YAEC-1339

Application of the FIBWR2 Core Hydraulics Code
to
BWR Reload Analysis

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ABSTRACT

The benchmark and validation effort for the transient critical power ratio methods using FIBWR2 computer code, written specifically for Boiling Water Reactor steady state and transient thermal hydraulic analysis, is summarized in this report. FIBWR2 is an upgraded and enhanced version of the FIBWR code, enhancing the steady state portions to accommodate new fuel designs with part length fuel rods and enhanced water rod designs and upgrading to include transient capability. The benchmarks for the transient simulations result in excellent agreement to accepted YAEC methodology, GE ATLAS test facility critical heat flux data, and exact analytic solutions.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

The calculation of Critical Power Ratios (CPR) reached during transient conditions for Boiling Water Reactors (BWRs) requires the application of thermal hydraulic models to evaluate the key parameters used in the applicable CPR correlation for the most limiting fuel assemblies (hot channels). The existing YAEC methodology, as approved for application to BWR reload analysis, utilizes the steady state FIBWR (Flow In Boiling Water Reactors) code to establish initial pressure drops and flow distributions for the transient calculation of thermal hydraulic conditions. The systems level transient thermal hydraulic conditions for the hot channel are then calculated using the RETRAN code. The resultant CPR is calculated using a vendor proprietary correlation with the TCPYA01 code. In this methodology, the FIBWR code is used to accurately model the complex flow geometry of the BWR core under steady state conditions with its multiple parallel flow channels and significant water tube and leakage bypass flow paths.

The FIBWR2 code is a new version of the FIBWR code designed to extend the BWR specific models used in the original FIBWR code to the analysis of transient thermal hydraulic conditions. The structure of the FIBWR2 program also accommodates the installation of subroutines for the calculation of CPR within the FIBWR2 coding. These features allow the FIBWR2 code to replace two separate codes (RETRAN and TCPYA01) used for hot channel analysis. FIBWR2 also includes features which allow explicit modeling of advanced fuel designs with axially variable active flow areas due to part length fuel rods and alternative water tube designs.

The purpose of this report is to describe the key models and demonstrate the applicability of the FIBWR2 program to the analysis of transient thermal hydraulic conditions representative of BWR fuel and core geometric including the implementation of CPR correlation within the FIBWR2 program coding. Key features added to the original FIBWR code to enable evaluation of transient thermal hydraulic conditions are identified and the nodalization and solutions scheme summarized. The performance of these FIBWR2 models is demonstrated by comparison of the results obtained using FIBWR2 for two problems with analytical solutions. The results of simulations of experimental test data obtained from a 16 rod test assembly configuration under both steady state and transient conditions using FIBWR2 (with the internal calculation of CPR) is presented and compared with both the test results and a similar simulation performed with the RETRAN/TCPYA01 models.

The performance of the FIBWR2 is then compared with qualified RETRAN base models for representative transient analysis performed for recent actual operating cycle conditions. The comparison of FIBWR2 and RETRAN based results for the reload transient analysis include minimum CPR values. For both the FIBWR2 and RETRAN based evaluations, the CPR is calculated using the same vendor proprietary CPR correlation. Application of the correlation for the RETRAN based evaluations is achieved by use of the TCPYA01 code while for the FIBWR2 results, the correlation was incorporated within the FIBWR2 program.

1.1 Overview of Transient CPR Analysis Methodology

A flow diagram of the current YAEC transient analysis methodology is presented in Figure 1-1. The CPR methodology includes three components involving analysis of thermal hydraulic conditions, they are:

- Steady state thermal hydraulic conditions for the specific core loading design using the FIBWR thermal hydraulics code. FIBWR provides core flow and pressure drop information to the lattice physics code, the fuel performance analysis and initial conditions for the RETRAN systems level calculations.

- Simulation of the overall plant system response to an Abnormal Operational Transient (AOT) using the RETRAN system level model, including the simulation of neutronic feedback using one dimensional kinetics. This calculation provides time dependent normalized power and pressure values as input boundary conditions for the CPR methodology.

- Calculation of the transient change in CPR for the limiting fuel bundle using the RETRAN/TCPYA01 code combination. FIBWR provides the initial power, active flow and bypass flow based on specific calculations for the fuel type analyzed.

The transient CPR calculation is referred to as the "hot channel" analysis since it simulates the response of the single highest power fuel assembly within the core loading to a plant transient. The hot channel analysis provides a CPR operating limit for the transient, such that the CPR safety limit for fuel cladding integrity (FCISL), the lowest allowable CPR defined by the fuel vendor, is not achievable should the event occur. The most restrictive operating limit is determined by analysis of a BWR's limiting AOT for a given reactor core design's fuel cycle.

Figure 1-2 shows the revised approach to the reload analysis using the FIBWR2 methodology to explicitly address the advanced fuel design. FIBWR2 replaces the FIBWR code in setting the initial steady state thermal hydraulic conditions for the lattice physics, fuel performance, systems level and hot channel calculations. This application of FIBWR2 is identical to that of FIBWR.

Additionally, since FIBWR2 has transient thermal hydraulic analysis capability and contains the vendor CPR correlation it provides an alternate to the RETRAN/TCPYA01 combination. It should be noted that a separate report [13] documents a summary of the qualifications carried out for the steady state portion of the use of FIBWR2.

1.2 FIBWR2 Background

The FIBWR code was developed as an accurate, steady state multichannel core hydraulic simulator for BWRs. The FIBWR methodology was designed specifically for the complex flow geometry in BWR cores, with many parallel fuel channels and other small but significant flow paths, such as water tubes and leakage flows to the bypass. The two-phase flow and pressure drop models selected for inclusion in FIBWR were specifically chosen for their excellent agreement under BWR non-LOCA transient conditions. FIBWR has been distributed by Yankee Atomic and the Electric Power Research Institute and widely used in the industry. FIBWR2 is a new version of FIBWR developed specifically to allow simulation of advanced fuel types with the same accuracy as FIBWR. It is also intended to enhance the present hot channel analysis of CPR methodology during postulated transients through the application of the more detailed representation of the fuel and core flow paths found in the FIBWR.

1.2.2 FIBWR2 Development and Verification Objectives

In the years since the original development of the original FIBWR, BWR fuel designs have become more complex, and computer speed and memory have greatly increased. In 1990, work began on FIBWR2, with the following six main objectives:

- To accommodate the new, more complex fuel designs and water tube types currently offered by BWR fuel vendors,

- To add transient capability, including simulation of transient variable axial power shape,

- To provide a more detailed representation of the transient core hydraulics for CPR calculations,

- To simplify the transient CPR methodology by structuring the program to facilitate implementation of CPR correlations in the code,

- To solve larger problems with more flow channels and more water tubes by improving the speed of the solution technique,

- To improve code portability and maintainability by conversion to FORTRAN77.

These modifications provide the capability to analyze new fuel designs and perform full core multi-channel thermal hydraulic analysis. FIBWR2 has capability to represent each fuel assembly in a BWR core discretely. A summary of the new features of FIBWR2 which achieve these objectives are presented in Table 1.1.

Although new capabilities were added and improvements were made to the original FIBWR coding and solution techniques, steady-state core flow, void and pressure drop distribution results have not changed. The FIBWR2 development effort was required to use the same pressure drop and void distribution models as the FIBWR code. These models were considered to be well validated and were previously documented in the original FIBWR report[1,2]. Only minimal changes and additions to original FIBWR models were made to support transient calculation capability. In Section 2.0, the original FIBWR models are briefly reviewed and the modifications which comprise FIBWR2 changes are documented.

FIBWR2 to FIBWR cross-code verification calculations were performed. Small differences were noted in the models of the original FIBWR code, which were revised during the development of FIBWR2. Additional differences were the result of the enhanced solution technique.

Modifications to enable the modeling of new fuel designs and water tube types were verified against steady-state analytical solutions. In addition, pressure drop measurements for several operating states of Vermont Yankee operation were used to validate steady-state FIBWR2 results. A

validation effort carried out for the steady state portions of the FIBWR2 code has been documented separate of this report [13]. It should be noted that the steady state exercise of FIBWR2 is consistent with the current method using FIBWR.

Transient solutions were verified against exact analytical solutions. Cross code comparisons to transient the hot channel RETRAN model were used to verify the fuel rod temperature calculation and transient pressure drop/flow distribution solution technique. Cross code void profile comparisons against RETRAN were also used to verify the implementation of the drift flux model in FIBWR2.

The FIBWR2 code was validated for hot channel analysis by comparison to the published 16 rod CHF Test Facility data [3,4,5,6]. These comparisons show that FIBWR2 with the vendor CPR correlation installed can adequately predict the onset of boiling transition.

1.2.3 Approval Status of FIBWR and RETRAN Hot Channel Methodology

The FIBWR[1,2] code was qualified by validation against analytical solutions and by comparison to measured plant data and other codes. Yankee received NRC approval of the FIBWR application submittal[7], and has used FIBWR as part of the NRC approved licensing methodology package since 1981. The RETRAN and TCPYA01 code combination was validated against Critical Heat Flux test facility results [3,4,5] and approved for the use [8] in establishing transient Minimum Critical Power Ratio based operating limits. RETRAN/TCPYA01 has been used for the past eleven reload cycles for Vermont Yankee.

1.3 Expected Uses of FIBWR2

FIBWR2 will be used for thermal-hydraulic evaluations of BWR cores during steady state operation and abnormal operational transients (AOTs). The steady state evaluations will provide input to lattice physics codes, fuel performance codes and transient codes. The steady state application of FIBWR2 is identical to the FIBWR application. The steady state application is documented in [13]. The code will be used for transient CPR evaluations as described in this report. FIBWR2 will, therefore, be used for steady state flow distribution analysis and for transient CPR evaluations.

FIBWR2 will not be used to analyze:

- Acoustic and/or Sonic Flow Phenomena, such as Choking or Water Hammer
- Horizontal Flow
- Significant Vapor Superheat (Exit Qualities Greater Than 1.0)
- LOCA Blowdown/Reflood, ADS actuation, CCFL
- Fuel Rod Heat Transfer Beyond Critical Power
- Fuel/Clad Deformation or Melt

1.4 Organization of Remainder of Report

Section 2 discusses the modifications to the FIBWR code to include transient capability. Section 3 presents the results of the comparison of FIBWR2 to two analytical solutions, an exponential flow decay and a sinusoidal flow oscillation. Benchmarks of FIBWR2 to the General Electric ATLAS test facility critical heat flux experiments are presented in Section 4. Comparison to the approved YAEC transient CPR methodology is summarized in Section 5. A summary of the conclusions for each of the benchmarks and qualification studies are reported in Sections 3-5 are presented in Section 6.

TABLE 1.1

Enhancements to FIBWR to create FIBWR2

- Improved Geometric Flexibility

  - Axially varying flow geometry
  - Advanced water tubes/water cross features
  - Multiple fuel rod geometries/fuel rod properties per flow channel

- Improved Numerics

  - For convergence at low-flow/low-power conditions

  - For transient multi-channel Critical Power Ratio (CPR) calculations needed to determine compatibility of new fuel designs in a mixed core

