YANKEE ATOMIC ELECTRIC COMPANY

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Method for Power/Flow Exclusion Region Calculation Using the LAPUR5 Computer Code

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ABSTRACT

This report documents the BWR stability assessment methodology implemented by the Yankee Atomic Electric Company. The objective of this methodology is to analytically determine the boundaries of the stability exclusion region, i.e., the range of power/flow operating states where instabilities could occur. This is accomplished primarily through the use of LAPUR5, a code developed by the Oak Ridge National Laboratory. LAPUR5 results were benchmarked against the results from the 1981 Vermont Yankee stability tests and Cycle 15 vendor calculations. In addition, several sensitivity studies were performed with LAPUR5 to evaluate the impact of modeling techniques and data uncertainties on the accuracy of the predictions. The comparison to the benchmark data confirms the validity of this methodology to predict the onset of an instability.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

SUMMARY

This report describes the Yankee Atomic Electric Company (YAEC) approach to analyzing the incipience of thermal-hydraulic instabilities in boiling water reactors (BWRs). This analytical capability is needed to identify changes to reactor core stability characteristics for a given fuel cycle so that appropriate plant and cycle specific operating limits (e.g., the power/flow exclusion region) can be determined.

Licensing criteria in 10CFR50 Appendix A, General Design Criteria 12 require that oscillations be prevented, or detected and suppressed prior to exceeding the specified acceptable fuel design limits. The BWR Owner's Group (BWROG) has developed a methodology to both identify conditions leading to an instability and determine reload core stability characteristics. The BWROG methodology was designed to be generic in nature and remain applicable for other organizations to use with different computer codes, as long as the alternate calculations have a similar approach and level of accuracy.

As part of the Option 1D long term stability solution approach, the stability exclusion region will be reevaluated each reload. Yankee has implemented the BWROG stability methodology using the LAPUR5 code. This methodology was validated through benchmarks to the 1981 Vermont Yankee stability tests, comparisons to the vendor calculations, and sensitivity studies of the computer code's modeling techniques. Results of the stability test benchmarks and the vendor comparisons are presented in detail in Sections 4 and 5 of this report.

It is concluded that an exclusion region analysis methodology based on LAPUR5 yields results which are reasonably accurate and within the uncertainty tolerance band typical of the current state-of-the-art. This methodology provides a reasonable approach for performing plant and cycle specific exclusion region analysis and fuel design studies.

1.0 INTRODUCTION

Thermal-hydraulic instability and the potential for power oscillations are of potential concern in Boiling Water Reactor (BWR) design and operation. Licensing criteria in 10CFR50 Appendix A, General Design Criteria 12 requires that oscillations be prevented, or detected and suppressed prior to exceeding the specified acceptable fuel design limits. The BWR Owner's Group (BWROG) has identified several long term solutions to the instability issue and developed an evaluation methodology [1]-[3] to analyze thermal-hydraulic instability. This methodology provides the means to both identify conditions leading to an instability and to determine reload core stability characteristics. The BWROG methodology was developed to be generic in nature, and remain applicable for other organizations to use with different computer codes, as long as the alternate calculations have a similar approach and level of accuracy.

As part of the Option 1D long term stability solution approach, the stability exclusion region, i.e., the range of power/flow operating states where instabilities could occur, will be reevaluated on a plant specific basis. In addition, the impact of cycle specific fuel loading and other core design changes on the reactor's stability characteristics will be assessed for each fuel cycle. Yankee Atomic implemented the BWROG stability methodology using LAPUR5, [4],[5] a code developed by the Oak Ridge National Laboratory to perform frequency domain stability analysis of BWRs. LAPUR5 was chosen because of its ease-of-use and its extensive benchmarking to stability tests conducted at both domestic and European BWRs, which is well documented and available in the public domain [6]-[15]. This report documents the BWROG stability assessment methodology as implemented and tested by Yankee Atomic.

LAPUR is one piece of a stability methodology; it must be supplied with input parameters from nuclear and thermal-hydraulic codes. The appropriate inputs for LAPUR5 were obtained from nuclear analysis codes used by Yankee in their NRC approved reload licensing methodology [24],[25]. These software tools worked well together and were found to be capable of performing stability analysis. These findings were determined through benchmarks to the 1981 Vermont Yankee stability tests[16], comparisons to the vendor calculations[22], and sensitivity studies of the computer codes modeling techniques.

The following sections describe the YAEC application of the BWROG method and analysis performed to validate the application. Section 2.0 provides a description of the exclusion region boundary calculational methodology using

LAPUR. Section 3.0 discusses how the exclusion region boundary calculational methodology was adopted from the BWROG approach. Section 4.0 presents results of benchmarks of the methodology against test data and vendor calculations. Sensitivity studies performed to validate the input assumptions are summarized in Section 5.0. The determination of the exclusion region boundary from the LAPUR cases is described in Section 6.0. Overall conclusions are found in Section 7.

2.0 EXCLUSION REGION METHODOLOGY

2.1 Overview

The objective of the BWROG exclusion region methodology is to locate the boundaries of the region in the power/flow operating domain where instabilities could occur. At the boundary, the instabilities remain small and the response of the coupled nuclear/hydrodynamic system can be reduced to a first-order set of linear equations. This type of calculational model lends itself to solution via Laplace transformation into the frequency domain where it is possible to directly determine the inverse transfer functions. Several well known codes, such as FABLE/BYPSS, STAIF, MAZDA, NUFREQ, and LAPUR5 use this frequency domain technique for stability analysis. These codes provide the margin to instability in terms of decay ratio. A predicted decay ratio greater than 1.0 indicates an instability can occur.

The stability analysis code selected was LAPUR [4], [5], which was specifically designed to analyze BWR cores. LAPUR5 was chosen because of its ease of use and extensive benchmarking. LAPUR has been validated against stability tests conducted at both domestic and European BWRs. Documentation of these benchmarking studies is available in the public domain [6]-[15]. Further benchmarking of LAPUR was conducted using the YAEC adaptation of the BWROG methodology and is presented in Section 4 of this report.

Inputs for LAPUR5 are obtained from the nuclear analysis codes currently used at Yankee in their NRC-approved reload licensing methodology. These codes include:

- CASMO3 for Lattice cross sections
- SIMULATE3 for 3D nodal simulation of the BWR core
- FIBWR for BWR core hydraulic analysis
- FROSSTEY2 for fuel rod modeling and equivalent Hgap.

The flow of data for this calculation is shown in the diagram presented in Figure 2-1. A more specific explanation of each codes' use is given in the next section.

2.2 Supporting Codes

CASMO3 is a multigroup two-dimensional transport theory code which calculates cross sections of LWR fuel lattices as a function of exposure, void fraction and control state. The Yankee CASMO model has been qualified [17] to calculate cross sections and reactor kinetics constants for BWR reload analysis.

SIMULATE3 is an advanced, three-dimensional two-group nodal code widely used for BWR fuel management, core follow, and reload analysis. The Yankee SIMULATE [18] model has been qualified to calculate parameters needed for reactor transient calculations, including void and Doppler reactivities and control rod worths. At YAEC, SIMULATE obtains its cross section inputs from CASMO and thermal-hydraulic inputs from FIBWR. The combination of CASMO/SIMULATE provides all kinetics information and power shapes to LAPUR5.

FIBWR is a steady-state thermal-hydraulic code specifically designed for BWR cores. FIBWR models the BWR geometry of many parallel channels with complex leakage flows to the bypass and water tubes. The Yankee FIBWR model [19] has been qualified for use in safety analysis. The FIBWR output is used in confirming the LAPUR5 hydraulic model calculated pressure drops.

