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Application of One-Dimensional Kinetics
to
Boiling Water Reactor Transient Analysis Methods

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ABSTRACT

This report presents a description of the application of the RETRAN one-dimensional kinetics neutronic feedback option to the Boiling Water Reactor transient analysis methods. The ability of the model to predict licensing basis transients is verified through comparison to Vermont Yankee results from the current point kinetics analysis, vendor calculations, and the recirculation pump trip test performed at Vermont Yankee in 1981. The intended application to generate operating limits is further supported by comparison against results of an alternate, statistical method which demonstrates the conservatism in the approach.

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1.0 INTRODUCTION

Yankee Atomic Electric Company (YAEC) currently uses the RETRAN computer code to analyze limiting transients and establish operating Minimum Critical Power Ratio (MCPR) limits for Boiling Water Reactor (BWR) reload analysis. The analysis methods, which received NRC approval in [1, 2], use the point-kinetics modeling option to represent transient-induced neutronic feedback. The RETRAN code, which has received generic NRC approval in [3], also contains a one-dimensional kinetics neutronic feedback model option which provides a more accurate transient power prediction than the conservative point-kinetics model. The inclusion of the one-dimensional kinetics model in YAEC's BWR analysis methods will be consistent with other approved methods for analyzing BWR reloads. This report documents the extension of YAEC's approved method to qualify the one-dimensional kinetics modeling option in RETRAN for use in future BWR transient analyses. The methods are verified through comparison to Vermont Yankee results from the current point kinetics analysis, vendor calculations, and the recirculation pump trip test performed at Vermont Yankee in 1981.

2.0 DESCRIPTION OF CURRENT LICENSING METHOD

2.1 General

The Boiling Water Reactor (BWR) RETRAN point-kinetics analysis method was approved by the NRC for Vermont Yankee Cycle 9. The analysis methods were submitted to the NRC for review in References [4, 5, 6] and received approval for use via References [1, 2]. The methods include a systems level calculation with point kinetics to determine the core wide power response to an anticipated event and a single fuel assembly model to calculate the limiting or hot channel response. A flow chart of the analysis process is shown in Figure 2.1.1 These methods have been used to support Vermont Yankee Cycles 9-14 reload analysis.

2.2 Current Methods Qualification

The current BWR reload licensing method utilizes the RETRAN-02 code for the core wide and hot channel analysis of the limiting events. RETRAN has received generic approval for use in licensing applications [3]. RETRAN has been used extensively by utilities and consultants to analyze a variety of transient thermal-hydraulic problems. The base RETRAN documentation [7] contains reports on comparisons of RETRAN results to separate effects tests, system effects tests, and power reactor startup and special tests. The Vermont Yankee model was built on this base level of qualification data through application of the BWR methods to analysis of:

1. Vermont Yankee startup tests [4].

2. The Peach Bottom series of turbine trip tests using Vermont Yankee methods to define the RETRAN input [4].

3. The Peach Bottom representative licensing analysis [6].

4. Sensitivity studies on various types of transients to provide assurance that a converged solution was obtained with the chosen method technique [4].

5. Comparisons to steady state and transient boiling transition data [5].

The results of these evaluations as well as reload analysis for the past five Vermont Yankee fuel cycles [References 8, 9, 10, 11, 12] have shown that the Vermont Yankee RETRAN model can predict a wide variety of transients and conservatively predict MCPR operating limits for reload cycles.

2.3 Licensing Analysis Methods

Past licensing analyses show that the anticipated events which result in the minimum core thermal margins for Vermont Yankee are:

1. Generator load rejection with complete failure of the Turbine Bypass System (GLRWOBP).

2. Turbine trip with complete failure of the Turbine Bypass System (TTWOBP).

3. Loss of Feedwater Heating (LOFWH).

These events are typically analyzed at exposure points at End of Full Power Life (EOFPL), EOFPL-1,000 MWd/St, and EOFPL-2,000 MWd/St. The loss of feedwater heating is also analyzed at Beginning of Full Power Life (BOFPL). Of the three thermal margin transients and exposure points, the TTWOBP at EOFPL produces the largest change in critical power ratio, and results in the most limiting MCPR operating limit. For the purposes of this report, the Cycle 9 TTWOBP at EOFPL has been used as the demonstration case. The Vermont Yankee TTWOBP is used in all phases of demonstrating the extension of the BWR licensing methodology.

The TTWOBP (and GLRWOBP) are pressurization transients whose power surge is eventually terminated by a reactor scram. The scram times assumed in the licensing analysis directly impact the calculated MCPR. The scram times that have been used are those expressed as the Technical Specification limits. There are two scram times in the Technical Specifications commonly referred to as Measured Scram Time (MST) and 67B. The times to four different insertions are presented in Table 2.3.1 for each scram time. The 67B scram based MCPR limits are a conservative backup to MST based limits in the event the periodic plant measurements indicate test times exceed MST.

As a conservative bound to the expected plant thermal power, the current licensing analysis assumes the power level to be 104.5% of the licensed value of 1,593 MW or 1,664 MW. This value corresponds to the actual steam flow limit of the turbine generator set and bounds any expected calorimetric measurement uncertainty. The typical deterministic uncertainty assumed to bound plant calorimetric power is 2%.

The transient power response is currently calculated using the classical point-kinetics model in RETRAN, which contains six delayed neutron groups and the 11 group fission decay model. The point-kinetics model assumes a fixed transient power shape for transient calculations due to its lack of spatial dependence. Briefly, the point-kinetics model, as applied in the Vermont Yankee methods, accounts for the reactivity effects of scram, moderator, and fuel temperature changes. Further details of the core power response model can be found in [4]. The methodology used in generating the RETRAN input kinetic parameters, scram reactivity, and feedback reactivity functions is addressed in the Vermont Yankee Core Physics Methods Report [13].

The thermal hydraulics of the reactor vessel is modeled in the core region with a Homogeneous Equilibrium Model (HEM) and 12 fluid volumes. Each fluid volume has a heat conductor with power of the heat conductor determined by the point-kinetics model. In essence, there are 12 separate point-kinetics nodes whose power feedback is determined by the relevant thermal hydraulic and heat conductor state properties existing at each of the axial levels. The relative contribution of each axial level is determined by the fixed axial power profile.

TABLE 2.3.1

Vermont Yankee Technical Specification Scram Speed Time Limits*

Position (% Inserted)	Time to Position (sec)	
	MST	67B
4.51	.358	.358
25.34	.912	1.096
46.18	1.468	1.860
87.84	2.686	3.419

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*These scram times are assumed in the licensing analysis.

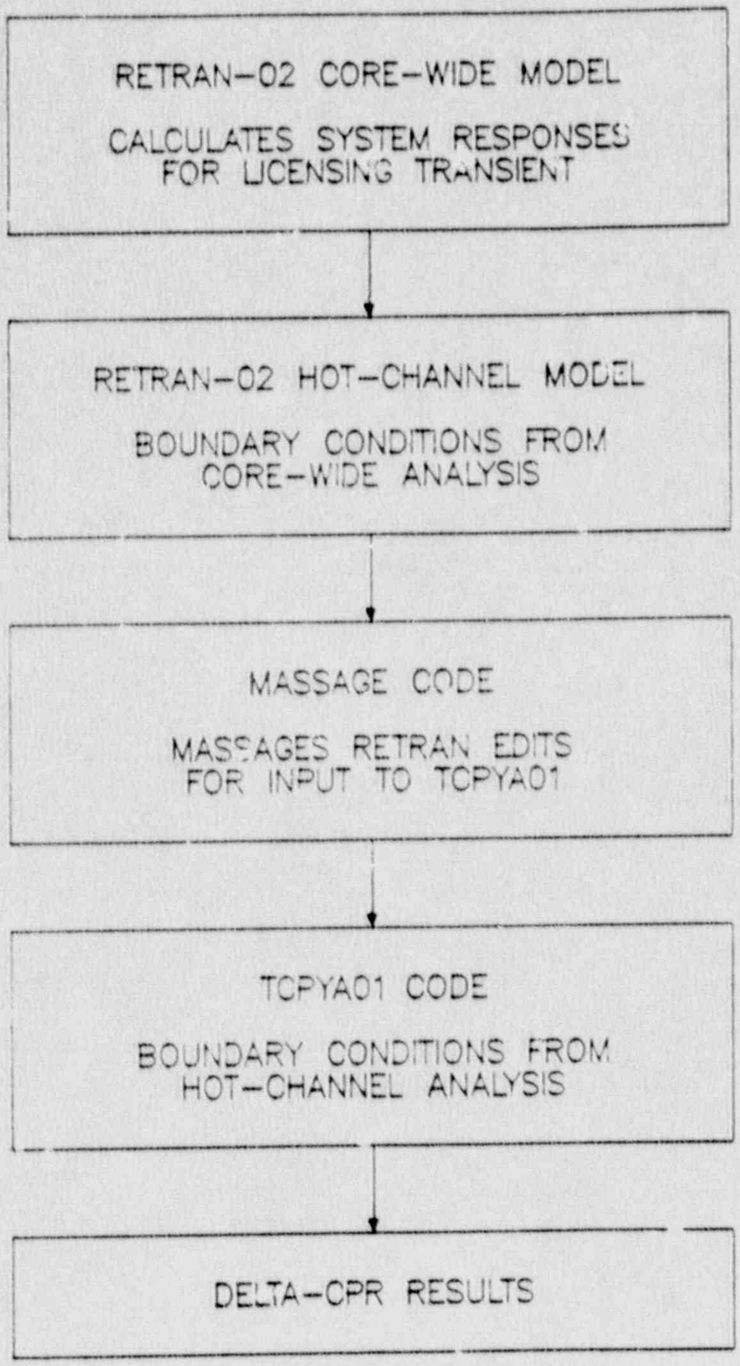

Figure 2.1.1

VERMONT YANKEE RELOAD ANALYSIS FLOW CHART

3.0 DESCRIPTION OF THE APPLICATION OF THE ONE-DIMENSIONAL KINETICS OPTION

The focus of this section is to describe the extension of the current licensing methods to the application of the one-dimensional kinetics option in RETRAN. The application of one-dimensional kinetics has resulted in other minor changes to the modeling to align the model for use of the more explicit neutronic feedback option. In particular, the algebraic water steam slip and subcooled void model options are utilized as opposed to the HEM option used in the point-kinetics application. Minor refinements in the reactor vessel model nodalization have been made to accommodate reflector regions for one-dimensional kinetics as well as to describe the actual core flow and bypass flow more precisely during the transient.

Section 3.1 describes the changes to the Vermont Yankee system level or core-wide model, including the use of one-dimensional kinetics, which was used to verify these methods. Section 3.1 also provides a discussion of the impact of the minor model refinements beyond the one-dimensional kinetics application. Section 3.2 is a brief summary of the methods used to generate the kinetics data for the core-wide model. Section 3.3 describes changes to the single channel or hot channel methods.

3.1 Core-Wide Model Modifications

This section describes the application of the RETRAN one-dimensional kinetics option, the slip and subcooled void options, and the vessel nodalization refinements made to the Vermont Yankee RETRAN core-wide model. All other aspects of this model remain unchanged from the point-kinetics version described in [4] and approved in [1, 2].

The core-wide model nodalization for the one-dimensional kinetics option is shown in Figure 3.1.1. To accommodate the reflective boundary conditions used in the one-dimensional option, Volumes 200 and 213 have been added. They represent lower and upper regions of the core adjacent to the fuel. Volumes 201 - 212 represent the active core region as in the current licensing model. Twenty-seven separate neutronic regions are modeled for consistency with the three-dimensional physics model. Each of the inactive core volumes (Volumes 200 and 213) contain one neutronic region.

Volumes 201-211 contain two axial neutronic regions and Volume 212 contains three axial regions. Each neutronic region receives appropriate cross section fitting coefficients from the SLICK code described in [14].

The multiple control state model is used with two control states for the pressurization events. The initial control state is either all rods out for EOFPL conditions or an appropriate state representing partial insertion of various control rods for exposure states prior to EOFPL. The final state is fully rodded, modelling post-scram conditions. The initial conditions represent a critical reactor state.

Twelve neutronic radial mesh intervals are used per neutronic region. This number of mesh intervals is based on dividing the fuel pin into intervals to approximate the mean free path of a neutron. A sensitivity analysis was performed on this parameter to optimize the number of mesh intervals.

A sensitivity analysis was performed to evaluate the required update frequency for the axial shape function. The sensitivities have shown that for severe pressurization events, it is necessary to update the axial shape function every timestep.

Minor modifications to the thermal hydraulic nodalization and options used in the Vermont Yankee point-kinetics model were made to make use of one-dimensional kinetics and more accurately represent the bypass flow during a transient. As discussed above, the reactor vessel nodalization has changed with the addition of Volumes 200 and 213 (see Figure 3.1.1) which represent the upper and lower inactive core regions. Individual representation of flow entering the fuel assembly water tubes versus flow entering the active core flow has been added to allow the fraction of flow entering the water tubes and core to vary during the transient. Junction 198 models the active core flow plus water tube flow, Junction 199 models the fuel bundle water tube flow, and Junction 200 the active core flow. As with the other core bypass flows lumped into Junction 16, the initial flow of Junction 198 is calculated using the FIBWR code [18].

The algebraic slip option is used in the core-wide model. It is the standard model used with one-dimensional kinetics for analysis of abnormal operational transients. The subcooled void option is also employed to more accurately describe the neutronic feedback in the subcooled regions of the core. These models are consistent with the three-dimensional physics code, SIMULATE-3, from which the one-dimensional physics data set is derived. Sensitivity analysis have been performed on each of these minor thermal-hydraulic model refinements. The results of the sensitivity analysis demonstrates that these refinements have a negligible impact relative to current methods.

3.2 Generation of Kinetics Data

The details of the methodology for the generation of the one-dimensional cross sections and kinetics parameters are presented in Reference 14. The general approach taken in developing the kinetics data is very similar to YAEC's current methodology [13]. The aim of the method is to take the neutronics effects as predicted by the three-dimensional nodal simulator, SIMULATE-3 [19], and functionalize them with the feedback variables used by RETRAN. This is achieved by running multiple SIMULATE-3 perturbation cases for each of the two control states. The types of perturbation cases run are representative of the transient of interest and cover the range of density and fuel temperature encountered during the transient. SIMULATE-3 also performs the spatial homogenization of the kinetics data and produces all the cross sections and kinetics parameters needed by RETRAN.

The SIMULATE-3 model [19] is used to predict the neutronic response of the core. In generating the kinetics data, the EPRI void model [20] is used. The EPRI void model is the basis of the algebraic slip and subcooled void models in RETRAN. Furthermore, it is the model used in the neutronics portion of our previous method [13]. To provide some insight into the differences between the new physics methods and our previous methods, a comparison of pressure and Doppler coefficients is presented in Table 3.2.1. The coefficient data presented is representative of the perturbation cases run to produce kinetics data for a licensing basis pressurization transient. The pressure coefficient is based on a three-dimensional calculation where the core pressure is perturbed with the thermal power and fuel temperature distributions fixed at the initial state condition. Thus, the pressure coefficient is a measure of void reactivity. The Doppler coefficient is produced by varying the three-dimensional temperature distribution while the density distribution is held constant. In performing these perturbation calculations, all other variables normally associated with cross sections (exposure, control history, fission product inventory, etc.) are held constant at the initial state condition. Data for two cycles at end of full power life conditions are presented. The results of the perturbation calculations show that there is very little difference in the pressure and Doppler coefficients produced by the new and previous physics methods.

The thermal-hydraulic model used in the generation of the kinetics data is virtually identical to the actual RETRAN model. Comparisons between this model and RETRAN results have been presented in Reference 14.

3.3 Hot Channel Model Modifications

3.3.1 Current Hot Channel Methods

Analysis of the limiting hot channel is performed to derive the change in Critical Power Ratio (ΔCPR) during the transient to derive the Operating Limit Minimum Critical Power Ratio (OLMCPR). The GEXL correlation is used in this analyses to predict transition boiling. The system level or core-wide analysis provides transient boundary conditions for the RETRAN hot channel analysis. The lower and upper plenum transient thermal hydraulic conditions and active core region core power fractions are the boundary conditions used in the RETRAN hot channel model. The hot channel runs also result in boundary conditions to drive the TCPYA01 computer code [5]. The results of the TCPYA01 runs are the Initial Critical Power Ratio (ICPR), the minimum CPR during the event analyzed and the decrease in CPR. The initial power level is chosen such that MCPR is the safety limit. Thus, the ICPR becomes the Operating Limit MCPR (OLMCPR).