  - For transient heat flux and Linear Heat Generation Rate (LHGR) edits

- Automated Linkage to Physics Codes

  - 3-D power readings from nuclear simulator files

- Automated Linkage to RETRAN

  - Boundary conditions for transients
  - Single (average) channel edits

- All FORTRAN77 for Ease of Maintenance

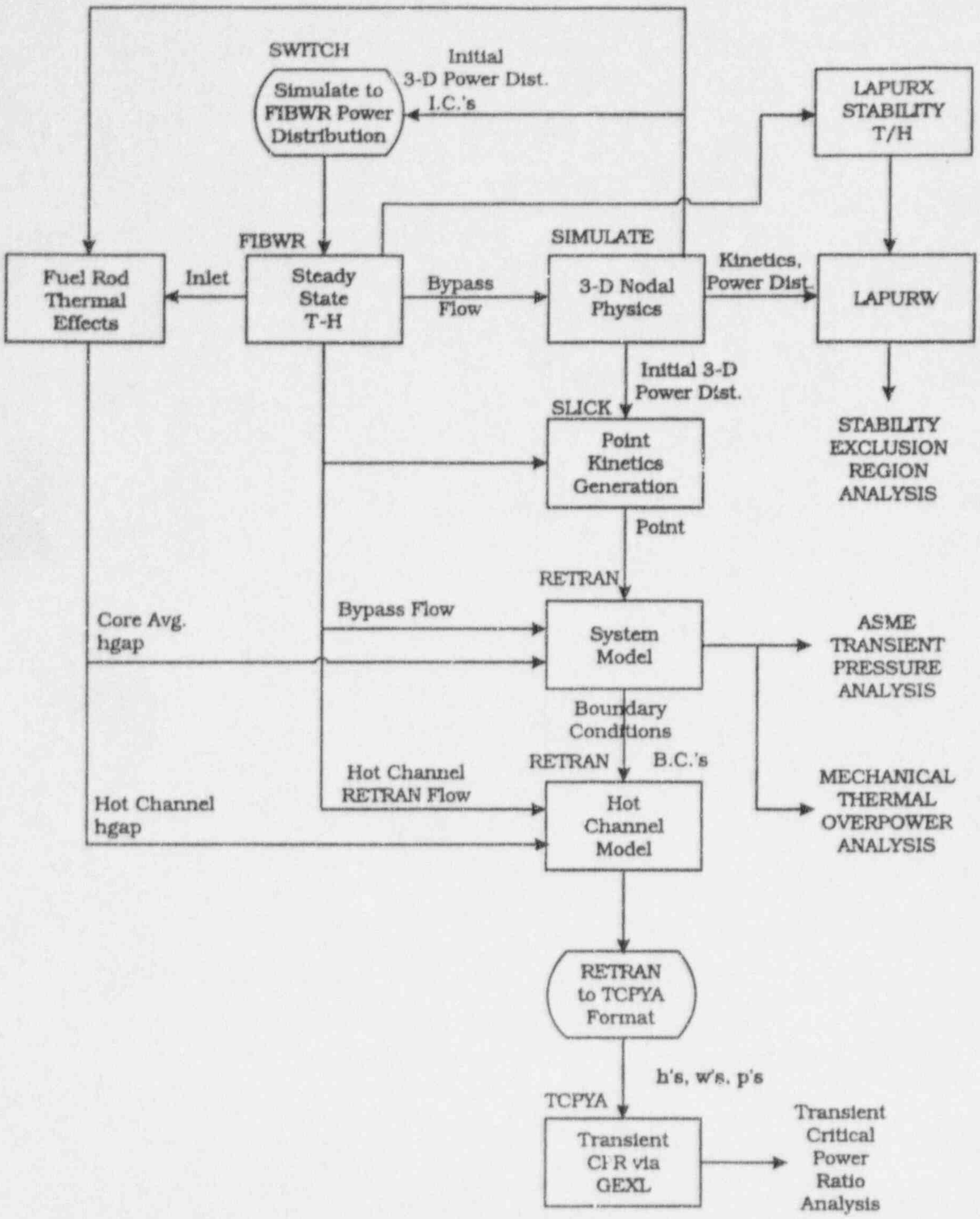

FIGURE 1-1

Flow Diagram of Existing Reload Methodology

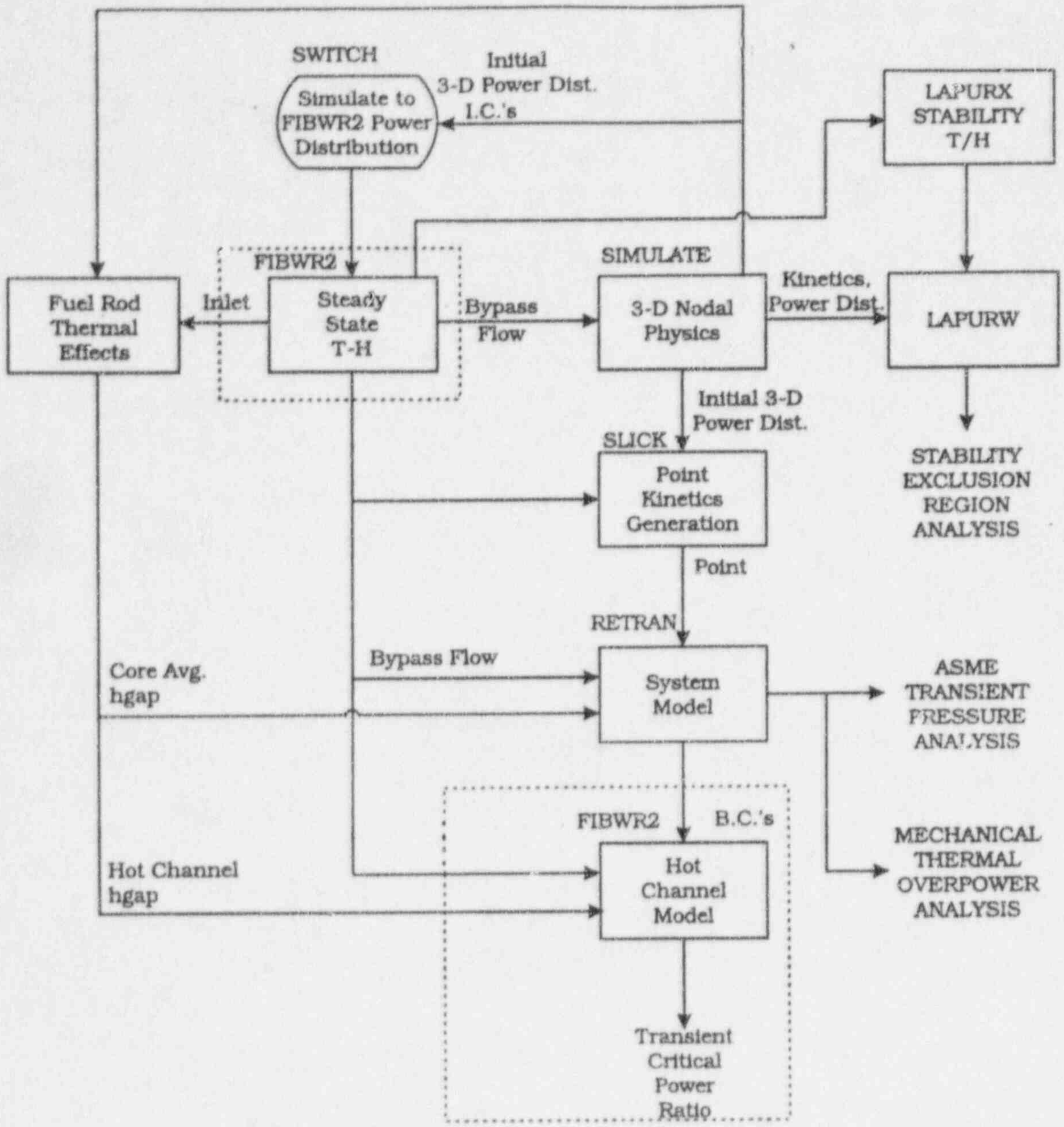

FIGURE 1-2

Flow Diagram of Reload Methodology with FIBWR2

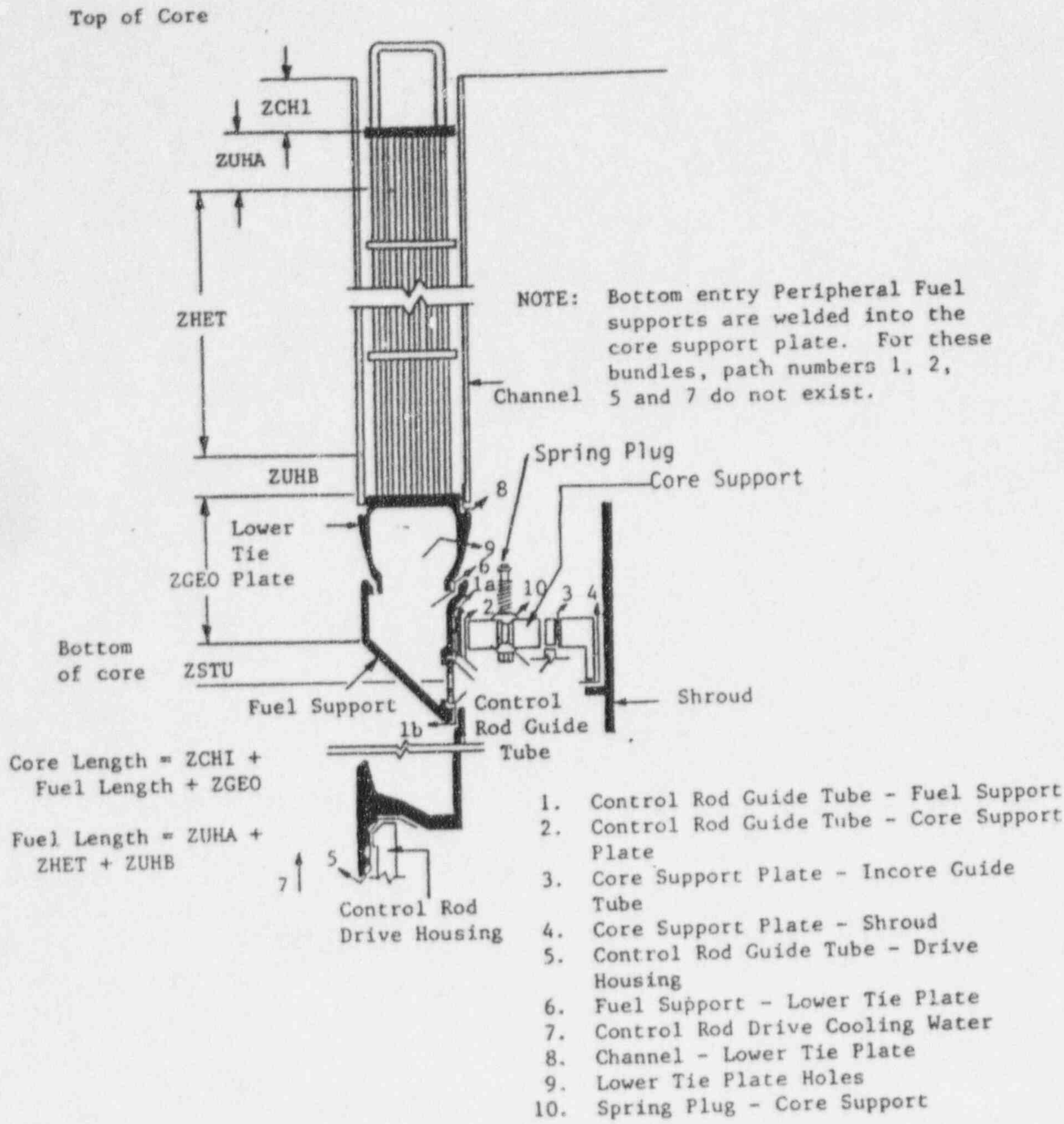

FIGURE 1-3

Flow Paths in a BWR Core

2.0 DESCRIPTION OF FIBWR2 CODE ENHANCEMENTS

This section describes the key features of FIBWR2 that allow detailed modeling of fuel and bypass paths, the capability to model enhanced fuel types, and addition of transient capability. Several of these key features are compared against the methodology employed in the current YAEC RETRAN hot channel model which is used to evaluate the response of the limiting fuel assembly to AOTs. Changes to the conservation equations used in the original FIBWR program and the solution closure relationship to enable transient capability are summarized in Section 2.1. The FIBWR2 core nodalization scheme, including the basic division of control cells, the specification of the active core zone, and the use of compound nodes to model the unheated portions of a fuel channel are described in Section 2.2. Section 2.3 describes the FIBWR2 solution scheme, which is similar to the original FIBWR code, but now accommodates a larger problem size. A separate and significant discussion in Section 2.4 focuses on the void and pressure drop models in FIBWR2 and RETRAN which forms the basis for the two codes differences in results.

2.1 FIBWR2 Conservation Equations

The mass and energy equations of the original FIBWR program are modified in the FIBWR2 program to allow thermal non-equilibrium between the liquid and vapor phases. Separate liquid and vapor mass conservation equations are used and the energy equation modified to assume that the vapor phase remains saturated while the liquid phase may be subcooled or superheated. The assumption that the vapor phase remains saturated is reasonable for BWR vessel conditions for those transients and accidents which maintain high pressure (>800 psia) and which do not involve acoustic or sonic flow phenomena such as might occur during the postulated Loss of Coolant Accident (LOCA). The FIBWR2 code therefore has four conservation equations compared with three conservation equations used in the FIBWR code.

The treatment of liquid and vapor conservation required the introduction of two terms in the conservation equations for the transfer of mass and heat between the two phases. These terms for the interphase mass and heat transfer are denoted GAMMA (Γ_{if}) and $H_{if}*A_{if}$, respectively, with Γ_{if} assumed proportional to $H_{if}*A_{if}$. At steady state conditions, the net interphasic heat transfer approaches its equilibrium value and the FIBWR2 equations are equivalent to the FIBWR equations.

The FIBWR2 program allows the specification of several different models for $H_{if}*A_{if}$. The recommended (and default) model for $H_{if}*A_{if}$ is based on the model included in the TRAC-BF1 program and described in Section 4.1 of Reference 2. Its basis is discussed in Section 4.1 of this reference. An alternate model is also available which transfers the proper amount of energy between phases each time step to maintain thermal equilibrium. This model is useful for cross code comparisons to codes such as RETRAN02 and VIPRE01, which assume thermal equilibrium is maintained between phases.

2.2 FIBWR2 Core Model

The FIBWR and FIBWR2 programs are specifically designed to model the complex flow paths of the BWR geometry. The FIBWR2 code also has enhance modeling capability relative to the original FIBWR code to explicitly model features of advanced fuel designs such as axially variable flow areas due to part length fuel rods and varied water tubes designs (atriums, watercrosses) which may have flow entrances and exits above or below the upper and lower tie plates. The FIBWR and FIBWR2 programs model all significant flow paths between the lower and upper flow plena.

Based on the specific input for the modeling application, the FIBWR2 code methodology allows the representation of the BWR core with a large number of active channel, water tube and bypass flow paths between the lower and upper plena. Internal to the FIBWR2 program, the flow paths are treated as cells with nodes and junctions with each cell a control volume for mass and energy.

The lower and upper plena are each modeled as single cells. The number of cells for the active channel flow path is specified by the user and is usually specified such that the unheated regions in the active channels above and below the active fuel zone with heated fuel rods are modeled with a single cell. These upper and lower unheated zones are modeled as compound nodes. The features of these nodes include flow area changes, flow restrictions and other geometric characteristics associated with the specific representation of the flow and fuel bypass paths leading to exiting from the fuel. The representation of the active channel lower unheated node in the FIBWR2 methodology is shown in Figure 2-2. It includes the flow paths from inlet orifices to the top of the fuel lower tie plate. The upper unheated zone is relatively simple compared to the lower unheated

region since only one flow path is needed. This upper node simulates the flow from the upper unheated region of the fuel to the flow expansion above the fuel channel.

The number of uniform cells used to model the active fuel zone is controlled by the user within limits specified during compilation of the program. The bypass flow paths are modeled using the same number of cells as the active channels. A typical value for the number of active and bypass flow path cells is 27, with 25 cells used to model the active fuel zone for consistency with reactor physics models. The number of cells used to model the water tube flow paths is specified during compilation of the program. A typical value for the number of water tube cells is 5. Cells may be connected by a "leakage flow path" which is assumed not to store either mass nor energy. A typical application of this nodalization scheme is illustrated in Figure 2-1.

The capability to specify leakage flow paths between cells is significant since it allows more detailed modeling of the pressure drops and flow rates of bypass flow paths through the core support plate and the water tube flow path than is possible with general purpose thermal hydraulic codes such as RETRAN. As a result, the effects of changes in pressure drop distributions which occur as a result of system-wide perturbations can be evaluated with FIBWR2 and allow the calculation of flow distributions into and leakage paths out of an individual fuel assembly during a transient.

2.3 FIBWR2 Solution Scheme

The FIBWR2 code is intended specifically for use in BWR steady state distribution analysis and transient CPR determination. The BWR specific application uses several simplifying assumptions, delineated below, which allows a code structure requiring only a simple explicit Euler solution technique. Though this technique was chosen in part because it was accommodated by the simplifying assumptions, it was also chosen since it minimizes numerical dissipation which is especially important in boundary conditions which fluctuate such as fast pressurization events or oscillations associated with an instability.

The FIBWR2 solution of the conservation equations uses the following simplifying assumptions:

- All the core flow channels experience the same overall pressure drop.
- The flow is one-dimensional everywhere, although the liquid and vapor may travel at different velocities, and even in different directions.
- Liquid/vapor density and temperature are at saturation at a uniform core pressure.
- The void and pressure drop relationships used in the steady state analysis are valid for the transient analysis.

All of the default void and pressure loss relationships in FIBWR have been retained in FIBWR2, including those for:

- Initiation of subcooled boiling,
- Relation of flow quality to equilibrium quality,
- Relation of void fraction to flow quality,
- Single-phase friction factor,
- Two phase multiplier for frictional losses, and,
- Two phase multiplier for local (form) losses.

Although flow paths are treated one-dimensional by FIBWR2, the thermal-hydraulic effects of complex flow patterns have been incorporated into the models and input coefficients for predicting flow quality, void fraction, and pressure drop. As discussed previously, an additional model for the vapor generation from flashing or condensation is required for transient simulations. FIBWR2 has

incorporated several options, the default model (used in the CPR methodology) is derived from TRAC BF-1 [12]. These assumptions are reasonable for analysis AOT and allow the fluid dynamics to be simplified the a four equation model. Separate mass conservation equations are used for the liquid and vapor phases, while the momentum and energy conservation equations have been combined. The numerical integration of the four conservation equations formed by the code assumptions is performed with the explicit Euler integration scheme for the parallel path flow network of nodes defined by FIBWR2 input.

The FIBWR2 numerical techniques utilize an implicit solution for the calculation of fuel rod temperatures which always results in a tri-diagonal matrix which can be solved rapidly. These conservation equations and fuel rod conduction models in the FIBWR2 solution scheme enable a FIBWR2 based simulation containing several channels with about two hundred nodes and heat structures to run acceptably on a DOS based personal computer. While this would be a relatively small FIBWR2 model, much larger models containing thousands of nodes can be readily accommodated on a workstation.

2.4 Differences in the RETRAN and FIBWR2 Thermal Hydraulic Models

In the process of establishing the FIBWR2 CPR methodology, the thermal hydraulic models used in RETRAN and FIBWR2 were reviewed to establish the potential differences and possible limitations in FIBWR2. The review found that the FIBWR2 thermal hydraulic models do differ from the models used by RETRAN02, primarily due to the BWR specific nature of the models in FIBWR2. In RETRAN02, subcooled voids are not modeled in the hydraulic solution for channel quality and a generalized model, appropriate for both horizontal and vertical flow, for the two phase form loss multiplier is used. FIBWR2 includes a subcooled void model. Other models available in FIBWR2 were developed specifically for vertical flow in rodded bundles. FIBWR2 uses flowing quality in the Baroczy friction multiplier model, while the Yankee RETRAN model uses the static quality. RETRAN does not explicitly calculate bypass and water tube leakage, nor calculates the quality change above the part length rods in new fuel designs. These differences will not generally affect system transient calculations, where the core is lumped into a single equivalent channel. However, these differences may impact the MCPR response, which is determined by the flow response of upper nodes the most limiting assembly.