FROSSTEY2 is a thermal-mechanical code for fuel rod analysis. The Yankee FROSSTEY2 model [20] has been qualified for use in safety analysis. Fuel to clad gap conductance is derived from the code for the LAPUR5 fuel model.

2.3 Validation of YAEC Approach

The exclusion region boundary calculations must represent a conservative estimate of power and flow conditions susceptible to an oscillation for the entire fuel cycle. The BWROG methodology has previously been determined to provide such conservatism in the vendor application by employing a combination of both best estimate and conservative inputs. In the YAEC application of the BWROG method, differences exist from the vendor as explained in the following section. To validate the YAEC application, a comprehensive validation scheme was used. This includes comparison to the 1981 Vermont Yankee stability tests, the Cycle 15 vendor calculations, and a set of sensitivity studies designed to expose general weakness in input data.

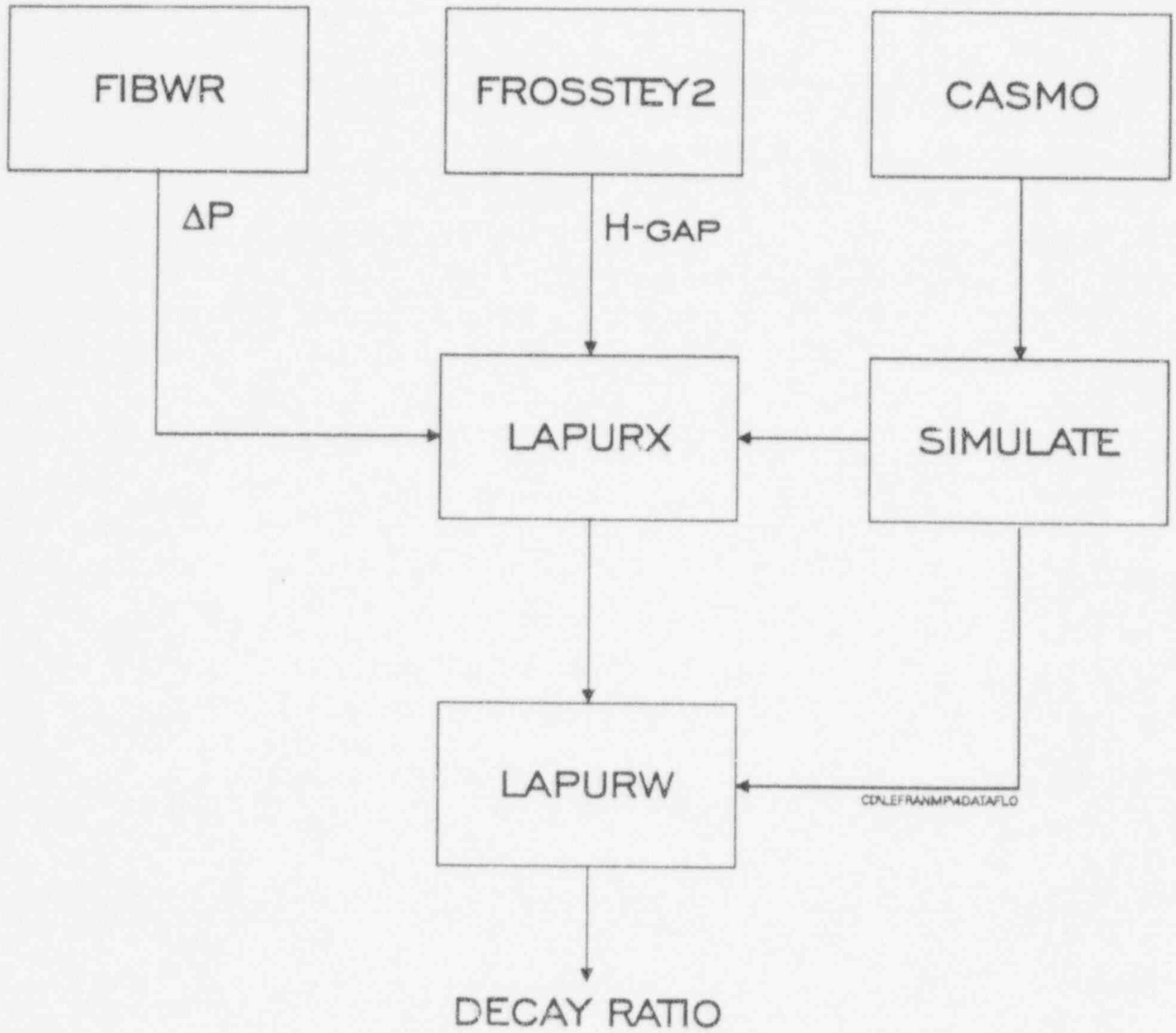

FIGURE 2-1

Dataflow Diagram - Input Data for LAPUR Stability Calculations

3.0 ADAPTION OF BWROG METHODOLOGY

The BWROG exclusion region methodology [1]-[3] has been adapted for use with the LAPUR5 Code for determining the power flow exclusion region boundary. A comparison of the salient features of the methodology and features implemented by YAEC to vendor calculation [22] is provided in Table 3.1. Adaptation of the BWROG methodology required some deviations in order to be consistent with the YAEC approved reload analysis methodology and the LAPUR5 Code input struct[illegible]s illustrated in Table 3.1, the differences include: core radial nodal[illegible]; treatment of axial shapes, fuel/clad gap conductance, generation of loss coefficients, and two-phase multipliers, generation of reactor kinetics, core bypass flow representation, and recirculation loop representation. The results of the benchmark to the 1981 Vermont Yankee stability tests and the vendor application provides validation of the YAEC application of the BWROG methodology. The input differences and additional details of the YAEC application are discussed further within the remainder of this section.

3.1 Radial Channel Grouping

The YAEC exclusion region methodology employs six groupings. The peripheral and hot assemblies are treated separately and the remaining four groupings are split among the central assemblies. The hot channel represented the core's highest powered assemblies. The methodology uses the hot channel decay ratio in checking susceptibility to a regional oscillation by comparing it and the core decay ratio on the BWROG criteria map. The central assemblies were divided by four equal power ranges, not by equal number of assemblies. This approach is similar to the vendor, except in the number of central assembly nodalization, where the vendor may employ more nodes. The validity of the YAEC method was demonstrated in the comparisons to the 1981 tests.

3.2 Treatment of Axial Shapes

Each radial node axial power shape, except for the hot channel, is derived from SIMULATE for each operating state analyzed. The hot channel shape is taken from the BWROG methodology which was confirmed to be conservative for calculating channel decay ratios. The exclusion region boundary method uses the axial shape from End of Cycle (EOC) Haling depletion cases to bound other possible power shapes during the cycle. This is consistent with the vendor method. For the 1981 stability test comparisons, the actual cycle exposures were used with SIMULATE rodded depletion cases to obtain all power shapes including the hot channel.

3.3 Fuel Clad Gap Conductance

While the BWROG procedure does not specify a specific approach to use of fuel clad conductance, the vendor has employed a multiplier of 1.6 to its calculated value. The YAEC approach employs the nominal value calculated for the reload analyses at end of cycle generated by the FROSSTEY code.

3.4 Generation of Reactor Kinetics

All kinetics input is derived from CASMO/SIMULATE. This includes density (void) and doppler reactivity, delayed neutron fractions, and constants, and effective neutron life time. The kinetics for the exclusion region boundary are calculated from EOC Haling cases to bound different times in the fuel cycle. Also, a 25% uncertainty is applied for treatment of uncertainties. This uncertainty is applied to point kinetics for the reload methodology. For the 1981 test comparison, the kinetics were calculated from the actual cycle exposure using a rodded depletion.