3.3.2 Hot Channel Model Modifications

The RETRAN hot channel model has been changed to maintain modelling consistency with the one-dimensional kinetics core-wide model nodalization (see Figure 3.1.1). The significant changes include the core bypass region (Volume 11, and Junctions 16, 18, and 199). Other nodalization adjustments are the addition of the upper and lower inactive core regions as Volumes 201 and 113 which are joined to the plenums and active core region with Junctions 1, 13, 198, and 213. The core bypass region is being explicitly represented in both the core wide and hot channel models. This allows the bypass flow to vary during the transient. The bypass region models all core bypass flow paths, while the core region model is a single fuel bundle. As with the core-wide model, the steady-state flows within the lumped bypass (Junction 16), the water tubes (Junction 199), and the hot channel (Junction 1) are determined by the FIBWR computer code. For each hot channel initial power, the FIBWR code is used to determine the bypass and active core flow splits using the same limiting 1.4 chopped cosine axial power distribution input in the hot channel model. The algebraic steam water slip model is employed for consistency with the core-wide model.

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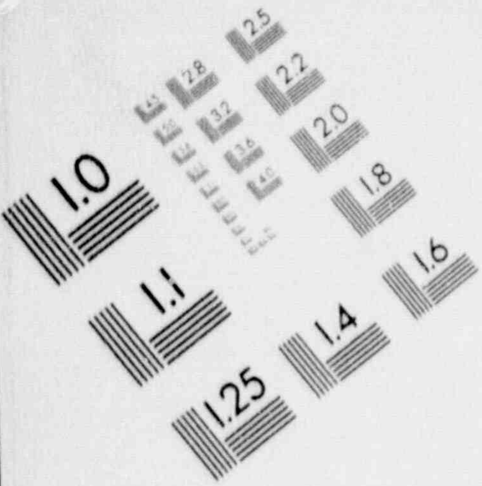

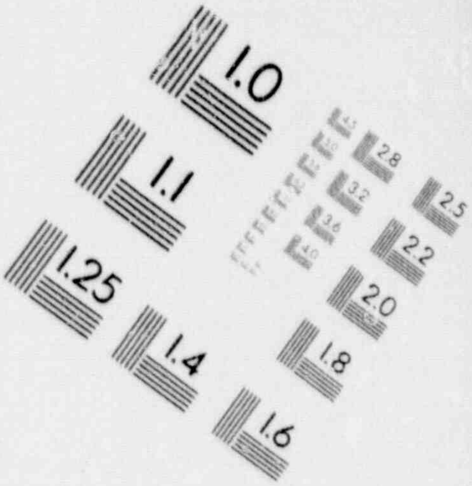

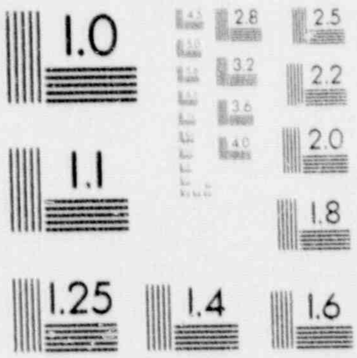

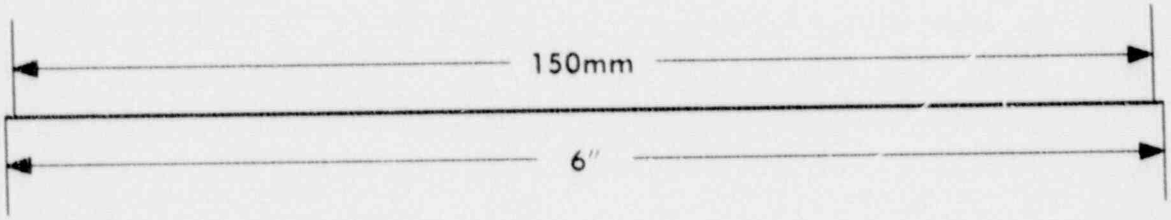

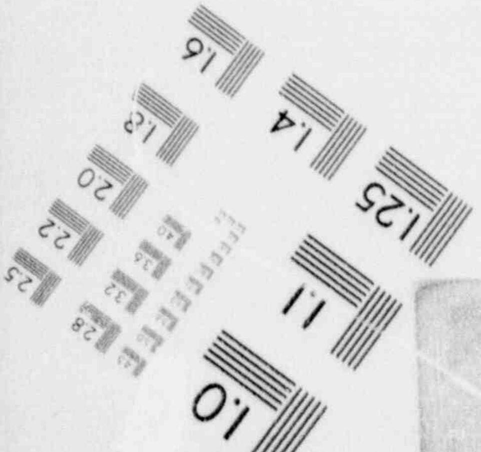

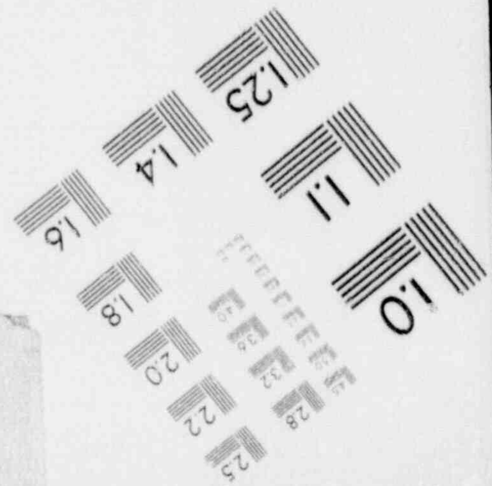

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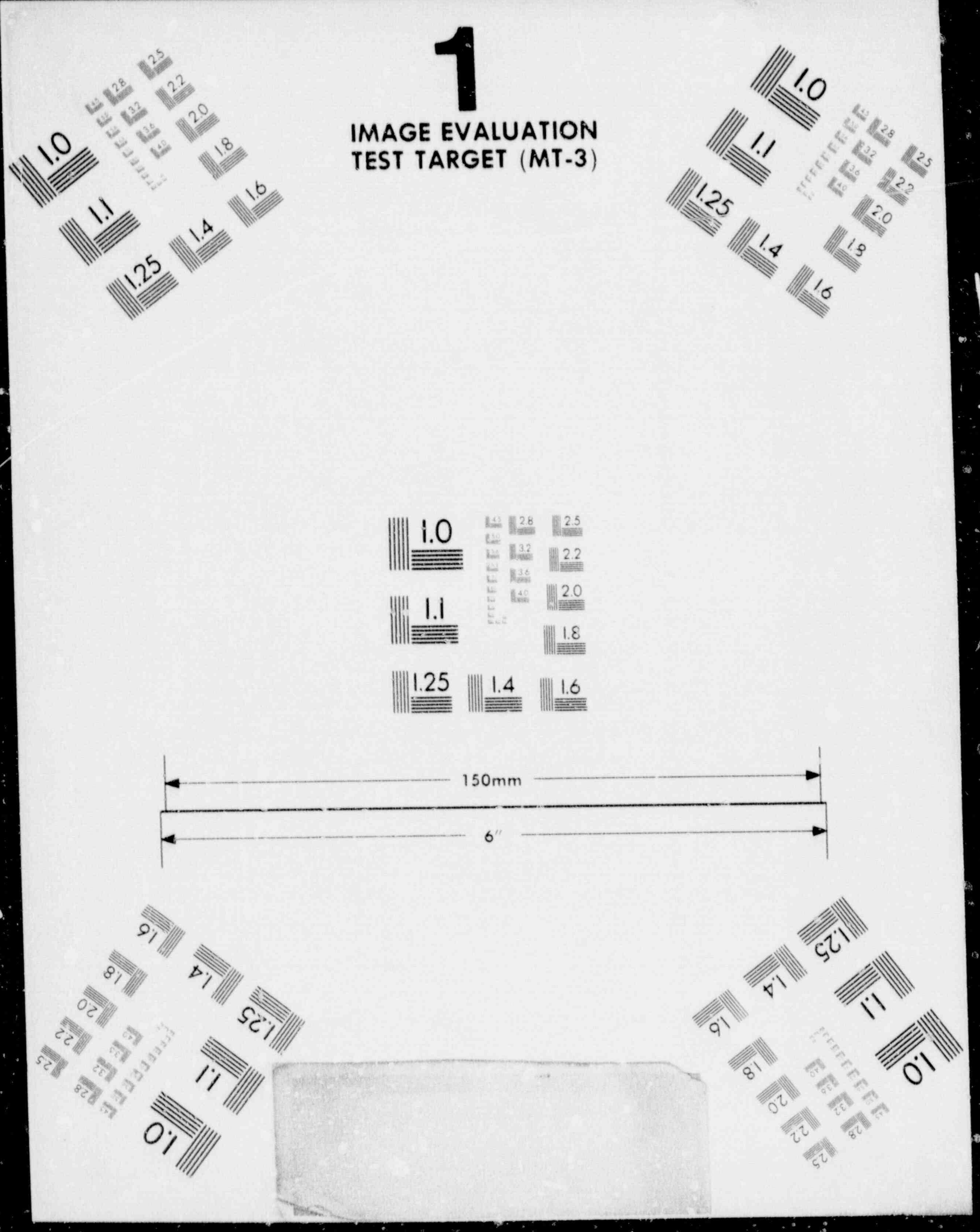

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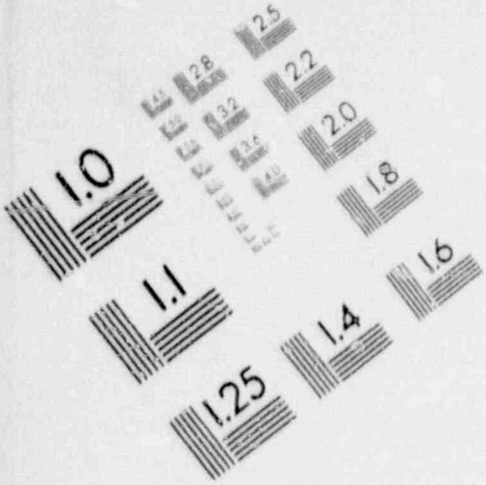

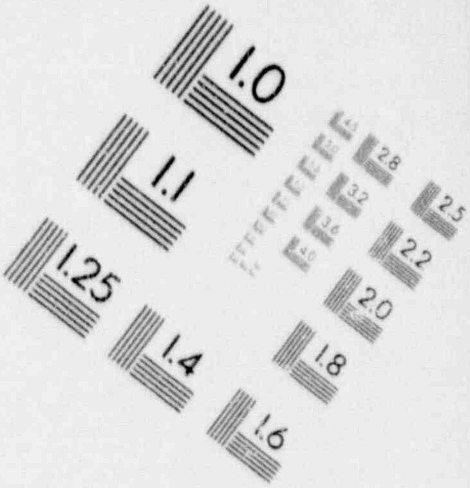

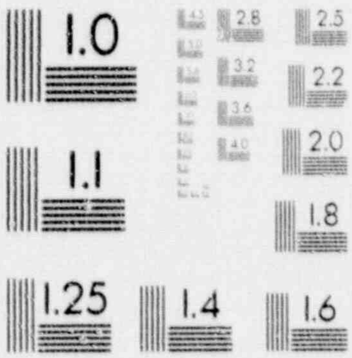

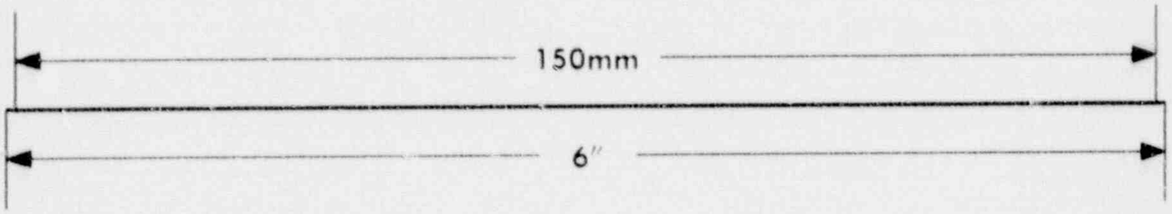

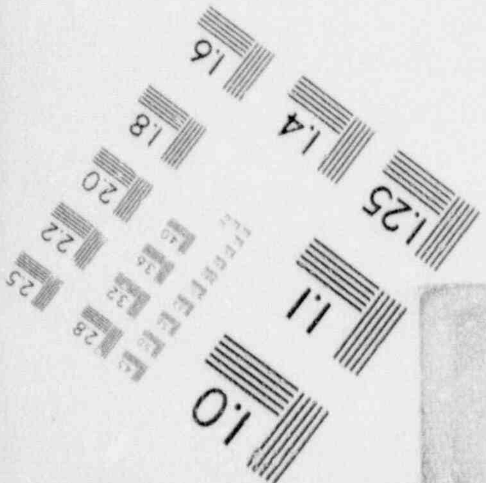

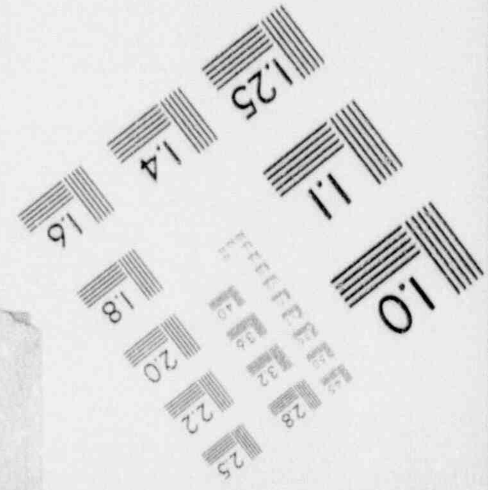

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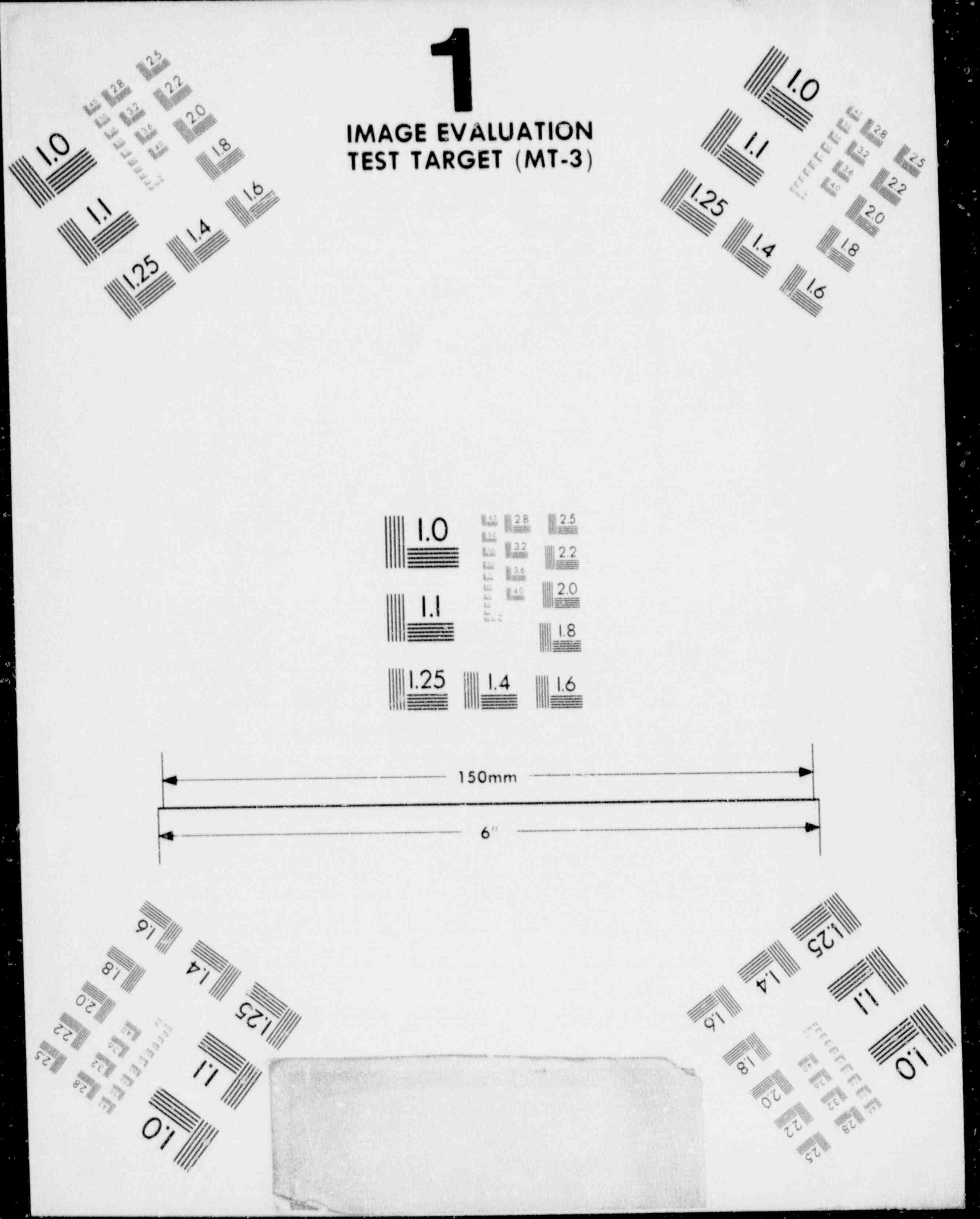


TABLE 3.2.1

Reactivity Coefficients Produced With Previous and New Reactor Physics Methods

	Doppler Coefficient (pcm/F)*		Pressure Coefficient (pcm/psi)	
Condition	Previous** Methods	New*** Methods	Previous Methods	New Methods
Cycle 9 EOFPL	-1.46	-1.43	+8.34	+8.47
Cycle 13 EOFPL	-1.57	-1.55	+8.26	+8.07

Notes

*pcm = $(k_{eff\text{-}perturbation} - k_{eff\text{-}initial})/k_{eff\text{-}perturbation} * 10^5$.

