and current operating strategies. In addition, extensive validation demonstrations have been performed utilizing actual core tracking data from several operating cycles at four Option I-D plants. The demonstration results show that the Exclusion Region (ER) licensing methodology described in this report is reasonably bounding.

The ODYSY procedure also introduces an additional boundary shape function that may be used to establish the ER boundary line. This is referred to as the Modified Shape Function (MSF). The previously approved boundary shape function is the Generic Shape Function (GSF).

ACRONYMS AND ABBREVIATIONS

1-D	One-dimensional
1Φ	Single phase
2Φ/1Φ Δp	Two-phase/single-phase pressure drop ratio
ABWR	Advanced Boiling Water Reactor
APRM	Average Power Range Monitor
APS	Axial Power Shape
BOC	Beginning of Cycle
BR	Buffer Region
BSP	Backup Stability Protection
BWR	Boiling Water Reactor
BWROG	BWR Owners' Group
CCC	Control Cell Core
CSAU	Code Scaling, Applicability and Uncertainty
DR	Decay Ratio
DSS-CD	Detect and Suppress - Confirmation Density
E1A	Enhanced Option 1-A
ECP	Engineering Computer Program
ELLLA	Extended Load Line Limit Analysis
EOC	End of Cycle
EPU	Extended Power Uprate
ER	Exclusion Region
FCL	Flow Control Line
FCV	Flow Control Valve
FTTC	Fuel Thermal Time Constant
FW	Feedwater
FWT	Feedwater Temperature
FWTR	Feedwater Temperature Reduction
GDC	General Design Criteria
GE	General Electric
GESTAR	General Electric Standard Application for Reactor Fuel
GSF	Generic Shape Function
HFCL	High Flow Control Line
ICA	Interim Corrective Action
LOCA	Loss of Coolant Accident
LTS	Long Term Solution
MELLLA	Maximum Extended Load Line Limit Analysis
MOC	Middle of Cycle
MSF	Modified Shape Function
NCL	Natural Circulation Line
ODYSY	One-Dimensional Dynamic Code for Stability
OPRM	Oscillation Power Range Monitor
PIRT	Phenomena Identification and Ranking Table
RPF	Radial Peaking Factor
RPS	Radial Power Shape
SER	Safety Evaluation Report
S3	SIMULATE-3
S3K	SIMULATE-3K
SLMCPR	Safety Limit Minimum Critical Power Ratio
SOLOMON	Stability On-Line ODYSY Monitor
TER	Technical Evaluation Report
THI	Thermal-Hydraulic Instability

1.0 INTRODUCTION

1.1 Background

ODYSY (**O**ne-Dimensional **Dy**namic Code for **S**tabilit**y**) is a best-estimate General Electric (GE) proprietary Engineering Computer Program (ECP) that incorporates a linearized, small perturbation, frequency domain model of the reactor core and associated coolant circulation system. The program may be used to predict hydrodynamic stability for both a single channel and a full reactor core. It will predict both core-wide mode coupled thermal-hydraulic and reactor kinetic instabilities and single channel thermal-hydraulic instabilities.

ODYSY is based on the approved ODYN transient model, including an axial one-dimensional (1-D) kinetics model extended to multiple channels [2]. It has axially varying void and Doppler reactivity feedback with improved flexibility in the fuel rod modeling to accommodate axial variations in fuel bundle geometry. The axial variation capability makes it ideal for evaluating the stability performance of advanced fuel designs that have axially varying geometry.

ODYSY is approved for Exclusion Region (ER) calculations using the procedure defined in Reference 1. This has been applied for licensing calculations for Option I-D and Option II Stability Long Term Solutions (LTS). It has also been used for new fuel licensing compliance with Amendment 22 of GESTAR II [1]. ODYSY has also been approved for Enhanced Option 1-A (E1A) boundary generation and reload validation analyses [6] as well as for Backup Stability Protection (BSP) evaluations in the Option III and DSS-CD LTS solutions. BSP regions determined by ODYSY consist of a Scram Region and a Controlled Entry Region.

The ODYSY calculation procedure described in Reference 1 imposed a decay ratio adder of 0.15 to the Option I-D and II ER methodology. This adder was specific to Option I-D and II and resulted in an equivalent ER size as produced by FABLE. The methodology improvements inherent to ODYSY were not credited in the Option I-D and II solutions at that time. Reference 1 states:

> "It is generally appropriate to use improved methods to reduce the margins in safety-related analysis. However, this is not being proposed for this application. The methodology for this application of ODYSY to BWR stability licensing calculations retains the same general level of conservatism as approved for FABLE. Though ODYSY is an improved method relative to FABLE, the methodology improvement has not been used to reduce the stability margin for stability licensing calculations."

These improvements were recognized later in the Option III and DSS-CD solutions. The 0.15 decay ratio adder is not applied in the licensing calculations for these stability solutions.

ODYSY has been extensively qualified for single channel thermal-hydraulic instabilities and for core-wide coupled thermal-hydraulic and reactor kinetics instabilities from full-scale BWR plant data. Samples of the full-scale qualification studies are provided in References 6 and 7.

1.2 Summary

This document demonstrates the use of ODYSY to establish a stability Exclusion Region (ER) on a BWR power/flow operating map consistent with the long-term stability solution that has been applied to the BWR being analyzed. Stability calculations are also performed with ODYSY to determine the change in reactor stability performance (i.e., the delta decay ratio, ΔDR) from a previously approved fuel design or plant configuration. This application report demonstrates that ODYSY analyses can be used in the core and hot channel decay ratio analysis process for licensing calculations.

GE has considered the requirements of Regulatory Guide 1.203, Transient and Accident Analysis Methods [8], when compiling this LTR. The Phenomena Identification and Ranking Table (PIRT) is generated and evaluated. In addition, the Code Scaling, Applicability and Uncertainty (CSAU) analysis is performed. The ODYSY code qualification bases, model accuracy and uncertainty have previously been documented to the NRC in Reference 6. Code scaling is not an issue since the benchmarks have been to full-scale reactor tests and events. An additional qualification study of an actual plant instability event in addition to those reported in Reference 6 is included in this report. The code uncertainty has been factored into the accepted ODYSY stability criterion map, which is the figure of merit for stability ER generation based on core and hot channel decay ratios. This LTR documents that the intended application of ODYSY for stability licensing calculations is within the approved applicability and range, and an uncertainty of greater than two standard deviations is incorporated into the stability criterion map.

1.3 Scope of Review

1.3.1 Exclusion Region (ER)

GE requests that the NRC approve the revised ER application procedure that removes the 0.15 decay ratio adder applied to the LTS Option I-D and II in Reference 1. Justifications for the removal of this adder include:

- The significant methodology improvements of the ODYSY code over the previously approved FABLE code, for example modeling of axial varying geometry of advanced fuel designs, 1-D kinetics, capability of exposure dependent calculations and consistency with the latest core simulator model.
- The methodology improvements were not credited in the Option I-D and II solutions when Reference 1 was submitted for NRC approval.
- The defense-in-depth nature of the Exclusion Region with primary SLMCPR protection being provided by the flow biased APRM flux scram.
- The conservative methodology of the application procedure itself, for example, Haling depletion to an extended exposure, 20% [[ ]] ODYSY uncertainty applied, conservative boundary shape function and feedwater temperature dependent regions.

1.3.2 Modified Shape Function

GE requests that the NRC approve the application of an ER boundary shape function called the Modified Shape Function (MSF), which is an alternative to the previously approved Generic Shape Function (GSF) defined in Section 2.9. The MSF is a shared element that is also applied to the Option III LTS as shown in Table 1-1.

1.3.3 Feedwater Temperature Dependent ER

GE requests that the NRC approve the application of multiple ERs that are implemented during operation at reduced feedwater temperature (FWT). For plants that are licensed for this mode of operation, a FWT dependent ER must be applied. An ER established for reduced FTW operation is more bounding than the ER established for nominal operating conditions and is therefore conservative. As shown in Table 1-1, FWT dependent ERs have already been applied for other stability solutions.

1.3.4 Haling Methodology

A key element of the ODYSY application procedure is the Haling methodology. The effectiveness of the Haling methodology relative to actual plant operating conditions is presented in Appendix A. Analyses were performed using eight cycles of operating data for four demonstration plants (i.e., two cycles per plant). The selected cycles of these four BWRs represent current operating practices (i.e., high energy cycles, advanced 10x10 fuel designs, power uprates and expanded operating domains). The evaluation demonstrated that the application procedure utilizing the Haling methodology results in a reasonably bounding ER when compared to the decay ratio predictions based on actual plant operating conditions, including operation with unexpected control rod patterns. The results presented in Appendix A for Option I-D plants supports the application of the Haling methodology for all LTS stability options. No additional NRC approval is required for the application of the Haling methodology to the LTS stability options shown in Table 1-1.

1.3.5 ODYSY Application in Other Long Term Solutions

As previously mentioned, ODYSY is used to establish stability regions on the power/flow map for all of the LTS options shown in Table 1-1. All of these solutions apply the same Haling methodology to determine the limiting cycle exposure condition and all solutions use a boundary shape function to define the stability region size. The demonstration in Appendix A supports the Haling methodology application to all LTSs.

Table 1-1. OSYSY Application Procedure for Long Term Solutions

LTS Option	DR Adder Previously Required	Haling Methodology Applied	Shape Function (GSF, MSF)	FWT Dependent ER Previously Required	Solution Specific LTR or Guideline
Option I-D	Yes	Yes	MSF, GSF	No	Reference 1
Option II	Yes	Yes	MSF, GSF	No	Reference 1
Option E1A	No	Yes	GSF	Yes	Reference 6
Option III	No	Yes	MSF, GSF	Yes	Reference 17
DSS-CD	No*	Yes	GSF	Yes	Reference 18 and 19

* Other restrictions may apply at the High Flow Control Boundary in the MELLLA+ domain as described in Reference 18.

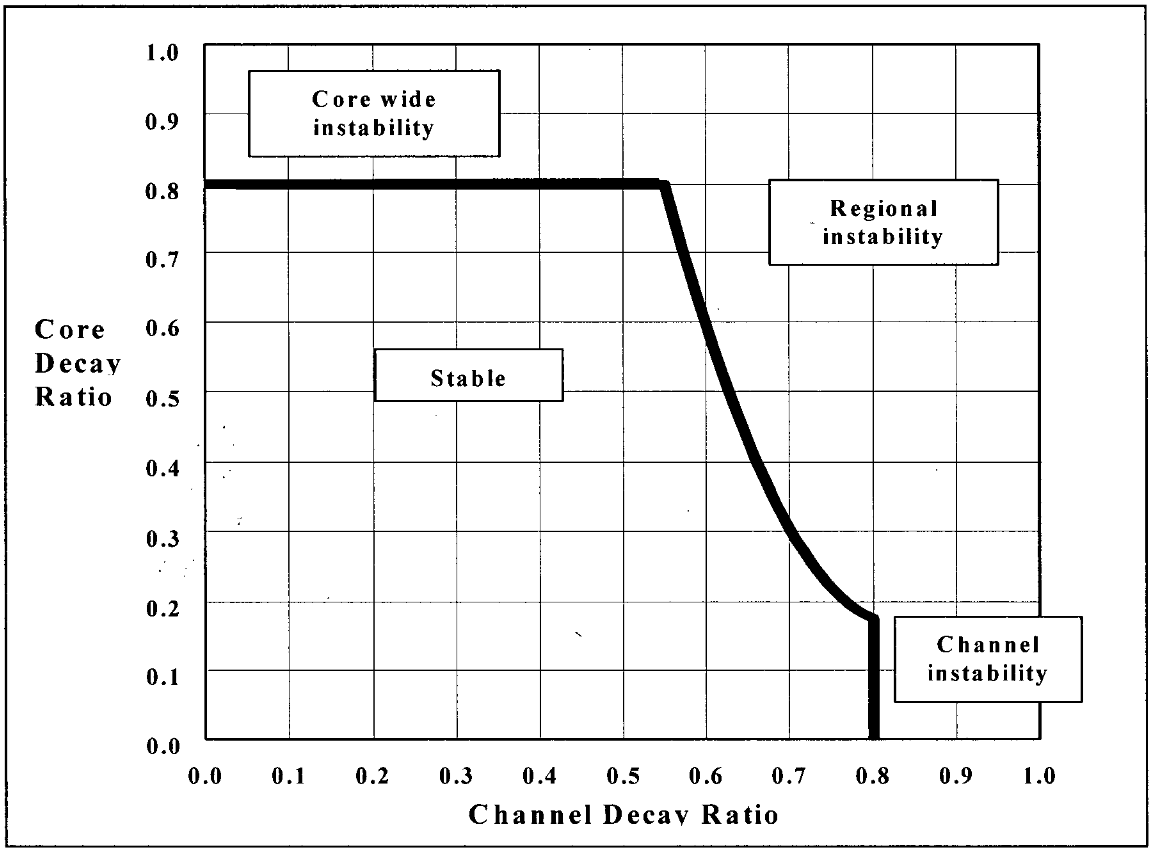

Figure 1-1. Stability Criteria Map

2.0 LICENSING REQUIREMENTS AND SCOPE OF APPLICATION

2.1 10CFR50 Appendix A

The *General Design Criteria (GDC) for Nuclear Power Plants* are stipulated in Appendix A to Part 50 of 10CFR. The stability licensing basis is set forth in GDC-12. This GDC requires assurance that power oscillations that can result in conditions exceeding specified acceptable fuel design limits are either not possible or can be reliably and readily detected and suppressed. Following the March 9, 1988, LaSalle-2 reactor instability event, GE and the BWR Owners' Group (BWROG) developed stability interim corrective actions (ICAs) [9] and stability long-term solutions [3]. Subsequently, GE developed the BSP methodology [17] that offered improved protection against THI events for Option III plants. The stability solutions are in the general category of prevention solutions ("power oscillations....are not possible") and detect-and-suppress solutions ("power oscillations....can be reliably and readily detected and suppressed.") Some solutions are considered to be combination solutions with both prevention and detect-and-suppress features.