3.5 Generation of Loss Coefficients and Two-Phase Multipliers

While the vendor employs standard design values, the YAEC approach requires matching of the LAPUR thermal hydraulic performance with the FIBWR Code calculations for the operating state analyzed. These comparisons ensure that single and two phase pressure drop, which can significantly impact stability calculations, are consistent with the hydraulic conditions used to calculate the power shapes taken from SIMULATE. An example of the use of the FIBWR data for preparing the LAPUR thermal hydraulic information is shown in Figure 3-1. The figure displays the void distribution from each code. The good agreement indicates the accuracy of this approach. The benchmark to the FIBWR output was found to provide a consistent method of determining core thermal hydraulic parameters including the interassembly flow, pressure drop, and void distributions.

3.6 Core Bypass Representation

The FIBWR code is used to calculate the reactor core flows including the active core flow and bypass flows. The flows are calculated for each operating condition analyzed. This approach is consistent with the reload analysis methodology.

3.7 Recirculation Loop Representation

The modeling of the recirculation loop is carried out by input of a gain and time constant. In LAPUR's dynamic equations, this is the equivalent of a flow resistance. These parameters describe the core pressure drop to flow transfer function. This transfer function is obtained by linearizing and Laplace transforming the fluid momentum equation applied to nodes within the recirculation system.

Susceptibility to an oscillation is dependent on the strength of the thermal-hydraulic resistances in the single phase flow region. The values of recirculation loop gain and time constant used in this study were calculated for each operating condition. A sensitivity study was also carried out to test the impact of these parameters on the accuracy of the predictions.

The 1981 tests represented an array of recirculation loop configurations, while the vendor comparisons addressed natural circulation flow and forced flow conditions. Each configuration and operating condition hydraulic resistance was calculated and represented in LAPUR with a gain and time constant.

<u>TABLE 3.1</u>

<u>Implementation Features of BWROG Exclusion Region Methodology</u>

<table>
<tr><th colspan="2">Modeling Feature</th><th>Vendor Implementation of BWROG Exclusion Region Methodology</th><th>YAEC Implementation of BWROG Exclusion Region Methodology</th></tr>
<tr><td colspan="2">Solution Approach</td><td>Frequency Domain (FABLE/BYPSS)</td><td>Frequency Domain (LAPUR5)</td></tr>
<tr><td colspan="2">Core Radial Nodalization</td><td>8 Radial Nodes Minimum</td><td>6 or 7 Radial Channels (7 is the LAPUR Maximum)</td></tr>
<tr><td colspan="2">Core Axial Nodalization</td><td>24 Nodes (in Heated Zone)</td><td>25 Nodes (in Heated Zone)</td></tr>
<tr><td rowspan="2">Axial Shapes</td><td>Hot Channels</td><td>Specified Shapes w/Bottom Peak (Node 3)</td><td>Most Limiting of
1) BWROG Shapes,
or
2) Hot Channel Shapes from EOC HALING</td></tr>
<tr><td>Other Channels</td><td>Core Average from EOC HALING</td><td>Core Average from EOC HALING</td></tr>
<tr><td colspan="2">Fuel Model H-Gaps</td><td>1.6 x Values Calculated By Vendor Licensing Models</td><td>Values Calculated By FROSSTEY2</td></tr>
<tr><td colspan="2">Loss Coefficients and Two-Phase Multipliers</td><td>Vendor Standard Design Values</td><td>LAPUR Input Selected to Match FIBWR Pressure Drops</td></tr>
<tr><td colspan="2">Reactor Kinetics</td><td>Density Reactivity Coefficients Calculated By Vendor Licensing Models at Most Negative Point in the Fuel Cycle</td><td>1.25 x Density Reactivity Coefficients Calculated By CASMO3/SIMULATE3 at most Negative Point in the Fuel Cycle.</td></tr>
<tr><td colspan="2">Core Bypass Flow Representation</td><td>Calculated By Vendor Licensing Models</td><td>Specified Flow Calculated by FIBWR</td></tr>
<tr><td colspan="2">Recirculation Loop Representation</td><td>Vendor Standard Design Representation</td><td>Represented via P/F Dependent Calculation for Time Constant and Gain</td></tr>
</table>

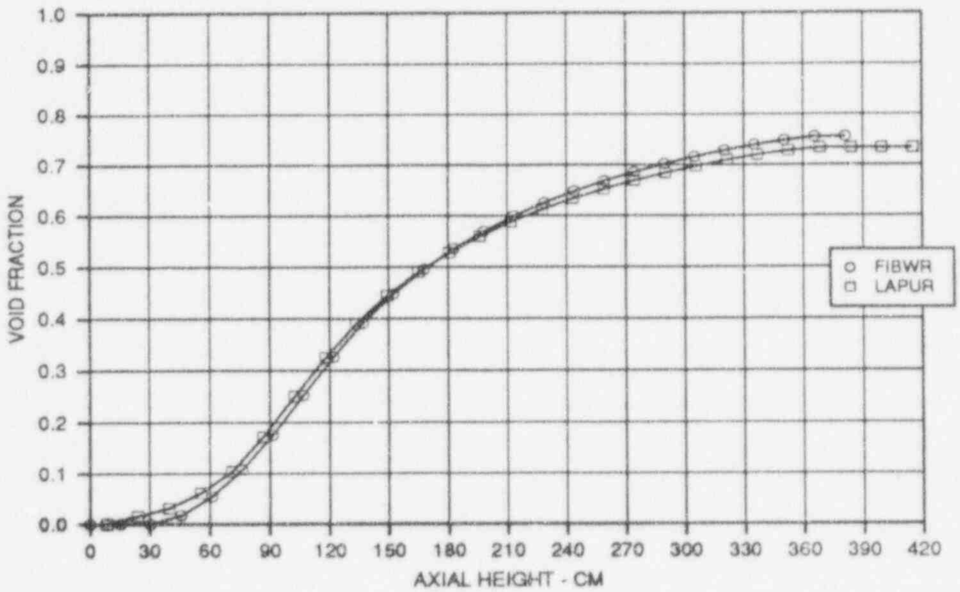

FIGURE 3-1

FIBWR vs. LAPUR Void Model Comparisons

4.0 BENCHMARKS

Validation studies were performed to assess the YAEC application of the BWROG exclusion region stability evaluation methodology. These studies include benchmarks to the 1981 Vermont Yankee stability tests and comparisons to the vendor calculations for Cycle 15.

4.1 LAPUR5 Predictions of 1981 Vermont Yankee Stability Tests

4.1.1 Stability Test Description

Twelve stability tests were conducted at Vermont Yankee in March of 1981. The stability tests were purposely designed to obtain test data close to the stability limits. These tests allowed qualification of Vermont Yankee's stability performance and qualification of stability analysis models.

The stability tests were carried out at core flows between minimum pump speed and natural circulation. The operating recirculation system configurations included natural circulation, single loop, and two loop operation. Test powers extended above the rated rod line. The average power ranged from 42.9% to 67.1% and the core flow rate from 31.7% to 38.5%. Test conditions of the statepoints chosen to benchmark are shown in Table 4.1. The tests benchmarked represented each of the operating configuration as well as a wide range of decay ratios.

The stability of the reactor system at each power and flow statepoint was tested by introducing pressure perturbations via rapid turbine control valve fluctuations. The pressure perturbations induced a core feedback and subsequent cyclical neutron flux response. A limit cycle oscillation occurred at test point 7, a flow rate near natural circulation and a power near the rated rod line (51.2% P, 32.6%F). The limit cycle was stopped by insertion of a few control rods. Test point 8 was also at the threshold of a limit cycle oscillation. All other test points were stable, including the highest power, lowest flow achievable without exceeding plant thermal limits, (i.e., linear heat generation rate or minimum critical power ratio) 67.1%P, 38.5%F. The decay ratios of the tests ranged from 0.36 to 1.0 and the resonant frequency of the oscillations ranged from 0.38 to 0.47 Hz. Eight test points of the twelve were benchmarked, to cover the range of decay ratios calculated for the tests. The eight tests also bound the range of conditions which include operation under natural circulation, with the recirculation loops in bypass mode, and under the normal two loops running configuration.