As part of the validation effort for the FIBWR2 CPR methodology, the model differences noted above were assessed to determine their impact on CPR performance and whether the FIBWR2 code provided the expected results. As will be discussed in more detail in the FIBWR2 and RETRAN CPR comparisons in Chapter 5, the majority of the difference in the transient performance of the two codes was found to be in the increased accuracy of the two phase multiplier in FIBWR2. This single difference changed the fuel channel active flow and the magnitude of the transient CPRs. The change in magnitude of CPR was consistent for the two limiting types of events at Vermont Yankee, the increase in pressure and decrease in feedwater temperature AOTs. The other codes' model differences did not identifiably impact the magnitude of CPR a given transient.

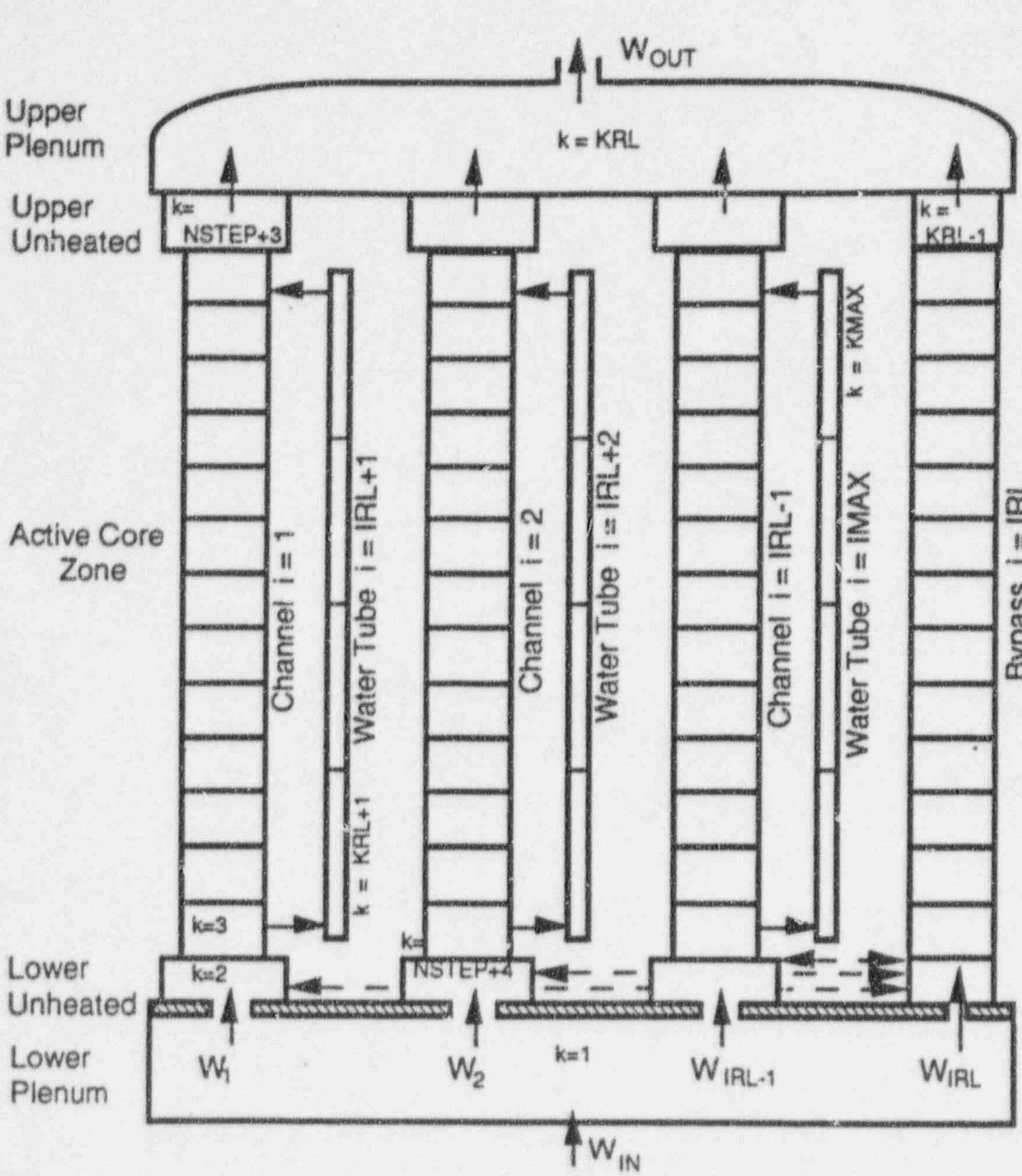

FIGURE 2-1

Nodalization Diagram

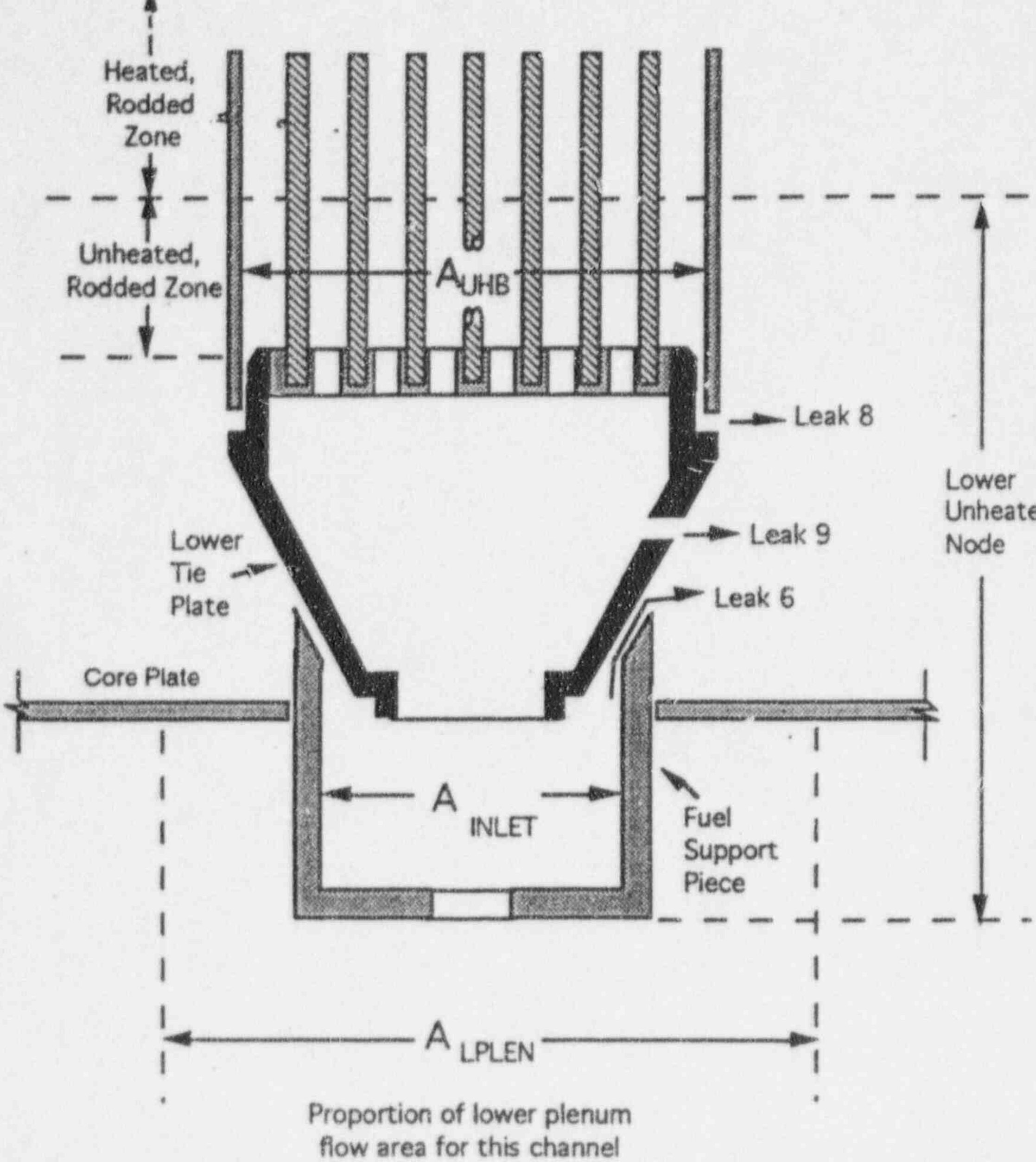

FIGURE 2-2

FIBWR2 Compound Lower Unheated Node

3.0 COMPARISON OF FIBWR2 WITH ANALYTIC SOLUTIONS

A valid test of a numerical procedure is to evaluate its prediction for a simplified problem for which an analytical solution may be obtained. Comparison to two analytic solutions are contained in this section to demonstrate that the enhance FIBWR conservation equations discussed in Section 2 have been correctly installed in FIBWR2. The first problem is an exponential flow decay transient. For the second problem, an oscillatory flow transient is simulated. The analytical solution is presented in Section 3.1, a verification of the steady state analytical solution in Section 3.2, and the results of the evaluation of each problem with FIBWR2 are compared to the results of the analytical solution in Sections 3.3 and 3.4.

3.1 Initial Conditions of Transient Two Phase Problems

To define a transient two phase problem with a general analytical solution for void fraction and mass flow, a number of simplifying assumptions were made. Specifically, the following assumptions were made:

- All water physical properties are evaluated at an assumed constant system pressure of 1000 psia.

- The liquid and vapor phases are in thermal equilibrium.

- Slip between the phases is evaluated using the drift flux model with the values of C_o and V_{gj} held constant.

- The power distribution along the length of the vertical heated channel is uniform and constant.

- The fluid entering the bottom of the channel is at saturated conditions.

- The system is at steady state conditions prior to the imposition of the inlet flow function.

- The flow into the channel is always positive.

Values of the parameters used to completely specify the initial conditions for the problems consistent with the above assumptions are presented in Table 3.1.

3.2 Comparison of the Steady-State Void Profile

The void profile of the initial steady state conditions can be determined analytically for each axial location by first noting that the total power delivered to the coolant, Q, at an axial location, z, for a uniform and constant power distribution is

$$Q = z\frac{Q_{tot}}{z_{tot}} \tag{1}$$

where Q_{tot} and z_{tot} are the total channel power and length, respectively.

All the power deposited in the coolant is used to change the phase of coolant from liquid to vapor since the coolant at the entrance to the channel is assumed to be at saturated conditions. At any axial location, the mass flow rate of the vapor is therefore the power that has been deposited divided by the heat of vaporization:

$$W_g = \frac{Q}{h_g - h_f} \tag{2}$$

For the initial steady state conditions, the mass flow is constant and the mass flow rate of the liquid portion of the two phase flow is:

$$W_f = W_{total} - W_g \tag{3}$$

The drift velocity is then calculated:

$$j = \frac{\left(\frac{w_f}{\rho_f} + \frac{w_g}{\rho_g}\right)}{A} \tag{4}$$

and the vapor velocity determined from the drift-flux relationship:

$$v_g = C_0 j + V_{gj} \tag{5}$$

Using the vapor velocity and vapor mass flow rate, the void fraction is:

$$\alpha = \frac{w_g}{A v_g \rho_g} \tag{6}$$

The void fraction profile calculated using the analytical solution presented above is compared to the initial void fraction profile evaluated with FIBWR2 in Figure 3-1. Inspection of Figure 3-1 indicates very good agreement between the analytical solution to the void fraction profile at the initial steady state conditions and the results of the FIBWR2 evaluation.

3.3 Description of Analytical Solution Technique

The general analytical solution for the void fraction profile under the assumptions specified in Section 3.1 is based on conservation of vapor mass:

$$\frac{\partial}{\partial t}(A\alpha\rho_g)+\frac{\partial}{\partial z}(A\alpha\rho_g v_g) = A\Gamma \tag{7}$$

When the expression for the vapor drift velocity of equation 5 is substituted into the above equation, the terms can be rearranged to yield the following expression by recognizing that the area, A, the drift-flux parameters, C_o and V_{gj}, and liquid and vapor densities, ρ_f and ρ_g, are assumed constant:

$$\frac{\partial\alpha}{\partial t}+(C_0 j+V_{gj})\frac{\partial\alpha}{\partial z} = \frac{\Gamma}{\rho_g}-\alpha C_0\frac{\partial j}{\partial z} \tag{8}$$

The terms of the left side of equation 8 can be interpreted as a material derivative:

$$\frac{D\alpha}{Dt} = \frac{\Gamma}{\rho_g}-\alpha C_0\frac{\partial j}{\partial z} \tag{9}$$

with a corresponding velocity of:

$$\frac{dz}{dt} = C_0 j+V_{gj} \tag{10}$$

When the initial conditions are known, equation 9 can be integrated to yield the void fraction at an axial location with that location determined by the relationship obtained by the integration of equation 10.

To perform these integrations, an expression for the drift velocity is required.

$$\frac{\partial j}{\partial z} = \Gamma\left(\frac{1}{\rho_g} - \frac{1}{\rho_f}\right) = k,\ say \tag{11}$$

where k is constant. The value of j at the inlet is determined by the inlet mass flow rate, which is:

$$j(z=0,t) = \frac{1}{A\rho_f}\left(W_0 + W_1 e^{-\beta t}\right) = j_0 + j_1 e^{-\beta t},\ say \tag{12}$$

when the inlet mass flow rate is assumed to be of the general form, $W = W_0 + W_1 e^{-\beta t}$. When equation 11 is integrated and combined with equation 12 the result is:

$$j(z,t) = j_0 + j_1 e^{-\beta t} + kz \tag{13}$$

which upon substitution into equation 10 yields the following expression for the axial location, z:

$$\frac{dz}{dt} - C_0 kz = C_0 j_0 + C_0 j_1 e^{-\beta t} + V_{gj} \tag{14}$$

This expression for the axial location, z, has the general solution:

$$z = \zeta e^{C_0 k t} + \eta e^{-\beta t} + \theta \tag{15}$$

where:

$$\eta = -\frac{C_0 j_1}{\beta + C_0 k} \tag{16}$$

$$\theta = -\frac{V_{gj} + C_0 j_0}{C_0 k} \tag{17}$$

and the value of ζ is determined by the initial conditions.

Similarly, substitution of equation 13 into equation 9 yields:

$$\frac{D\alpha}{Dt} + \alpha C_0 k = \frac{\Gamma}{\rho_g} \tag{18}$$

which has the general solution:

$$\alpha = \lambda e^{-C_0 k t} + \mu \tag{19}$$

where:

$$\mu = \frac{\Gamma}{\rho_g C_0 k} \tag{20}$$

and the value of λ is determined by the initial conditions.

Values for the parameters ζ and λ must be determined if the void fraction is to be determined for a selected axial location and time. The value of ζ can be determined by solving equation 15 directly for ζ using the selected values of axial location and time. The value of λ can be determined if the value of the void fraction can be determined for either any time or any axial location. Since the initial void fraction as a function of axial location is given by equation 6, if the value of the axial location, z is ≥0 as determined using equation 15, at time t=0, the value of the void fraction is known and equation 19 can be used to determine the value of λ. If the value of the axial location, z is <0 at time t=0 as determined using equation 15, equation 15 can be used to iteratively solve for the time at which the value of z=0. Using this time and the assumption that water entering the inlet channel is at saturated conditions, i.e., the void fraction is zero, the value of λ can be determined using equation 19. With the values of ζ and λ determined in this manner, the value of the void fraction for the selected axial location and time are known by equations 15 and 19.