**Lattice calculation with CASMO-1; 3-D nodal calculation with SIMULATE-YA.

***Lattice calculation with CASMO-3; 3-D nodal calculation with SIMULATE-3.

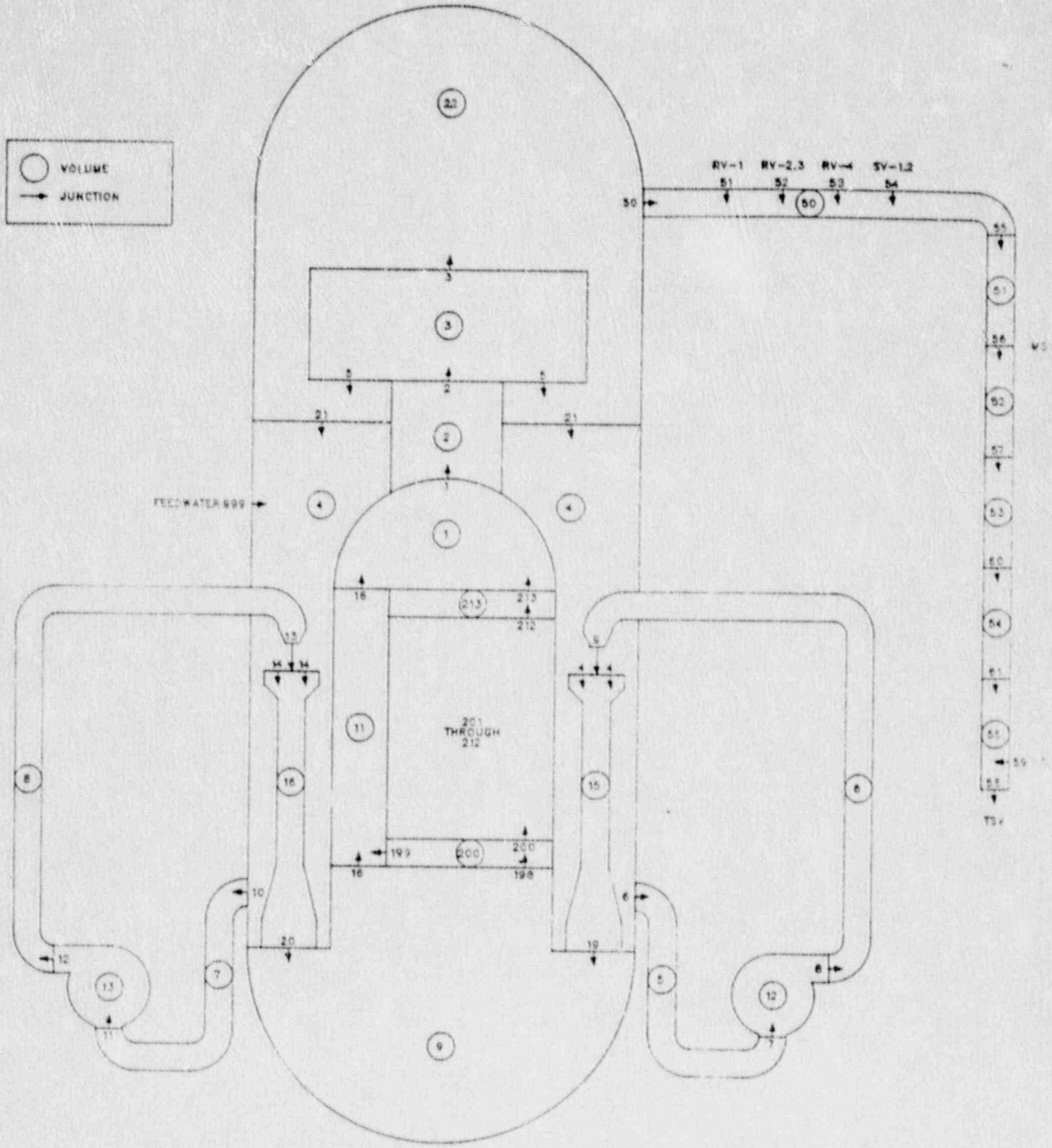


Figure 3.1.1

VERMONT YANKEE CORE WIDE RETRAN MODEL NODALIZATION

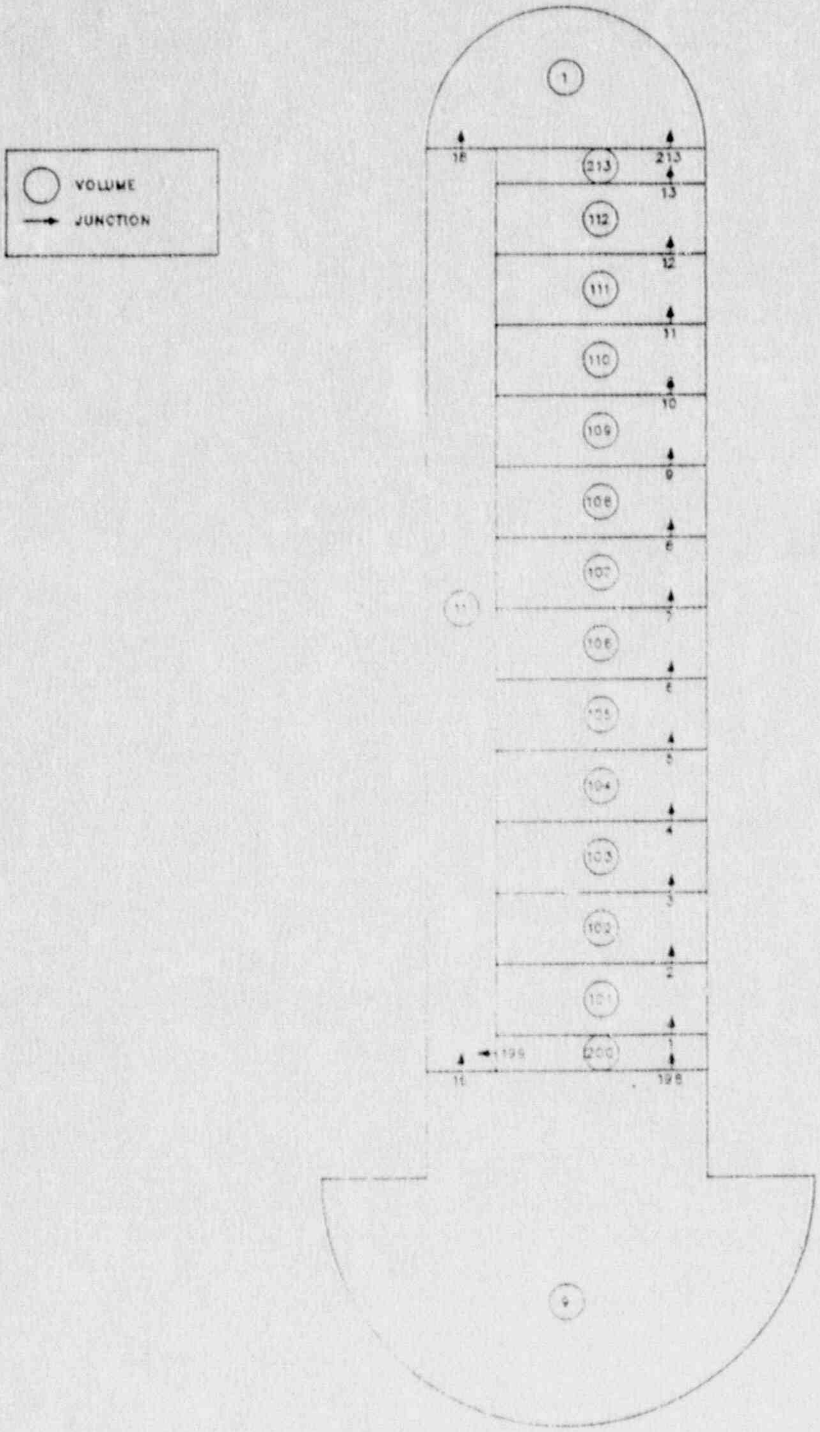


Figure 3.3.

VERMONT YANKEE HOT CHANNEL RETRAN MODEL NODALIZATION

4.0 VERIFICATION OF ONE-DIMENSIONAL KINETICS APPLICATION

An extensive effort has been made to verify the application of one-dimensional kinetics in the RETRAN model. The verification consists of comparison to:

- Previous qualification of the point-kinetics method through the Peach Bottom turbine trip tests and Peach Bottom representative licensing case.
- The current Vermont Yankee results using the point-kinetics method.
- Vendor (General Electric (GE)) one-dimensional kinetics calculations for Vermont Yankee.
- Vermont Yankee data via the Cycle 8 Recirculation Pump Trip (RPT) test.

The verification effort addresses a wide-range of analysis to demonstrate the adequacy of the one-dimensional kinetics application. It is the integrated set of comparisons listed that make up the verification of the one-dimensional kinetics application.

The analysis previously completed to compare with the Peach Bottom tests demonstrates the method's ability to predict mild pressurization events and points out the conservatism in the methods. The Peach Bottom representative licensing case simulates a severe pressurization event. In comparison to others (GE and Brookhaven National Laboratory) who have also analyzed the licensing case, YAEC's BWR point-kinetics method was shown to be a conservative predictor of integrated transient power and thus MCPR operating limit. The comparison of Vermont Yankee results using point and one-dimensional kinetics methods demonstrates consistancy in the application of the one-dimensional kinetics option. The similarity of YAEC's BWR one-dimensional kinetics method to other approved one-dimensional methods is shown by comparison to GE licensing calculations carried out for Vermont Yankee Cycle 9. Analysis of the Vermont Yankee Cycle 8 RPT test allows comparison of the one-dimensional kinetics application to actual plant data.

4.1 One-Dimensional Versus Point-Kinetics Application

4.1.1 Review of Previous Qualification Work

A review of part of the previous analyses to qualify the point-kinetics method is presented to highlight important results relative to the extension of the methods to one-dimensional kinetics. Reference 4 discusses the results of a comparison to the Peach Bottom series of turbine trip tests. The Peach Bottom turbine trip tests were mild pressurization events whose power transients were overturned by the increase in voiding within the core. In contrast, the power transient for a more severe licensing basis pressurization event requires core voiding and scram reactivity to turn the transients. Figures 4.1.1 though 4.1.3 are comparisons of YAEC's point-kinetics methods results to the Peach Bottom tests (TT1, TT2, and TT3) for the neutron power response repeated from Reference 4. The figures show that YAEC's methods overpredicted the Peach Bottom power responses. The thermal-hydraulic responses of this modeling approach were in good agreement with the test data except for steam dome pressure which was higher due to the overpredicted power. Thus, the comparison to the Peach Bottom tests proved that the point-kinetics method would overpredict the response to a pressurization event which is a conservative treatment for licensing analysis. These comparisons demonstrate the point-kinetics method conservatively predicts the transient thermal-hydraulic response of a BWR.

Reference 6 discussed results of a representative licensing case analysis of a Peach Bottom 2 Turbine Trip Without Bypass (TTWOBP) using the point-kinetics method. This analysis has become a standard analysis for those qualifying BWR methods. At the time the YAEC's analysis was carried out, Brookhaven National Laboratory (BNL) and GE had also analyzed the Peach Bottom 2 TTWOBP problem. Reference 6 contains comparison of the point-kinetics response to BNL and GE. This comparison allows a more representative assessment of the neutronic feedback mechanisms and response to a severe pressurization event in line with the intended application of the method.

The point-kinetics analysis methods for the standard Peach Bottom licensing problem resulted in a more severe transient simulation than either BNL or GE by generation of more power before the transient is suppressed by the scram. The prediction of the neutron power compared to BNL or GE is shown in Figure 4.1.4. Note that YAEC's methods case predicts the generation of more energy and results in a more severe event.

Overall, YAEC's point kinetics method results in a more conservative simulation of a severe pressurization event due to the generation of more energy.

4.1.2 Comparison of Point and One-Dimensional Kinetics Methods

A comparison of the Vermont Yankee results using the point and one-dimensional kinetic methods is shown in Figures 4.1.5 through 4.1.10. The event-simulated was the EOFPL Cycle 9 TTWOBP using the MST Technical Specifications scram times. This event set the operating limit for end of Cycle 9. The one-dimensional kinetics case responds faster to the pressurization and is terminated more quickly by scram than the point-kinetics method. This difference in behavior of the point and one-dimensional kinetics is consistent with that shown in studies by EPRI in Reference (17).

In addition to the core-wide simulation of the Vermont Yankee Cycle 9 TTWWOBP, the hot channel analysis was performed to determine the differences in transient ΔCPR. The point-kinetics model yielded a .23 ΔCPR, whereas, the one-dimensional kinetics predicted a .18 ΔCPR. The gain of 0.05 is attributed to the more accurate modelling of the axial power shape change (during a severe overpressurization event like the TTWOBP) associated with one-dimensional kinetics. This gain is consistent with the observed differences in response between the two methods. The predicted ΔCPR from the one-dimensional kinetics calculation is also consistent with vendor calculation as discussed in Section 4.1.3.

The conclusions that may be drawn from the point kinetics and one-dimensional kinetics comparison are:

- The differences of the neutron power response of the point and one-dimensional kinetics applications is as expected and consistent other calculations in Reference (17).

- The difference is attributed to explicit representation of the axial power shape changes during the transient.

- The one-dimensional kinetics model and subsequent hot channel analysis shows a decrease in transient ΔCPR of .05 over the point-kinetics analysis for the same Vermont Yankee Cycle 9 TTWOBP at EOFPL. This is consistent with the neutron power differences and consistent with vendor calculations (Section 4.1.3).

4.1.3 Comparison to Vendor Calculations

Comparisons to vendor one-dimensional kinetics (GE) calculations for Vermont Yankee Cycle 9 (Reference 15) were carried out to show the similarity of one-dimensional kinetics methods and a previously approved one-dimensional kinetics method which was also compared to the Peach Bottom turbine trip tests. The transient simulated was a Vermont Yankee Cycle 9 TTWOBP. GE used 67B Technical Specification scram times, so the one-dimensional kinetics case described above was changed to the 67B scram times and run. The results of the comparison are shown in Figures 4.1.11 through 4.1.15. The neutron power responses (Figure 4.1.11) are nearly identical. The peak neutron power predicted by GE was 528%, while YAEC's one-dimensional methods resulted in 530%. The pressure response of the two simulations is compared in Figure 4.1.14. The overall Vermont Yankee one-dimensional kinetics results are in good agreement with the vendor's calculations.

A hot channel simulation was carried out with YAEC's one-dimensional method. The resulting transient ΔCPR was 0.22, which is similar to the vendor's calculation of 0.21.

The comparison to the vendor calculation demonstrates:

- The neutron power and steam dome pressure response are nearly identical, thus, demonstrating the similarity of both the neutronic and thermal-hydraulic modeling.

- YAEC's one-dimensional kinetics method behaves similar to an approved vendor method.