Core and hot channel decay ratio calculations are only required for solutions that include a prevention element. The implemented stability long-term solutions that have prevention features and require decay ratio calculations are E1A, Option I-D, and Option II [1, 3, and 4]. NRC approval of licensing methods used for ER analyses implies that the methods are capable of assessing the capacity to prevent a reactor instability consistent with the solution licensing bases "as it relates" to the GDC.

2.2 Instability Prevention Solutions

NRC Bulletin 88-07 Supplement 1, "Power Oscillations in Boiling Water Reactors," [10] endorsed the ICAs and the BWROG program to develop generic long-term solutions. The long-term solutions developed by GE and the BWROG are described in NEDO-31960-A [3]. Long-term solutions I-A and I-D each have an ER as an instability prevention feature as described in NEDO-31960-A. The TER on these solutions identified concerns with the I-A solution, which led to the development of the E1A solution as documented in NEDO-32339-A, Revision 1 [4]. Currently, two plants have implemented Option II that includes the ER as an element of the solution. Therefore, decay ratio calculations to determine an ER are required for stability licensing calculations for solutions E1A, I-D and II.

2.3 New Fuel Licensing

New GE fuel designs are licensed under the GE Standard Application for Reactor Fuel, NEDE-24011-P-A, GESTAR II [5]. The stability compliance of GE BWR fuel designs is demonstrated on a generic basis. Section 1.1 of GESTAR II states: "Fuel design compliance with the fuel licensing acceptance criteria constitutes USNRC acceptance and approval of the fuel design without specific USNRC review," the stability licensing acceptance criteria are given in Section 1.1.8 of GESTAR II:

a. The stability behavior, as indicated by core and limiting channel decay ratios, must be equal to or better than a previously approved GE fuel design, or

b. If the core and limiting channel decay ratios are not equal to or better than a previously approved GE fuel design, it must be demonstrated that there is no change to the exclusion zone (the exclusion zone corresponds to a boundary on a power/flow operating map of constant decay ratio equal to the stability acceptance criteria).

Therefore, decay ratio calculations to determine the relative stability performance of a new fuel design or to determine the impact on an ER are required for new fuel licensing.

2.4 Application Procedure

The application procedure will use the ODYSY code to perform decay ratio calculations and determine conservative ER boundaries. ODYSY includes a kinetics model, a fuel heat transfer model, a channel thermal-hydraulic model and a recirculation system model. The model description is provided in Reference 7. As noted in Reference 1, "the ODYSY model represents a significant improvement in the phenomenological modeling of the design parameters and evaluation conditions over previously approved models such as FABLE."

A procedure is specified for decay ratio calculations with ODYSY that produces an appropriate and conservative stability ER boundary. The procedure incorporates the following features:

- 1-D kinetics are modeled.
- Doppler reactivity feedback is included.
- Conservative hot channel axial power shapes are used.
- Spacer friction loss coefficients are based on clean spacers, consistent with the qualification bases used on ODYN [2].
- Up to 19 channel groups are used to model the radial power distribution.
- Capability to model the axial geometry variation of advanced fuel designs.
- Exposure dependent calculations provide an accurate representation of the core and hot channel decay ratio behavior throughout the cycle.

Standard design values are used in the analysis for the thermal-hydraulic data. These values are consistent with GE methods for other transient and accident analyses and are necessary to ensure consistency between the various analytical calculations performed for a stability analysis.

The procedure is used to define the ER endpoints on the High Flow Control Line (HFCL) and the Natural Circulation Line (NCL). A region boundary shape function is used to define the region boundary between the HFCL and NCL endpoints (Section 2.9). The combination of the model, inputs, application procedure and a shape function produces an appropriate and conservative stability ER boundary.

The step-by-step procedure is provided in Section 5.

2.5 Conformance with CSAU Methodology

The NRC has issued a regulatory guide and standard review plan on analytical computer codes [8]. The guideline defines the procedures, methods and concepts that are acceptable to the NRC staff for the development and assessment of evaluation models used to analyze transient and accident behavior. The guide specifically endorses the use of Code Scaling, Applicability, and Uncertainty (CSAU) methodology to document the acceptability of transient and accident analysis methodologies.

The proposed application of ODYSY for BWR stability ER licensing calculations addresses all the elements of the NRC-developed CSAU evaluation methodology [13]. The CSAU report describes a rigorous process for evaluating the total model and plant parameter uncertainty for a nuclear power plant calculation. The rigorous process for applying realistic codes and quantifying the overall model and plant parameter uncertainties represents the best available practice. While the CSAU methodology was developed for application to loss-of-coolant accidents (LOCAs), there are no technical reasons that prevent CSAU methodology from being applied to other analyses such as stability calculations. A statistical process very similar to the CSAU methodology was applied by the NRC in the safety evaluation of the current ODYN based licensing methodology for transient calculations [14]. ODYN is the time domain model that was used to create the frequency domain code ODYSY. The CSAU methodology consists of 14 steps as documented in Reference 13. These steps are addressed for the current ODYSY application as outlined in Table 2-1.

Table 2-1. Code Scaling, Applicability and Uncertainty Evaluation

CSAU Step	Description	Addressed In
1	Scenario Specification	Sections 2.8 &4.3
2	Nuclear Power Plant Selection	Section 2.10
3	Phenomena Identification and Ranking	Section 3.0
4	Frozen Code Version Selection	Sections 2.7 & 4.4
5	Code Documentation	References 6 & 7
6	Determination of Code Applicability	Section 4.1
7	Establishment of Assessment Matrix	Section 4.2
8	Nuclear Power Plant Nodalization Definition	Section 4.7
9	Definition of Code and Experimental Accuracy	References 6 & 7
10	Determination of Effect of Scale	Section 4.8
11	Determination of the Effect of Reactor Input Parameters and State	Sections 4.4 & 4.5
12	Performance of Nuclear Power Plant Sensitivity Calculations	Section 4.9, Reference 4
13	Determination of Combined Bias and Uncertainty	References 6 & 7
14	Determination of Total Uncertainty	Section 2.7.2, References 6 & 7

2.6 Implementation Requirements

The implementation of ODYSY into actual stability licensing analysis is contingent on the review and approval of the application procedure described in Section 5 by the NRC.

2.7 Review Requirements For Updates

ODYSY is a controlled computer code under the ECP quality assurance requirements. The code version that has been used for this analysis is ODYSY05. This version of the code is "frozen" under GE ECP requirements in accordance with the CSAU methodology for a "frozen" code.

All code changes will be reported to the Licensee(s) for their use in preparing 10CFR50.59 evaluations. However, to effectively manage the future viability of ODYSY for stability licensing calculations, GE proposes the following requirements for modifications to the approved ODYSY code. All changes to a particular version, including those considering the deviation criteria in Section 2.7.1, will be documented within the ECP change and qualification documentation.

2.7.1 Updates to ODYSY Code

A code version that involves modifications to the basic models described in References 6 and 7 may <u>not</u> be used for stability licensing calculations without NRC review and approval.

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]] Similarly, the numerical methods may be modified to improve code performance or convergence provided that the changes meet the above deviation criteria.

2.7.2 Updates to ODYSY Model Uncertainties

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Since the NRC has explicitly approved the ODYSY stability criteria map [4], the criteria map will not be modified for licensing calculations without NRC review and approval. If new data becomes available that allows specific model uncertainties to be reassessed, the model uncertainty will not be revised for stability licensing calculations without NRC review and approval.

2.8 Evaluation Scenario

The ODYSY calculation is a frequency domain code, hence an "evaluation scenario" is not meaningful since a time domain transient response cannot be calculated in the frequency domain. Rather, evaluation conditions are specified. The ODYSY calculation is performed at specified points on the power/flow map with appropriate core and reactor conditions such as power shapes, core inlet temperature, etc. The conditions are defined in accordance with the proposed application procedure defined in Section 5.

2.9 Region Boundary Shape Functions

The ODYSY application procedure defines state points on the HFCL and the NCL that meet the region boundary generation stability criteria. The region boundary is then defined with a shape function. The shape function is a fit to the power/flow state points with all points along the boundary line representing a constant decay ratio. Two boundary shape functions are defined: (1) the Generic Shape Function (GSF), and (2) the Modified Shape Function (MSF).

2.9.1 Generic Shape Function

The GSF has been approved by the NRC and is documented in Reference 3:

$$P = P_B \left(\frac{P_A}{P_B} \right)^{\frac{1}{2}\left[\frac{W-W_B}{W_A-W_B} + \left(\frac{W-W_B}{W_A-W_B} \right)^2 \right]} \tag{2-1}$$

where:

P = a core thermal power value on the region boundary (% of rated),
W = the core flow rate corresponding to power, P, on the region boundary (% of rated),
P_A = core thermal power at point A (% of rated on the HFCL),
P_B = core thermal power at point B (% of rated on the NCL),
W_A = core flow rate at point A (% of rated on the HFCL), and
W_B = core flow rate at point B (% of rated on the NCL).

2.9.2 Modified Shape Function

The MSF is defined by the following equation:

$$P = P_B \left(\frac{P_A}{P_B} \right)^{\left[\frac{W-W_B}{W_A-W_B} \right]} \tag{2-2}$$

The Equation 2-2 terms are defined to be the same as the Equation 2-1 terms. Since the MSF produces a flatter region boundary, a validation analysis is performed every cycle for reload licensing applications to confirm that the stability criteria are satisfied. Validation calculations are performed to demonstrate that all power/flow points along the boundary will produce a decay ratio that is the same or lower than the decay ratios of the power/flow state points on the HFCL and the NCL. This validates that the application of the MSF produces a conservative region boundary.

2.9.3 Comparison of Shape Functions to Actual DR Calculation

The application of either region boundary shape function will provide a conservative ER for the Option I-D and II stability solutions. A comparison of the ER established by the MSF and GSF to a line of constant decay ratios determined by ODYSY is shown in Figure 2-1. As demonstrated in this figure, both shape functions result in conservative ERs.

2.10 Nuclear Power Plant Selection

The included plant types are BWR/2s, BWR/3s, BWR/4s, BWR/5s, BWR/6s, the Advanced BWR (ABWR) and other similar non-GE BWR types. Jet pump, natural circulation and internal recirculation pump plant designs are included. For the jet pump designs, the recirculation flow control systems include motor-generator designs, flow control valve designs and variable speed pump designs. Application of the ODYSY kinetics, fuel heat transfer and channel thermal-hydraulic models are identical for the listed power plant designs. The only major difference is in modeling of the steam separators and circulation system. Since ODYN has been qualified for each of these configurations, and ODYSY is simply the frequency domain transformation of the ODYN model, ODYSY is also applicable to each of these recirculation systems.

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Figure 2-1. MSF/GSF Versus ODYSY Constant Decay Ratio

3.0 PHENOMENA IDENTIFICATION AND RANKING

The critical parameters for stability ER calculations are core and channel decay ratios. The values of the critical parameters are determined by the governing physical phenomena. To delineate the important physical phenomena, it has become customary to develop phenomena identification and ranking tables (PIRTs), in which phenomena are ranked with respect to their impact on the critical parameters. The most cost efficient, yet sufficient, analysis reduces all candidate phenomena to a manageable set by identifying and ranking the phenomena with respect to their influence on the critical parameters.

Phenomena identification and ranking is somewhat different for ODYSY, since it is not a time domain code. Normally, a PIRT is developed with regard to the timing of an event. For ODYSY, the frequency domain response is based on design parameters and evaluated conditions. Hence, the PIRT is developed from this perspective. The design parameters and the important conditions are investigated for their impact on the critical safety parameter, in this case the decay ratio. The processes and phenomena associated with each component are examined. Cause and effect are differentiated. After the processes and phenomena have been identified, they are ranked with respect to their effect on the critical safety parameters for the evaluation.

The PIRTs represent a consensus of GE expert opinions. PIRTs are developed with only the importance of the phenomena in mind and are independent of whether or not the model is capable of handling the phenomena.