The above solution for the void fraction profile for an inlet flow function of the form, $W = W_0 + W_1 e^{-\beta t}$ is valid for both real and complex values of the parameters W_0, W_1 and β. A FORTRAN program was written to evaluate results based on this analytical solution.

3.4 Flow Decay Transient

The FORTRAN program to evaluate a flow decay transient. The inlet flow function parameters selected to yield a flow decay condition consisted of all real values and were:

$$W(t) = 111500\, e^{-5t}\ lb/hr \tag{21}$$

The results of the analytical solution to the flow decay transient as evaluated using the FORTRAN code are presented along with the results of a FIBWR2 evaluation of the same conditions in Figure 3-2 for the exit void fraction. The difference between the analytical and FIBWR2 based void fraction values were insignicant. Values of the analytical and FIBWR2 based exit mass flow rates are presented in Figure 3-3. The agreement between FIBWR2 and the results based on the analytical solution are very good for the flow decay transient.

3.5 Oscillatory Flow Transient

The FORTRAN program was used to evaluate an oscillatory flow transient. The inlet flow function parameters selected to yield the oscillatory flow function include both real and imaginary values. The real part of this flow function is equivalent to:

$$W(t) = 111500 + 108000 \sin(5t) \tag{22}$$

The results of the analytical solution to the oscillatory flow transient for the exit void fraction are presented in Figure 3-4. The results obtained from evaluation of the oscillatory flow with a nominal FIBWR2 model with 24 axial nodes are also presented in Figure 3-4. The agreement between the results of the analytical solution and nominal FIBWR2 based evaluations is very good early in the transient. However, during the latter portion of the transient period evaluated, the nominal FIBWR2 results do not predict the rapid changes in exit void fraction calculated with the analytical solution. By inspection of these results it can be determined that the void fraction is changing more rapidly than the relatively large control cell node volumes of the nominal FIBWR2 model can resolve. Therefore the inability of the nominal FIBWR2 model with 25 nodes to predict the rapid changes in exit void fraction is not unexpected. To demonstrate the impact of control cell node volume, a FIBWR2 model of the oscillatory flow transient with 50 nodes was prepared. The exit void fraction results obtained from this 50 node FIBWR2 model are also presented in Figure 3-4. Inspection of Figure 3-4, indicates that the agreement between the results based on the analytical solution and the 50 node FIBWR2 model are nearly exact for the duration of the transient modeled.

3.6 Summary of Results for the Analytic Comparisons

The results of FIBWR2 evaluations were compared to results based on the analytical solution to two transient flow problems initiated from the same initial conditions. The void fraction profile calculated with FIBWR2 for the initial steady state conditions was essentially the same as the results obtained from the evaluation of the analytical solution. Very good agreement between the FIBWR2 and analytical solution based results for the exit void fraction and exit flow were obtained for the flow decay transient conditions evaluated. Agreement between the FIBWR2 and analytical solution exit void fraction results for the oscillatory flow transient conditions was shown to be dependent upon the number of nodes selected for use in the FIBWR2 model. This dependence of the number of nodes is to be expected for thermal hydraulics codes employing a control cell method for this type of transient. These comparisons and the results obtained demonstrate the appropriateness and correct implementation of the conservation equations, thermal hydraulic correlations, and numerical procedures of FIBWR2. It should also be noted that for transients involving oscillatory behavior, the number of nodes chosen is particularly important. For flow decay transients, the choice of 25 nodes was appropriate as demonstrated by the excellent agreement with the analytical solution.

TABLE 3.1

Initial Conditions Assumed for Transient Two Phase Problems

Parameter/Property at 1000 psia	Value	Units
Water inlet enthalpy	542.6	Btu/lb
Initial mass flow rate at inlet	111500	lb/hr
Channel power	1.00	MW
Channel length	12	ft
Channel flow area	16.056	in^2
Drift flux coefficient C_o	1.13	- -
Drift flux coefficient V_{gj}	1	ft/s
Saturated liquid density	46.3156	lb/ft^3
Saturated vapor density	2.2423	lb/ft^3
Saturated liquid enthalpy	542.6	Btu/lb
Saturated vapor enthalpy	1192.8422	Btu/lb