4.2 Reactor Coolant Pump Trip Test Comparison

A simulation of the Vermont Yankee Cycle 8 recirculation pump trip test was performed with the Vermont Yankee one-dimensional kinetics model. The simulation shows the ability of the modeling methods to predict actual plant data.

The Cycle 8 RPT test was initiated from 82.9% power and 86% core flow conditions by the simultaneous trip of the Motor Generator (MG) set drive motors from the control room. The MG set trip resulted in a power and flow coast to 43% power/32% flow under natural circulation conditions. The Vermont Yankee RETRAN models were initialized at the test conditions using the plant data summarized in Reference 16 and employing the same techniques used in the licensing model. One-dimensional kinetics physics data was generated for the RPT test conditions using the same methods employed for licensing conditions via the SLICK code discussed in Section 3.2 and Reference 14.

Figures 4.2.1 through 4.2.5 show the results of the RPT test simulation. The flow response is largely a function of the inertial characteristics of the Recirculation System, with a secondary influence resulting from the core reactivity characteristics. The MG set speed (Figure 4.2.5) predicted by the models is an accurate match to the test data. The simulated core flow (Figure 4.2.3) follows the test data closely indicating the thermal-hydraulic and recirculation's control systems are properly modeled. The core power (Figure 4.2.1) matches the plant data well, verifying that the core reactivity characteristics are properly simulated.

This comparison of the Vermont Yankee one-dimensional kinetics RETRAN application to plant test data clearly demonstrates the continued accuracy of the physics and transient analysis methods.

4.3 Summary of Verification Effort

The verification effort has demonstrated that application of YAEC's BWR one-dimensional kinetics modeling option responds accurately when compared to test data and a variety of other analysis. The comparisons have verified that:

- The basis for the one-dimensional kinetics RETRAN modelling method, the point-kinetics modelling method, is a conservative predictor of transient power as demonstrated in the Peach Bottom turbine trip test comparisons.

- The point kinetics method results in a conservative simulation of a severe pressurization event in comparison to either the GE or BNL result in the Peach Bottom licensing case.

- The differences in transient ΔCPRs are as expected, the one-dimensional kinetics methods results in a smaller ΔCPR (.18) than the point kinetics method (.23) in response to the typically limiting Vermont Yankee transient (TTWOBP, measured scram time).

- YAEC's one-dimensional kinetics methods compare very well to approved vendor calculations.

- The one-dimensional kinetics methods predict the Vermont Yankee Cycle 8 RPT test data accurately.

The verification effort shows that the one-dimensional kinetics application is appropriate for simulation of both mild and severe thermal-hydraulic transients. The use of one-dimensional kinetics option in severe pressurization events, used for calculating plant operating limits, has shown the expected gain in transient ΔCPR. Section 5.0 provides a discussion of intended licensing approach with the one-dimensional kinetics option and the treatment of uncertainties in the one-dimensional application. A comparison of the one-dimensional application to an alternate, statistical treatment of uncertainties demonstrates the continued conservatism in YAEC's BWR analysis methods.