Table 3-1 was developed to identify the phenomena that influence stability calculations. The impact on the core and hot channel decay ratio is indicated for the design parameters and evaluation conditions. The ranking of the phenomena is done on a scale of high importance to low importance or not applicable, as defined by the following categories:

- *High importance (H):* These phenomena have a significant impact on the critical or primary safety parameters.
- *Medium importance (M):* These phenomena have a moderate impact on the critical or primary safety parameters.
- *Low importance (L):* These phenomena have an insignificant impact on the critical or primary safety parameters.
- *Not applicable (N/A):* These phenomena have no impact on the critical or primary safety parameters.

For application of ODYSY to stability licensing calculations, the ODYSY uncertainty has already been determined from full scale test data and is documented in References 6 and 7. Therefore, the PIRT is not used to define qualification studies or associated uncertainties. However, the PIRT is used to (1) identify the important phenomena which are then compared to the modeling capability of the code to assess whether the code has the necessary models to simulate the phenomena, (2) cross-reference the key phenomena qualification basis to ensure that the qualification data are adequate to assess and qualify the code models, and (3) examine the range of the key phenomena as compared with the corresponding range for the intended application to ensure that the code has been qualified for the highly ranked phenomena over the appropriate range.

Table 3-1. Phenomena Identification & Ranking Table - Stability Calculations

ID	Design Parameter or Evaluated Condition The design parameters and evaluation conditions are examined for their impact on each critical stability parameter H = High M = Medium L = Low N/A = Not Applicable	Critical Stability Parameters Core Decay Ratio	 Hot Channel Decay Ratio	Comments
Core and Fuel Design Parameters				
A1	[[			
A2				
A3.1				
A3.2				
A3.3				
A4.1				
A4.2				
A4.3				
A4.4				
A4.5				
A4.6				
A4.7				
A5.1				
A5.2				
A6				
A7				
A8				]]
Evaluation Conditions				
B1.1	[[			
B1.2				
B1.3				
B1.4				
B2.1				
B2.2				
B2.3				
B3.1				
B3.2				
B3.3				
B4.1				
B4.2				
B4.3				
B4.4				
B4.5				
B4.6				
B4.7				]]

4.0 APPLICATION OF ODYSY TO STABILITY LICENSING CALCULATIONS

The objective of this section is to demonstrate the applicability of ODYSY for the analysis of stability licensing calculations in BWRs. To accomplish this objective, the capability of the ODYSY models to treat the highly ranked phenomena and the qualification assessment of the ODYSY code for core and hot channel decay ratios are examined in the next two subsections.

4.1 Model Capability

The ODYSY code consists of four main models:

- Reactor kinetics model – neutronic parameters are collapsed from a 3-D PANACEA wrap-up and evaluated in a 1-D kinetics model that includes void and Doppler reactivity feedback.

- Fuel heat transfer model – consists of a 1-D radial conduction model for the fuel rod cladding, gap and fuel pellet.

- Channel thermal-hydraulics model – consistent with other GE design methods, it has a drift flux correlation including subcooled void modeling.

- Recirculation system model – the upper plenum, steam separators, downcomer and recirculation system are modeled as hydraulic regions.

These four models are considered when evaluating the applicability of the code to model the key phenomena for stability calculations identified in generating the PIRTs, as described in Section 3.0. The capability of the code to simulate these key phenomena is indicated in Table 4-1; a "X" in the table indicates that the model is capable of simulating the specific phenomena. Review of the ODYSY model capability concludes that all of the important phenomena identified in the PIRT (Table 3-1) are addressed in ODYSY.

Table 4-1. Phenomena & ODYSY Capability Matrix - Stability Calculations

ID	Model Element Description ⇒ Important Phenomena ⇓	Reactor Kinetics Model	Fuel Heat Transfer Model	Channel Thermal-Hydraulics Model	Recirculation System Model
Core and Fuel Design Parameters					
A1	[[				
A2					
A3.1					
A3.2					
A3.3					
A4.1					
A4.2					
A4.3					
A4.4					
A4.5					
A4.6					
A4.7					
A5.1					
A5.2					
A6					
A7					
A8					]]
Evaluation Conditions					
B1.1	[[				
B1.2					
B1.3					
B1.4					
B2.1					
B2.2					
B2.3					
B3.1					
B3.2					
B3.3					
B4.1					
B4.2					
B4.3					
B4.4					
B4.5					
B4.6					
B4.7					]]

4.2 Qualification Assessment

Typical qualification assessments address individual models and/or application events. This is not necessary for ODYSY, since all of the qualification assessments have been for full-scale tests and events in actual BWR's. The range of parameters addressed in full-scale tests and events is consistent with the intended application range of the key design parameters and evaluated conditions identified in the PIRT (Table 3-1). Therefore, it is concluded that the code has been qualified for the highly ranked phenomena over the appropriate range.

The qualification studies are documented in References 6 and 7, and a supplemental qualification study is documented in Section 6 of this report. Based on the key phenomena identified in the PIRT, these qualification studies cover a range of design parameters and conditions sufficient to qualify the code models. Qualification studies for full-scale events and tests produce an integrated total model uncertainty. References 6 and 7 state that the ODYSY calculated core decay ratios are accurate to within a standard deviation of [[ ]], and channel decay ratios are accurate to within a standard deviation of [[ ]]. Therefore, applying a model uncertainty of [[ ]] to both the core and channel decay ratios (as shown on the ODYSY stability criteria map, Figure 1-1) provides an uncertainty margin of [[ ]].

4.3 Instability Events

There are basically two types of events evaluated for reactor stability:

- Pseudo steady-state (e.g., during a reactor startup) – core flow and reactor power are both being increased. Increasing reactor power at a greater rate than core flow is increased can be destabilizing.
- Transient flow event (e.g., a recirculation pump runback or trip event) – core flow is decreased and power generally follows the flow control line corresponding to the initial condition when the flow transient event occurred. A runback reduces core flow more dramatically than power is reduced and can be destabilizing.

Since ODYSY is a frequency domain code, these events are evaluated by specifying appropriate and conservative analysis inputs and initial conditions.

4.4 Analysis Inputs

The specific code input will be developed consistent with the application LTR. Code inputs can be divided into four broad categories: (1) geometry inputs; (2) model selection inputs; (3) initial condition inputs; and (4) plant parameters. The geometry inputs are used to specify diameter, thickness, length, area, volume, etc. [[

]] Model selection inputs are used to select the features of the model that apply for the intended application. The initial conditions are addressed in Section 4.5 and the plant parameters are addressed in Section 4.6.

4.5 Initial Conditions

Initial conditions are those conditions that define the reactor state at which the calculation is to be performed. Initial conditions include the Evaluation Condition parameters listed in Table 4-1, except for the recirculation system definition, which is a plant parameter. Two conditions are defined for calculating core and hot channel decay ratios to determine a stability licensing basis ER. The two conditions are:

- Steady-state operation on the NCL. The associated core average axial power shape is based on a rated power/rated flow Haling depletion at the actual power and NCL flow rate being analyzed. Since the Haling depletion is exposure dependent, this produces an exposure dependent result for the core decay ratio on the NCL. The initial condition on the NCL is assumed to be Xenon free.

- A flow runback along the HFCL from the full power/minimum flow state point on the power/flow operating map. The associated core average axial power shape is based on a rated power/minimum flow Haling depletion at the actual power and HFCL flow rate being analyzed. Since the Haling depletion is exposure dependent, this produces an exposure dependent result for the core decay ratio on the HFCL. The initial condition on the HFCL is assumed to be constant at the initial operating condition.

The associated void coefficient is also dependent on the power/flow state point and exposure being analyzed. This produces an exposure dependent result for the core and hot channel decay ratio at each condition being analyzed.

The initial conditions specified for the condition being analyzed are obtained from core simulator (PANACEA) wrap-ups and the ISCOR thermal-hydraulic base deck.

4.6 Plant Parameters

Plant parameters are those plant and cycle specific values that are required to describe the plant being evaluated. Plant parameters include design information such as the Core and Fuel Design parameters listed in Table 4-1, as well as Evaluation Condition parameters such as the recirculation system definition. The plant parameters can have a significant impact on the core and hot channel decay ratio calculations. For example, the core inlet orifice size impacts the single-phase (1Φ) pressure drop and the two-phase/single-phase pressure drop ratio ($2\Phi/1\Phi$ Δp). A plant with a tight core inlet orifice design will have a high 1Φ pressure drop and a low $2\Phi/1\Phi$ Δp ratio. This type of design has been shown to have relatively low core and channel decay ratios. An identical plant with a loose core inlet orifice would have a reduced 1Φ pressure drop and a higher $2\Phi/1\Phi$ Δp ratio. The loose orifice design has been shown to have relatively larger core and channel decay ratios.

The plant design inputs are obtained from the ODYN base deck for the plant being analyzed and core simulator (PANACEA) wrap-ups used in the reload licensing analysis.

4.7 Effects of Nodalization

The comparable nodalization strategy for ODYSY is reflected in the axial power shape, the number of channels used to model the core, and the number of regions used to model the ex-core thermal-hydraulics.

- A 25-node axial power shape and core thermal-hydraulics model are used, consistent with the associated nuclear methods. This gives a very accurate representation of the axial variation in the core as it affects core and hot channel decay ratios, which is consistent with the approved transient evaluation model (ODYN).
- Up to nineteen channel groups are used to model the core based on channel geometry and power distribution. This gives a very accurate representation of the radial power distribution for calculating the core decay ratio.
- The ex-core regions (upper plenum, steam separator, downcomer, recirculation system, lower plenum) are modeled separately according to the region modeling in ODYN. The recirculation system model includes options for external recirculation pumps with jet pumps, external recirculation pumps without jet pumps and internal recirculation pumps.

This nodalization strategy has been used in previous qualification studies [6, 7], as well as the supplemental qualification studies in Section 6. This nodalization strategy provides the code accuracy documented in References 6 and 7.

4.8 Effects of Scale

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4.9 Sensitivity Analysis

Sensitivity studies have been performed for ODYSY as documented in Appendix E of Reference 4. Additional sensitivity studies are reported in Reference 15. Sensitivity studies include evaluations of xenon concentration, boiling boundary height, axial flux shape, radial peaking factor, feedwater temperature and cycle exposure. These sensitivities were used when the best-estimate ODYSY application procedure was established for E1A validation studies. The E1A ODYSY stability application procedure is compared to the proposed ER procedure in Table 5-2.

Two key studies have been performed with regard to the Haling methodology. The first is a sensitivity study that compares the Haling axial power shape (APS) to the rodded depletion APS from a reload licensing analysis. The second study examines the adequacy of the Haling methodology relative to actual plant operating data.

4.9.1 APS Sensitivity Study

A sensitivity study has also been performed on the impact of using a Haling depletion or a rodded depletion as it impacts the core average axial power shape (APS). A sample plant with an equilibrium cycle of GE14 fuel (10x10 fuel rod array) was used for the sensitivity study. Cycle characteristics include a high energy core design, an approximately 5% power uprate and a MELLLA operating domain. The stability calculations are based on actual rodded burn core simulator predictions developed for reload licensing applications. The predicted end-of-cycle (EOC) exposure based on this rodded depletion was 14600 MWd/ST. The Haling exposure cases are first burned to a bounding EOC exposure of 15650 MWd/ST, then back-burned to the beginning of cycle (BOC), then burned to the desired exposure using the Haling power shape. A state point near minimum pump speed along the HFCL is used, corresponding to 63.3% power and 38.0% core flow for the sample plant used in this sensitivity study. The Haling case hot channel decay ratio calculation use the hot channel APS overlay specified for the licensing calculation procedure. The rodded depletion cases use no hot channel APS overlay.

4.9.2 Adequacy of Haling Methodology Study

The Haling APS's, as a function of exposure, are shown in Figure 4-1. The rodded APS's at similar exposures are shown in Figure 4-2. The corresponding core and channel decay ratios using the ODYSY procedure described in Section 5 are compared in Figures 4-3 and 4-4, respectively. [[

]] In summary, it is appropriate to use the Haling burn in the ODYSY procedure.

An additional validation study has been performed utilizing actual plant operating data through the cycle. [[

]] The results of this validation study are presented in Appendix A. From these results it can be concluded that the proposed ODYSY application procedure is both adequate and reasonably bounding

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Figure 4-1. Haling Core Average Axial Power Shape vs. Exposure

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Figure 4-2. Rodded Core Average Axial Power Shape vs. Exposure

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Figure 4-3. Core Decay Ratio Comparison: Haling vs. Rodded Burn

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Figure 4-4. Channel Decay Ratio Comparison: Haling vs. Rodded Burn

5.0 ODYSY STABILITY LICENSING APPLICATION PROCEDURE

This section of the report defines the proposed ODYSY procedure for stability ER licensing calculations.