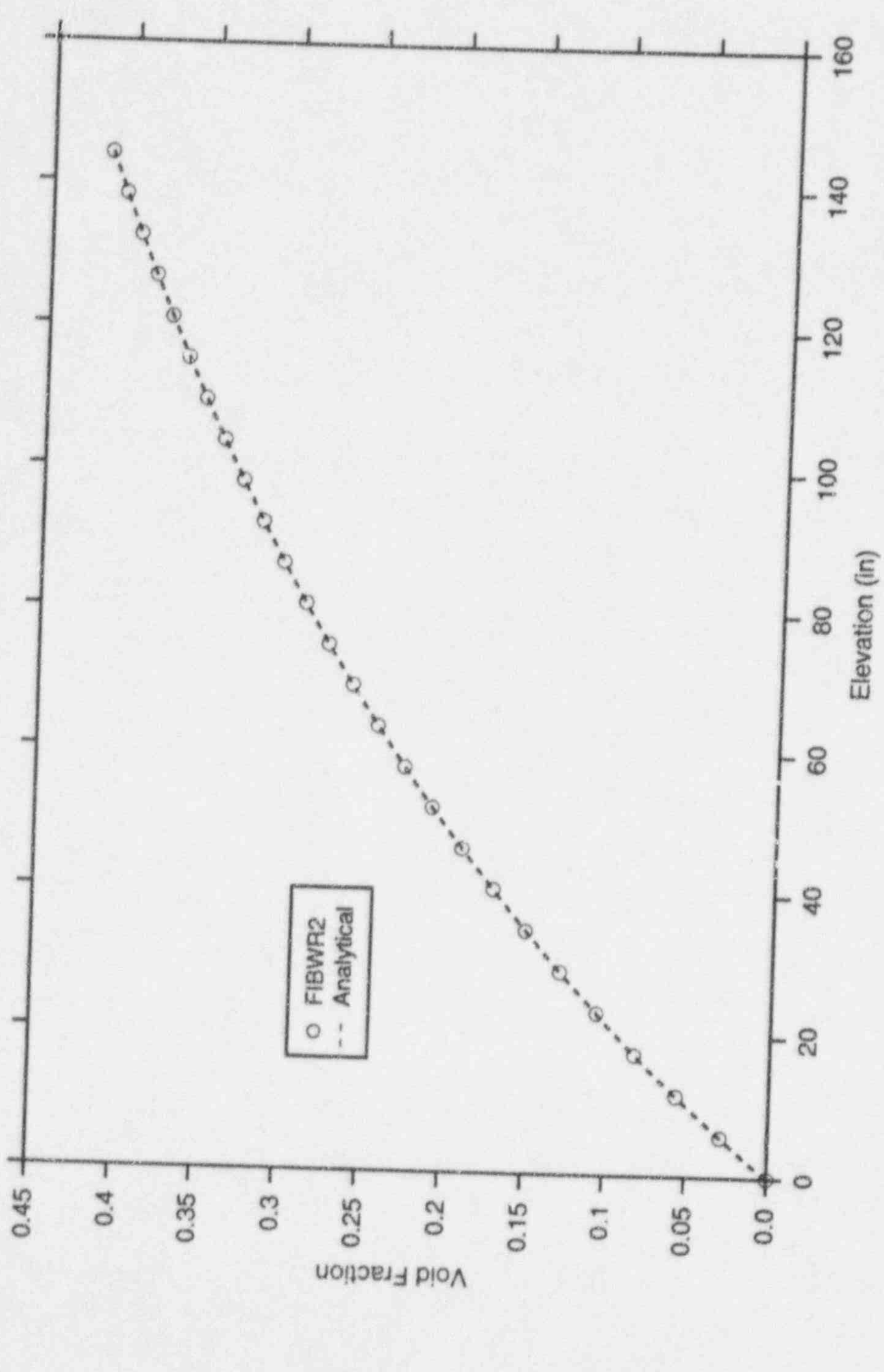

FIGURE 3-1

Steady State Void Fraction Comparison

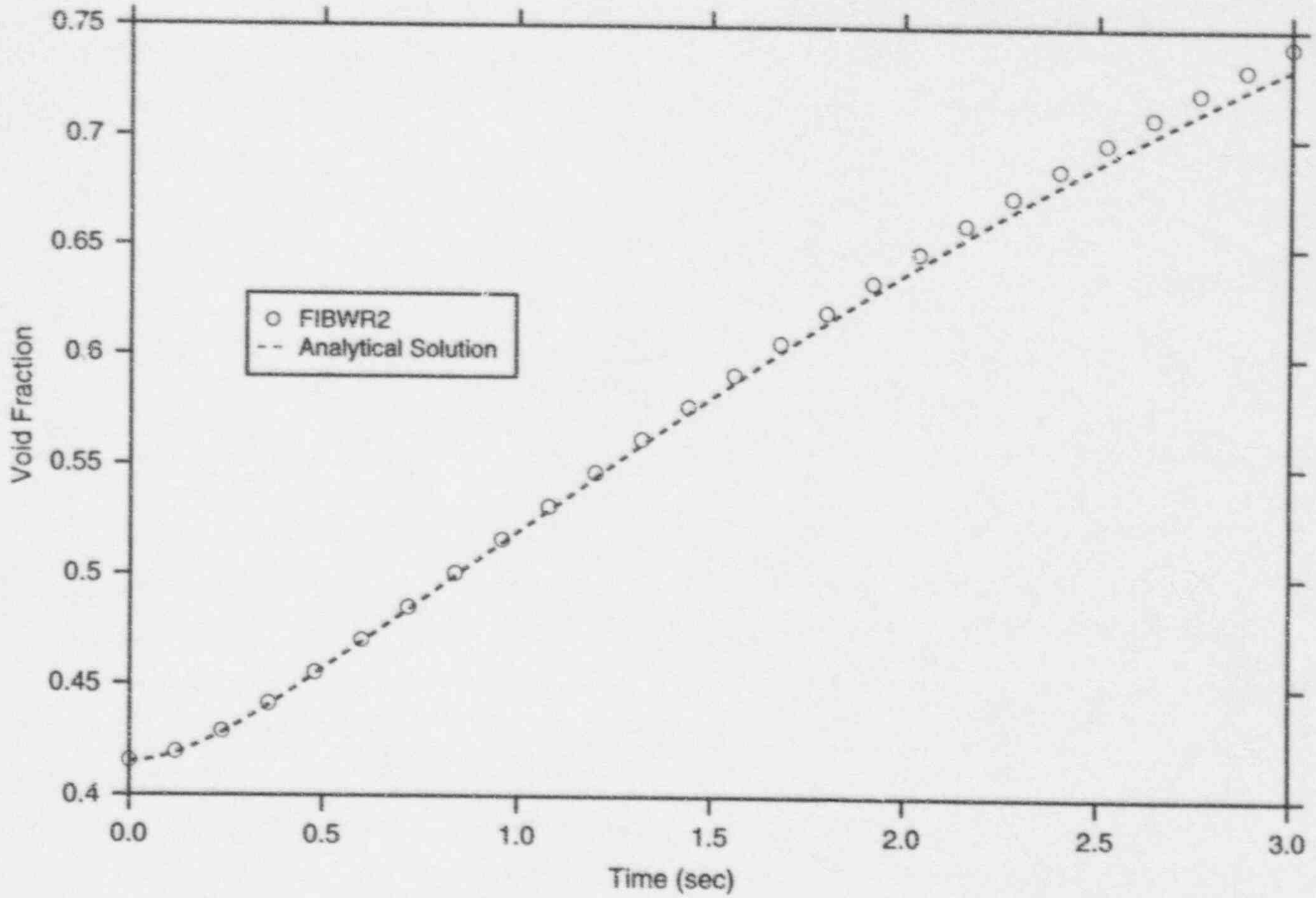

FIGURE 3-2

Flow Decay Transient - Void Fraction

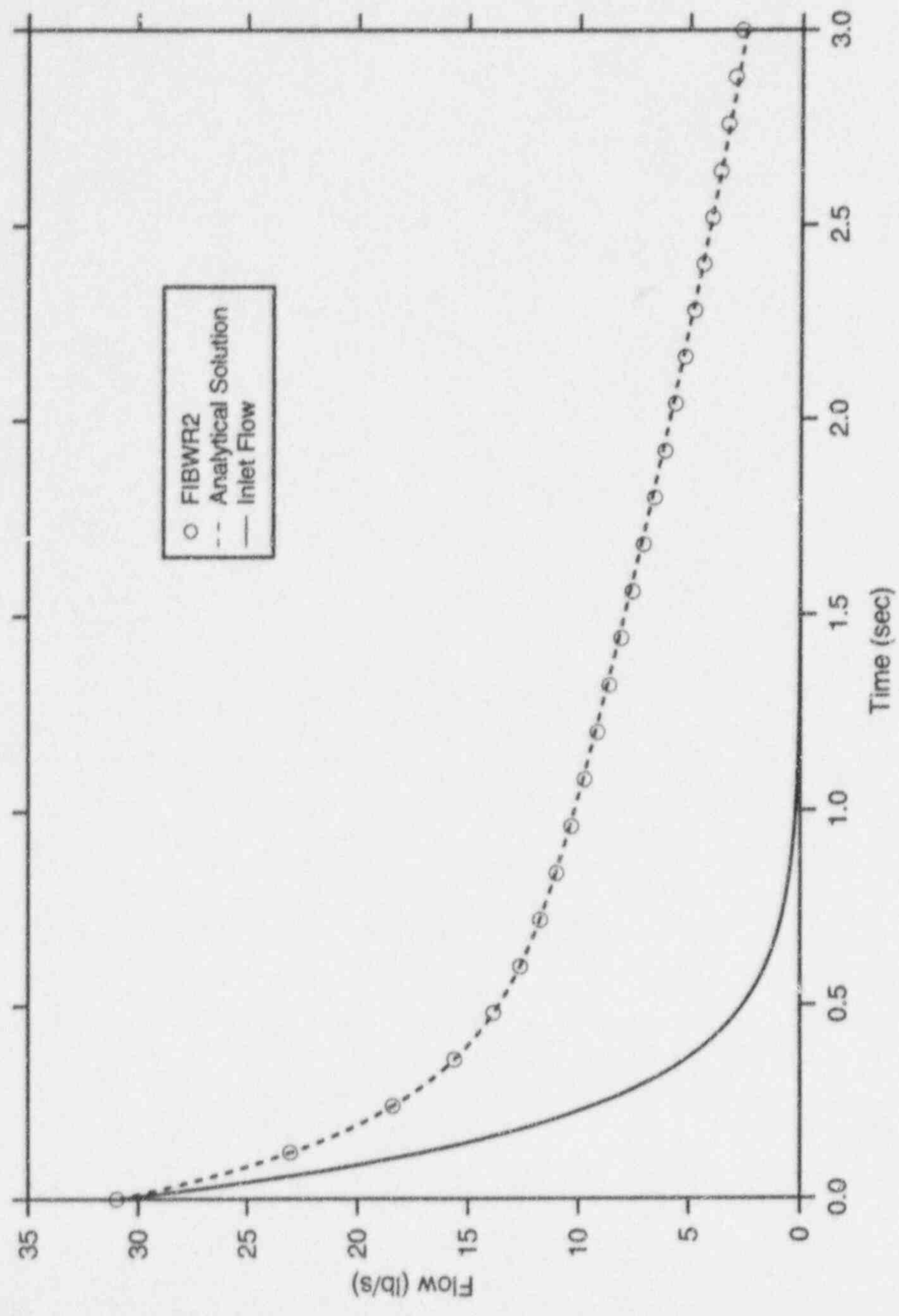

FIGURE 3-3

Flow Decay Transient - Exit Mode Flow Rates

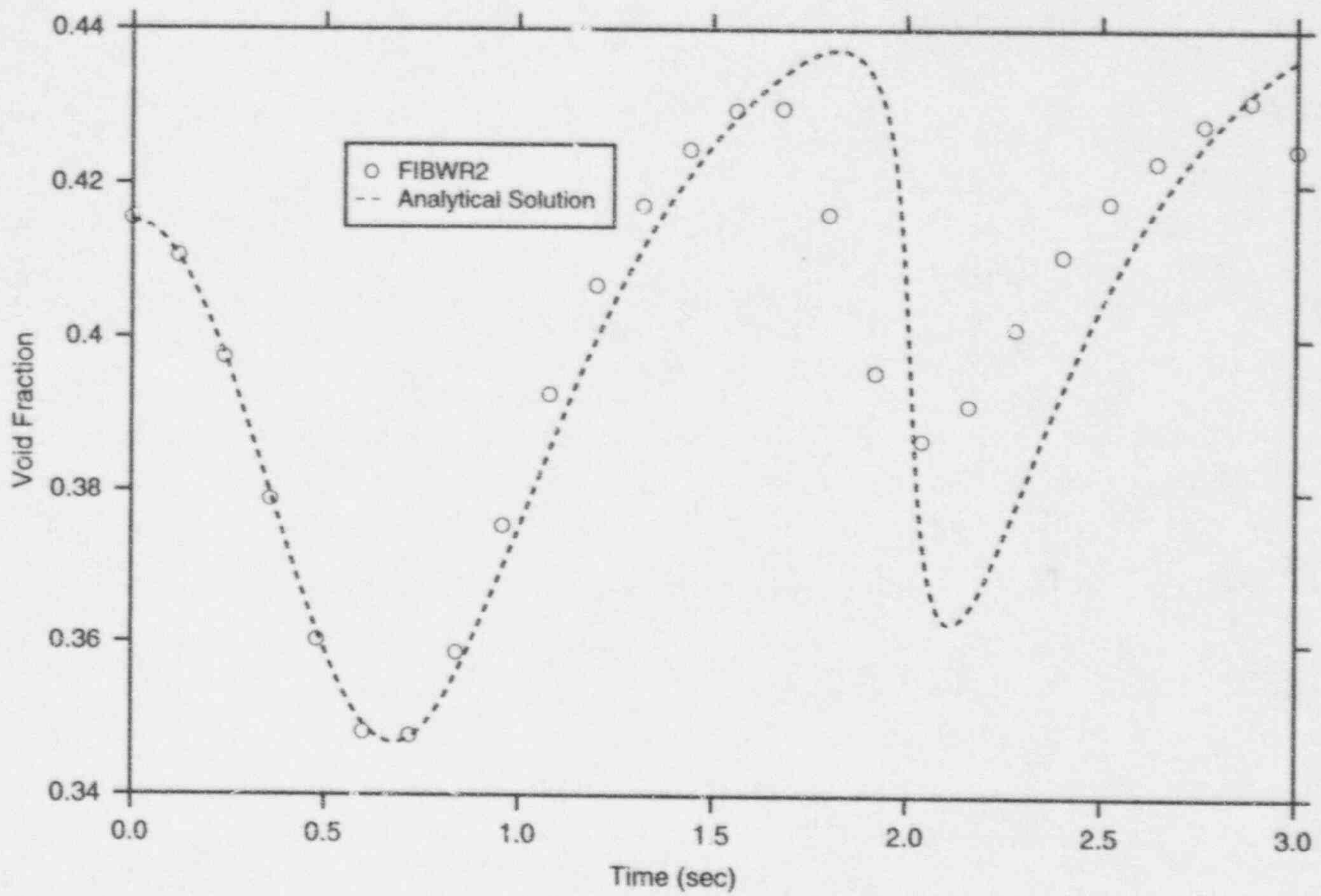

FIGURE 3-4

Flow Oscillation Transient - Void Fraction - 25 Nodes

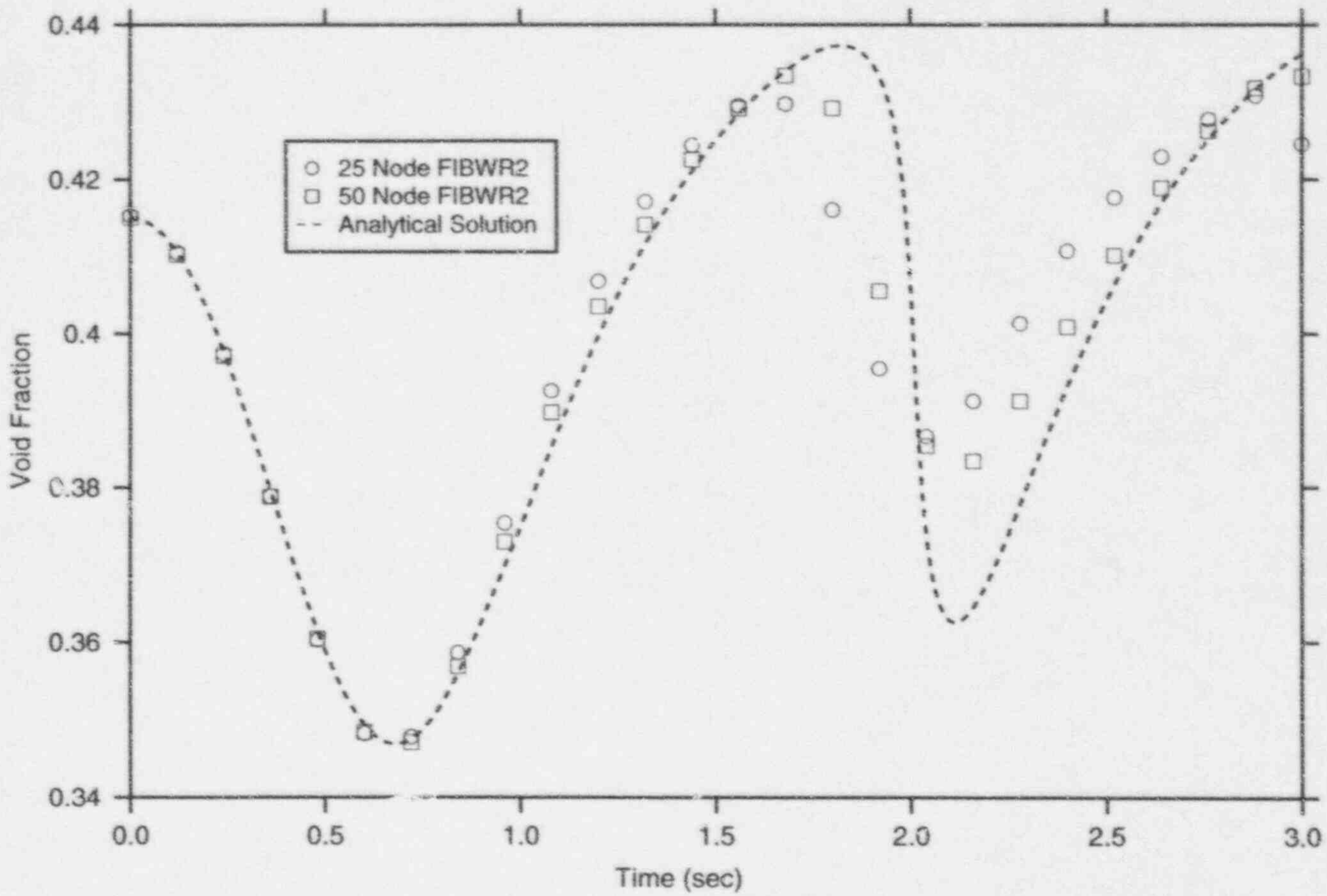

FIGURE 3-5

Flow Oscillation Transient - Void Fraction - 50 Nodes

4.0 COMPARISON OF FIBWR2 TO CRITICAL HEAT FLUX DATA

Qualification of FIBWR2 was performed against selected Critical Heat Flux (CHF) experimental test data for the 16 rod electrically heated test section identified as 16R-2 [3,4,5]. The tests selected for simulation were those tests with flow rates within the validated range of the General Electric proprietary Critical Power Ratio (CPR) GEXL correlation. These tests were conducted with values of mass flux in the range from 0.25 to 1.0 Mlbm/hrft^2, pressures in the range from 800 to 1,000 psia, and inlet subcooling in the range from 22 to 165 Btu/lbm. The 16 rod tests are representative of the fuel assemblies used in boiling water reactors and were specifically designed and conducted to produce conditions which result in transition boiling as indicated by a rapid rise in the temperature of the heated surface. A base FIBWR2 model was developed and used in combination with test specific data to simulate 50 steady state and 27 transient tests.

4.1 Simulation of Steady State and Transient 16 Rod Tests

Information describing the general configuration of the experimental test program [3,4,5] was used to construct a base FIBWR2 model. The 16 rod test bundle was constructed with direct heaters with variable cladding wall thickness along the length to provide a chopped cosine heat flux distribution with a peak to average value of 1.387. The heat flux distribution was simulated by specifying an axial power profile. The 16 rods were modeled using one hot rod and one lumped rod for the remaining 15 rods with 24 axial geometry nodes. The varying cladding thickness was simulated by an appropriate number of lattices and rod types to model the hot and lumped rods.

The onset of transition boiling and the associated changes in the heat transfer regime is predicted by empirical correlations such as the proprietary General Electric GEXL and GEXL-PLUS correlations. FIBWR2 is structured to allow implementation of fuel vendor specific correlations within the program coding. The calculated parameters required for boiling transition correlations can therefore be provided either for post processing or used within the FIBWR2 program execution to calculate parameters such as CPR to assess the approach to the onset of transition boiling.

Simulations of the steady state conditions under which the onset of boiling transition was observed during the 16 rod tests were performed using the FIBWR2 base model. The CPR values

calculated using FIBWR2 for each of the 50 steady state tests are plotted as a function of the measured critical power for each test in Figure 5-1. Inspection of Figure 5-1 indicates that for all steady state tests, the onset of boiling transition, (i.e., CPR <1.00) was predicted within about ±5% and that the variation of the calculated CPR from a nominal value of 1.0 decreases slightly as the measured critical power increases. For these 50 steady state tests, the mean of the FIBWR2 based CPR values was 1.007 with a standard deviation of 0.0186. These results indicate that the 16 rod test configuration was appropriately represented by the FIBWR2 base model and that the CPR correlation was properly implemented within the FIBWR2 program coding structure. For comparison, the mean and standard deviation of the CPR value for these same 50 steady state cases obtained from simulations using the RETRAN and TCPYA01 models were 1.006 and 0.0182 [9].

Transient 16 rod test conditions were simulated to demonstrate the capability of FIBWR2 in conjunction with a CPR correlation to adequately predict the onset of boiling transition under changing thermal hydraulics conditions in a fuel assembly. This demonstration tests FIBWR2's ability to appropriately evaluate the changing thermal and hydraulic parameters at locations within the assembly and the fidelity of the CPR correlation. Therefore, the capability of a model to adequately predict the timing, and even the occurrence of the onset of boiling transition under test conditions where boiling transition was observed, is dependent on both the analysis of the transient thermal hydraulic conditions and the empirical CPR correlation. In the following paragraphs, the results of the FIBWR2 based simulations are compared with the test results and the results of similar RETRAN based simulations for a total 27 transient test cases. The 27 transient test cases which were simulated with both FIBWR2 and RETRAN consisted of 13 flow decay with constant power cases, 12 flow and power decay cases and 2 flow and power increase cases. For each of these 27 transient cases, the time of onset of boiling transition was taken to be the time at which a rapid rise in surface temperature was indicated in the reported test data. BWR MCPR methodology uses a "best fit" CPR correlation, therefore, these simulations did not always predict CPR values equal to or less than 1.0. The time at which the CPR value was equal to 1.0 was taken as the calculated time of onset of boiling transition for the cases where the CPR went below 1.0.

The onset of boiling transition was calculated to occur during 20 of the 27 transient simulations. These times are plotted against the measured times of the onset of boiling transition in Figure 5-2. The variance (root mean square) of the differences between the measured times and the

times calculated based on the FIBWR2 simulations for these 20 transient cases is 0.458 seconds. The same 27 transient cases were simulated using the RETRAN and TCPYA01 models [10] with the onset of boiling transition calculated to occur during 19 of the 27 transient cases. The variance of the differences between the measured and RETRAN and TCPYA01 calculated times of the onset of boiling transition is 0.593. The small variance for both the FIBWR2 and RETRAN simulations indicate good agreement with the experimental results with slightly better agreement for the FIBWR2 simulations relative to the RETRAN simulations.

Comparison of the CPR values and times of boiling transition calculated based on FIBWR2 simulations of experimental test data demonstrate the capability of FIBWR2 to accurately calculate thermal hydraulic parameters necessary for the prediction of the onset of boiling transition under both steady state and transient conditions. In addition, the good agreement between the results of the FIBWR2 based simulations and the results of the RETRAN and TCPYA01 model simulations, previously approved for hot channel analysis, further demonstrates the applicability of FIBWR2 to steady state and transient thermal hydraulic analysis.

4.2 Sensitivity Studies

Sensitivity studies were performed to document the impact of three representative alternative choices that may be selected for simulations using FIBWR2. The three alternative modeling specifications considered were axial nodalization, void model and time step size. The 16 rod test cases for the 13 flow decay with constant power transients were selected for the sensitivity studies based on the relative severity of the change in thermal hydraulic conditions experienced in these transients. For each case, the results of the FIBWR2 sensitivity studies were compared to a base case FIBWR2 simulation. The base case FIBWR2 simulations used 24 axial nodes, the EPRI void model and minimum and maximum time step sizes of 0.001 and 0.005 seconds, respectively.

The calculated times of the onset of boiling transition for the axial nodalization sensitivity study which reduced the base case number axial nodes from 24 to 12, the void model sensitivity study which specified the use of the homogeneous model and the time step size sensitivity study which increased the minimum and maximum time step sizes to 0.01 and 0.05 seconds, respectively, are compared against the results for the base case simulations in Figure 5-3 for all cases for which

the onset of boiling transition was calculated. Inspection of Figure 5-3 indicates that specification of each of the alternate simulation options produces a negligible effect on the calculated time of boiling transition onset. Based on these studies it is concluded that the base case time steps and nodalization (0.01 seconds and 24 nodes) are adequate for a FIBWR2 hot channel model. As indicated in Section 2, the nodalization may be dependent on the type of transient to be simulated; thus, a sensitivity study may be required to ensure convergence of results. Convergence would be obtained if the parameter changed did not significantly change the results.

4.3 Summary of 16 Rod Test Simulations

The FIBWR2 program was used to simulate selected steady state and transient test cases of 16 rod critical heat flux experiments. The results of these simulations were compared with both the test data and the results of RETRAN simulations of the same test data. The FIBWR2 based evaluations of the CPR for the steady state cases were in good agreement with the test data results and similar RETRAN simulations. The results of the FIBWR2 based evaluations of the time of onset of boiling transition for the transient cases were also in good agreement with reported test data results. For those transient cases for which the onset of boiling transition was calculated, the variance between the calculated and measured times based on the FIBWR2 simulations was slightly less than for similar RETRAN simulations. The good agreement between the FIBWR2 results and both the test data and the results of the RETRAN simulations demonstrate the capability of the FIBWR2 models in conjunction with critical power correlations to adequately predict the onset of boiling transition. Furthermore, the results of sensitivity studies which specified different modeling options for axial nodalization, void model and time step size demonstrate the adequacy and robustness of FIBWR2 over a range of values and available alternative specifications. To obtain convergence of the FIBWR2 simulations a sensitivity study on time step and nodalization may be required.