4.1.2 Model Input

The model input includes both LAPURX and LAPURW data sets. Data in these sets fall into three categories: physical/mechanical properties of the VY plant and Cycle 8 which do not change for each test point, plant operating conditions and power distributions which change for each point, and various adjustable user options. The input that differs between test points are the core state inputs, the axial power distribution, and the radial region relative power. In addition, test points 1, 5, 6, and 12 have different inlet and outlet hydraulic loss coefficients due to recirculation loop flow rates which are much higher than the remaining test points. The LAPURW input that differs between test points are the recirculation loop gain and time constant and the overall density reactivity (void) coefficient.

The reactivity coefficients and power shape data were calculated using SIMULATE rodded depletions. Figure 4-1 shows three 1D plots with the core average axial power shape, exposure shape and control rod density for test point 7.

4.1.3 LAPUR Test Results

The LAPUR results for the 1981 test are listed in Table 4.2 and plotted in Figure 4-2 in terms of core decay ratio. Decay ratio is the figure of merit used in stability analysis to determine the proximity to unstable conditions, a decay ratio of 1.0. In general, the results are within the commonly accepted tolerance for a decay ratio calculation, 20%.

4.2 Cycle 15 Application to BWROG Methodology

4.2.1 Problem Description

This study compares the fuel vendor calculations to core and hot channel decay ratio results obtained with the YAEC application of the BWROG methodology. The vendor calculations are those used to obtain the exclusion region boundary for Cycle 15 as a demonstration of the applicability of the methodology to Vermont Yankee. The fuel vendor calculations for Vermont Yankee (VY) are documented in Reference [22]. This report has been previously reviewed and approved by the NRC.

4.2.2 Model Input

The power/flow points calculated are provided in Table 4.3. Twelve points are provided, of which five are on the natural circulation line. For each power/flow condition, SIMULATE branch cases were run using rodded depletions to calculate the reactivity coefficients at their most negative point in the fuel cycle. HALING EOC calculations were used to generate axial and radial power shapes. In addition to physics data, cycle specific inputs included gap heat transfer coefficients (from FROSSTEY) and hydraulic data (bypass flows and loss coefficients from FIBWR).

4.2.3 Results

Table 4.3 and Figure 4-4 contain the results of the YAEC and vendor calculations for the core average and channel decay ratios. The BWROG methodology uses core average decay ratios for determining the exclusion region boundary. The channel decay ratio provides an indication of the plant susceptibility to regional oscillations by comparing the core and channel decay ratios to the BWROG criterion map. The procedure for obtaining the exclusion region boundary and comparison to the criteria map for the YAEC calculations is illustrated in Section 6.0.

The results for the core average decay ratio calculations show good general agreement within the band of 20% for all but the highest decay ratio point (PNT 4). As stated previously, the stability codes are designed to be most accurate to a decay ratio of 1.0 due to the use of linearized dynamic equation transformation. For the purpose of calculating the exclusion region boundary, the differences are inconsequential.

The hot channel results for the YAEC applications indicate a comparable decay ratio for all points. The largest difference exists for the natural circulation points (30% flow) but are within the anticipated accuracy of these benchmarks. Section 6.0 will provide a comparison of these YAEC results to the BWROG criterion map.

TABLE 4.1

Vermont Yankee Stability Test Conditions

Test Point	Power % (MW)	Total Core Flow % (Mlbm/hr)	Recirculation Loop Flow % (Mlbm/hr)	Core Inlet Subcooling (Btu/lbm)	Dome Pressure (psia)
1	51.1 (814.02)	38.5 (18.48)	5.29	40.42	968.3
2	42.9 (683.30)	31.9 (15.31)	NC**	42.27	961.5
4	42.9 (683.4)	31.7 (15.22)	.47*	42.55	961.9
5	48.1 (766.23)	38.3 (18.39)	5.24	38.59	965.9
6	57.2 (911.20)	38.5 (18.48)	5.39	44.18	973.8
7	51.2 (815.62)	32.6 (15.65)	NC**	47.98	968.9
9	48.1 (766.22)	32.4 (15.55)	.47*	46.01	966.0
12	63.1 (1005.18)	38.5 (18.48)	5.29	47.89	978.4

* Computed by RETRAN. Measured values unavailable at very low flow conditions.
** Natural Circulation

TABLE 4.2

Results of LAPUR Benchmark of Vermont Yankee Stability Tests

Test Point	Core Power (%)	Core Flow (%)	Mode	Sub-cooling ΔH (Btu/lb)	Axial Power Profile	Decay Ratio		Resonant Frequency (Hz)	
						Test	LAPUR	Test	LAPUR
1P	51.1	38.46	2L	40.42	~cos	0.36	0.49	0.40	0.37
2P	42.9	31.90	NC	42.27	~cos	0.45	0.60	0.38	0.33
4P	42.9	31.67	BYP	42.55	~cos	0.47	0.61	0.38	0.33
5P	48.1	38.31	2L	38.59	~cos	0.40	0.49	0.41	0.37
6P	57.2	38.52	2L	44.18	bottm pk	0.74	0.69	0.44	0.37
7N	51.2	32.58	BYP	47.98	bottm pk	1.00	0.85	0.43	0.34
9P	48.1	32.42	BYP	46.01	bottm pk	0.81	0.80	0.42	0.33
12P	63.1	38.46	2L	47.89	bottm pk	0.84	0.77	0.46	0.39

2L = Two Loop
NC = Natural Circulation
BYP= Two Loop Pump Discharge Valves Closed

TABLE 4.3

Results of LAPUR Comparisons to Vendor Calculations for Cycle 15

Point	% Power	% Flow	Core Decay Ratio		Hot Channel Decay Ratio	
			Vendor	LAPUR	Vendor	LAPUR
1	67.4	45.0	0.80	0.90	0.31	0.40
2	60.7	40.0	0.96	0.96	0.40	0.43
3	56.6	35.0	1.18	1.08	0.51	0.51
4	52.4	30.0	1.58	1.15	0.65	0.60
5	47.2	30.0	1.26	1.06	0.52	0.47
6	41.9	30.0	1.00	0.87	0.41	0.36
7	36.9	30.0	0.81	0.66	0.34	0.28
8	31.9	30.0	0.63	0.44	0.24	0.14
9	44.7	34.4	0.96	0.89	0.34	0.32
10	44.7	39.4	0.70	0.76	0.24	0.24
11	53.9	38.7	0.95	0.90	0.34	0.35
12	53.9	43.7	0.72	0.76	0.26	0.27