5.1 Model Features

The key features of the ODYSY model are described in Table 5-1. The channel thermal hydraulics in ODYSY uses the more accurate drift flux formulation and models axial varying geometry such as part length fuel and water rods. The ODYSY ex-core hydraulics model considers the specific regions, including upper plenum, steam separator, downcomer, recirculation system and lower plenum as separate hydraulic regions. This is more accurate than the numerical transfer function used to represent the entire ex-core flow path in earlier models. ODYSY has a 1-D radial conduction model for the fuel rod. ODYSY also produces an exposure dependent calculation, since it includes exposure dependent inputs such as void coefficient, Doppler coefficient and core average axial power shape.

5.2 Application Procedure

This application procedure is designed to produce a conservative estimate of the region on the power/flow map that has the potential for reactor instability. The application procedure for licensing basis decay ratio calculations is summarized as follows:

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5.3 Description of Key Input Parameters

Table 5-2 provides a list of the key input parameters used in the ODYSY procedure.

5.3.1 Void Coefficient

The actual exposure dependent void coefficient (in terms of nuclear void coefficient/delayed neutron fraction) is used in the calculation. The void coefficient is based on the actual core and cycle configuration being analyzed. This produces an exposure dependent decay ratio calculation.

5.3.2 Thermal-Hydraulics Data

Standard design values for thermal-hydraulics data are used in the analysis. These values are consistent with updated GE methodology (i.e., Method B) used in current design procedures for transient and accident analysis and are necessary to ensure consistency between the various calculation methodologies.

5.3.3 Axial Power Shape

The core average axial power shapes (APS) are based on a Haling depletion and are specific to the exposure point being calculated. For calculations on the NCL, the actual off-rated power/flow conditions are used to define the APS, with the initial condition based on a rated power/rated flow Haling depletion. For calculations on the HFCL, the actual off-rated power/flow conditions are used to define the APS, with the initial condition based on a rated power/minimum flow Haling depletion. The minimum flow, defined as the lowest flow at which rated power can be achieved (often called the ELLLA or MELLLA point), is used since this is in fact the highest core flow boundary on which the plant is licensed to operate.

The hot channel APS is overlaid to produce a conservative hot channel result.

5.3.4 Radial Power Distribution

Up to nineteen (19) channel groups are used to model the radial power distribution. The hot channel option is used for each fuel type present in the core based on the maximum radial power. Channel grouping is adequate to model each of the fuel support casting orifice types (central, intermediate and peripheral) that are present in the core.

5.3.5 Pellet-Clad Gap Conductance

Core average pellet-clad gap conductance is determined for each fuel type at the appropriate core thermal power condition using currently approved licensing models. The ODYSY procedure performs a best-estimate calculation using the nominal gap conductance in the analysis. This is consistent with the model qualification assumptions.

5.3.6 Feedwater Temperature

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5.3.7 Other Inputs

Additional inputs such as plant heat balance data, recirculation loop resistance, separator loss coefficients, reactor component dimensions, fuel physical parameters and material properties are based on standard design values.

5.4 Procedure Application to Stability Solutions

The procedure described will be applied to Option I-D ER boundary generation for each reload. The Option II ER calculation procedure is identical to the Option I-D procedure.

5.5 Procedure Demonstration for Recent Instability Events

The procedure described in this section was used to calculate ERs for two plants that recently experienced thermal-hydraulic instability (THI). The purpose of this exercise was to demonstrate the conservatism of the calculated ER boundary relative to the actual power/flow conditions where the THI events occurred.

A reactor instability event occurred at a U.S. BWR/5 on July 24, 2003. The BWR/5 is designed with a flow control valve (FCV) recirculation system. The instability occurred near peak hot excess reactivity after an unexpected plant transient that included a downshift of both recirculation pumps and a runback of the FCVs. Core flow was reduced from 94% to 28% of rated and power was reduced from 100% to 35% of rated. After several minutes, decreasing feedwater temperature raised the power to approximately 45% of rated, at which time the reactor was scrammed. This transient evolution is illustrated in Figure 5-1. As can be seen in the figure, the calculated ER provides significant margin to the power/flow condition where the instability event occurred. It is also important to note that the instability at this power/flow condition produced slowly growing power oscillations that were readily detected and suppressed by the Oscillation Power Range Monitor (OPRM) system prior to any significant oscillation amplitude. The SLMCPR was protected throughout the THI event.

A reactor instability event occurred at a U.S. BWR/6 on December 23, 2004. The instability occurred after an unexpected plant transient that included a downshift of both recirculation pumps. Core flow was reduced from 99% to 33% of rated and power was reduced from 100% to 44% of rated. After several minutes, decreasing feedwater temperature raised the power to approximately 55% of rated, at which time the reactor was scrammed. This transient evolution is illustrated in Figure 5-2. As can be seen in the figure, the calculated ER provides significant margin to the power/flow condition where the instability event occurred. It is also important to note that the instability at this power/flow condition produced slowly growing power oscillations that were readily detected and suppressed by the OPRM system prior to any significant oscillation amplitude. The SLMCPR was protected throughout the THI event.

5.6 Conservatism of Procedure

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Additional conservatism is adopted in the Option I-D solution by the implementation of a Buffer Region (BR) that is outside the ER. The BR is established as follows:

a) Expand the ER 5% in core flow along the HFCL and 5% in core power along the NCL.

b) Expand the ER by performing an ODYSY calculation, according to the proposed ER procedure using a target core decay ratio of 0.65, along the HFCL and the NCL.

c) From steps a and b above, select the end points along the HFCL and the NCL that produces the largest BR.

The BR provides a region of awareness that is a defense-in-depth feature of the Option I-D solution. Operation within the BR is acceptable but requires the operability of an on-line stability monitor that is used to predict the margin to stability prior to entry and to calculate the margin to stability while inside the BR. Additional information regarding on-line stability monitor experience is provided in Appendix B. Note there is no BR for the Option II solution.

Several demonstration analyses are provided in Section 7 of this report to illustrate the application of the ODYSY procedure for both nominal and reduced FWT operation.

Table 5-1. ODYSY Model Features

Modeling	ODYSY
Reactor Kinetics	• 1-D kinetics with void and Doppler feedback • Parameters collapsed from 3-D PANACEA wrap-up
Channel Thermal-Hydraulics	• Drift flux formulation with subcooled voids • Consistent with other GE design methods
Ex-Core Hydraulics	• Upper plenum, steam separator, downcomer, recirculation system, modeled as hydraulic regions
Fuel Heat Transfer	• 1-D radial conduction model for cladding, gap and fuel
Axial Geometry	• Models axial varying geometry in advanced fuel designs
Core simulator	• Input from PANAC11 or earlier versions

Table 5-2. Comparison of ODYSY Application Procedures

Application	Proposed ODYSY ER Procedure	E1A ODYSY Validation Procedure
Reactivity coefficients	Exposure dependent 1-D kinetics model void coefficient Includes Doppler coefficient	Same as proposed ODYSY procedure except based on EOC Haling - not exposure dependent
Thermal-hydraulic data	Standard values consistent with transient and accident analysis methods currently in use (ISCOR Method B [16])	Same as proposed ODYSY procedure
Core average axial power shape (APS)	On the NCL, use the exposure dependent off-rated APS from full power Haling depletion On the HFCL, use the exposure dependent off-rated APS from a minimum flow at rated power Haling depletion	Same as proposed ODYSY procedure except based on EOC Haling - not exposure dependent
Xenon concentration	On the NCL, no Xenon On the HFCL, constant Xenon at the initial operating condition	Same as proposed ODYSY procedure
Hot channel APS	Overlay a conservative hot channel APS	Same as proposed ODYSY procedure
Radial power distribution	19 channel groups used to model core	Same as proposed ODYSY procedure
Gap conductance	Use core average gap conductance	Same as proposed ODYSY procedure
Spacer model	Clean spacer loss coefficients [2]	Same as proposed ODYSY procedure
Stability Criteria	As shown in Figure 1-1	Same as proposed ODYSY procedure

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Figure 5-1. Procedure Demonstration for U.S. BWR/5 Instability Event

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Figure 5-2. Procedure Demonstration for U.S. BWR/6 Instability Event

6.0 SUPPLEMENTAL QUALIFICATION STUDIES

6.1 Original Qualification Database

ODYSY was qualified primarily against Vermont Yankee, LaSalle, KRB, Cofrentes and Leibstadt data. ODYSY was also qualified against TRACG predictions of channel instability for LaSalle and Leibstadt. The original qualification database is documented in References 6 and 7. This database resulted in the core and channel decay ratio uncertainty documented in Section 2.7.2.

6.2 Supplemental Qualification Database

A reactor instability event occurred at a non-U.S. BWR/5 on January 24, 1995. ODYSY calculations were performed to determine the core and channel decay ratios when the reactor instability occurred and to determine the effectiveness of proposed actions to allow plant restart without experiencing a reactor instability.

The BWR/5 is designed with a flow control valve (FCV) recirculation system. The instability occurred while preparing for recirculation pump up-shift during a reactor startup in the middle of an operating cycle. The plant was operating at about 36% rated power and 38% rated core flow, which is near the 66% rod line with normal feedwater temperature for the power/flow operating state. The plant was operating with the FCVs partially open and both recirculation pumps on low speed. The normal procedure is to partially close both FCVs to reduce core flow, shift the recirculation pumps to high speed, and then gradually open the FCVs to increase core flow. In this instance, when the operators closed the FCVs, the plant conditions changed to ~31.8% power, as indicated on the Average Power Range Monitor (APRM) and 32% core flow and a core-wide mode reactor instability developed. There was some uncertainty on the initial power and power level following the flow reduction. Other indications are that power may have been 33.1% of rated when the oscillation began.

As flow was being decreased, the power oscillations grew slowly to an amplitude of ~11% peak-to-peak, as indicated on the APRM. The flow reduction and oscillation growth to reach a limit cycle oscillation took about 4 minutes. After ~1-2 minutes of limit cycle oscillations, the operator increased core flow by opening the FCVs and the oscillation magnitude decreased to ~3% peak-to-peak. A manual scram was initiated ~7 minutes after the flow reduction had been initiated (this plant was not using stability Interim Corrective Actions under the requirements of NRC Bulletin 88-07, Supplement 1 [10] at the time this event occurred).

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Table 6-1. Supplemental BWR/5 Instability Event Qualification Studies

Condition	Description	Xenon Assumption	Core Decay Ratio	Channel Decay Ratio
1	Prior to last control rod withdrawal, approximately one-half hour before the event	Constant Xenon at 16% power	0.65	0.13
2	After control rod withdrawal, prior to flow reduction	Constant Xenon at 16% power	0.68	0.19
3a	After FCV closure at initiation of reactor instability, 31.8% power, 32% core flow	Constant Xenon at 16% power	0.89	0.48
3b	Repeat of Case 3a with a transient Xenon model	Transient Xenon model	0.94	0.50
3c	Repeat of Case 3a with a transient Xenon model and at 33.1 % power	Transient Xenon model	1.04	0.54
4	Restart with rod pattern specified by GE to provide a high core average boiling boundary	Constant Xenon at 16% power	0.53	0.00

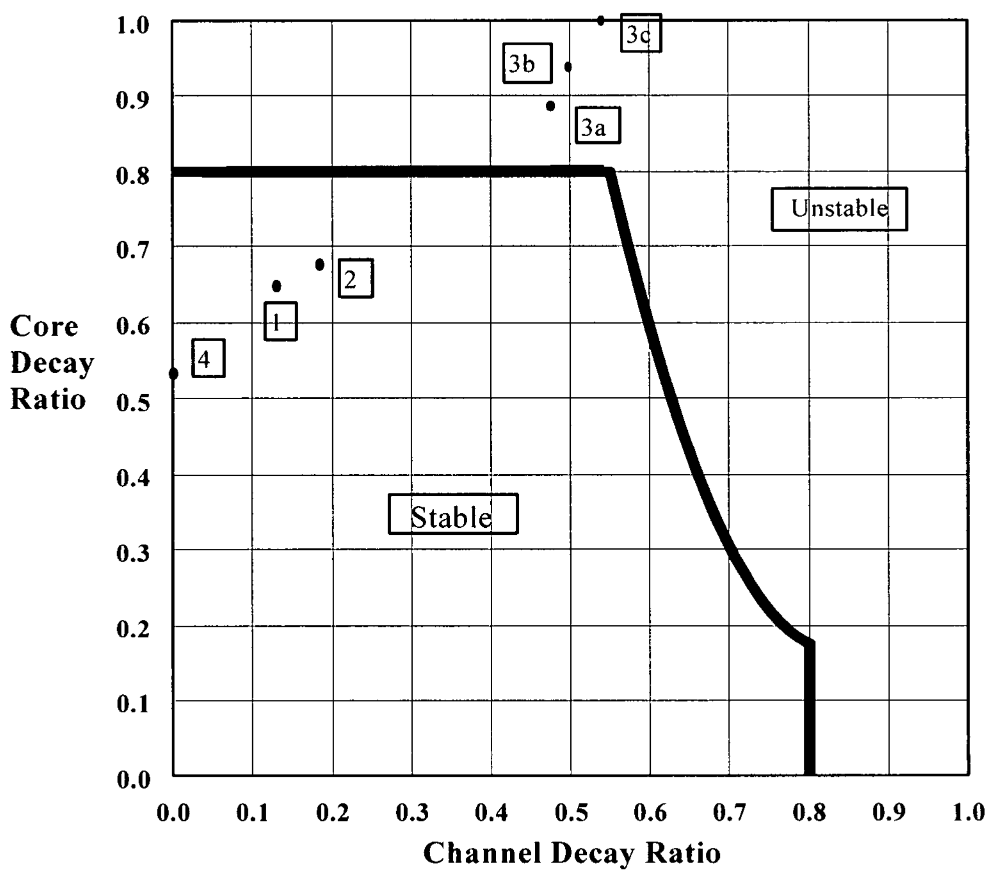

Figure 6-1. Supplemental BWR/5 Instability Event Qualification Studies

7.0 ER DEMONSTRATION ANALYSES

The analyses provided in this section are examples of the proposed process and representative of how the ER procedure will be applied. Demonstration analyses are provided for the Option I-D ER generation, for the Option I-D ER generation at reduced FWT and for evaluation of the stability licensing requirements of new fuel licensing. The Option I-D demonstration analyses are performed for a recent cycle for four different plants. The ERs were determined for a target core decay ratio of 0.80. The Option I-D demonstration analyses also include ERs for operation with FWTR for the same four plants. The new fuel licensing demonstration analysis shows the ODYSY procedure result for two previously approved GE fuel designs.