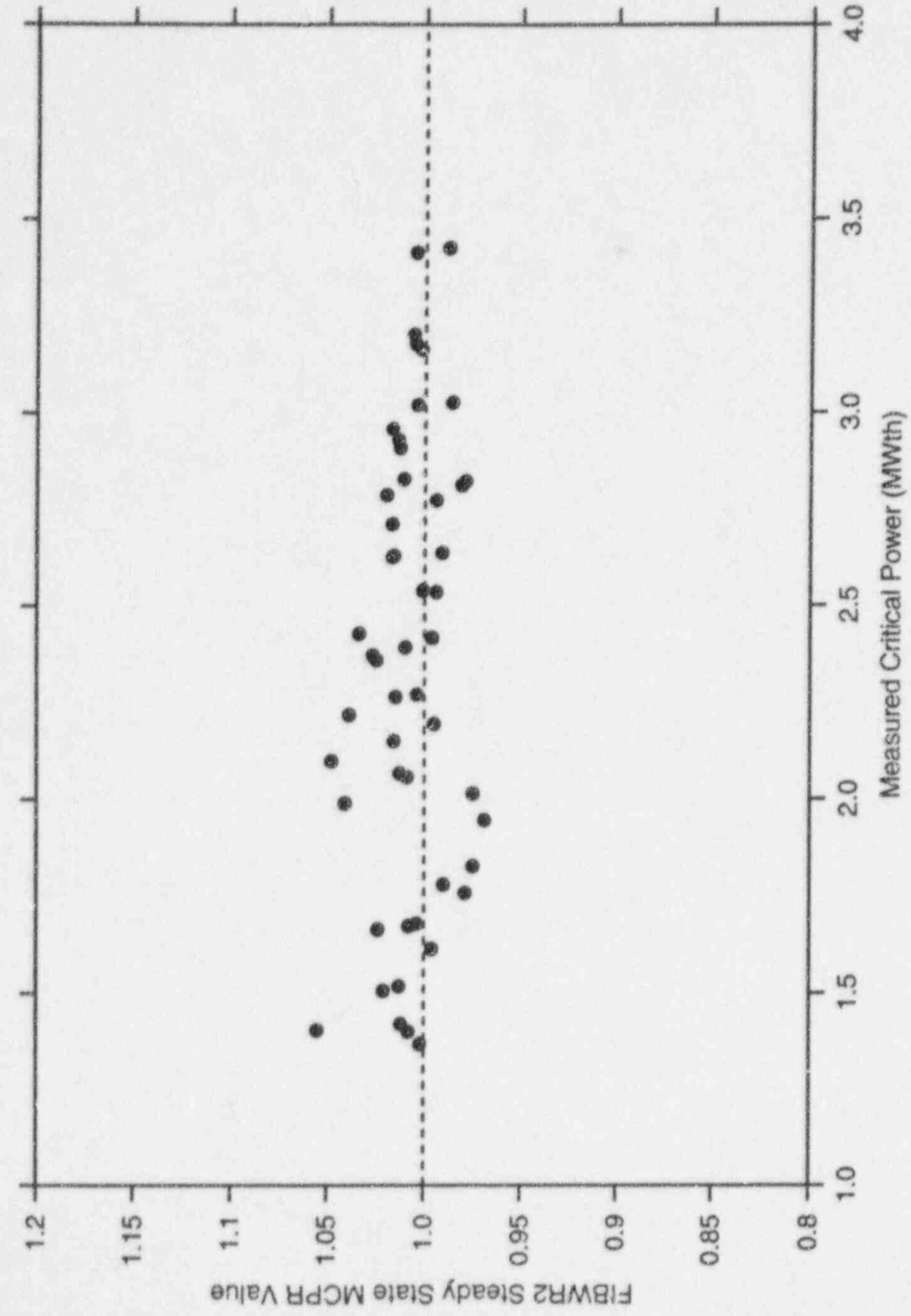

FIGURE 4-1

FIBWR2 Steady State 16 Rod CPR Results

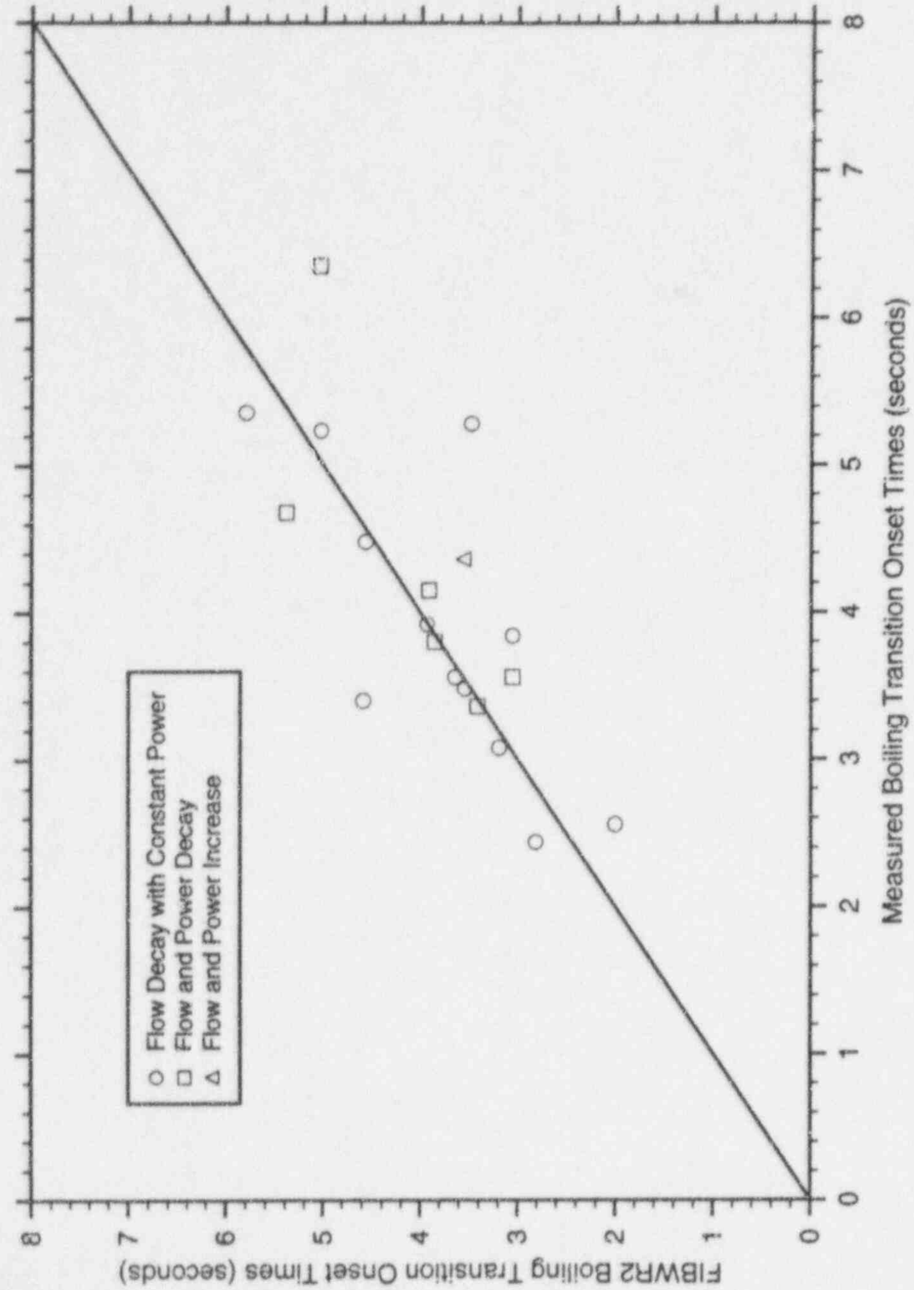

FIGURE 4-2

FIBWR2 Transient 16 Rod Boiling Transition Onset Results

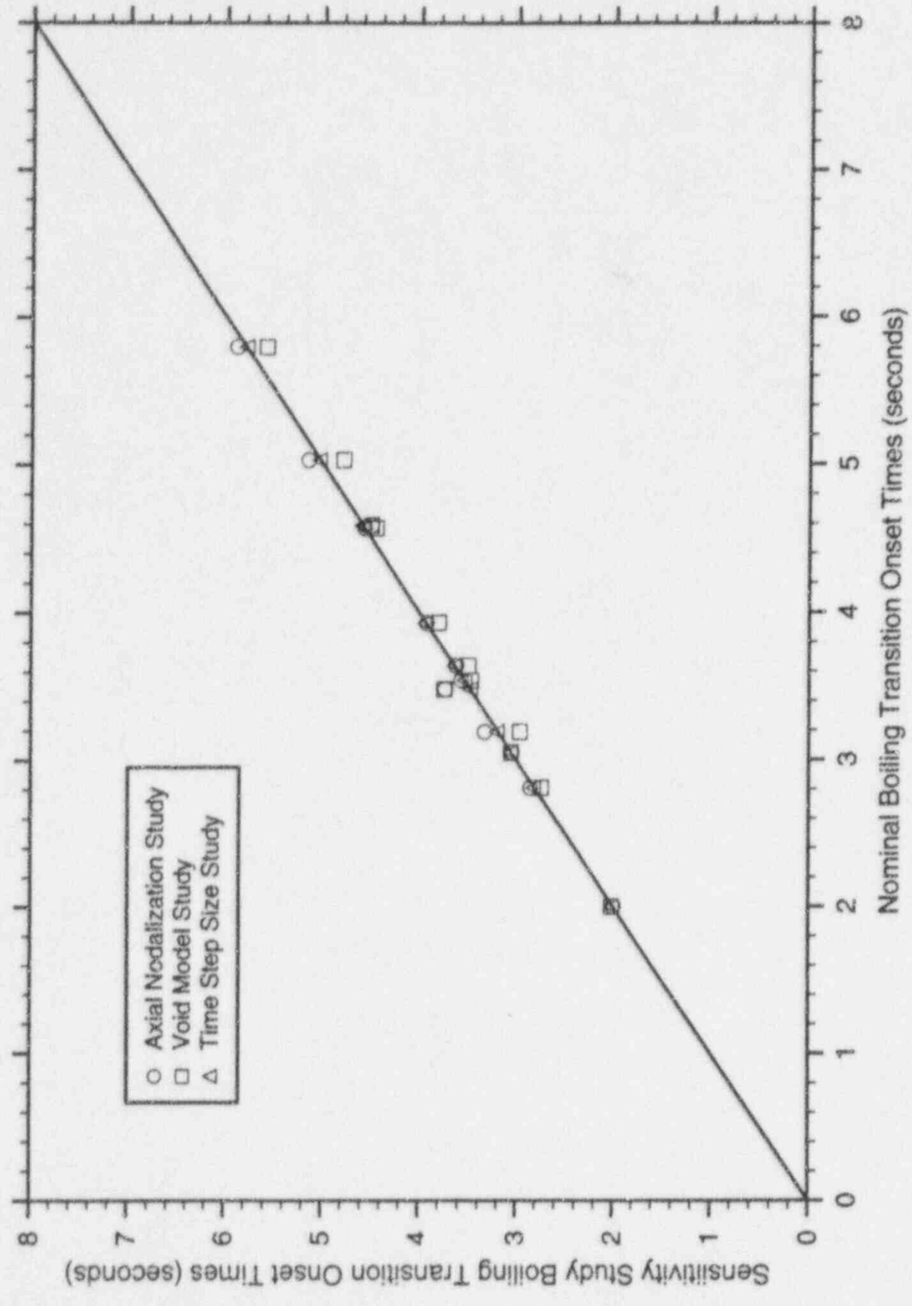

FIGURE 4-3

ATLAS 16 Rod Test CPR Predictions - Sensitivity Study Results

5.0 FIBWR2 TRANSIENT HOT CHANNEL PERFORMANCE

The applicability of the FIBWR2 code to the evaluation of transient hot channel thermal hydraulic conditions, including the calculation of CPR, is demonstrated by comparison to similar evaluations performed using the RETRAN and TCPYA01 hot channel methodology. The RETRAN and TCPYA01 models are currently used in the YAEC BWR reload analysis methodology [7,8,10]. Comparison of FIBWR2 and RETRAN hot channel hydraulic parameters for two characteristic anticipated transients is presented along with the change in CPR values for several limiting and near limiting postulated events. Differences in the thermal hydraulic parameters and in the change in CPR calculated for these events are identified and determined to be primarily the result of differences in the modeling of two phase multipliers for local form losses in the respective models; these will be discussed further in Section 5.2.

5.1 Hot Channel Methodology

The objective of the hot channel methodology is to evaluate the thermal hydraulic conditions of the fuel assembly that most nearly approaches the onset of boiling transition during postulated events. The approach of the hot channel to the onset of boiling transition is determined by the postulated event and the initial conditions of the hot channel and core.

In the current YAEC BWR reload analysis methodology a RETRAN model of the plant and its controls is utilized to establish the system wide response to the postulated event. This system wide response is used to set boundary conditions of upper and lower plena pressures and normalized power response for a second RETRAN model of the hot channel. The RETRAN hot channel model consists of a single fuel assembly, a core bypass region and upper and lower plena. The pressure loss coefficients of the RETRAN hot channel model are adjusted as necessary to make the pressure drop and flow distributions agree with the results of a FIBWR analysis which models the various core flow paths in detail.

The transient thermal hydraulic conditions for the single hot channel fuel assembly is then evaluated using the RETRAN hot channel model and the boundary conditions set by the system wide RETRAN model transient response. The calculated hot channel thermal hydraulic performance

parameters are subsequently evaluated using the TCPYA01 model to calculate the initial and minimum CPR values for the fuel assembly.

In an iterative process, the initial power level of the fuel assembly in the RETRAN hot channel model is then adjusted until the change in CPR caused by the event of interest approaches the predicted onset of boiling transition or safety limit minimum CPR value. The safety limit minimum CPR value is the lowest allowable CPR and is set based on the combined uncertainties associated with the experimental data used to construct the CPR correlation, instrument, power distribution, core power and core flow uncertainties. The value of the safety limit minimum CPR is typically on the order of 1.08.

The capability of the FIBWR2 program to calculate both transient thermal hydraulic conditions and initial and minimum CPR values permits the RETRAN hot channel and TCPYA01 models to be replaced with a single code. Furthermore, the greater detail in modeling the BWR specific fuel and core geometry and the capability to use thermal hydraulic models specifically developed for application to BWR conditions available with the FIBWR2 code allows greater fidelity in modeling the pressure drop and flow distributions than can be obtained with the RETRAN hot channel model.

5.2 Hot Channel Results

Comparisons of FIBWR2 based calculations associated with the evaluation of hot channel response are presented for both key thermal hydraulic parameters and for the resulting change in CPR for selected postulated transient events. Key thermal hydraulic parameters values are presented for FIBWR2 and RETRAN transient evaluations of two postulated events with the same initial, and therefore the same transient, hot channel power levels. As expected, the two codes calculated thermal hydraulic parameters are different due to the differences in the thermal hydraulic models. This causes a difference in the minimum CPR calculated for each event. In addition to the comparison of thermal hydraulic parameters, the change in CPR values calculated using the FIBWR2 and RETRAN based hot channel models are also presented for several postulated events.

5.2.1 Comparison of Thermal Hydraulic Parameters

Key values of the transient thermal hydraulic conditions for the evaluation of CPR are the active coolant flow and void fraction. Comparison of these parameters calculated with the FIBWR2 and RETRAN transient hot channel models are presented for a pressurization event and an increased subcooling event. These events are the Generator Load Rejection Without Bypass (GLRWOBP) pressurization event and the Inadvertent High Pressure Core Injection (IHPCI), Loss of Feedwater Heater (LOFWH) and Loss of Stator Cooling (LOSC) events resulting in an increase in core subcooling. All cases were analyzed for Vermont Yankee.