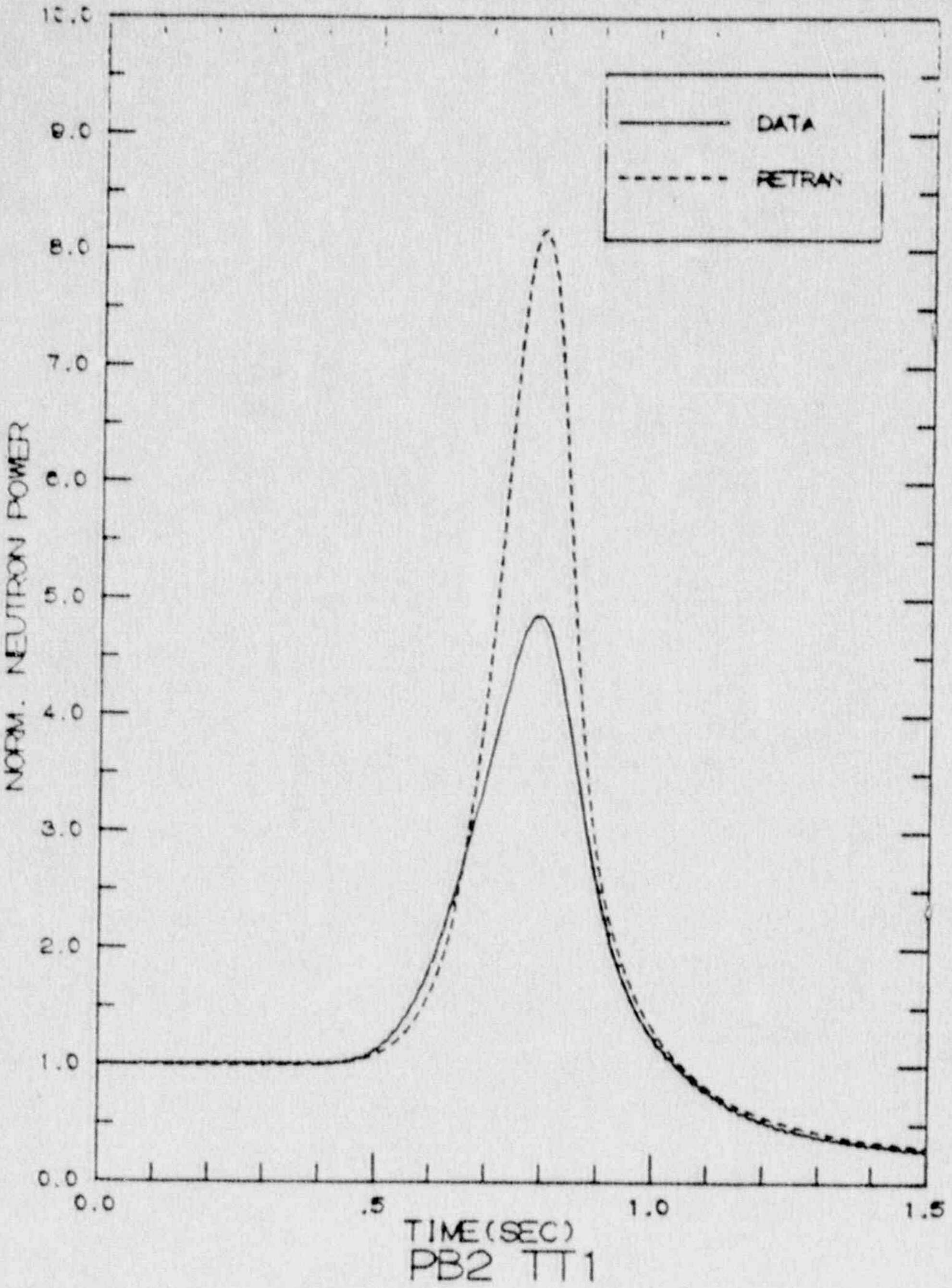


Figure 4.1.1

PEACH BOTTOM-2 TURBINE TRIP TEST 1

NEUTRON POWER VS. TIME

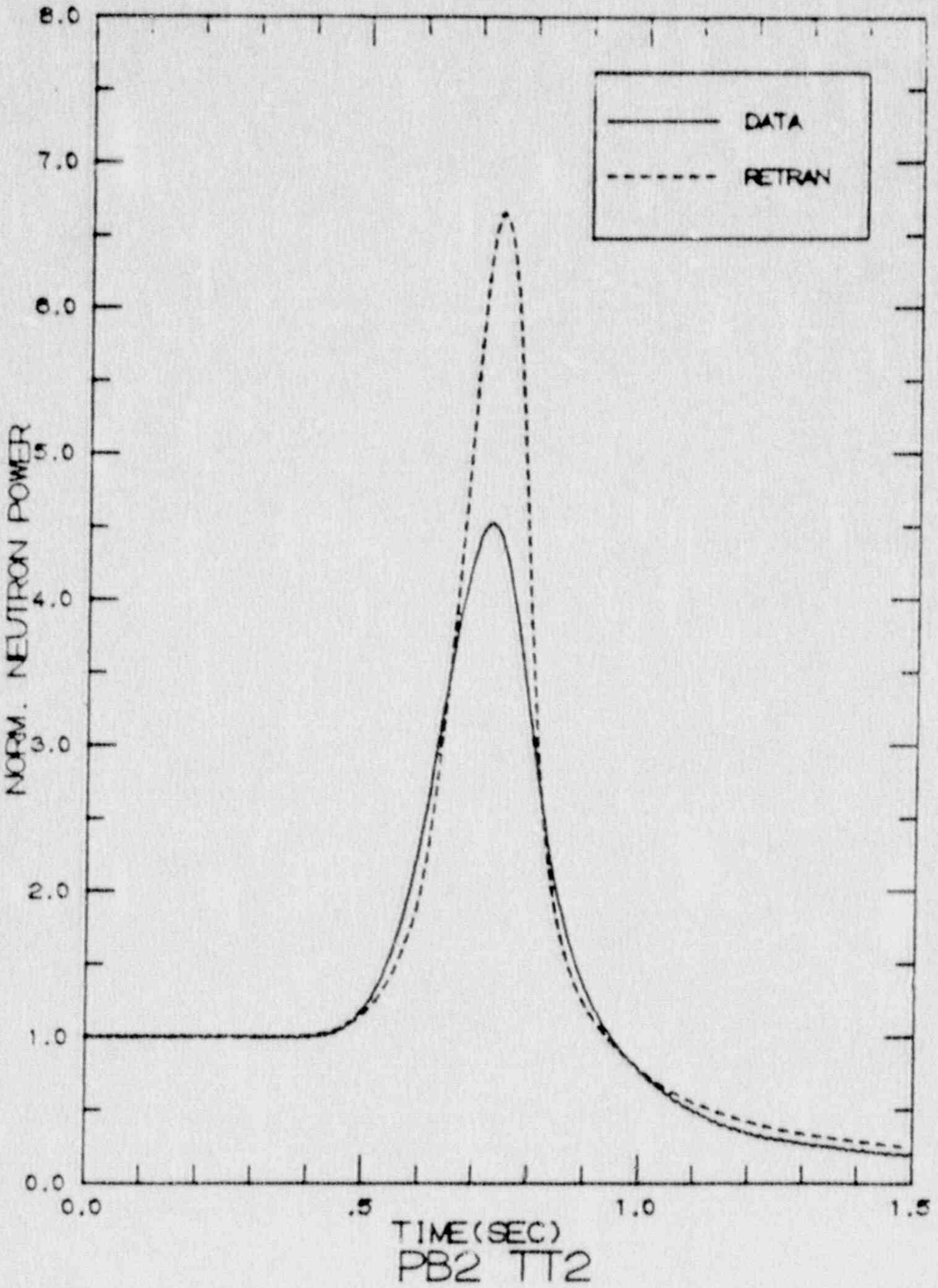


Figure 4.1.2

PEACH BOTTOM-2 TURBINE TRIP TEST 2

NEUTRON POWER VS. TIME

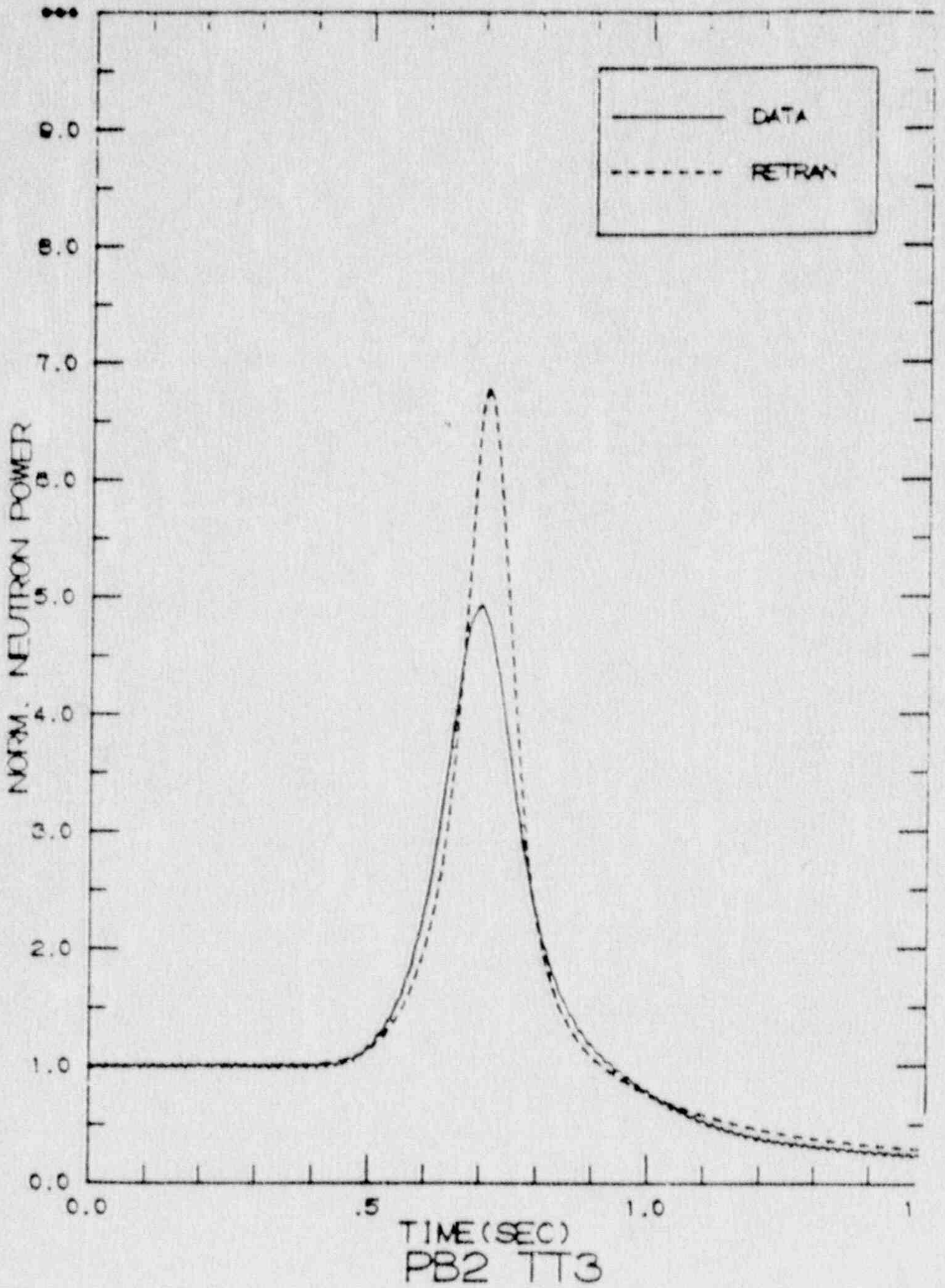


Figure 4.1.3

PEACH BOTTOM-2 TURBINE TRIP TEST 3

NEUTRON POWER VS. TIME

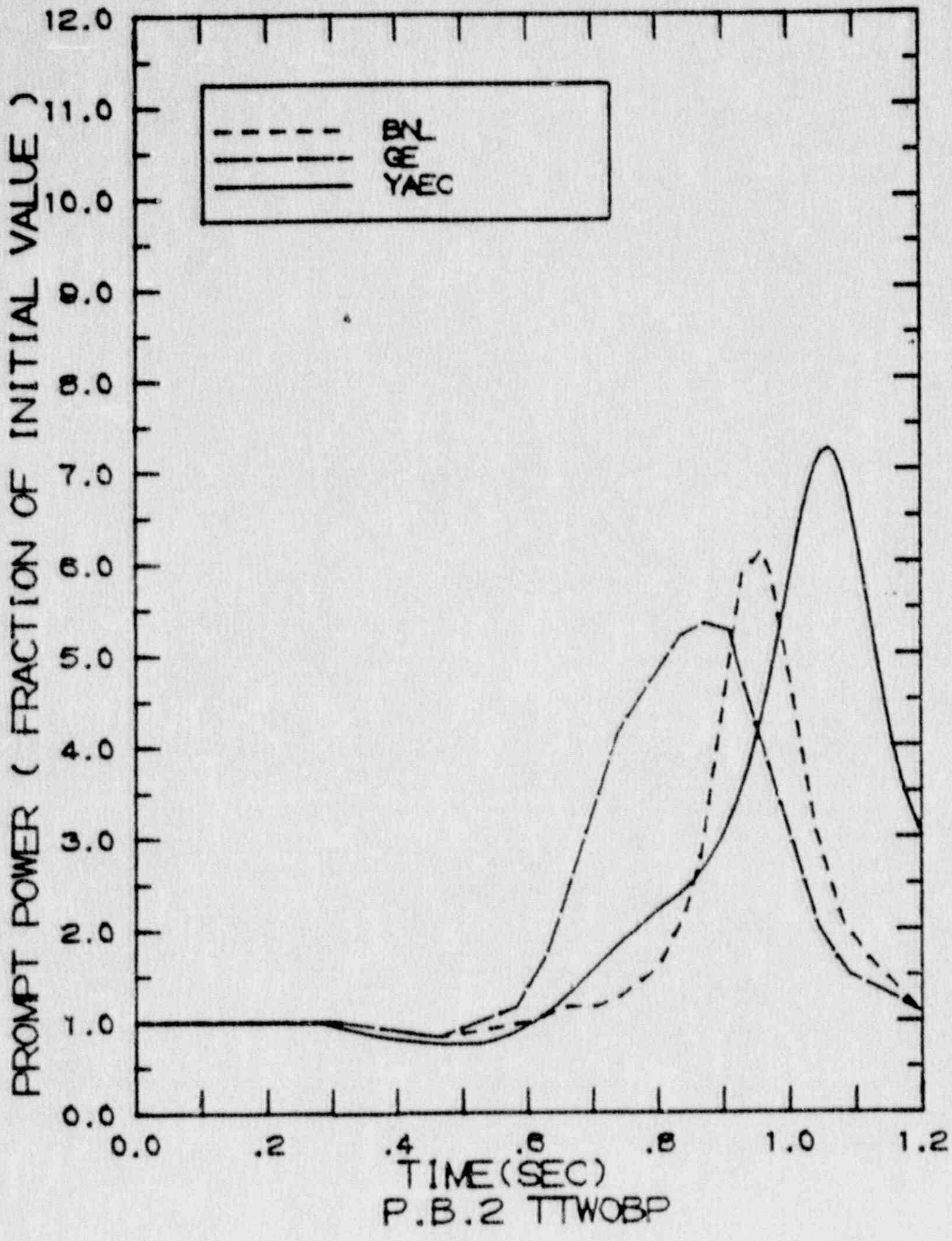
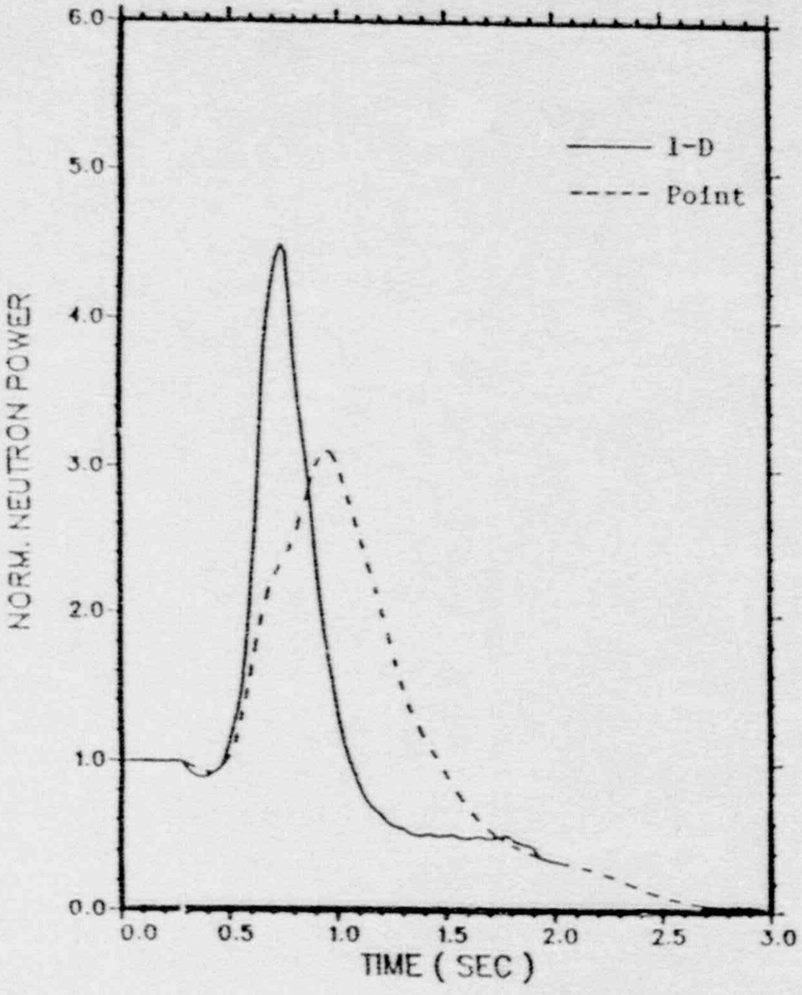