The calculation process for the Option II ER is identical to the Option I-D process. Therefore, a separate demonstration analysis for Option II is not necessary.

7.1 Option I-D Demonstration Analyses

The ER and BR are calculated for every cycle. Calculations have been performed for recently completed cycles for four Option I-D plants to demonstrate the application of the ER procedure. All plants utilized advanced fuel designs and expanded operating domains (i.e., 10x10 fuels with axially varying geometry and Maximum Extended Load Line Limit Analysis (MELLLA) domain). The core designs and control rod pattern strategies vary, depending on cycle energy requirements and reload batch sizes. Table 7-1 provides a description of the plants selected for these demonstrations.

Table 7-1. Description of Demonstration Plants

Plant /Size	Core Loading by Fuel Type	Operating Domain	Bounding Cycle Length MWd/ST	% Original Licensed Power	Type of Operation
A / 368	10x10 - 100%	EPU MELLLA	16255	120	Conventional - A1,A2,B1,B2
B / 368	10x10 - 66% 9x9 - 34%	MELLLA	13725	100	Conventional - A1,A2,B1,B2
C / 560	10x10 - 100%	MELLLA	16050	104.1	Conventional - A1,A2,B1,B2
D / 548	10x10 - 70% 9x9 - 30%	MELLLA	11600	100	Control Cell Core - A2

7.1.1 ER Demonstration 1 - Plant A

Plant A is representative of a high energy core loading pattern with an advanced fuel design (100% 10x10 design), MELLLA operating domain and Extended Power Uprate (EPU). Based on the application procedure described in Section 5, a bounding cycle exposure of 16255 MWd/ST was determined. PANACEA Haling wrapups were generated assuming this exposure value in accordance with the procedure. ODYSY calculations were then performed along the HFCL and the NCL to establish the limiting cycle exposure for each of these conditions. The ER endpoints along the HFCL and the NCL that produce a calculated core decay ratio of 0.80 were then determined. The ER endpoints must also satisfy the ODYSY stability acceptance criterion previously shown in Figure 1-1. The results of the ER calculations are presented in Table 7-2. The ER boundary based on the MSF is shown in Figure 7-1.

Table 7-2. Plant A Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

[[

]]

Figure 7-1. Plant A MSF Exclusion Region

7.1.2 ER Demonstration 2 - Plant B

Plant B represents a high energy core loading pattern with advanced fuel designs (66% 10x10 design and 34% 9x9 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 13725 MWd/ST was determined. The results of the ER calculations are presented in Table 7-3. The ER boundary based on the MSF is shown in Figure 7-2.

Table 7-3. Plant B Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

[[

]]

Figure 7-2. Plant B MSF Exclusion Region

7.1.3 ER Demonstration 3 - Plant C

Plant C represents a high energy core loading pattern with an advanced fuel design (100% 10x10 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 16050 MWd/ST was determined. The results of the ER calculations are presented in Table 7-4. The ER boundary based on the MSF is shown in Figure 7-3.

Table 7-4. Plant C Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

[[

]]

Figure 7-3. Plant C MSF Exclusion Region

7.1.4 ER Demonstration 4 - Plant D

Plant D represents a medium energy core loading pattern with advanced fuel designs (70% 10x10 design and 30% 9x9 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 11600 MWd/ST was determined. The results of the ER calculations are presented in Table 7-5. The ER boundary based on the MSF is shown in Figure 7-4.

Table 7-5. Plant D Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

[[

]]

Figure 7-4. Plant D MSF Exclusion Region

7.2 ER Demonstration with Feedwater Temperature Reduction

Feedwater temperature reduction (FWTR) will have an impact on stability due to increased core inlet subcooling. Table 3-1 has identified core inlet subcooling to have a high impact on both core and channel stability. The previous application procedure in Reference 1 did not distinguish between normal and reduced feedwater temperature operation since the 0.15 decay ratio adder sufficiently accounted for such small variation in operating conditions (FWTR ~ < 50°F). With the removal of this adder, the proposed calculation procedure will be implemented as part of the reload licensing requirement. It will require the determination of a FWTR dependent ER that is larger than the nominal feedwater temperature ER.

It should be noted that for some plants, engineering analyses may establish a reduced operating domain that is required for FWTR implementation. For example, the licensed operating domain may be reduced such that the highest licensed flow control line becomes the 100% rod line rather than the MELLLA/ELLLA boundary that would be allowed for normal FWT operation. It should be noted that the ER for FWTR shall never be smaller than the ER for normal FWT operation.

ER demonstrations with FWTR are performed for the same four plants previously described in Table 7-1.

7.2.1 FWTR Demonstration 1 - Plant A

The results of the ER calculations are presented in Table 7-6 for 50°F and 100°F FWTR. Comparison of the FWTR dependent ERs and the nominal ER based on normal FWT is shown in Figure 7-5.

Table 7-6. Plant A Exclusion Region End Points for FWTR

FWTR	Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
50°F	HFCL	[[				
	NCL					
100°F	HFCL					
	NCL					]]

[[

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Figure 7-5. Plant A MSF Exclusion Region for FWTR

7.2.2 FWTR Demonstration 2 - Plant B

The results of the ER calculations are presented in Table 7-7 for 50°F and 100°F FWTR. Comparison of the FWTR dependent ERs and the nominal ER based on normal FWT is shown in Figure 7-6.

Table 7-7. Plant B Exclusion Region End Points for FWTR

FWTR	Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
50°F	HFCL	[[				
	NCL					
100°F	HFCL					
	NCL					]]

[[

]]

Figure 7-6. Plant B MSF Exclusion Region for FWTR

7.2.3 FWTR Demonstration 3 - Plant C

The results of the ER calculations are presented in Table 7-8 for 50°F and 100°F FWTR. Comparison of the FWTR dependent ERs and the nominal ER based on normal FWT is shown in Figure 7-7.

Table 7-8. Plant C Exclusion Region End Points for FWTR

FWTR	Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
50°F	HFCL	[[				
	NCL					
100°F	HFCL					
	NCL					]]

[[

]]

Figure 7-7. Plant C MSF Exclusion Region for FWTR

7.2.4 FWTR Demonstration 4 - Plant D

The results of the ER calculations are presented in Table 7-9 for 50°F and 100°F FWTR. Comparison of the FWTR dependent ERs and the nominal ER based on normal FWT is shown in Figure 7-8.

Table 7-9. Plant D Exclusion Region End Points for FWTR

FWTR	Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
50°F	HFCL	[[				
	NCL					
100°F	HFCL					
	NCL					]]

[[

]]

Figure 7-8. Plant D MSF Exclusion Region for FWTR

7.3 New Fuel Licensing

Amendment 22 of GESTAR II [5] provides the stability requirements for generic new fuel licensing. The requirements are described in Section 2.3. To document compliance with these requirements, core and channel decay ratio calculations are performed for the new fuel design and compared to a reference fuel design. If the new fuel is more stable, then it is acceptable for generic fuel licensing. If the new fuel design is less stable, then a comparison must be made to show that there is not a significant difference between an ER for the reference fuel design and an ER for the new fuel design.

The calculations are performed at a typical state point on the rated rod line near the point of minimum recirculation pump speed. The actual point is not significant since a benchmark to the reference fuel design is done at exactly the same state point. The calculation is performed for two basic plant designs: a "loose" orifice in the core inlet fuel support piece and a "tight" orifice in the core inlet fuel support piece. [[

]] The reference fuel design is a standard GE 8x8 fuel design, designated as P8x8R.

The Amendment 22 evaluation for GE14 was originally documented in Reference 16. That evaluation was performed with FABLE. To demonstrate the application of ODYSY to new fuel licensing, the Amendment 22 study is repeated using the ODYSY ER procedure. The core and channel decay ratios as a function of exposure for the reference fuel design and the new fuel design (GE14) are provided in Table 7-10. The results are plotted versus exposure in Figures 7-9 to 7-12. [[

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The limiting results for the GE14 and the reference fuel design are provided in Table 7-11. [[

]] Therefore, according to the GESTAR II stability licensing acceptance criteria, it is necessary to evaluate the impact on the ER. The corresponding HFCL and NCL endpoints on the power/flow map for the reference fuel design and GE14 are provided in Table 7-12. The ERs are plotted in Figure 7-13. This illustrates that there is an insignificant difference between the P8x8R and GE14 ERs, which would support generic licensing approval for the GE14 fuel design.

Table 7-10. Amendment 22 P8x8R - GE14 Comparison: Decay Ratio Vs. Exposure

Exposure	Reference Design (P8x8R)		New Design (GE14)	
	Core Decay Ratio	Channel Decay Ratio	Core Decay Ratio	Channel Decay Ratio
Loose Orifice Design				
0	[[			
200				
2000				
4000				
6000				
7800				
7891				]]
Tight Orifice Design				
0	[[			
200				
2000				
4000				
6000				
7800				
7891				]]

n/c – not calculated

Table 7-11. Amendment 22 P8x8R - GE14 Comparison: Limiting Decay Ratio

	Loose Orifice Plant		Tight Orifice Plant	
	Core Decay Ratio	Channel Decay Ratio	Core Decay Ratio	Channel Decay Ratio
Amendment 22 ODYSY-Based Comparison				
Reference Design (P8x8R)	[[			
New Design (GE14)				
Δ Decay Ratio (P8x8R – GE14)				]]

Table 7-12. Amendment 22 Comparison Loose Orifice Plant: ER Endpoints

Flow Condition	P8x8R ER Endpoints		GE14 ER Endpoints	
	Power (% rated)	Core Flow (% rated)	Power (% rated)	Core Flow (% rated)
HFCL	[[			
NCL				]]

[[

]]

Figure 7-9. Amendment 22 Loose Orifice Plant: Core Decay Ratio vs. Exposure

[[

]]

Figure 7-10. Amendment 22 Loose Orifice Plant: Channel Decay Ratio vs. Exposure

[[

]]

Figure 7-11. Amendment 22 Tight Orifice Plant: Core Decay Ratio vs. Exposure

[[

]]

Figure 7-12. Amendment 22 Tight Orifice Plant: Channel Decay Ratio vs. Exposure

[[

]]

Figure 7-13. Amendment 22 Comparison Loose Orifice Plant: ER on Power/Flow Map

7.4 ER Demonstration Summary

The demonstration analyses illustrated application of the ODYSY procedure for the generation of the Option I-D ER for nominal operating conditions and for operation at reduced FWT. The four plants selected for these demonstrations capture recent cycles that contain advanced fuel designs, utilize expanded operating domains and adopt current operating strategies. The ODYSY procedure as it applies to stability licensing requirements for new fuel designs was also discussed.

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APPENDIX A - HALING VALIDATION ANALYSES WITH MSF

The Option I-D Haling methodology validation analyses provided in this appendix are performed for two recent cycles for four plants, or a total of eight cycles in all. The demonstration plants are described in Table A-1. The ERs were determined for a target core decay ratio (DR) of 0.80 and the ER and BR boundaries were established using the MSF.

A.1 Option I-D Haling Methodology Versus Operating Plant Data

The validations presented herein are rather extensive. One of the major objectives was to demonstrate the adequacy and conservatism of the licensing basis procedure relative to actual plant operating data. For each cycle, approximately 25 to 30 data points were selected that represent actual operating statepoints selected at intervals of about 500 MWd/ST or less. A flow runback was assumed to occur along the rod line established by the initial statepoint condition. The initial statepoint condition is the most likely condition from which a flow reduction event is initiated that ultimately results in operation near the ER since the majority of an operating cycle is spent at rated power. An ODYSY calculation was performed at the intersection of the rod line and the ER boundary established by the proposed licensing basis procedure presented in Section 5 (i.e., core decay ratio of 0.80 and MSF application) for each statepoint.