The GLWOBP event was selected as a typical pressurization event. The power level and the upper plenum pressure during the event, determined from the system wide RETRAN evaluation, and used as boundary conditions for both the FIBWR2 and RETRAN hot channel models, are presented in Figures 5-1 and 5-2, respectively. The active coolant flow for the event calculated by the FIBWR2 and RETRAN transient hot channel models is presented in Figure 5-3. The initial active coolant flow rates are nearly identical. The exit void fraction is similarly presented for the two models in Figure 5-4. The initial void fractions are different due to the water tubes models in each code. In the RETRAN simulation of the water tube, the water tube flow is modelled to exit above the channel active flow. In the FIBWR2 model, the water tube flow recombines with the coolant flow in the fuel assembly at the actual height associated with the fuel design, which is six inches below the top of the active fuel. This difference in the water tube flow exit heights results in different channel exit void fractions observed in Figure 5-4, but does not impact the minimum CPR which occurs below the exit of the water tubes.

As the GLRWOBP event progresses, the active coolant flow rates calculated by the two models remain nearly the same until the pressure starts to increase at about 0.5 seconds. At this time, differences in the two phase pressure losses in the fuel assembly begin to occur. As expected, the models also indicate decreasing exit void fraction due to the pressurization starting at about 0.5 seconds. With this decrease in void fraction, the two-phase pressure loss of the hot channel begins to decrease.

Due to the decrease in two phase pressure loss at this time, an increase in hot channel active coolant flow is observed for both the FIBWR2 and RETRAN models. However, the increase in active coolant flow calculated with the FIBWR2 model is larger than that calculated with the RETRAN model. This difference in calculated active coolant flow is due to the modeling of the two phase form loss multiplier between the two codes. As described in Section 2.4, the RETRAN local form loss two phase multiplier is less sensitive to changes in the void fraction than the corresponding FIBWR2 model. As a result, RETRAN calculates a smaller change in pressure loss and a subsequent smaller change in flow rate than FIBWR2. As previously discussed the FIBWR2 local form loss multiplier is a BWR fuel specific model and is a more accurate representation than RETRAN for this application. As will be discussed in Section 5.2.2, while the RETRAN code provides a conservative prediction of transient CPR, FIBWR2 provides a more accurate result.

The Loss of Stator Cooling (LOSC) event was selected as a representative increase in subcooling event since it generally results in the largest change in transient CPR. The power level and the upper plenum pressure during the event, determined from the RETRAN core wide evaluation and used as boundary conditions for both the FIBWR2 and RETRAN hot channel models, are presented in Figures 5-5 and 5-6, respectively. The active coolant flow for the event calculated by the FIBWR2 and RETRAN transient hot channel models is presented in Figure 5-7. As was seen for the GLRWOBP event, the initial active coolant flow rates are nearly identical. The exit void fraction for the two models are presented in Figure 5-8. The difference in the exit void fraction is similar to that observed for the GLRWOBP pressurization event and as noted in the discussion of the results for that event is the result of differences between the two models in the modeling of the water tube flow.

For the LOSC event the exit void fraction increases slowly as expected due to the core power rise. The greater sensitivity of the FIBWR2 local form loss two phase multiplier to void fraction causes a slightly greater pressure increase than the RETRAN model. As a result, the FIBWR2 calculated hot channel active flow is slightly less than the active coolant flow calculated with the RETRAN model. The FIBWR2 simulation thus predicts a larger change in transient CPR. These results will be discussed further in the following section.

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5.2.2 Comparison of Calculated CPR Values

Evaluations of the change in CPR using the transient capability of FIBWR2 as an alternative to the use of the RETRAN transient hot channel model and TCPYA01 were conducted for several postulated events. The results for selected pressurization and increased subcooling events for both the RETRAN and FIBWR2 based models are presented in Tables 5.1 and 5.2, respectively.

The largest difference in the change in CPR calculated using the two models was for the Turbine Trip without Bypass (TTWOBP) event at the end of full power life (EOFPL) reported in Table 5.1. The change in CPR calculated for this event was the most limiting for both the RETRAN and FIBWR2 based hot channel models. The reduction of about 0.051 in the calculated change in the CPR for this event using the FIBWR2 hot channel model is due to the greater sensitivity of the local form loss two phase multiplier of FIBWR2 relative to RETRAN. These results are consistent with the changes in hot channel active flow calculated with each code previously discussed in Section 2.4 and as shown in Section 5.2.1. While the RETRAN code predicts a lower active flow and more conservative transient CPR for the pressurization event, the local form loss two phase multiplier model in FIBWR2 code is more applicable to the conditions found under BWR conditions than the more general model available with the YAEC RETRAN hot model.

In comparison, the FIBWR2 hot channel results for the increased subcooling events result in slightly larger changes in CPR (about +0.01) than RETRAN. The results obtained for the subcooling transients are consistent with the results for the LOSC discussed in Section 5.2.1. The FIBWR2 model predicts a smaller active flow rate for all cases and subsequently an increase in the transient CPR. The FIBWR2 results provide the most accurate representation of the subcooling events.

TABLE 5.1

Calculated CPR Values for Pressurization Events

Event/Notes*	RETRAN/TCPYA01 ΔCPR	FIBWR2 ΔCPR	Difference RETRAN-FIBWR2
TTWOBP/MST/EOFPL	0.239	0.21	0.029
TTWOBP/MST/EOFPL-1	0.176	0.157	0.019
TTWOBP/MST/EOFPL-2	0.099	0.077	0.022
TTWOBP/MST/ELLA	0.088	0.055	0.033
TTWOBP/67B/EOFPL	0.307	0.256	0.051
TTWOBP/67B/EOFPL-1	0.216	0.197	0.019
TTWOBP/67B/EOFPL-2	0.141	0.12	0.021
TTWOBP/67B/ELLA	0.134	0.087	0.047
GLRWOBP/MST/EOFPL	0.22	0.192	0.028
GLRWOBP/MST/EOFPL-1	0.152	0.127	0.025
GLRWOBP/MST/EOFPL-2	0.071	0.038	0.033
GLRWOBP/MST/ELLA	0.068	0.028	0.040
GLRWOBP/67B/EOFPL	0.281	0.236	0.045
GLRWOBP/67B/EOFPL-1	0.212	0.18	0.032
GLRWOBP/67B/EOFPL-2	0.122	0.108	0.014
GLRWOBP/67B/ELLA	0.127	0.068	0.059

*Notes:

All events initiated from nominal full power and flow conditions unless otherwise noted

GLRWOBP - Generator Load Rejection without Bypass
TTWOBP - Turbine Trip without Bypass
MST - Measured Scram Time
67B - Table 67B Scram Times
EOFPL - End of Full Power Life; -1, minus 1 GWD/STU; -2, minus 2 GWD/STU
ELLA - Extended Load Line Limit Analysis initial conditions of 100% Power/87% Flow

TABLE 5.2

Calculated CPR Values for Subcooling Events

Event/Notes*	RETRAN/TCPYA01 ΔCPR	FIBWR2 ΔCPR	Difference RETRAN-FIBWR2
LOFWH/EOFPL	0.135	0.141	-0.006
LOFWH/EOFPL-1	0.108	0.115	-0.007
LOFWH/EOFPL-2	0.107	0.114	-0.[illegible]
LOFWH/BOL	0.109	0.114	-0.005
IHPCI/EOFPL	0.112	0.118	-0.006
IHPCI/EOFPL-1	0.113	0.119	-0.006
IHPCI/EOFPL-2	0.118	0.119	-0.001
IHPCI/BOL	0.113	0.119	-0.006
LOSC/EOFPL	0.135	0.139	-0.004
LOSC/EOFPL-1	0.135	0.14	-0.005
LOSC/EOFPL-2	0.134	0.14	-0.006
LOSC/BOL	0.135	0.14	-0.005

*Notes:

All events initiated from nominal full power and flow conditions unless otherwise noted

LOFWH	- Loss of Feedwater Heating
IHPCI	- Inadvertent High Pressure Coolant Injection actuation
LOSC	- Loss of Stator Cooling
EOFPL	- End of Full Power Life; -1, minus 1 GWD/STU; -2, minus 2 GWD/STU
BOL	- Beginning of Life