Figure 4.1.4

PEACH BOTTOM-2, TTWOBP, COMPARISON OF NEUTRON POWER PREDICTIONS

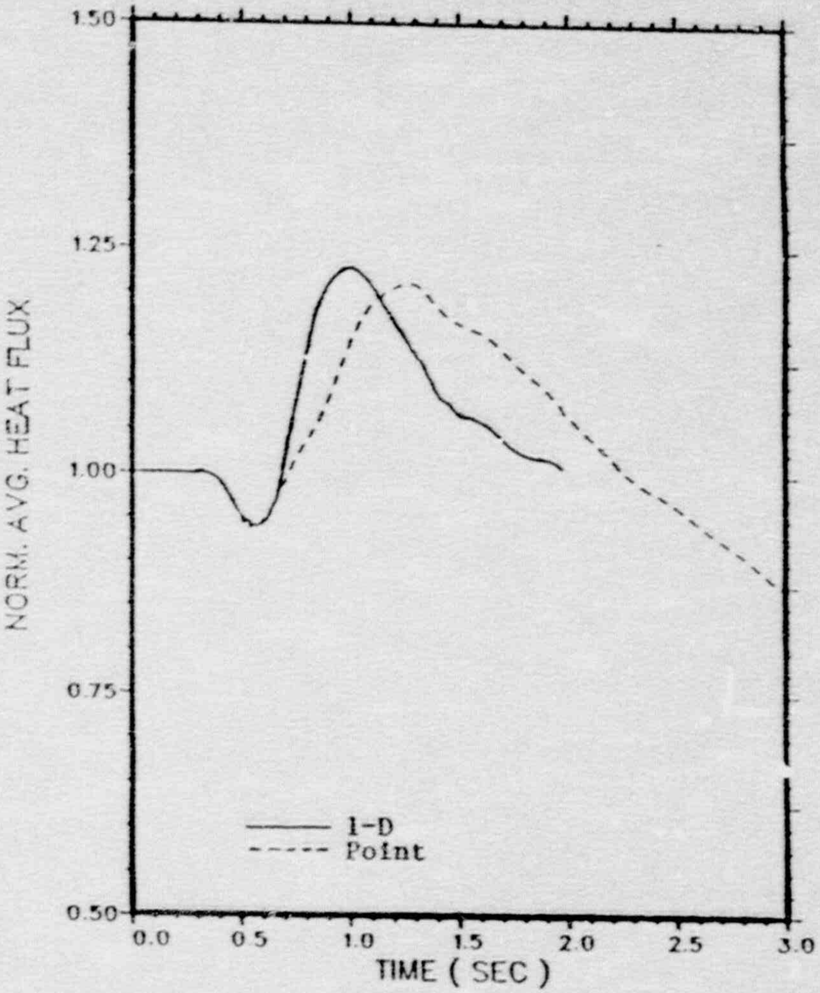


TTWOBP EOFPL MST

Figure 4.1.5

1-D VS. POINT

NORM. NEUTRON POWER

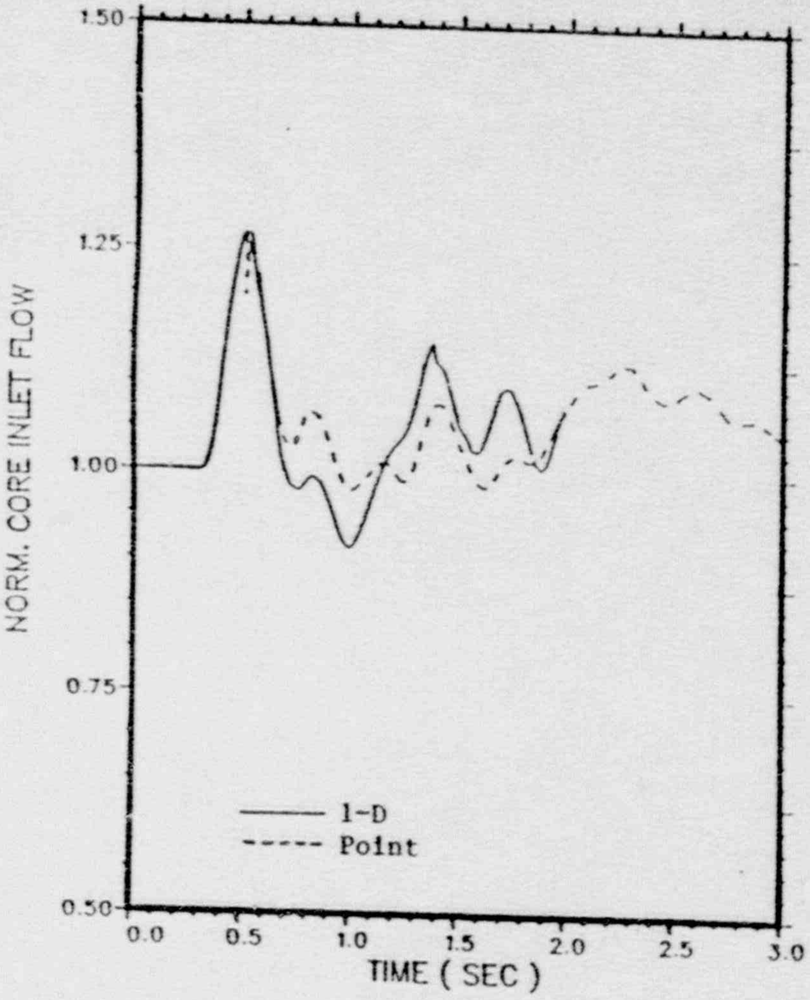


TTWOBP EOFPL MST

Figure 4.1.6

1-D VS. POINT

NORM. AVG. HEAT FLUX

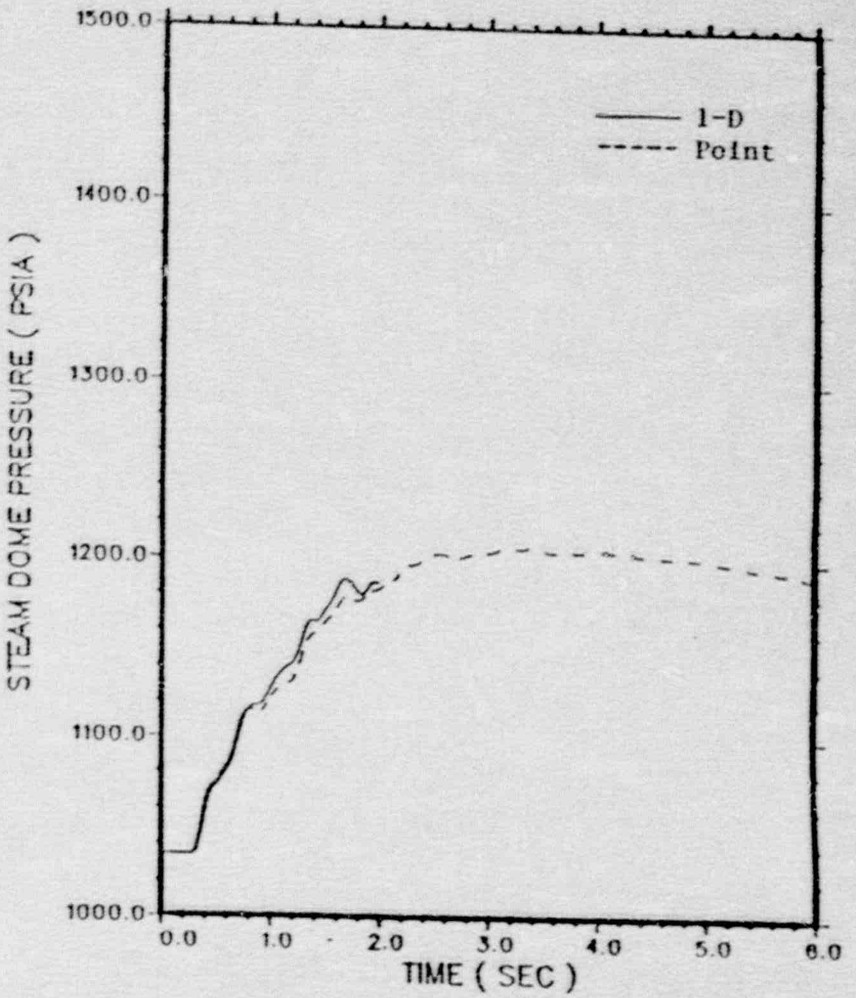


TTWOBP EOFPL MST

Figure 4.1.7

1-D VS. POINT

NORM. CORE INLET FLOW

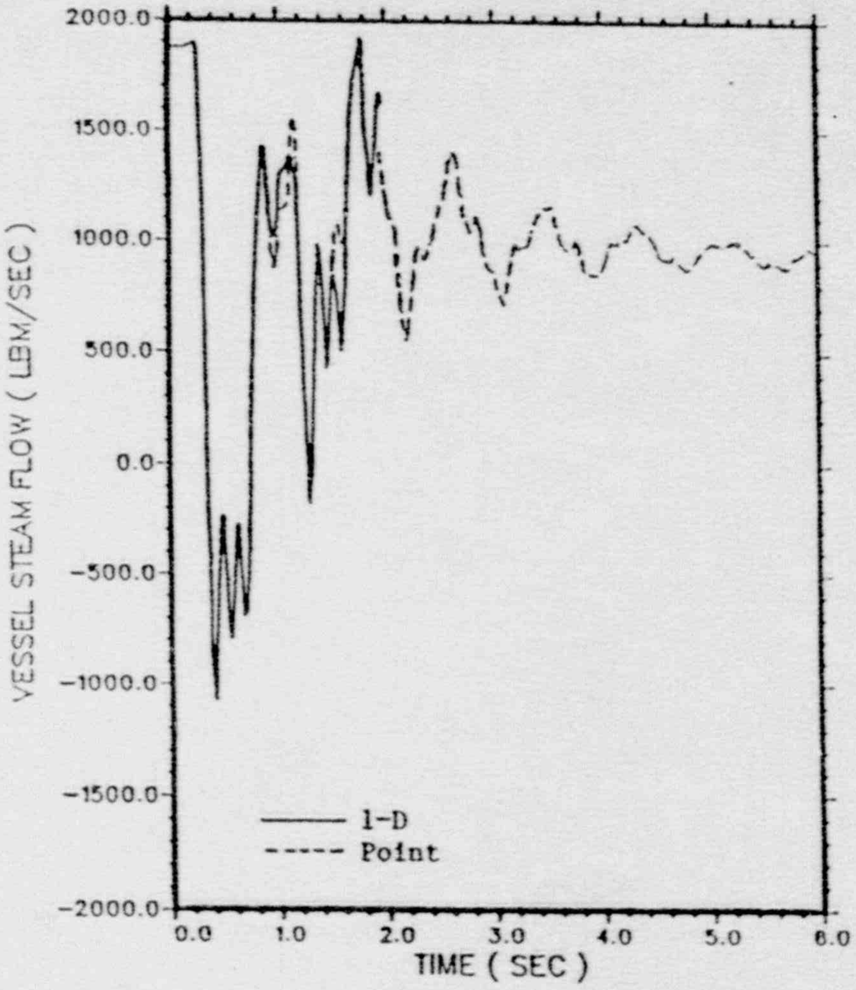


TTWOBP EOFPL MST

Figure 4.1.8

1-D VS. POINT

STEAM DOME PRESSURE

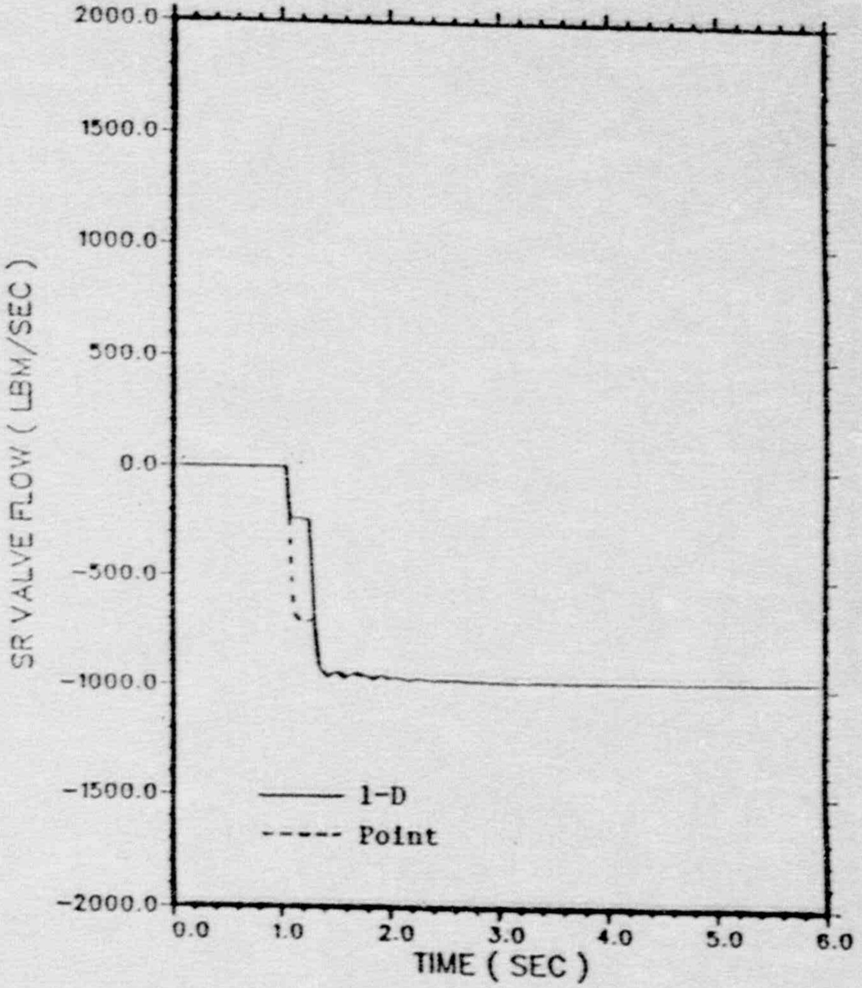


TTWOBP EOFPL MST

Figure 4.1.9

1-D VS. POINT

VESSEL STEAM FLOW

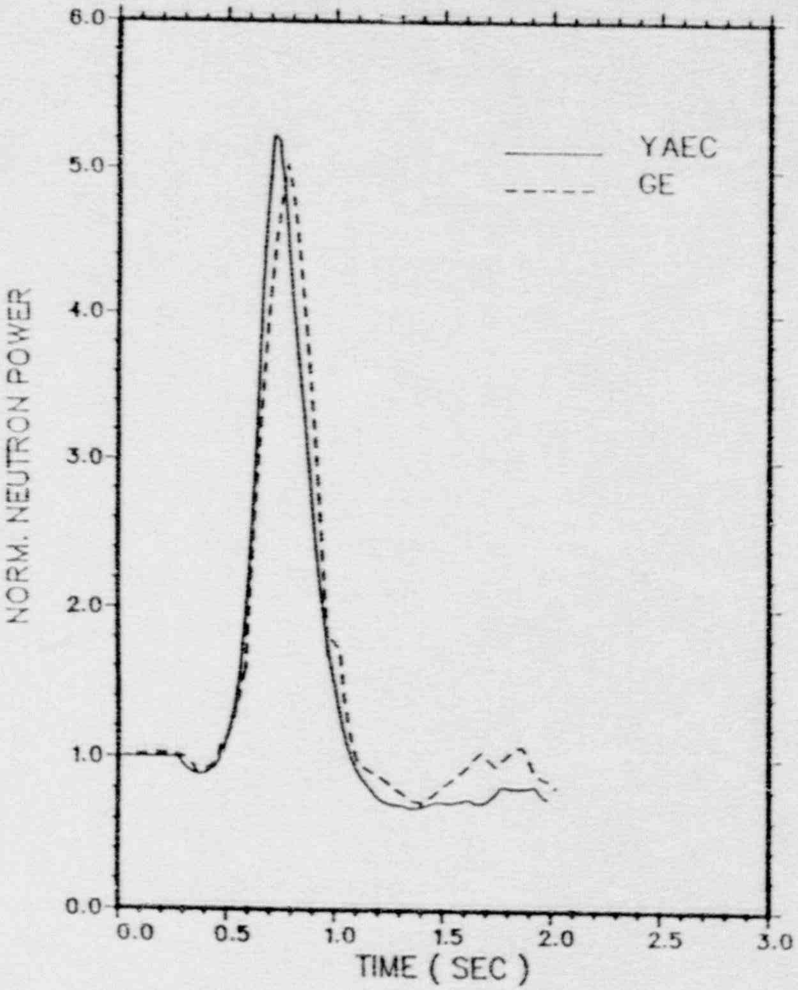


TTWOBP EOFPL MST

Figure 4.1.10

1-D VS. POINT

SR VALVE FLOW

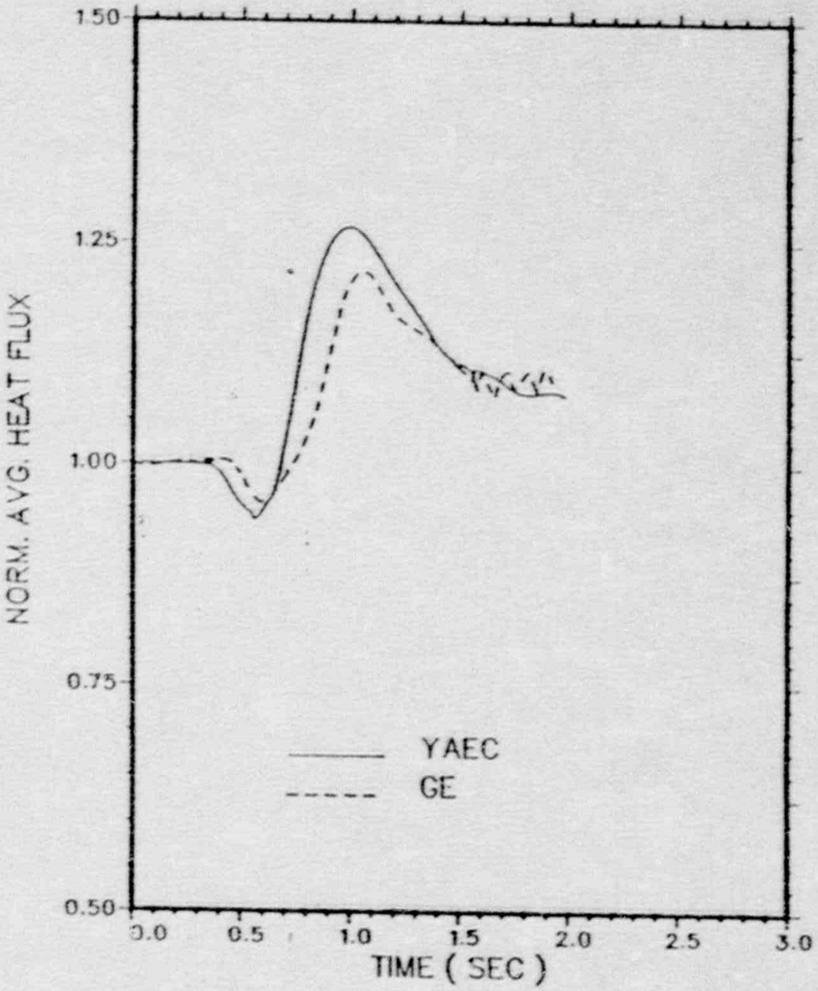


TTWOBP EOFPL

Figure 4.1.11

METHODS COMPARISON

NORM. NEUTRON POWER

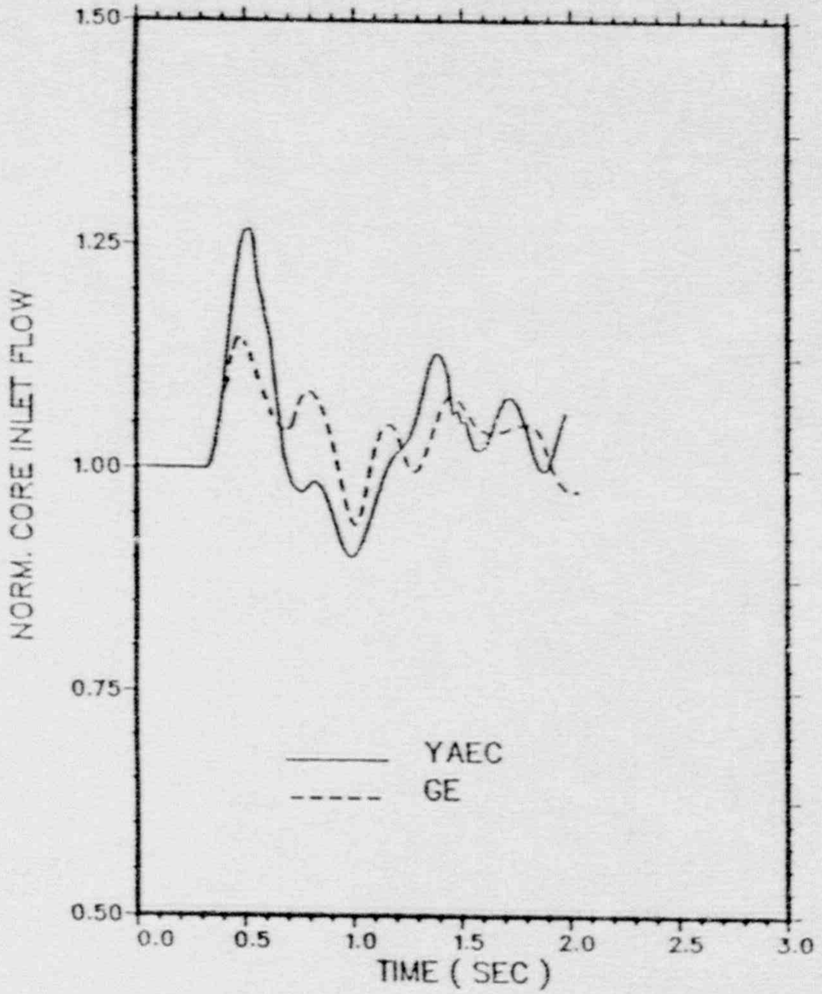


TTWOBP EOFPL

Figure 4.1.12

METHODS COMPARISON

NORM. AVG. HEAT FLUX

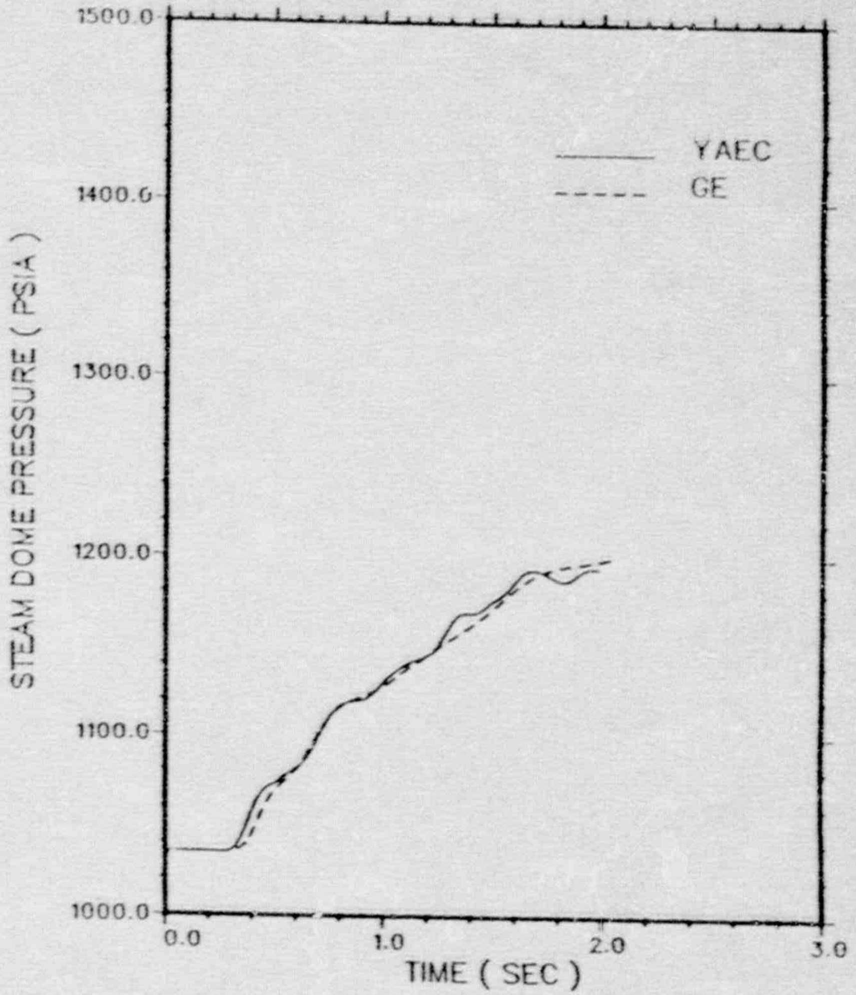


TTWOBP EOFPL

Figure 4.1.13

METHODS COMPARISON

NORM. CORE INLET FLOW

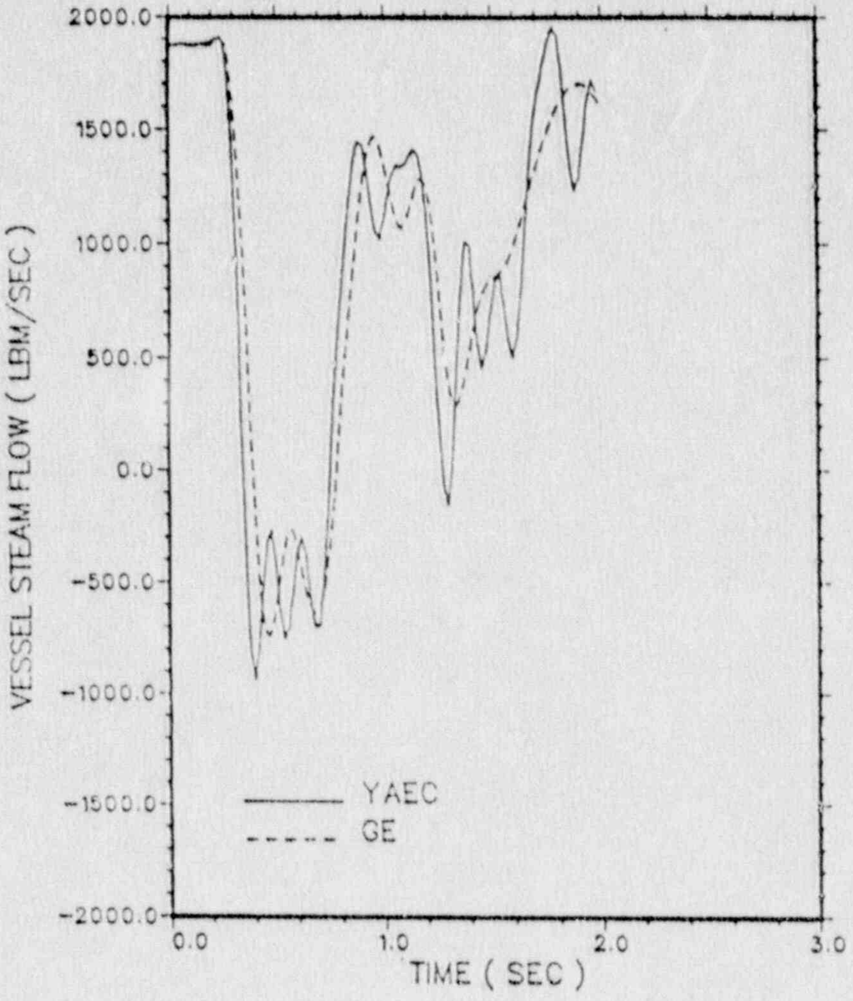


TTWOBP EOFPL

Figure 4.1.14

METHODS COMPARISON

STEAM DOME PRESSURE



TTWOBP EOFPL

Figure 4.1.15

METHODS COMPARISON

VESSEL STEAM FLOW

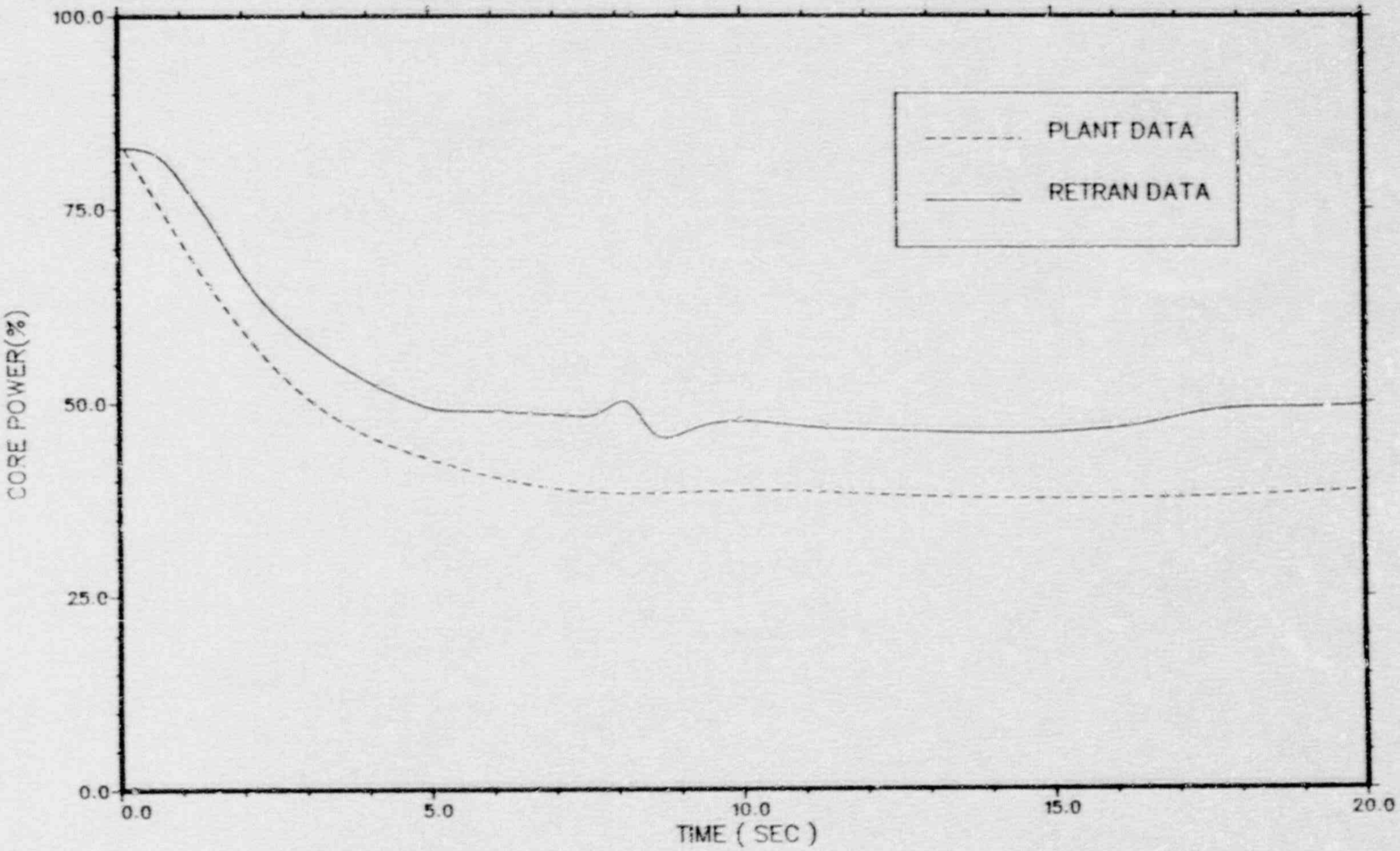


Figure 4.2.1

RPT TEST COMPARISON

CORE POWER

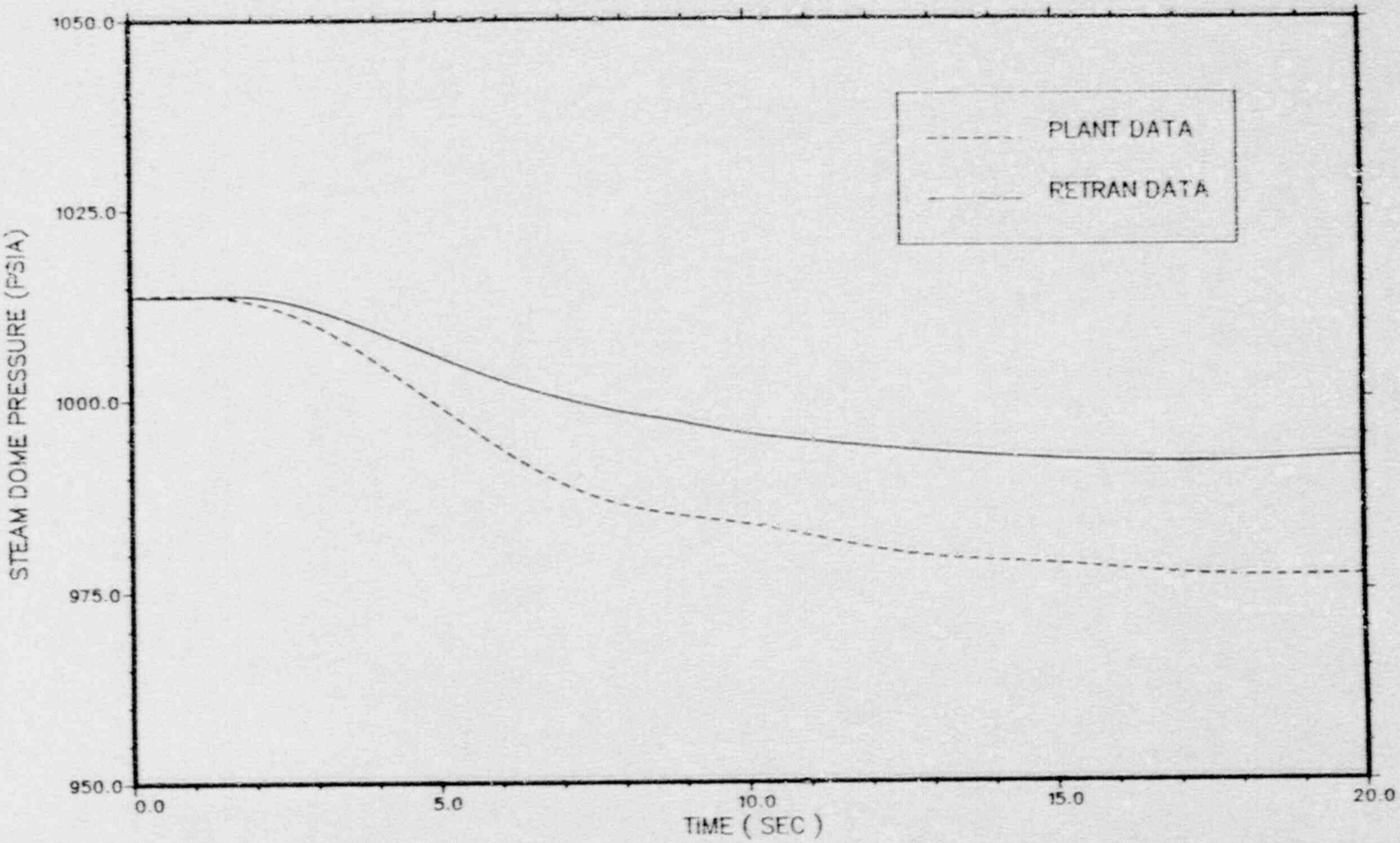


Figure 4.2.2

RPT TEST COMPARISON

STEAM DOME PRESSURE

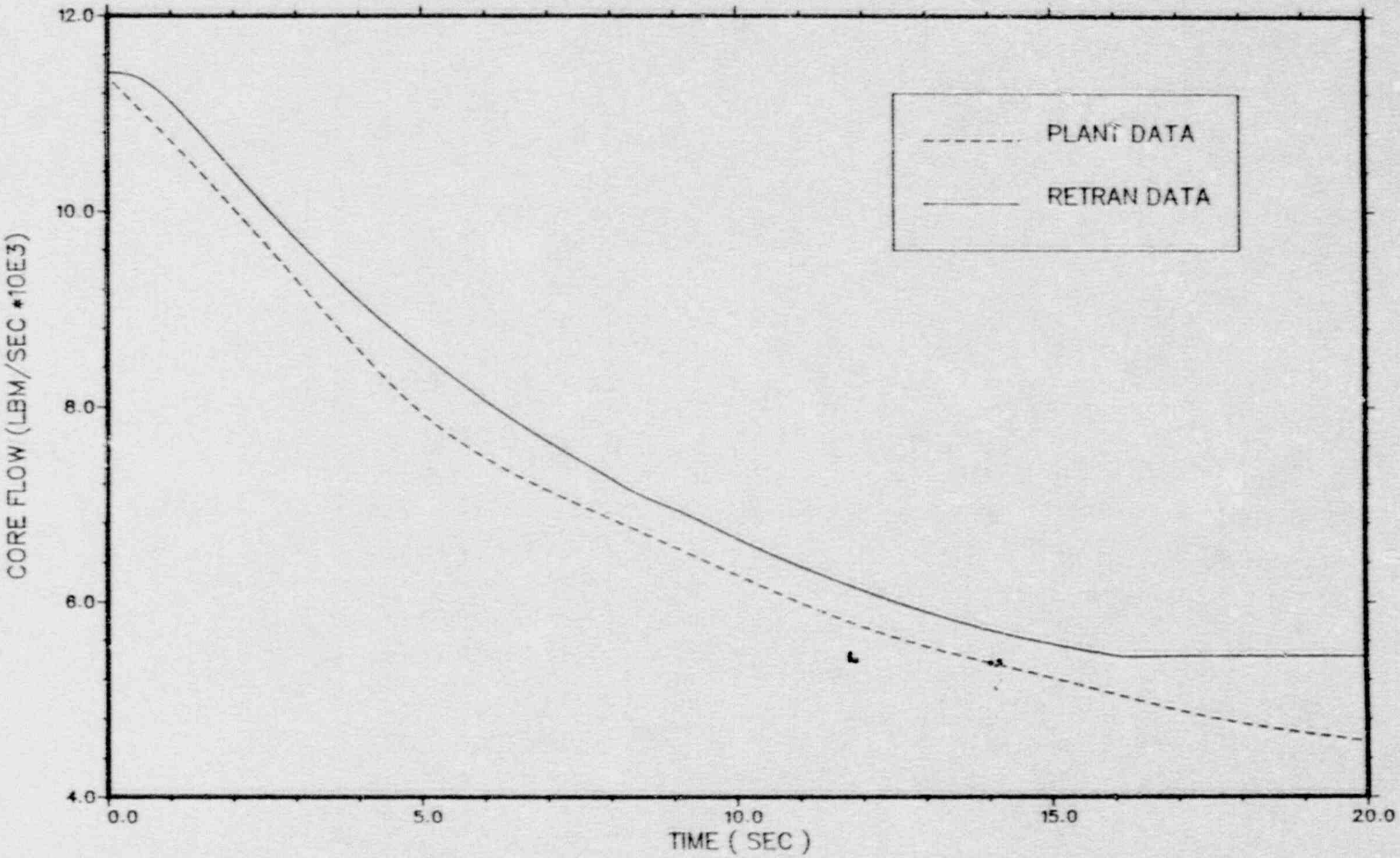


Figure 4.2.3

RPT TEST COMPARISON

CORE FLOW

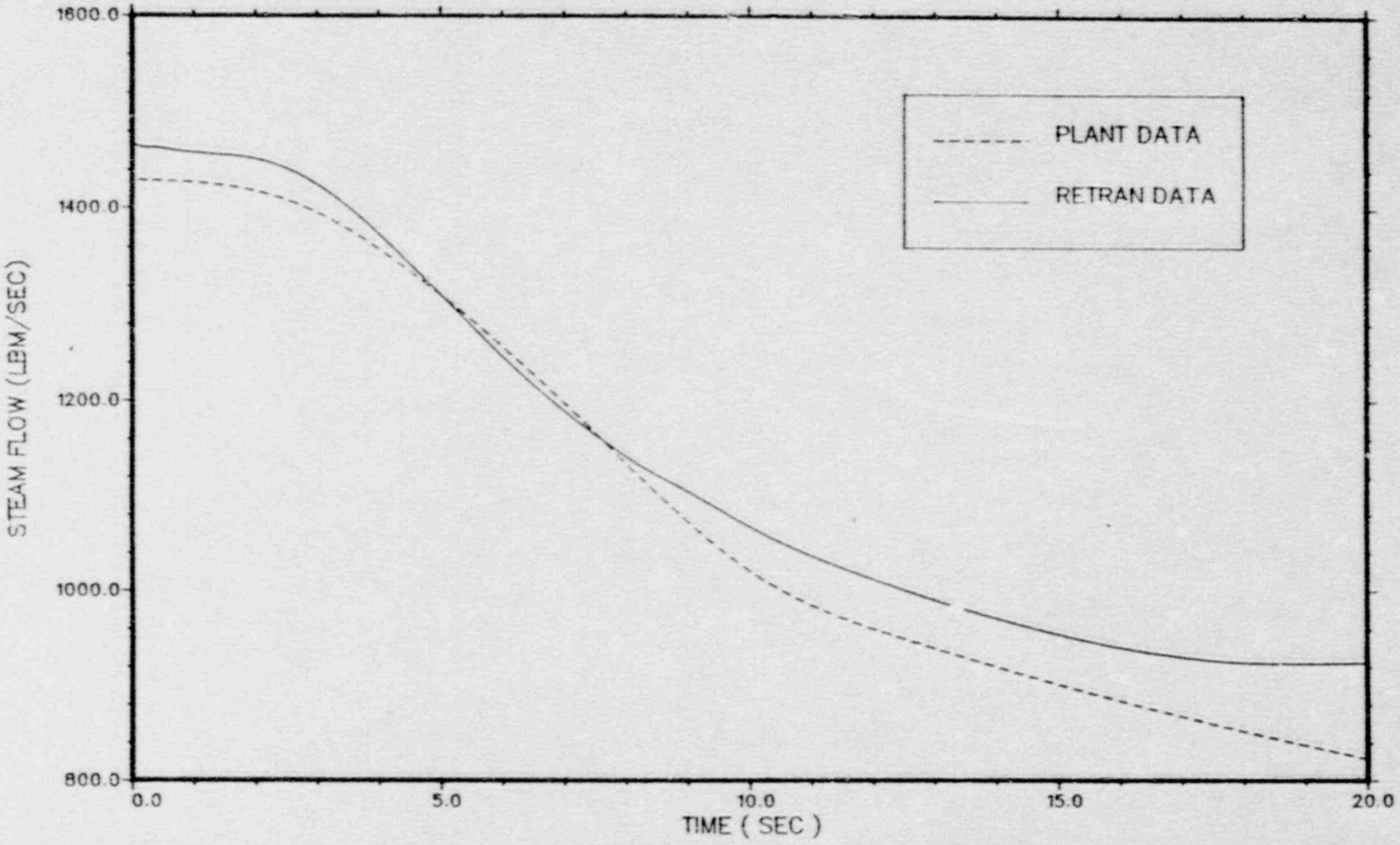


Figure 4.2.4

RPT TEST COMPARISON

STEAM FLOW

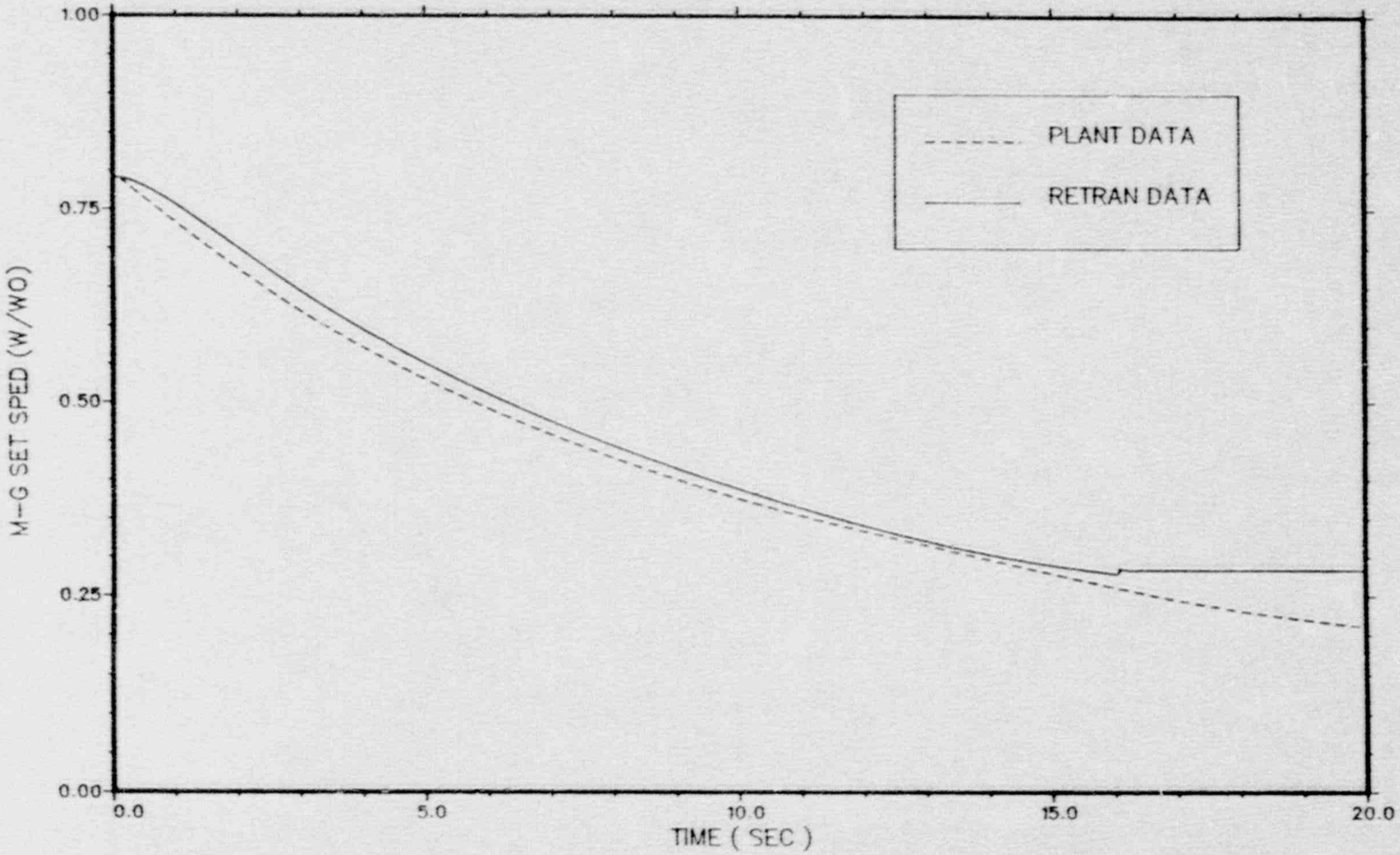


Figure 4.2.5

RPT TEST COMPARISON

M-G SET SPEED

5.0 LICENSING APPROACH AND TREATMENT OF UNCERTAINTIES

This section outlines the intended BWR licensing approach with the one-dimensional kinetics RETRAN option. It reports the results of a comparison of the licensing approach applied to Vermont Yankee with an alternate method which treats analysis uncertainties statistically. The comparison demonstrates that YAEC's BWR licensing approach with one-dimensional kinetics continues to be a conservative method for calculating MCPR operating limits.

5.1 Specific Licensing Application

The application of the one-dimensional option in RETRAN to perform licensing analyses will be treated in the same fashion as current approved methods. The current approved point kinetics method assumes an initial power level of 104.5% for the RETRAN core-wide calculations. The initial power level for the one-dimensional kinetics method will be 102% of the rated value, which is the typical calorimetric power uncertainty. All other initial conditions and RETRAN inputs like initial steam flow, scram position versus time (MST and 67B), etc., are set at values identical to the current analysis. The primary difference between the proposed and the current licensing methodologies is that the one-dimensional kinetics model replaces the current point kinetics. The core-wide and hot channel calculation methods remain the same except for minor differences explained in previous sections of this report.

Many input parameters to RETRAN, including the transient initial conditions, are conservative. Table 5.1 lists the conservative input parameters in the licensing basis model relative to the expected values. There are other inputs which have been used at their expected values. Overall, we have found this licensing approach to be conservative. The next section will describe the alternate statistical approach to the treatment of uncertainties which demonstrates the conservatism in the proposed one-dimensional kinetics licensing approach.

5.2 Treatment of Uncertainties

The statistical treatment of uncertainties in the application of the one-dimensional kinetics option is based on the use of a statistical method to derive a value of transient ΔCPR with a 95% probability (ΔCPR 95). Thus, if the limiting transient which sets the OLMCPR actually occurs, there is a 95% probability the safety limit CPR will not be exceeded.

The ΔCPR 95 was calculated by statistical convolution of scram speed uncertainties with an overall model uncertainty. Convolution of statistical functions is a common practice, and the numerical technique used to perform the convolution is described in Reference (21). The assumed scram time is the single most sensitive parameter in the severe pressurization event analysis, so it received an individual statistical treatment. The statistical function or Probability Distribution Function (PDF), in terms of ΔCPR, used to obtain the scram speed uncertainties was derived from a response surface fit. The response surface methodology employed is further described in Appendix A. The response surface fit was based on the Cycle 9 TTWOBP cases used for the verification described in Section 4.0 with plant-specific scram times plus uncertainties substituted for the MST scram times. A range of uncertainties were applied to the mean scram times which resulted in five RETRAN cases to fit the response surface.

The derivation of a model uncertainty consisted of performing uncertainty studies of sensitive inputs and combining the result of the individual uncertainty studies by the square root sum of squares method. The uncertainties study is further described in Appendix B. The square root sum of squares method assumes the listed combined uncertainties are normally distributed around their mean. The value of uncertainty used in each study was assumed to represent at least a two sigma value, which is needed to obtain 95% probability. Many of the uncertainty studies addressed input that are considered to be conservative but did not have an explicitly applied uncertainty. The most significant of these are the void and Doppler uncertainty studies. Though this treatment may result in compounding of uncertainties it reinforces the statistical argument to show the conservatism in the YAEC's BWR licensing approach.