For calculations utilizing actual plant operating data, it should be noted that the calculation procedure is similar to the licensing basis in that constant xenon at the initial statepoint condition and equilibrium feedwater temperature at the final analysis statepoint condition are assumed. However, the hot channel APS will be based on the actual power shape and not the hard bottom peaked licensing power shape. The core average APS is based on the actual rodded depletion through the cycle and not a Haling depletion. Finally, the calculation is performed along the rod line established by the initial operating statepoint and not the highest licensed rod line.

Results are presented in Figures A-1 through A-8. The licensing basis decay ratios based on a Haling depletion through the cycle and the decay ratios based on the actual plant data using the calculation process described above are shown. A total of two decay ratio curves described as follows are provided:

- Haling Curve - the DRs are based on a Haling depletion, consistent with the licensing basis calculation, and along the highest licensed flow control line (e.g., MELLLA or ELLLA) or the NCL. Hence, the maximum core DR will be 0.80 at the most limiting exposure point in the cycle, typically at or near EOC.
- Actual Curve - for forced flow conditions, the DRs are determined at the intersection of the ER boundary based on the MSF and a rod line that is determined by the initial statepoint based on actual plant operating data. The flow runback is assumed to follow this rod line and not the highest licensed flow control line. Consequently, each ODYSY calculation will most likely occur on a different rod line. Constant xenon and equilibrium FWT are assumed. For natural circulation conditions, the DRs are determined at the intersection of the ER boundary and the NCL. Zero xenon and equilibrium FWT are assumed.

These comparisons demonstrate the adequacy and conservatism of the licensing basis procedure relative to actual plant operation.

Table A-1. Description of Demonstration Plants and Cycles

Plant (Size)	Cycle	Core Loading by Fuel Type	Operating Domain	Bounding Cycle Length MWd/ST	% Original Licensed Power	Type of Operation
A (368)	N	10x10 - 72% 9x9 - 28%	EPU MELLLA	15420	120	Conventional - A1,A2,B1,B2
	N+1	10x10 - 100%	EPU MELLLA	16255	120	"
B (368)	N	10x10 - 35% 9x9 - 65%	ELLLA	12100	100	"
	N+1	10x10 - 66% 9x9 - 34%	MELLLA	13725	100	"
C (560)	N	10x10 - 100%	ELLLA	15900	104.1	"
	N+1	10x10 - 100%	MELLLA	16050	104.1	"
D (548)	N	10x10 - 47% 9x9 - 53%	MELLLA	9617	100	Control Cell Core - A2/A1
	N+1	10x10 - 70% 9x9 - 30%	MELLLA	11600	100	Control Cell Core - A2

A.1.1 Demonstration 1 - Plant A Cycle N

Plant A Cycle N is representative of a high energy core loading pattern with advanced fuel designs (72% 10x10 design and 28% 9x9 design), Maximum Extended Load Line Limit Analysis (MELLLA) operating domain and Extended Power Uprate (EPU). Based on the application procedure described in Section 5, a bounding cycle exposure of 15420 MWd/ST was determined. PANACEA Haling wrapups were generated assuming this exposure value in accordance with the procedure. Calculations were then performed along the HFCL and the NCL to establish the limiting cycle exposure for each of these conditions. The ER endpoints along the HFCL and the NCL that produce a calculated core decay ratio of 0.80 were then determined. The results of the ER calculations are presented in Table A-2.

Table A-2. Plant A Cycle N Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant A Cycle N are illustrated in Figure A-1a. The region boundary lines were established using the MSF. This figure also presents the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. This demonstration is intended to show the adequacy and conservatism of the licensing basis procedure relative to actual plant data. Figure A-1b shows the decay ratio results on the stability acceptance criterion map. Figures A-1c and A-1d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-1a. Figures A-1e and A-1f show the results at natural circulation conditions.

A.1.2 Demonstration 2 - Plant A Cycle N+1

Plant A Cycle N+1 represents a high energy core loading pattern with advanced fuel designs (100% 10x10 design), MELLLA operating domain and EPU. For this demonstration, a bounding cycle exposure of 16255 MWd/ST was determined. The results of the ER calculations are presented in Table A-3.

Table A-3. Plant A Cycle N+1 Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant A Cycle N+1 based on the MSF are illustrated in Figure A-2a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-2b shows the decay ratio results on the stability acceptance criterion map. Figures A-2c and A-2d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-2a. Figures A-2e and A-2f show the results at natural circulation conditions.

A.1.3 Demonstration 3 - Plant B Cycle N

Plant B Cycle N represents a medium energy core loading pattern with advanced fuel designs (35% 10x10 design and 65% 9x9 design) and Extended Load Line Limit Analysis (ELLLA) operating domain. For this demonstration, a bounding cycle exposure of 12100 MWd/ST was determined. The results of the ER calculations are presented in Table A-4.

Table A-4. Plant B Cycle N Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant B Cycle N based on the MSF are illustrated in Figure A-3a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-3b shows the decay ratio results on the stability acceptance criterion map. Figures A-3c and A-3d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-3a. Figures A-3e and A-3f show the results at natural circulation conditions.

A.1.4 Demonstration 4 - Plant B Cycle N+1

Plant B Cycle N+1 represents a high energy core loading pattern with advanced fuel designs (66% 10x10 design and 34% 9x9 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 13725 MWd/ST was determined. The results of the ER calculations are presented in Table A-5.

The ER and BR for Plant B Cycle N+1 based on the MSF are illustrated in Figure A-4a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-4b shows the decay ratio results on the stability acceptance criterion map. Figures A-4c and A-4d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure at the analysis statepoints shown in Figure A-4a. Figures A-4e and A-4f show the results at natural circulation conditions.

Table A-5. Plant B Cycle N+1 Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

A.1.5 Demonstration 5 - Plant C Cycle N

Plant C Cycle N represents a high energy core loading pattern with advanced fuel designs (100% 10x10 design), a power uprate to 104.1% of the original licensed power level and ELLLA operating domain. For this demonstration, a bounding cycle exposure of 15900 MWd/ST was determined. The results of the ER calculations are presented in Table A-6.

Table A-6. Plant C Cycle N Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant C Cycle N based on the MSF are illustrated in Figure A-5a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-5b shows the decay ratio results on the stability acceptance criterion map. Figures A-5c and A-5d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-5a. Figures A-5e and A-5f show the results at natural circulation conditions.

A.1.6 Demonstration 6 - Plant C Cycle N+1

Plant C Cycle N+1 represents a high energy core loading pattern with advanced fuel designs (100% 10x10 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 16050 MWd/ST was determined. The results of the ER calculations are presented in Table A-7.

Table A-7. Plant C Cycle N+1 Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant C Cycle N+1 based on the MSF are illustrated in Figure A-6a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-6b shows the decay ratio results on the stability acceptance criterion map. Figures A-6c and A-6d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-6a. Figures A-6e and A-6f show the results at natural circulation conditions.

It should be noted that this cycle operated with failed fuel assemblies from about 10350 MWd/ST to the end of cycle, at about 15000 MWd/ST. Power suppression control rods were inserted next to the failed fuel at about 10670 MWd/ST in order to limit any further degradation of the fuel and to allow for continued operation. At end of cycle, the reactor was shut down with two control rods fully inserted and two control rods approximately 66% inserted. The final core power level was 84.5%.

A.1.7 Demonstration 7 - Plant D Cycle N

Plant D Cycle N represents a low energy core loading pattern with advanced fuel designs (47% 10x10 design and 53% 9x9 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 9617 MWd/ST was determined. The results of the ER calculations are presented in Table A-8.

Table A-8. Plant D Cycle N Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant D Cycle N based on the MSF are illustrated in Figure A-7a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-7b shows the decay ratio results on the stability acceptance criterion map. Figures A-7c and A-7d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-7a. Figures A-7e and A-7f show the results at natural circulation conditions.

A.1.8 Demonstration 8 - Plant D Cycle N+1

Plant D Cycle N+1 represents a medium energy core loading pattern with advanced fuel designs (70% 10x10 design and 30% 9x9 design) and MELLLA operating domain. For this demonstration, a bounding cycle exposure of 11600 MWd/ST was determined. The results of the ER calculations are presented in Table A-9.

Table A-9. Plant D Cycle N+1 Exclusion Region End Points

Flow Condition	Power (% Rated)	Flow (% Rated)	Core Decay Ratio	Channel Decay Ratio	Feedwater Temperature °F
HFCL	[[				
NCL					]]

The ER and BR for Plant D Cycle N+1 based on the MSF are illustrated in Figure A-8a along with the initial statepoints based on actual core tracking data and the analysis statepoints based on a flow runback scenario as previously described. Figure A-8b shows the decay ratio results on the stability acceptance criterion map. Figures A-8c and A-8d show the core and channel decay ratio results at forced flow conditions as a function of cycle exposure for the analysis statepoints shown in Figure A-8a. Figures A-8e and A-8f show the results at natural circulation conditions.

A.2 Option I-D Haling Validation Conclusions

The Haling validation analyses documented in this appendix provides an extensive demonstration of the adequacy of the licensing basis assumptions relative to actual plant data. Core tracking data from a total of eight recent cycles were used for this validation. The initial statepoints represent the most likely condition from which a flow runback event would be initiated that ultimately results in operation near the ER since the majority of an operating cycle is spent at rated conditions. The final analysis statepoints at which the calculations are performed capture a realistic set of input conditions that are likely to occur at operating BWRs today.

It should be noted that the varying operating strategies employed at these four different Option I-D plants have captured a wide range of control rod patterns and axial power shapes. For example, Plants A, B and C have implemented a conventional core loading strategy due to their high cycle energy requirements and large reload batch sizes. This type of core loading design requires that all four control rod sequences - A1, A2, B1 and B2 - are utilized throughout the cycle for reactivity control, to maintain acceptable radial and axial power distributions and thermal limits, etc. Alternating these four sequences throughout the cycle mitigates control blade history effects on low exposure fuel bundles and improves core wide burnup. In the case of Plant D, a control cell core (CCC) loading strategy has been employed. This type of loading strategy can be applied when cycle energy requirements and corresponding reload batch sizes are sufficiently low. Only the A2 control rod locations are used for reactivity control and maintaining acceptable radial and axial power distributions and thermal limits. In the case of one plant (i.e., Plant C Cycle N+1), failed fuel assemblies at around two-thirds of the way into the cycle resulted in operation with power suppression rods and operation that deviated from the planned set of control rod patterns. Consequently, this study captured both planned and unplanned operating scenarios and demonstrated that the Haling methodology used in the application procedure produces a reasonably bounding ER.

Table A-10 provides a summary of the key results from this study. [[

]] Based on the validation results presented in this appendix, it can be concluded that the ODYSY licensing basis procedure utilizing Haling methodology is both adequate and reasonably bounding in establishing the ER boundary.