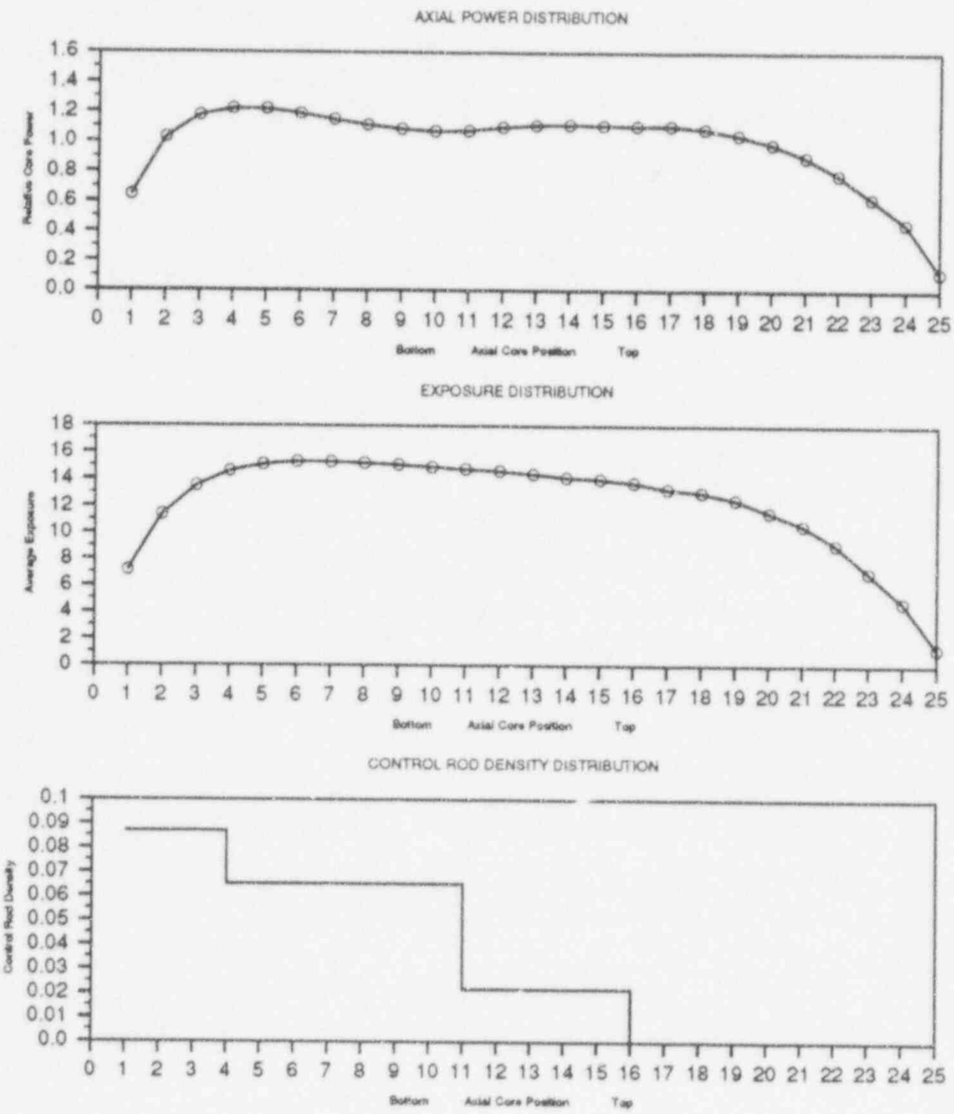

FIGURE 4-1

Core Conditions as Calculated by SIMULATE at Test Condition 7N

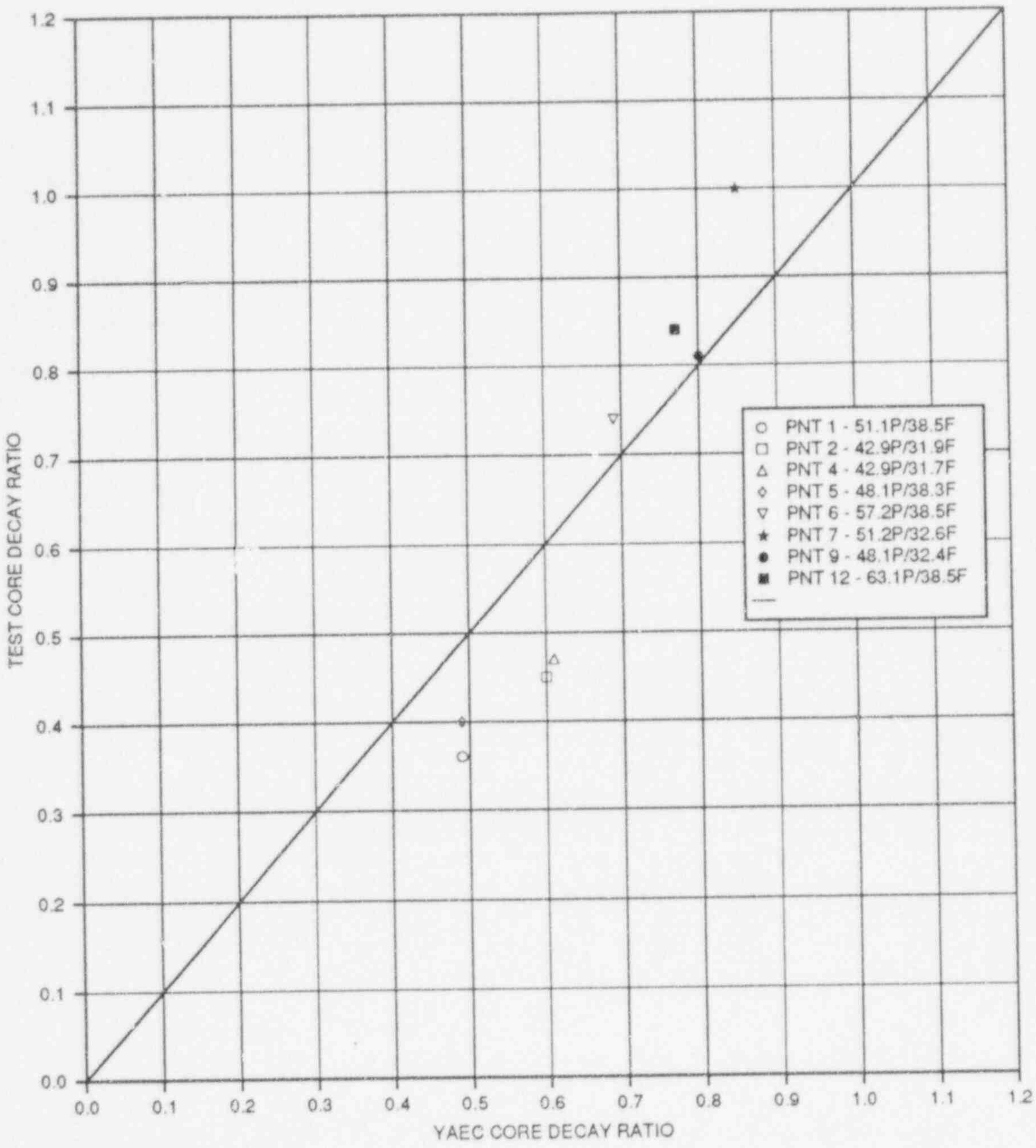

FIGURE 4-2

Comparison of Decay Ratio Vermont Yankee Stability Tests

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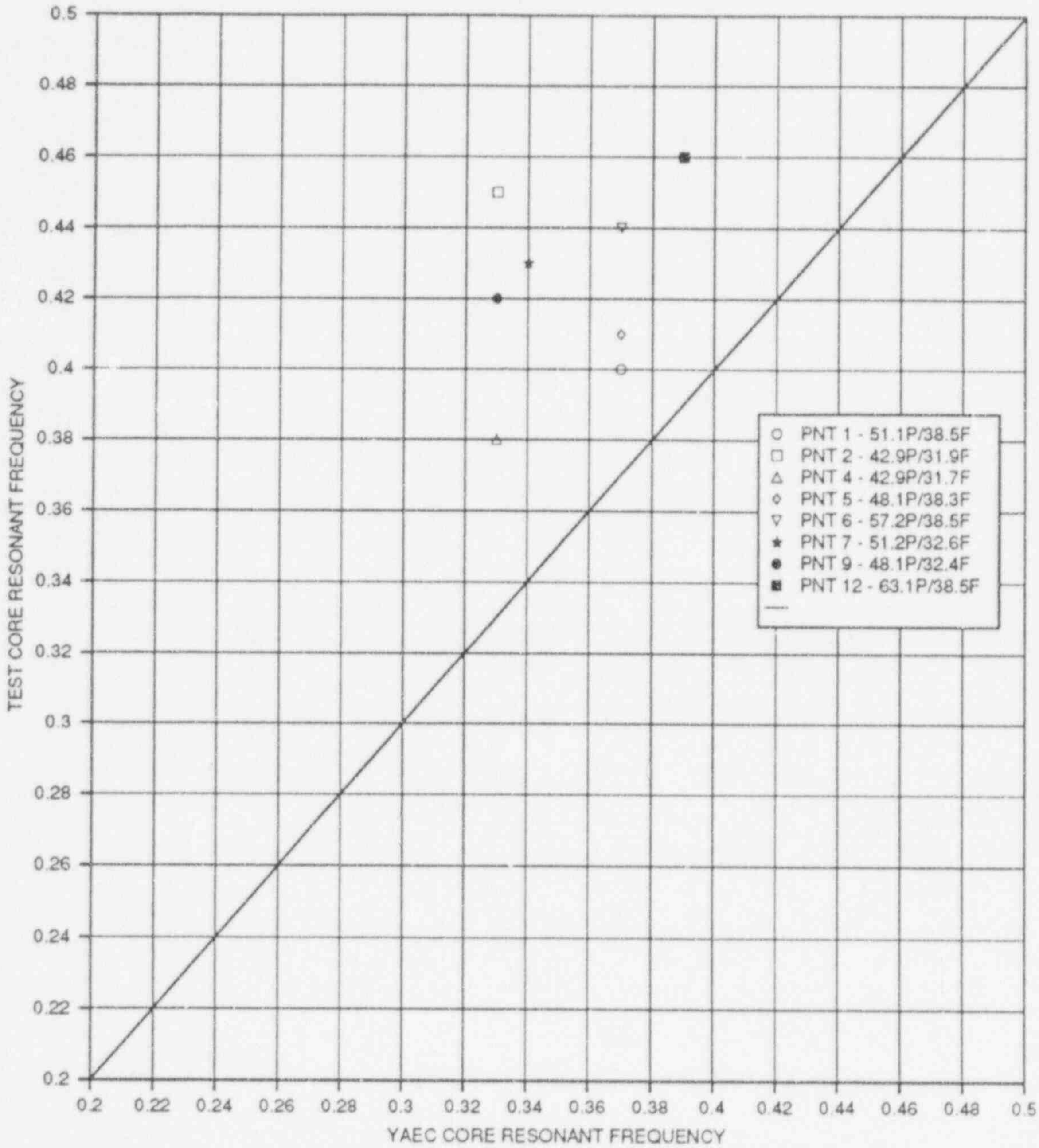

FIGURE 4-3

Comparison of Resonant Frequency for Vermont Yankee Stability Tests

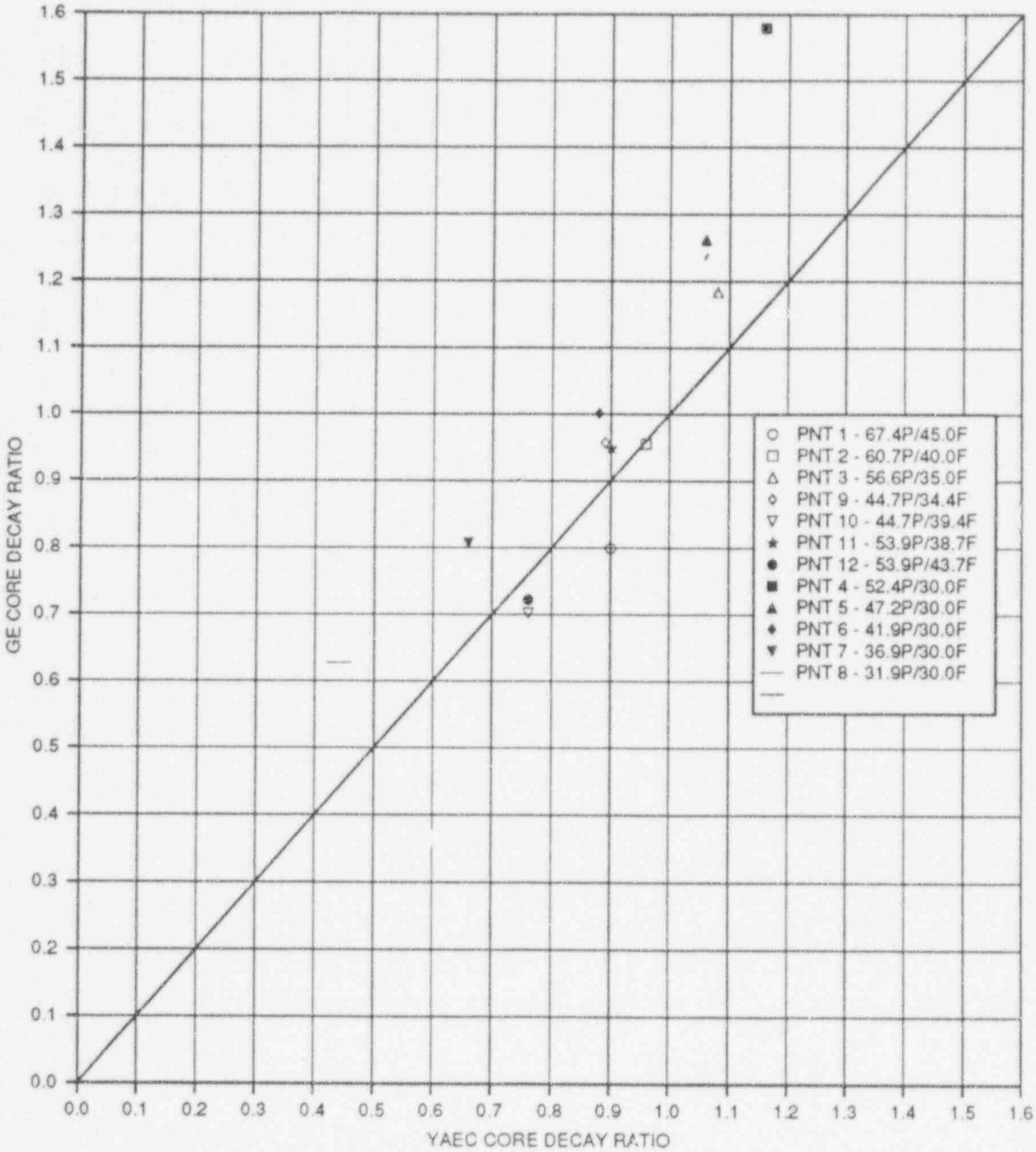

FIGURE 4-4

Comparison of Decay Ratios to Vendor Calculations for Cycle 15

5.0 SENSITIVITY STUDIES PERFORMED

Many input parameters and modeling technique variations were tested to gain insight into the LAPUR code operation to determine the key parameter sensitivities in relation to the benchmark results for the 1981 stability tests. Results of these sensitivity analyses were quantified as changes in the test data core decay ratio and resonant frequency predictions. The sensitivity studies performed included:

- Reactor Kinetics Data
- Recirculation Loop Gain and Time Constant
- Core Pressure Drop
- Gap Conductance
- Feedwater Enthalpy

The result of the sensitivity studies are contained in Table 5.1. Each case is described in the following subsections.