Using the method discussed in Appendix A, the PDF value of ΔRCPR associated with a 95% probability of the scram speed response surface is 0.127. The statistical combination of the RETRAN model uncertainties results in a mean ΔRCPR value of 0.04. By convoluting the two statistical functions, a ΔCPR of 0.18 was obtained. A 29% model uncertainty is accommodated through this method. This value of model uncertainty is typical of other licensees. TVA in (22) reported a 25% model uncertainty.

5.3 Comparison of Licensing Approach to the Statistical Method

A representative Vermont Yankee one-dimensional kinetics licensing case (Cycle 9 TTWOBP, 102% Power) was analyzed using the approach described in Section 5.1 to compare with the statistically derived ΔCPR discussed in Section 5.2. The licensing case ΔCPR was 0.174. As stated previously, the statistical ΔCPR95 was 0.186. Due to the conservatisms that remain in the licensing model and the conservative method taken in the statistical analyses to derive ΔCPR95 it is concluded that the two methods result in equivalent ΔCPRs. Therefore, the licensing method is a conservative approach for deriving MCPR operating limits.

Further refinement of the statistically derived ΔCPR would result in a smaller ΔCPR95. Additionally, the statistical approach taken here uses a one variable response surface where others [22] have used two or more variables. Treatment of other significant parameters such as the void uncertainty, for example, in response surface would result in a smaller statistically derived ΔCPR.

TABLE 5.1

Transient Model Inputs and Initial Conditions Compared to Expected Values

Item	Expected Value	Licensing Basis Analysis
Power/Exposure Distribution	Nominal	Conservative target
Initial Power (%NBR)	≤ 100.	102.0
Initial Steam Flow (%NBR)	≤ 100.	102.0
Initial Core Flow (%NBR)	Nominal	Design value
Initial Dome Pressure (psig)	1020	1020
Feedwater Temperature	< Max. value	Max. value
Vessel to Relief Vlv Pressure Drop (psi)	Nominal (< 15)	Max. (15)
Vessel to Steam Header Pressure Drop (psi)	< 42.	46.
Control Rod Initial Insertion	Nominal pattern	Minimum scram worth configuration
Control Rod Motion	Rods at different speeds	All rods at same speed (conservative)
CRD Scram Time (seconds to 20% Insertion)	Nominal (approximately 0.71)	Tech. spec. upper limit
Scram Setpoints	More conservative than tech. spec.	Tech. spec. limiting value
Protection System Logic Delay (msec)	Nominal (30)	Max. (50)
Number of Relief Vlv's	4	4
Relief Vlv Capacity	Nominal	Nominal
Relief Vlv Setpoint	Nominal	Nominal
Relief Vlv Response (msec delay/msec stroke)	Nominal (300/1000)	Slowest spec. (400/150)
Turb. Stop/Control Vlv Stroke Time (msec)	Nominal (150/310)	Nominal (100/310)
Turb. Bypass Vlv Response (msec to 80% open)	Nominal (200)	Slowest spec. (300)
Recirculation Pump Trip Delay (msec)	Nominal (135)	Maximum spec. (175)
Recirculation Pump Coastdown Constant (sec)	Nominal (4.0)	Conservatively slow (4.5)
Flow Control Mode	Manual	Manual
Controller Settings	Nominal	Nominal
Separator Inertia	Split between inlet and exit junctions	All on inlet junction
Fuel Rod Gap Conductance	Nominal, varying axially and during transient	Conservative, uniform axially and constant during transient

6.0 CONCLUSIONS

In this report, the proper use of the RETRAN one-dimensional kinetics model in the BWR transient analysis methods has been demonstrated and the continued conservatism in the licensing approach has been confirmed. To recap the verification process summarized in the report:

- The comparison of the point kinetics method to the Peach Bottom turbine trip test demonstrates that for relatively mild pressurization events where the power surge is suppressed by core voiding, YAEC's BWR method overpredicts the tests. Overprediction of pressurization events is a conservative treatment in licensing analysis. The comparison also demonstrated the accuracy of the thermal hydraulic portions of the modelling method.

- The point kinetics method analysis of the Peach Bottom representative licensing case shows that YAEC's BWR method overpredicted the BNL and GE results, which is a conservative treatment in licensing analysis.

- The BWR point and one-dimensional kinetics methods comparison pointed out the differences in the two methods The one-dimensional model behaved exactly as expected when compared to the differences shown in the EPRI studies in Reference (17).

- The comparison of YAEC's one-dimensional kinetics method to GE's one-dimensional kinetics calculations showed the closeness in behavior of the two methods and that YAEC's method predicted the same transient results as an approved method.

- The Vermont Yankee Cycle 8 RPT calculations demonstrated that the one-dimensional method could be used to accurately predict plant transient test data.

- The use of an alternate statistical method to calculate the transient ΔCPR for the typically most limiting Vermont Yankee event, the TTWOBP, has proved that adequate conservatism exists, at a 95% probability, in YAEC's BWR licensing method to accommodate model uncertainties.

- The conservatisms identified by the statistical method analysis demonstrates that the licensing approach application of the one-dimensional kinetics option remains appropriately conservative for generating cycle-specific operating limits.

The BWR licensing method demonstrated in this report with the Vermont Yankee Cycle 9 EOFPL TTWOBP will also be applied to the other pressurization events normally analyzed for a reload cycle as well as the LOFWH which is a subcooling event.