Table A-10. Summary Table of Validation Results

Plant	Cycle	Number of Exposure State Points	Number of Points Over 0.80		Peak Core Decay Ratio (HFCL / NCL)
			Along the ER Boundary	On the Natural Circ Line	
A	N	[[			
	N+1				
B	N				
	N+1				
C	N				
	N+1				
D	N				
	N+1				
Totals					]]

[[

]]

Figure A-1a. Plant A Cycle N MSF Exclusion Region and Analysis Points

[[

]]

Figure A-1b. Plant A Cycle N Decay Ratio Criterion Map

[[

]]

Figure A-1c. Plant A Cycle N Core Decay Ratio Comparisons

[[

]]

Figure A-1d. Plant A Cycle N Channel Decay Ratio Comparisons

[[

]]

Figure A-1e. Plant A Cycle N Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-1f. Plant A Cycle N Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-2a. Plant A Cycle N+1 MSF Exclusion Region and Analysis Points

[[

]]

Figure A-2b. Plant A Cycle N+1 Decay Ratio Criterion Map

[[

]]

Figure A-2c. Plant A Cycle N+1 Core Decay Ratio Comparisons

[[

]]

Figure A-2d. Plant A Cycle N+1 Channel Decay Ratio Comparisons

[[

]]

Figure A-2e. Plant A Cycle N+1 Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-2f. Plant A Cycle N+1 Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-3a. Plant B Cycle N MSF Exclusion Region and Analysis Points

[[

]]

Figure A-3b. Plant B Cycle N Decay Ratio Criterion Map

[[

]]

Figure A-3c. Plant B Cycle N Core Decay Ratio Comparisons

[[

]]

Figure A-3d. Plant B Cycle N Channel Decay Ratio Comparisons

[[

]]

Figure A-3e. Plant B Cycle N Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-3f. Plant B Cycle N Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-4a. Plant B Cycle N+1 MSF Exclusion Region and Analysis Points

[[

]]

Figure A-4b. Plant B Cycle N+1 Decay Ratio Criterion Map

[[

]]

Figure A-4c. Plant B Cycle N+1 Core Decay Ratio Comparisons

[[

]]

Figure A-4d. Plant B Cycle N+1 Channel Decay Ratio Comparisons

[[

]]

Figure A-4e. Plant B Cycle N+1 Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-4f. Plant B Cycle N+1 Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-5a. Plant C Cycle N MSF Exclusion Region and Analysis Points

[[

]]

Figure A-5b. Plant C Cycle N Decay Ratio Criterion Map

[[

]]

Figure A-5c. Plant C Cycle N Core Decay Ratio Comparisons

[[

]]

Figure A-5d. Plant C Cycle N Channel Decay Ratio Comparisons

[[

]]

Figure A-5e. Plant C Cycle N Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-5f. Plant C Cycle N Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-6a. Plant C Cycle N+1 MSF Exclusion Region and Analysis Points

[[

]]

Figure A-6b. Plant C Cycle N+1 Decay Ratio Criterion Map

[[

]]

Figure A-6c. Plant C Cycle N+1 Core Decay Ratio Comparisons

[[

]]

Figure A-6d. Plant C Cycle N+1 Channel Decay Ratio Comparisons

[[

]]

Figure A-6e. Plant C Cycle N+1 Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-6f. Plant C Cycle N+1 Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-7a. Plant D Cycle N MSF Exclusion Region and Analysis Points

[[

]]

Figure A-7b. Plant D Cycle N Decay Ratio Criterion Map

[[

]]

Figure A-7c. Plant D Cycle N Core Decay Ratio Comparisons

[[

]]

Figure A-7d. Plant D Cycle N Channel Decay Ratio Comparisons

[[

]]

Figure A-7e. Plant D Cycle N Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-7f. Plant D Cycle N Channel Decay Ratio Comparisons on NCL

[[

]]

Figure A-8a. Plant D Cycle N+1 MSF ER and Analysis Points

[[

]]

Figure A-8b. Plant D Cycle N+1 Decay Ratio Criterion Map

[[

]]

Figure A-8c. Plant D Cycle N+1 Core Decay Ratio Comparisons

[[

]]

Figure A-8d. Plant D Cycle N+1 Channel Decay Ratio Comparisons

[[

]]

Figure A-8e. Plant D Cycle N+1 Core Decay Ratio Comparisons on NCL

[[

]]

Figure A-8f. Plant D Cycle N+1 Channel Decay Ratio Comparisons on NCL

APPENDIX B - STABILITY MONITORING EXPERIENCE

The requirements for an on-line stability monitor at Option I-D plants provides additional defense in depth to the ER. This appendix describes the main features of the on-line stability monitor and provides several examples of its application.

B.1 Description of the On-Line Stability Monitor

In addition to an administratively controlled plant-cycle specific ER and BR, Option I-D plants have also introduced an on-line stability monitor. The GE monitoring system is referred to as SOLOMON (Stability On-Line ODYSY Monitor). SOLOMON uses live plant data to determine the power-flow operating state point relative to the stability ER and BR, and uses 3D Monicore output and ODYSY to evaluate and predict core and hot channel decay ratios that provide an indication of stability margin. Evaluations are performed upon automatic or manual demand.

There are two main components of GE's SOLOMON BWR stability monitoring system. The first component monitors and promptly detects reactor operation within the user-defined regions of the core power-flow map. There are basically three regions of interest to the plant operator:

- The ER, where plant operating procedures require immediate actions to exit the region in order to avoid potential reactor instabilities.
- The BR, where planned maneuvers, such as plant startup or control rod pattern adjustments, may result in temporary operation within the region. SOLOMON calculations of predicted and actual margins are desirable here. Option I-D plants are free to operate with in this region provided the on-line stability monitor is operational and calculated decay ratios are below the specified stability criterion.
- The normal operating region, which includes the area of acceptable operation outside of the BR. Usually no SOLOMON calculations are required within this region.

The second main component of SOLOMON uses ODYSY to calculate the core and hot channel decay ratio. The decay ratios are then compared to the stability acceptance criterion map to indicate the overall stability margin.

Some plants use a non-GE stability monitor called SIMULATE-3K (S3K). S3K is the transient version of the SIMULATE-3 (S3) advanced nodal code for on-line stability monitoring. These plants also use GARDEL, the S3 model for reactor core monitoring. S3K and GARDEL work in a similar fashion to SOLOMON and 3DMonicore in that they use live plant data to provide an indication of stability margin. Calculations of core-wide and regional stability are performed automatically, and may be manually demanded if desired.

B.2 On-Line Stability Monitor Data

On-line stability monitoring data under actual operating conditions have been collected for several Option I-D plants. The collected data cover three typical scenarios where operation near the BR can be expected, for example reactor startup, control rod pattern adjustments and reactor shutdown. Utilization of an on-line stability monitor allows the reactor operator to confirm the stability margin during a power/flow maneuver near the BR. Predictive cases may also be run prior to any maneuver. These examples clearly demonstrate that an on-line stability monitor provides an additional degree of protection to the ER and BR as well as added conservatism to the Option I-D solution.

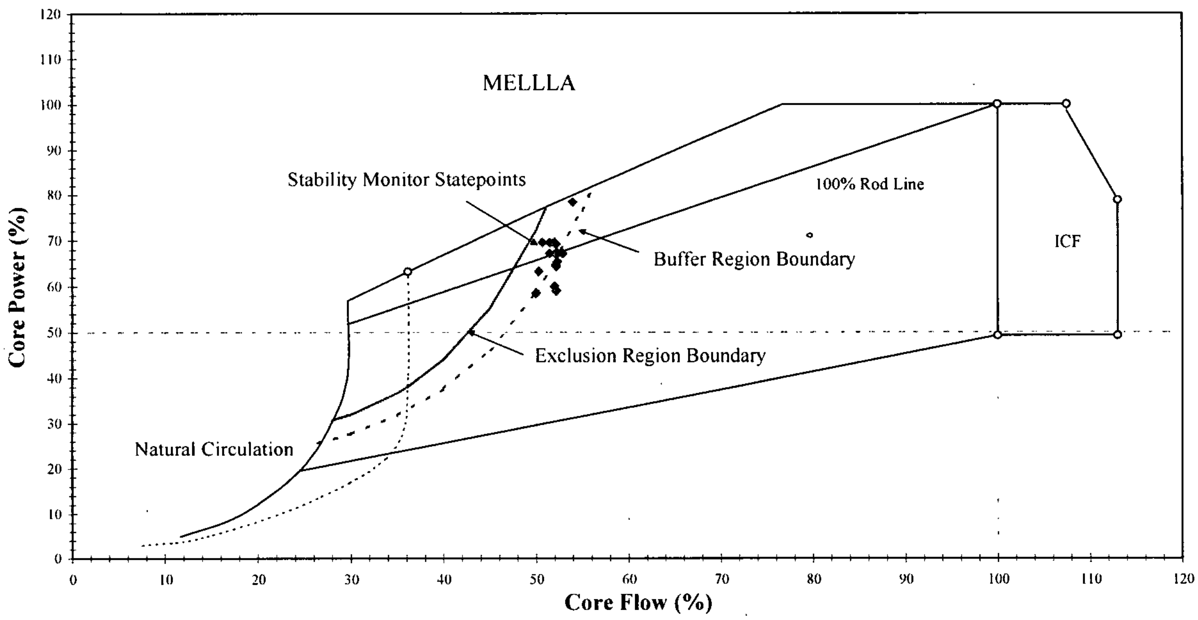

Figure B-1a. Plant A Stability Monitor Statepoints on the Power/Flow Map

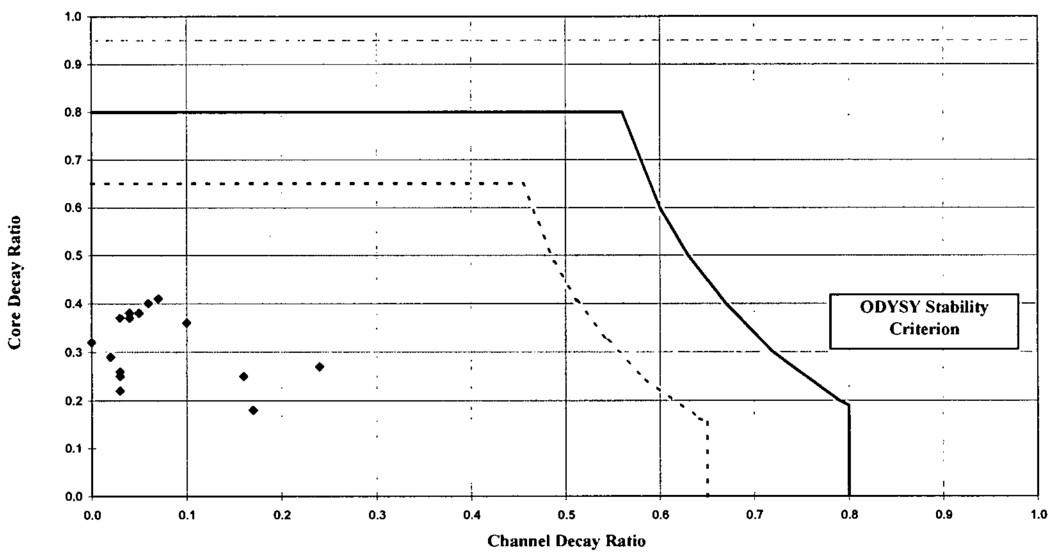

Figure B-1b. Plant A Calculated Stability Monitor Decay Ratios (SOLOMON)

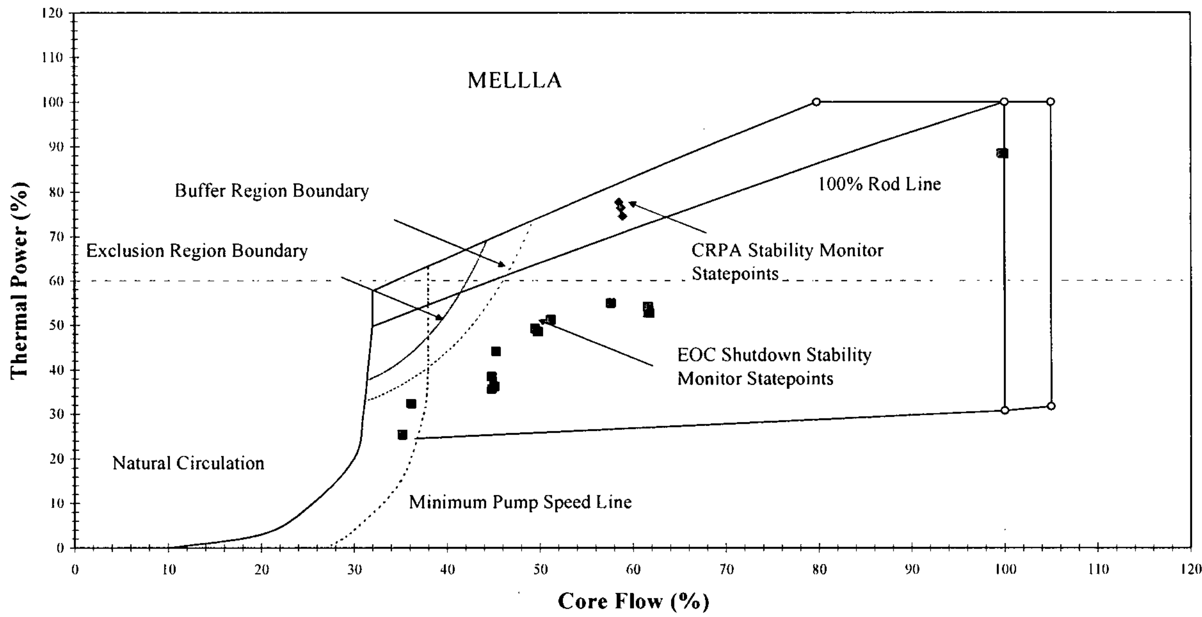

Figure B-2a. Plant B Stability Monitor Statepoints on the Power/Flow Map

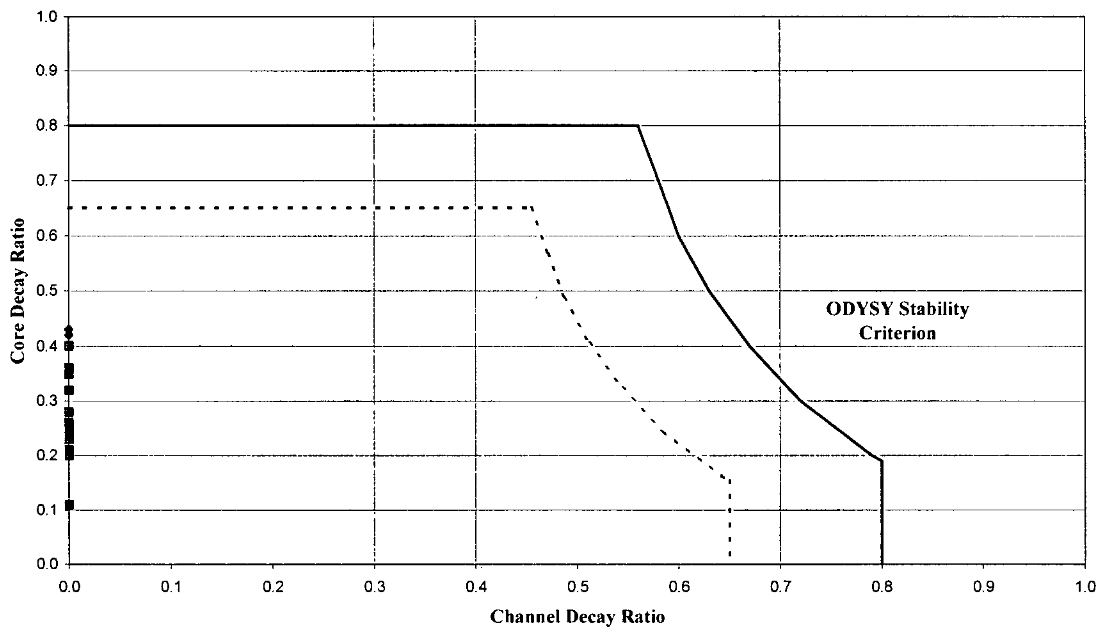

Figure B-2b. Plant B Calculated Stability Monitor Decay Ratios (SOLOMON)