5.1 Reactor Kinetics Data

The reactor kinetics data were derived from SIMULATE rodded depletion cases. SIMULATE branch cases were performed at the initial power/flow/xenon conditions for the stability test point. From these branch cases, perturbation cases were run with SIMULATE. These perturbation cases were used to determine the change in reactivity for a given change in thermal-hydraulic conditions. The base or reference case provides the steady state axial power shape. Kinetics data sets were derived using a rodded depletion SIMULATE case which had been generated to provide core follow information. The model technique used has previously been proven to give accurate results in comparisons [18] to plant travelling incore probe (TIP) data in terms of predicted versus actual power shape during startup and low power conditions.

Two approaches were tried for the actual generation of kinetics coefficients. In one approach, a small (10 psi) pressure perturbation was imposed on the core and the core average density reactivity coefficient (DRC) and nodal DRC values (as a table of DRC vs. relative water density) determined. This is similar to the method used for plant transients, and mimics the pressure oscillations used to initiate the stability tests at Vermont Yankee. A second method was also tried, which calculated the DRCs from SIMULATE branch cases with slightly different flows. The sensitivity comparison of the two sets of data was carried out for test points 1 and 7. Both methods predicted nearly identical values for the DRCs and the resultant decay ratio values for the tests, indicating that either DRC generation procedure is acceptable.

5.2 Recirculation Loop Gain and Constant

Since the recirculation loop resistance can vary with flow and the operating configuration a sensitivity study was carried out for two Test points, 7 and 12. Test point 7 was carried out under natural circulation conditions, while Test point 12 had two recirculation loops operating. Thus, for the natural circulation test, a wide variation (50%) in the two parameters was tested, since the design value was for two loop operation. For Test Point 12, a narrow variation (10%) was used as a sensitivity study. As shown in Table 6.1, the recirculation loop parameters did not have a large effect on the calculated decay ratio. Therefore, the recirculation loop parameters as calculated are adequate.

5.3 Core Pressure Drop

The core pressure drop and especially the ratio of single phase to two-phase pressure drop are significant factors in the prediction of an instability. The base cases used the two-phase multiplier as a means to obtain the core pressure drop predicted by FIBWR. As a sensitivity to the ratio of single phase to two-phase pressure drop, the single phase losses used in the base case 7 was varied by 10%. To maintain the FIBWR predicted core pressure drop, the two-phase multiplier was the adjusted accordingly. The results show the expected trend, that with additional two-phase pressure drop, the decay ratio increases and with increased single phase loss, the decay ratio decreases. Since the base case was within the accepted accuracy (20%), adjustments were not made to the base value.

5.4 Gap Conductance

The fuel to clad gap conductance directly impacts the power feedback effects of the oscillation. Though the gap conductances (H-gap) used are thought to be accurate representations of the conditions of the tests, a sensitivity study was run on this parameter because of its importance.

The H-Gap values in the base case were ~1200 BTU/hr/ft^2/°F for unpressurized fuel and 2400 BTU/hr/ft^2/°F for pressurized fuel. For the sensitivity study these values were increased to 2400 and 3600, respectively. This change increased the decay ratio and resonant frequency from 0.85 @ 0.34 Hz to 0.89 @ 0.35 Hz. As expected, the increase in fuel energy transfer resulted in a higher decay ratio. Adjustments to the gap conductance values were not warranted since the decay ratio obtained with the modified values did not significantly increase the accuracy of the result.

5.5 Feedwater Temperature

It is well known that a drop in feedwater temperature will cause an increase in the proximity to an instability. The purpose of the sensitivity cases run with LAPUR were to assess the impact on decay ratio of potential variances in the test data. The test data contained less than a 1% error in temperature measurement. For the sensitivity cases a variance of +/- 5°F in feedwater temperature was applied to the test data, resulting in a 0.72°F change in core inlet subcooling. This study was run for Test point 7. The decay ratio increases from 0.85 @ 0.34 Hz to 0.86 @ 0.34 Hz for the higher subcooling. The approach in using the nominal feedwater temperature is appropriate for stability analysis.

5.6 Sensitivity Study Conclusions

The input parameters studied here represent the significant variables which may impact the generation of an exclusion region boundary. The variations used in the sensitivity cases indicate that the LAPUR5 input changes respond as expected. Further, it was found that the use of the nominal input parameters provides a reasonable approach for generating data for stability analysis.

TABLE 5.1

Results of LAPUR Sensitivity Studies

SENSITIVITY PARAMETERS		DECAY RATIO			FREQUENCY (Hz)			TEST POINT ID
		Sensitivity	Base	Test	Sensitivity	Base	Test	
Recirc Loop Gain	50% High	.94	.85	1.0	.34	.34	.43	7
	50% Low	.73	.85	1.0	.34	.34	.43	7
Recirc Loop Time Constant	50% High	.82	.85	1.0	.34	.34	.43	7
	50% Low	.85	.85	1.0	.35	.34	.43	7
Fuel H-gap Conductance	High H-gap (+1200)	.89	.85	1.0	.35	.34	.43	7
Core Pressure Drop	10% High	.82	.85	1.0	.34	.34		7
	10% Low	.89	.85	1.0	.34	.34		7
Feedwater Enthalpy	-5 Btu/lb	.86	.85	1.0	.34	.34	.43	7
	+5 Btu/lb	.85	.85	1.0	.34	.34	.43	7

6.0 GENERATION OF THE EXCLUSION REGION BOUNDARY

This section illustrates the use of the exclusion region methodology by demonstrating the generation of the power/flow boundary from the Cycle 15 stability calculations.

6.1 Derivation of Exclusion Region Boundary

In the BWROG methodology, several operating conditions enveloping the expected exclusion region boundary are selected for calculation of stability margins. These operating conditions are referred to as probe points. Probe points are chosen to bracket the exclusion region intercept with the natural circulation line, while additional points bracket the region intercept with the rated rod line. Additional probe points are chosen near the boundary or intermediate power/flow conditions. The probe point decay ratios are obtained through analysis via the BWROG methodology. These values were interpolated to determine the location of the exclusion boundary using a decay ratio of 0.8. This value represents the BWROG criteria for determining the conditions for oscillation.

The power/flow points forming the exclusion region boundary are fit to a quadratic equation to enable location of the boundary. The next section provides an example of the exclusion boundary creation and a comparison to the vendor calculations.

6.2 Exclusion Region Calculation Comparison

Using the eight probe points taken from Table 4.3, shown in Table 6.1, decay ratios were calculated using the YAEC application of the BWROG methodology. These values were interpolated to determine the exclusion region boundary points listed in Table 6.2. The exclusion region calculated with the YNSD method is shown Figure 6-1.

The exclusion region methodology calculations may also be used to determine a plant's susceptibility to a regional oscillation. Figure 6-2 presents the Cycle 15 core and channel decay ratio for the YAEC application plotted on the BWROG criteria map. Generally, a high channel decay ratio indicates a tendency for regional oscillations. As shown for the Vermont Yankee calculations, sufficiently low decay ratio exists for the hot channel to conclude regional oscillations are of low probability.

TABLE 6.1

Results of LAPUR Probe Point Analysis

Test Point	% Power	% Flow	LAPUR Decay Ratio
6	41.0	30	.87
7	36.9	30	.66
1	67.4	45	.90
2	60.7	40	.96
9	44.7	34.4	.89
10	44.7	39.4	.76
11	53.9	38.7	.90
12	53.9	43.7	.76

TABLE 6.2

Cycle 15 Exclusion Region Boundary Points[22]

Flow %	Power %
30	39.83
37.90	44.70
42.24	53.90
45	57.80

Using the Cycle 15 analysis as a guide, the eight probe points projected for analysis of future cycles include:

1 & 2) 36.9P/30F and 41.9P/30F. These two points bracket 36.71% power/30% flow.

3 & 4) 57.P/45F and 60.7P/40.0F. These two points fall on the 100% rod line and bracket 64.7% power/45% flow.