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APPENDIX A

Determination of ΔCPR 95 Through a Response Surface Approach

The objective of the statistical evaluation is the development of the Probability Distribution Function (PDF) for RCPR (= ΔCPR/ICPR) given the statistical distribution of the key transient input variables. The variable RCPR is a generally accepted figure of merit for deriving operating limits. The probability distribution of ΔCPR is then utilized to obtain the value of RCPR which has 95% probability of not being exceeded by the operating plant if the limiting event occurs. The direct approach to developing the RCPR probability distribution would be to run trials with the RETRAN model with the key inputs selected randomly from their uncertainty distribution. However, the Monte Carlo approach requires a large number of trials to develop a precise probability distribution so direct simulation of each trial with the RETRAN model is impractical. Instead, a response surface is constructed which predicts the RETRAN model calculated value of RCPR as a function of the value of the key inputs. The response surface is developed by fitting model results to a polynomial with the key transient inputs as independent variables. The advantage of the response surface is that far fewer model calculations are required to develop an accurate response surface than directly develop the probability distribution on RCPR.

In the approach to demonstrate conservatism in the BWR licensing method, a one variable response surface, which treats scram time, has been employed.

The response surface used in the statistical approach is of the form shown in Equation A-1.

$$RCPR = (A_o + A_1 *SS + A_2 *SS^2 + RSU) \qquad (A-1)$$

where

SS = Random value of time (seconds) to 25% scram insertion minus the nominal value.

RSU = Random response surface fitting error.

Ai = Response surface fitting coefficients.

In order to develop the fitting coefficients (A_i) for the response surface, five RETRAN simulations were performed. The procedure used was an orthogonal central composite design process for two parameter levels (Reference (A.1)). Table A.1 shows the values of scram speed which were utilized. A standard least square fitting technique is utilized to determine the coefficient A_i.

The trial values for the time to 25% scram insertion were assumed to be normally distributed. The mean time to 25% control rod insertion following scram solenoid de-energization was assumed to be 0.796 seconds with a standard deviation of 0.0457 seconds. These values are conservative relative to measured data for Vermont Yankee.

A standard deviation of .003 (with a 0.0 mean) for the fitting error was employed to generate the response surface uncertainty (variable RSU) by randomly selecting from a normal distribution for each trial evaluation of the response surface evaluation of the response surface.

The fitted response surface (Equation A-1) along with the uncertainty distribution for each input variable was evaluated for 100,000 trials to obtain the required PDF. Each trial selects a random value for each variable in accordance with their assumed uncertainty distribution.

A sensitivity study was performed to assess the RETRAN model uncertainty (Appendix B). Based on this study, the model uncertainty (.04 ΔRCPR at two sigma) was conservatively assumed to be normally distributed with a mean of 0.0 and a standard deviation of .02. The effect of the model uncertainty on the response surface PDF was determined by convoluting the response surface PDF with the model uncertainty PDF.

To obtain the RCPR value (RCPR95) which is greater than 95% of the trials, the PDF is integrated from the lowest interval up to the value at which 95% of the trials have been accumulated. A RCPR95 value of 0.147 was obtained. The ΔCPR95 value is calculated from the following equation:

$$\Delta CPR95 = \frac{1.07 * RCPR95}{1 - RCPR95} \qquad (A-2)$$

A value of 0.184 was obtained.

APPENDIX B

Model Uncertainty Study

A sensitivity study was performed to quantify the net uncertainty in RCPR due to uncertainties associated with the key parameters in the RETRAN licensing model. Uncertainties were applied only to those significant parameters which were either not assumed at their bounding values or were not treated statistically in the response surface. The base case for all sensitivity studies is the Cycle 9 TTWOBP (EOFPL) model at 100% power level with a Vermont Yankee specific mean time to 25% scram insertion of .7960 seconds. The other initial conditions were set at values identical to the licensing analysis case except for the perturbed parameter.

A summary of the sensitivity study of the TTWOBP event is presented in Table B.1. The table shows, for each parameter analyzed, the uncertainty applied. This table presents the change from the base case the maximum core average fuel rod heat flux (Δq), and the change in the ratio of transient ΔCPR over initial CPR (RCPR).

The various uncertainty components were combined by the root mean square method and a net uncertainty in RCPR of 0.02% was obtained. This uncertainty was used to derive the ΔCPR95 value in Appendix A.

TABLE B.1

RETRAN Model Uncertainty Study Results

	Δq (%)	ΔRCPR**
Void Coefficient More Negative (13%)	8.21	0.037*
Doppler Coefficient Reduced (10%)	3.27	0.006*
Prompt Moderator Heating Reduce 25%	-0.25	-0.002
Double Recirc Loop Fluid Inertia	-0.85	-0.004
Double Jet Pump Fluid Inertia	-0.11	-0.003
Increase Jet Pump M Ratio by 8%	1.18	0.008*
Decrease Steam Dome Volume 5%	1.07	0.006*
Increase Steam Line Inertia 10%	1.51	0.010*
Reduce Steam Line Pressure Drop 8%	0.58	0.003*

* Indicates items included in determination of uncertainty in model RCPR.

** $\Delta RCPR = RCPR - RCPR_{BASE}$