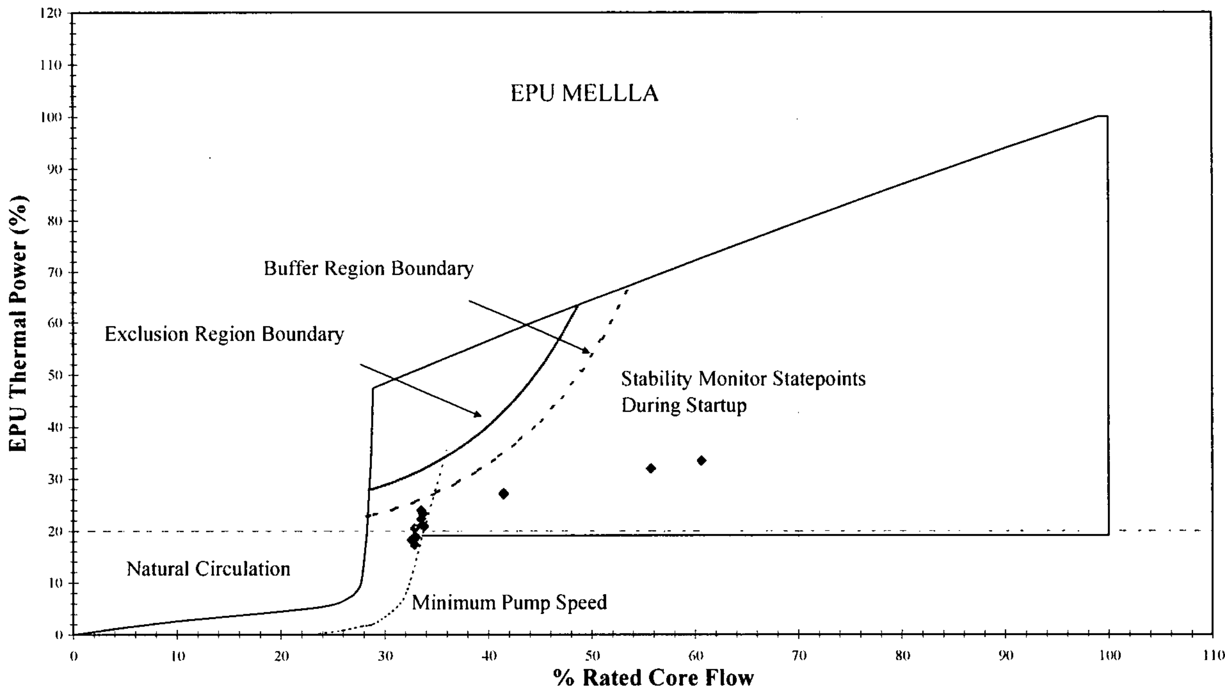

Figure B-3a. Plant C Stability Monitor Statepoints on the Power/Flow Map

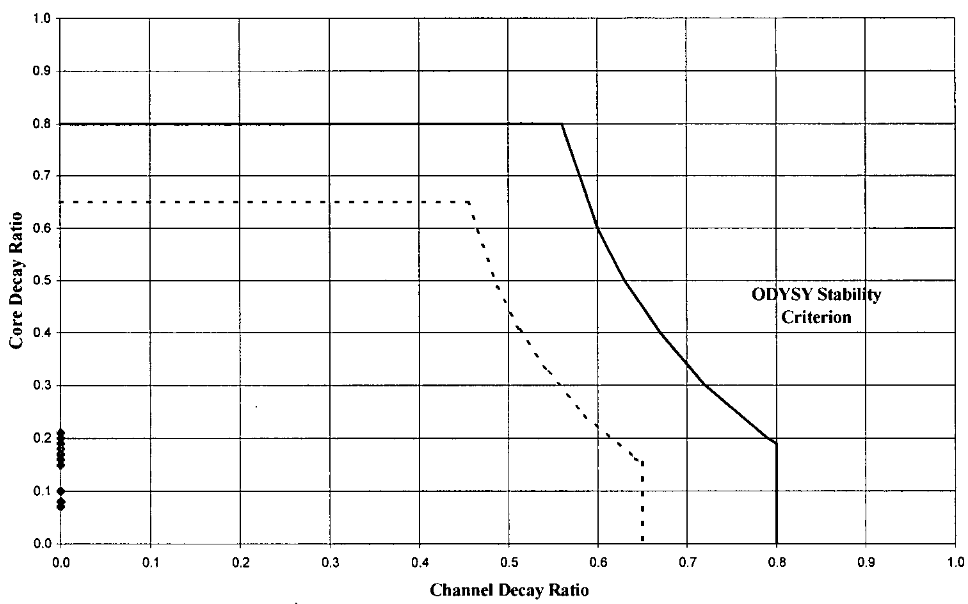

Figure B-3b. Plant C Calculated Stability Monitor Decay Ratios (SOLOMON)

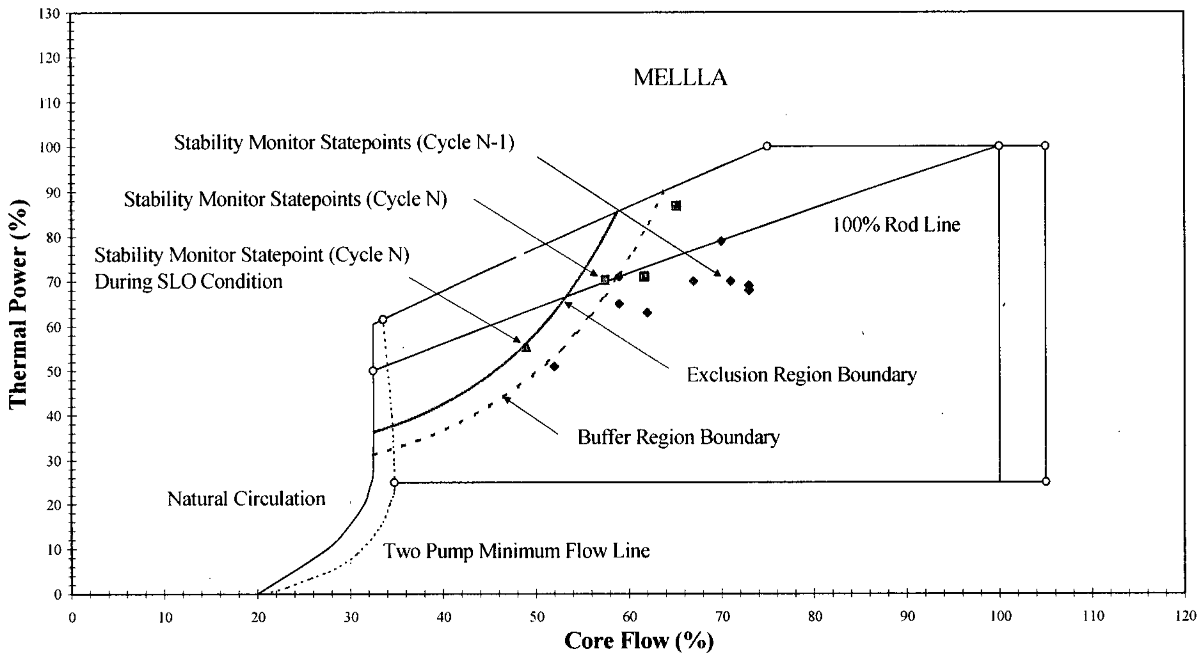

Figure B-4. Plant D Stability Monitor Statepoints on the Power/Flow Map

Table B-1. Plant D Calculated Stability Monitor Decay Ratios (S3K/GARDEL))

Exposure GWd/MT	Power (%)	Flow (%)	Global DR	Regional DR
Cycle N-1 Statepoints				
0.0	63.0	62.0	0.33	0.041
2.6	51.0	52.0	0.31	0.000
2.6	65.0	59.0	0.46	0.001
2.6	71.0	59.0	0.53	0.000
2.8	70.0	71.0	0.30	0.001
4.8	70.0	67.0	0.42	0.001
5.4	79.0	70.0	0.42	0.000
6.9	68.0	73.0	0.27	0.001
6.9	69.0	73.0	0.27	0.025
Cycle N Statepoints				
0.0	71.0	61.7	0.40	0.037
0.0	70.2	57.5	0.47	0.215
0.0	86.9	65.2	0.46	0.091
1.50	55.5	49.0	0.47	0.25

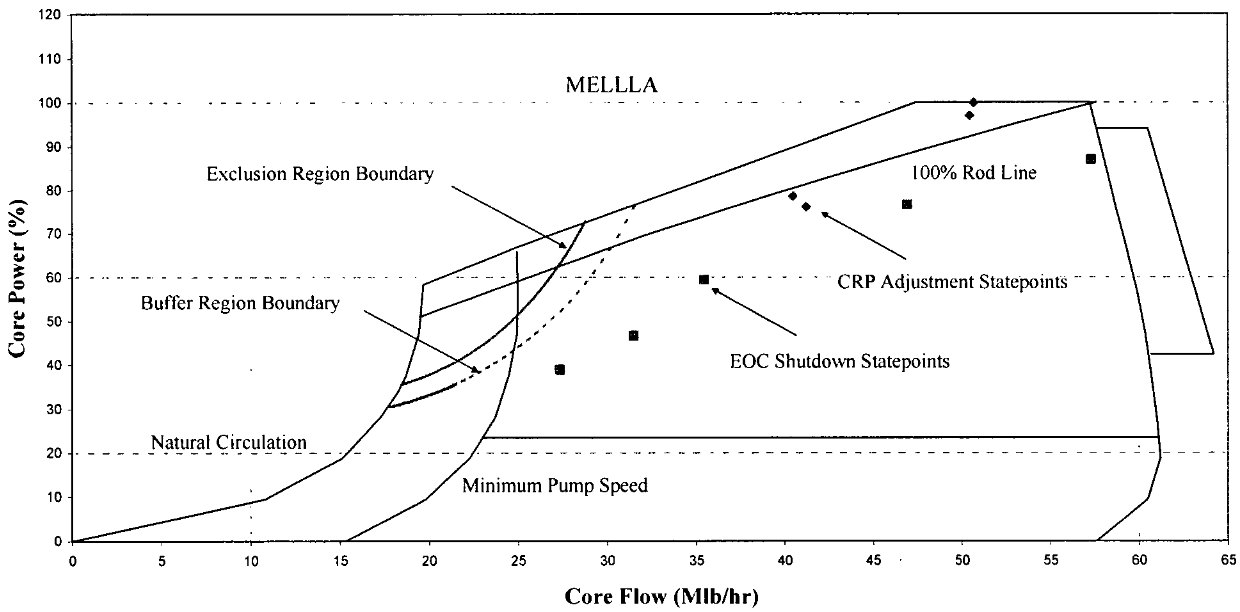

Figure B-5. Plant E Stability Monitor Statepoints on the Power/Flow Map

Table B-2. Plant E Calculated Stability Monitor Decay Ratios (S3K/GARDEL)

Exposure	Power (%)	Flow (%)	Global DR	Regional DR
EOC-3 months	78.6	70.3	0.48	0.050
EOC-3 months	76.1	71.6	0.39	0.000
EOC-3 months	97.0	87.6	0.24	0.009
EOC-3 months	99.9	88.0	0.24	0.011
EOC	87.0	99.5	0.13	0.001
EOC	76.6	81.5	0.17	0.000
EOC	59.4	61.6	0.30	0.001
EOC	46.7	54.7	0.33	0.008
EOC	38.9	47.5	0.20	0.000