5 & 6) 44.7P/34.4F and 44.7P/39.4F. These two points bracket 44.7% power/37.48% flow.

7 & 8) 53.9P/38.7F and 53.9P/43.7F. These two points bracket 53.9P% power/41.97% flow.

These four core decay ratio pairs will be interpolated to determine the power/flow operating conditions for the decay ratio limits specified in Section 7.1 above.

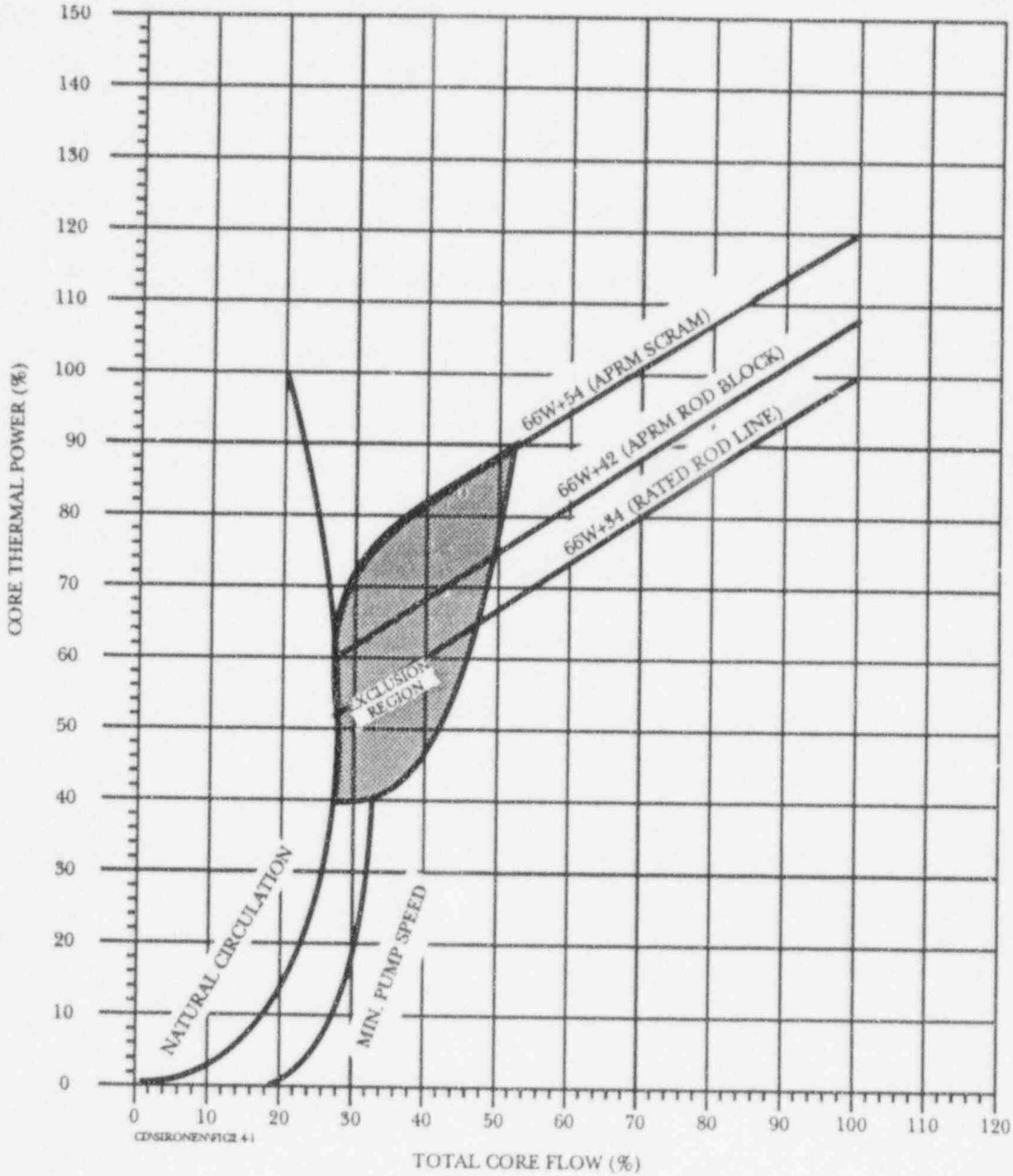

FIGURE 6-1

Example Exclusion Region Calculation for VY

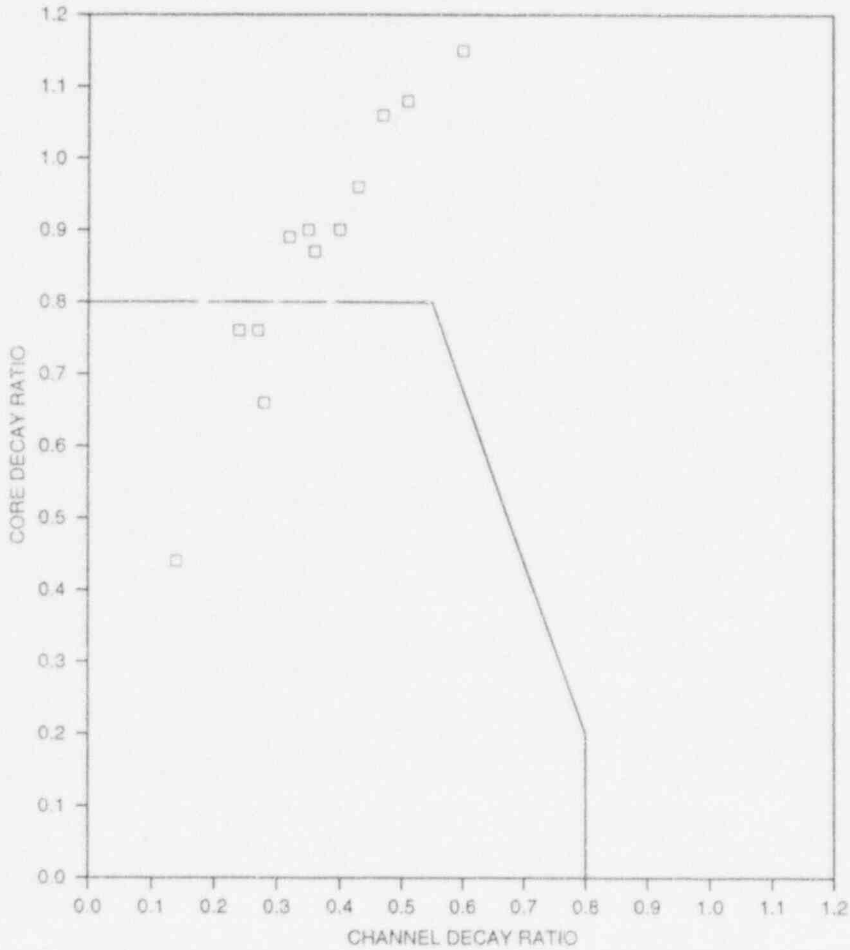

FIGURE 6-2

Cycle 15 Stability Criteria Map

7.0 CONCLUSIONS

The results presented demonstrate that LAPUR provides overall good agreement with stability test data and with the fuel vendor calculated decay ratios for Vermont Yankee. LAPUR5 predicted the decay ratios within 0.2 at the higher decay ratios. The sensitivity studies (Section 5) performed with the LAPUR5 code support the range of accuracy observed in the benchmark cases. Each study provided insight on the modeling techniques used as well as the proper procedure to integrate the LAPUR5 computer code with the existing reload analysis codes to predict plant specific stability exclusion regions for operating BWRs. The YAEC application of the BWROG exclusion region methodology provides a valid means of conservatively deriving power/flow conditions for a given fuel cycle.

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