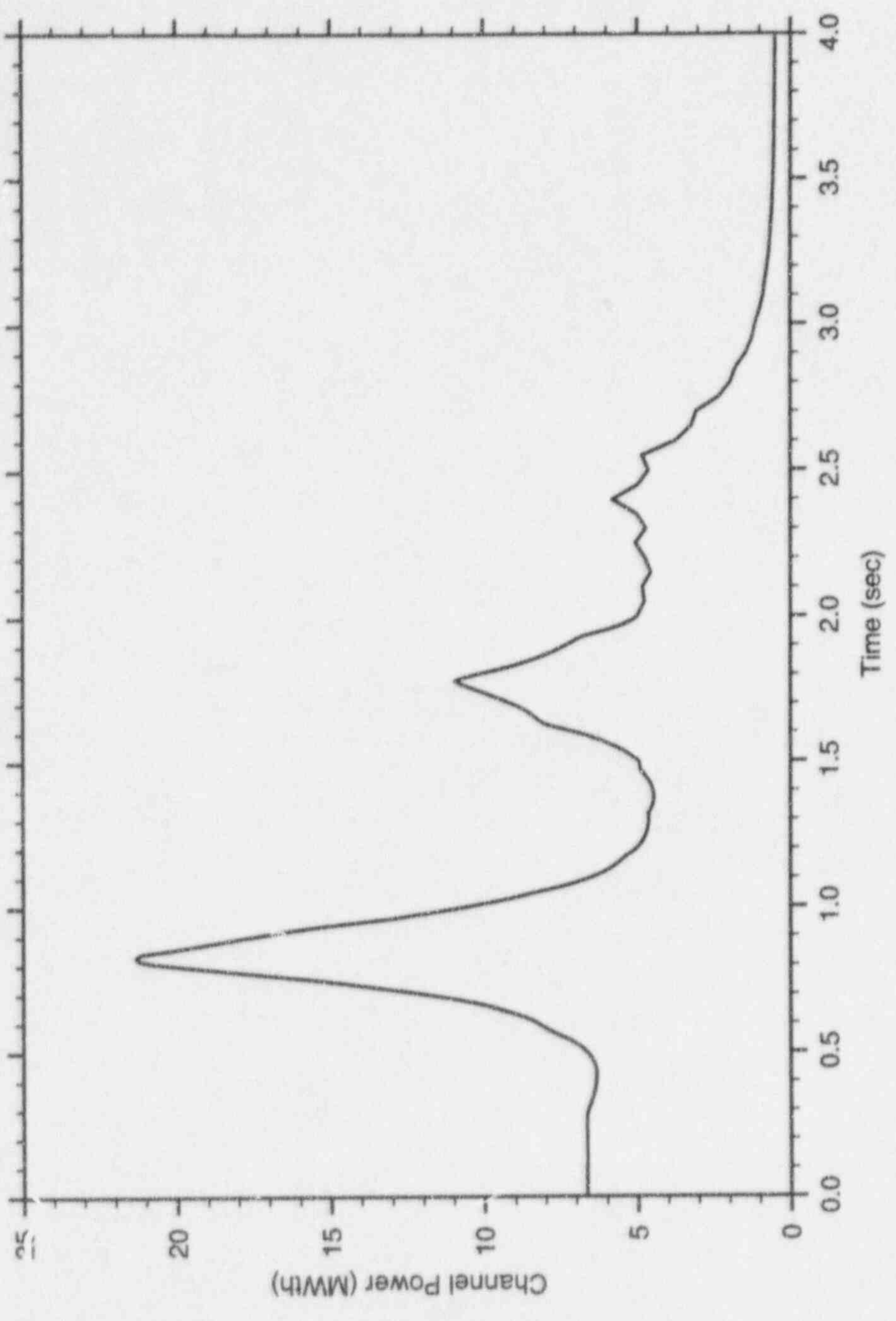

FIGURE 5-1

GLRWOBP Boundary Conditions Channel Power

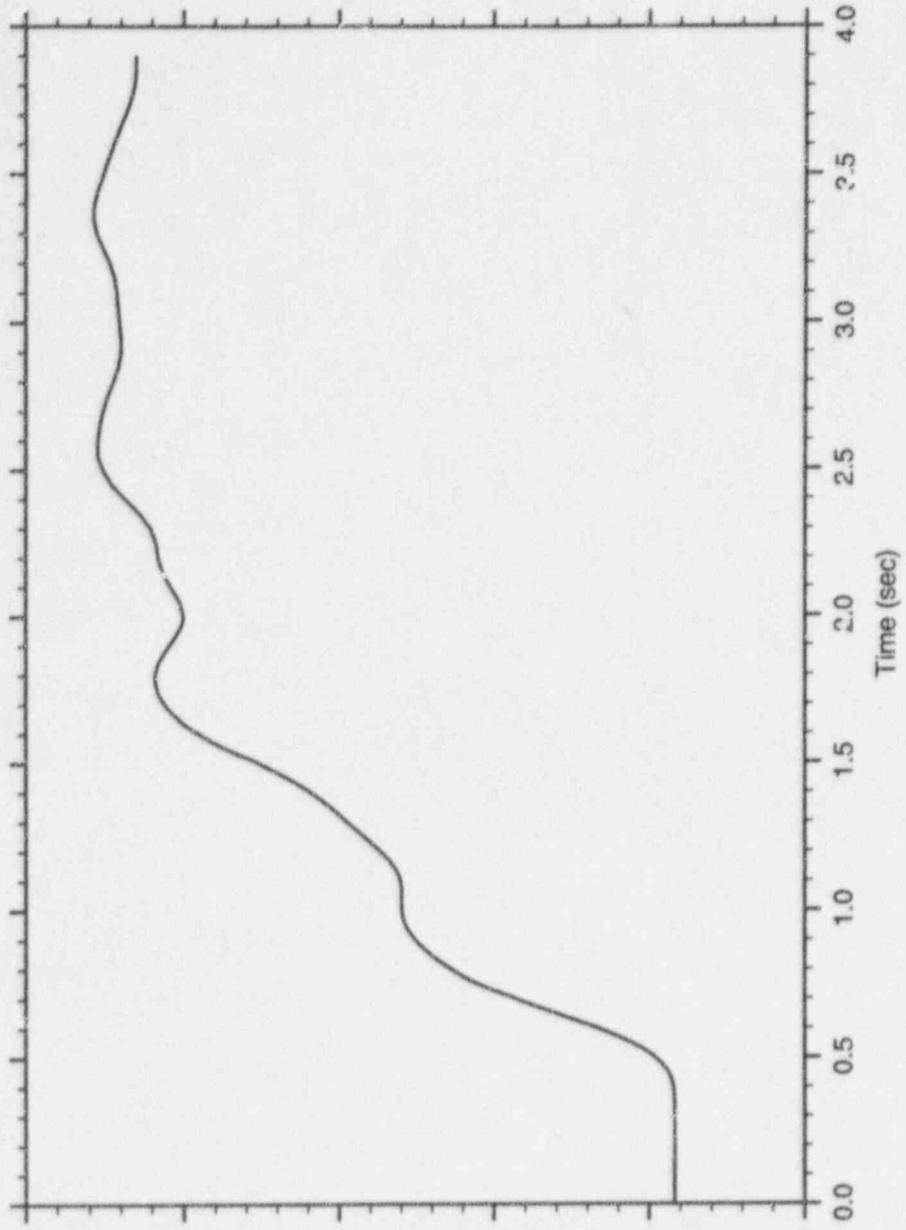

FIGURE 5-2

GLRWOBP Boundary Conditions - Upper Plenum Pressure

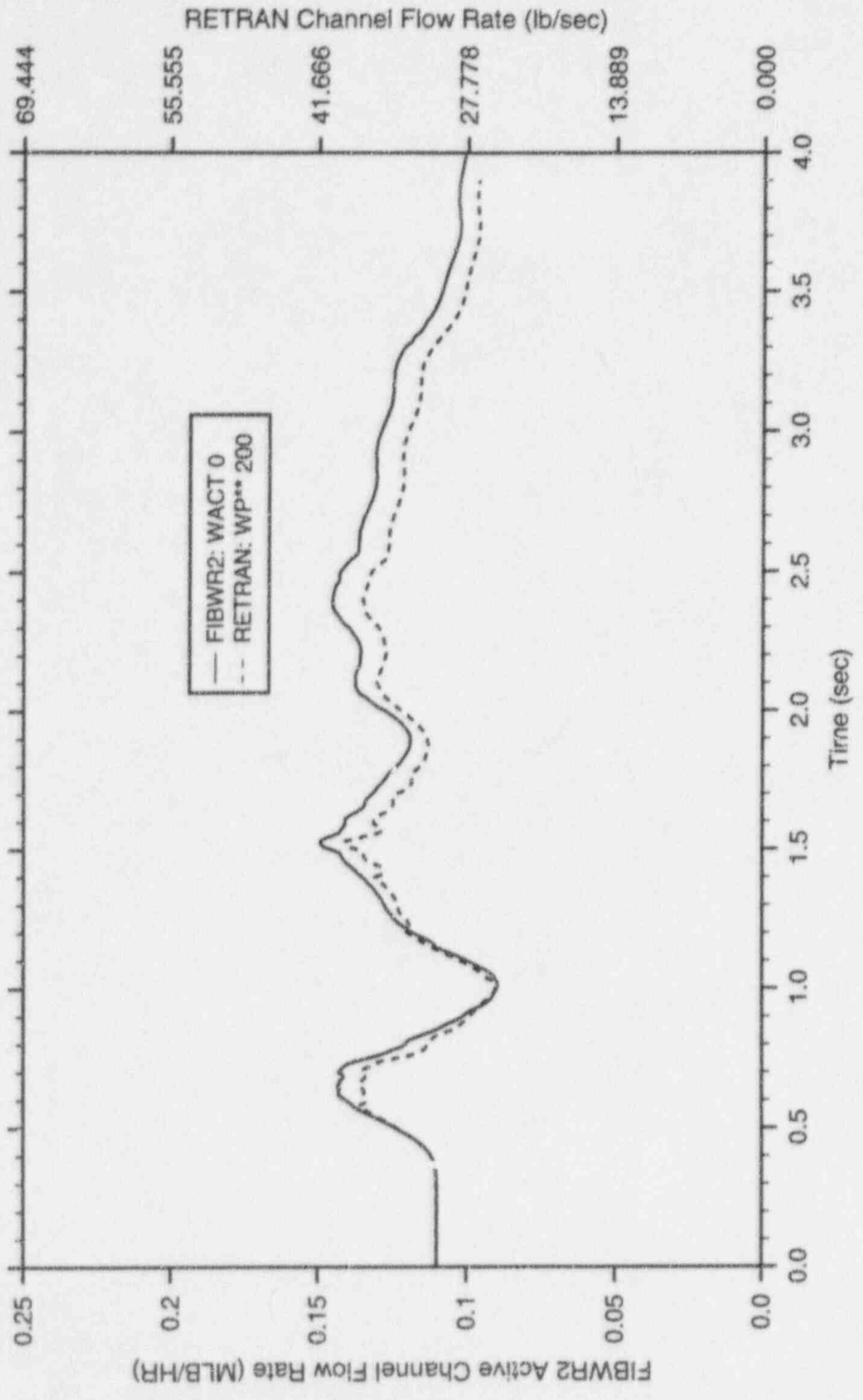

FIGURE 5-3

GLRWOBP Results - Active Channel flow Rate

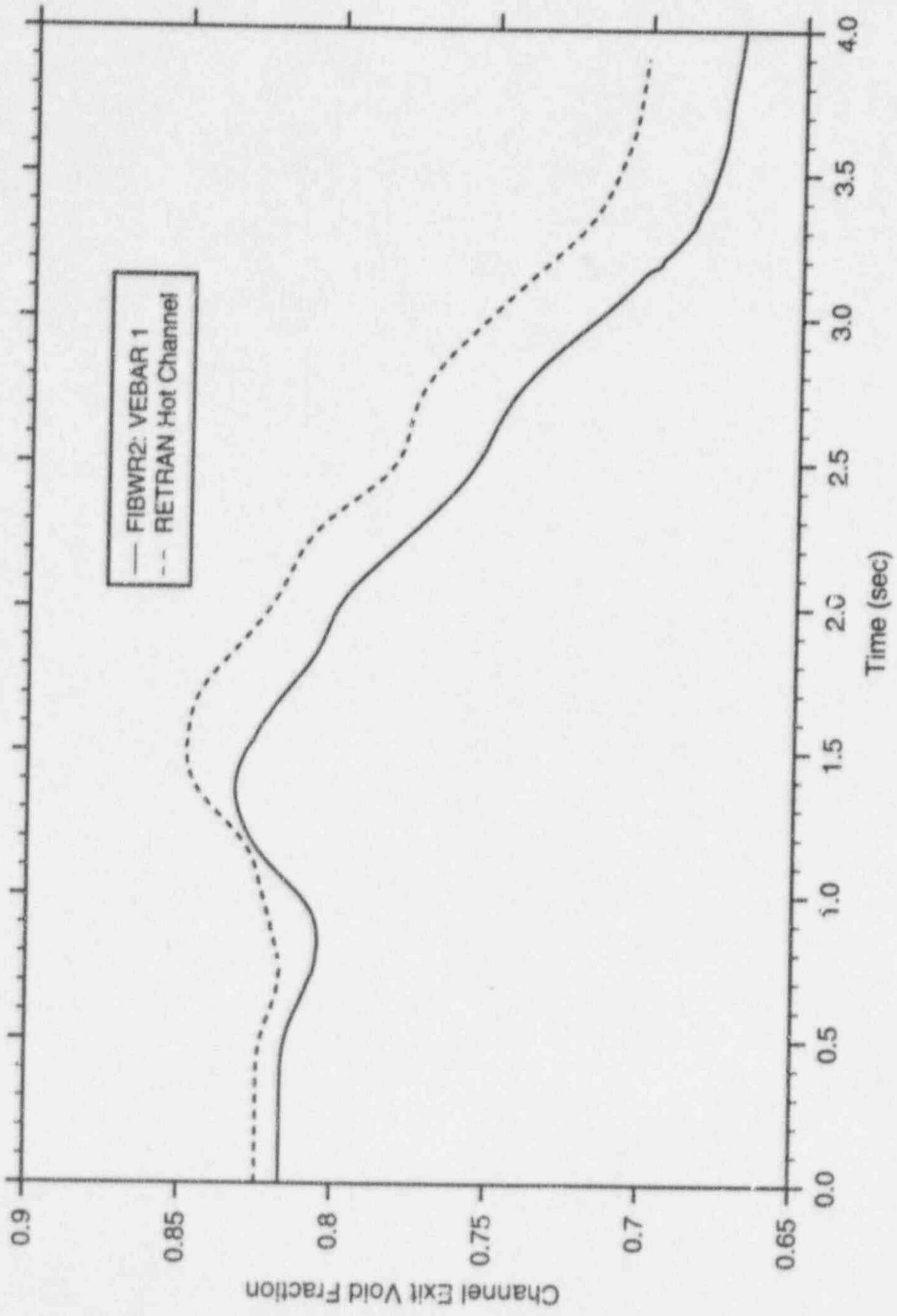

FIGURE 5-4

GLWOBP Results - Channel Exit Void

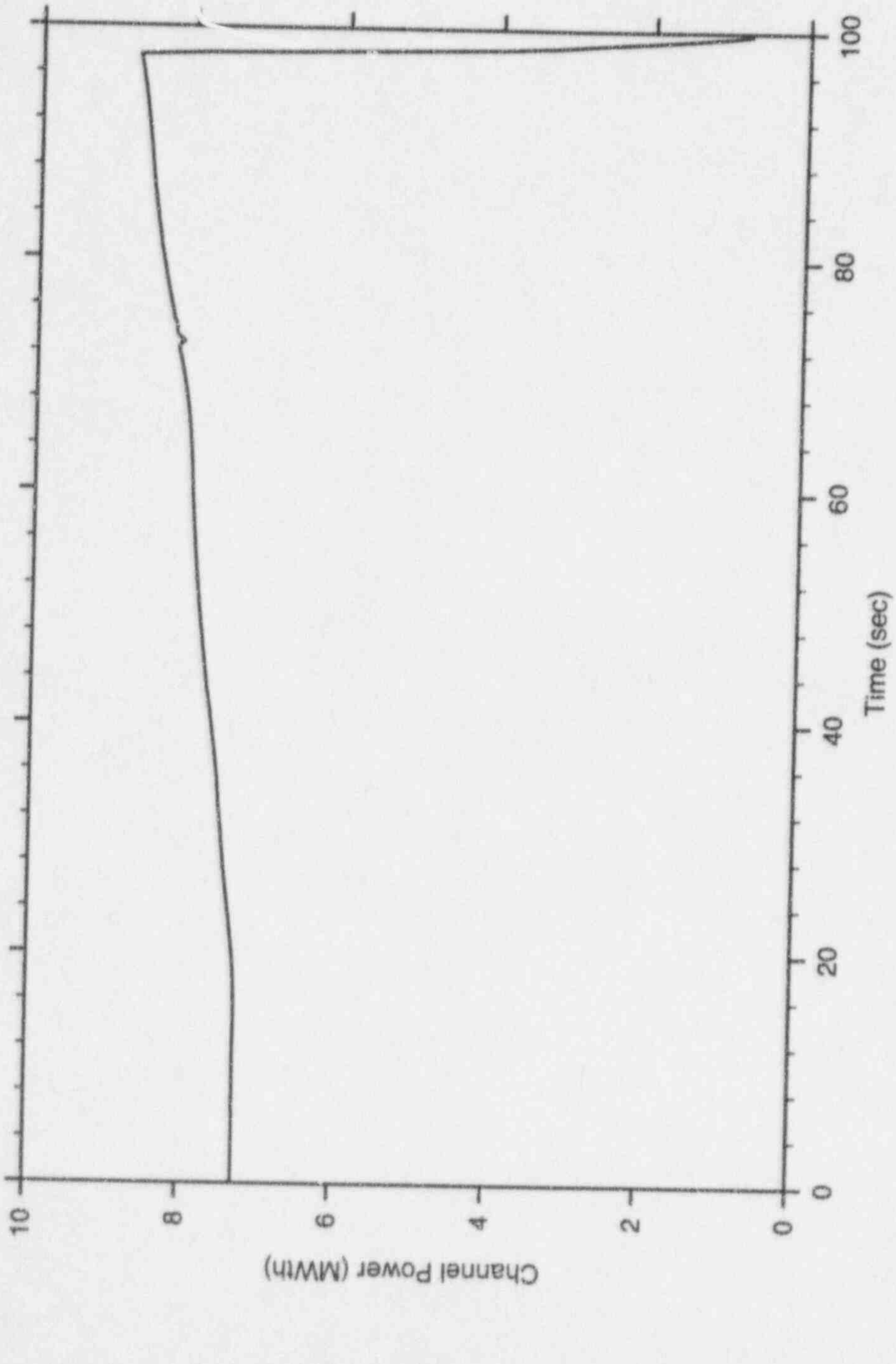

FIGURE 5-5

LOSC Boundary Conditions - Channel Power

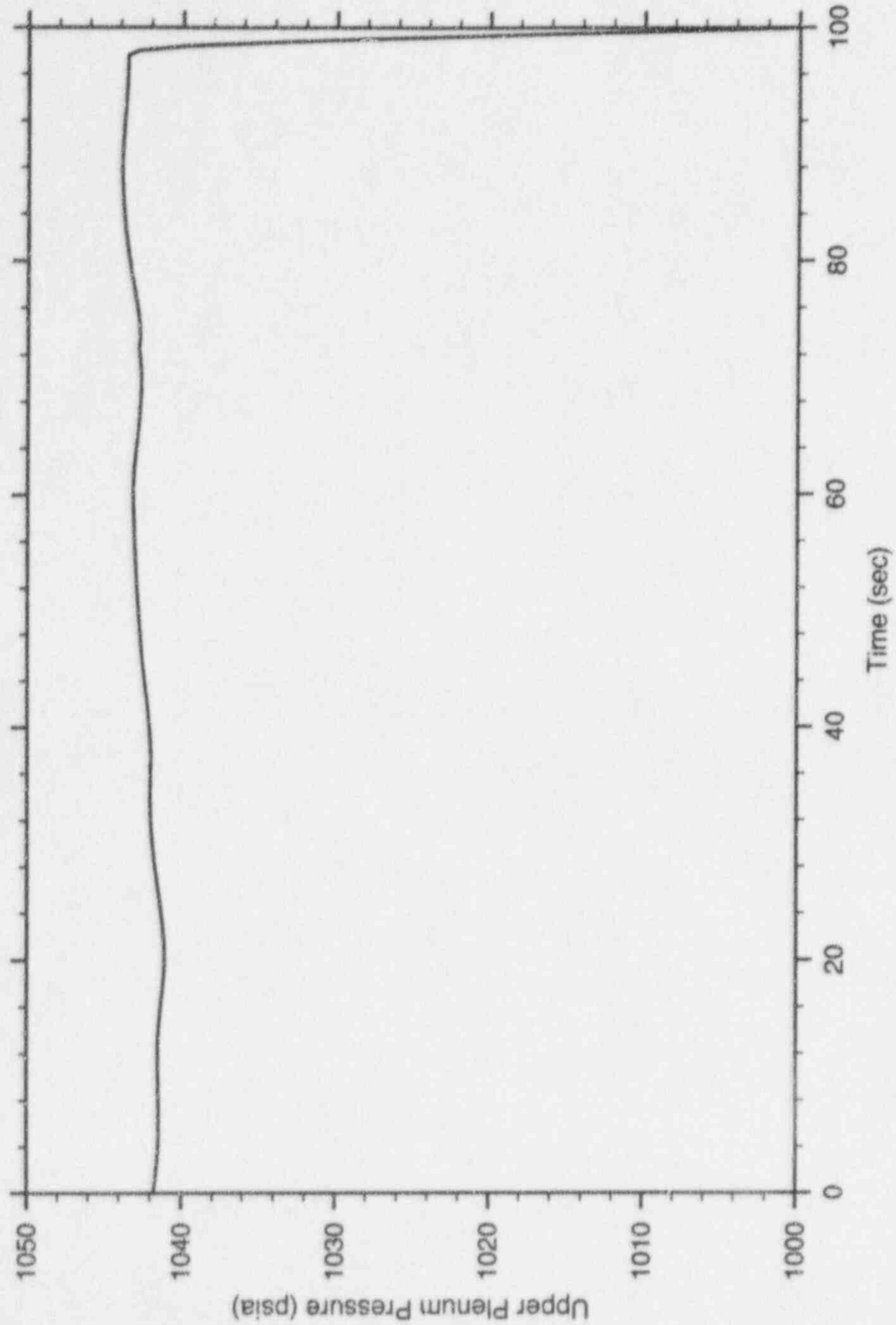

FIGURE 5-6

LOSC Boundary Conditions - Upper Plenum Pressure

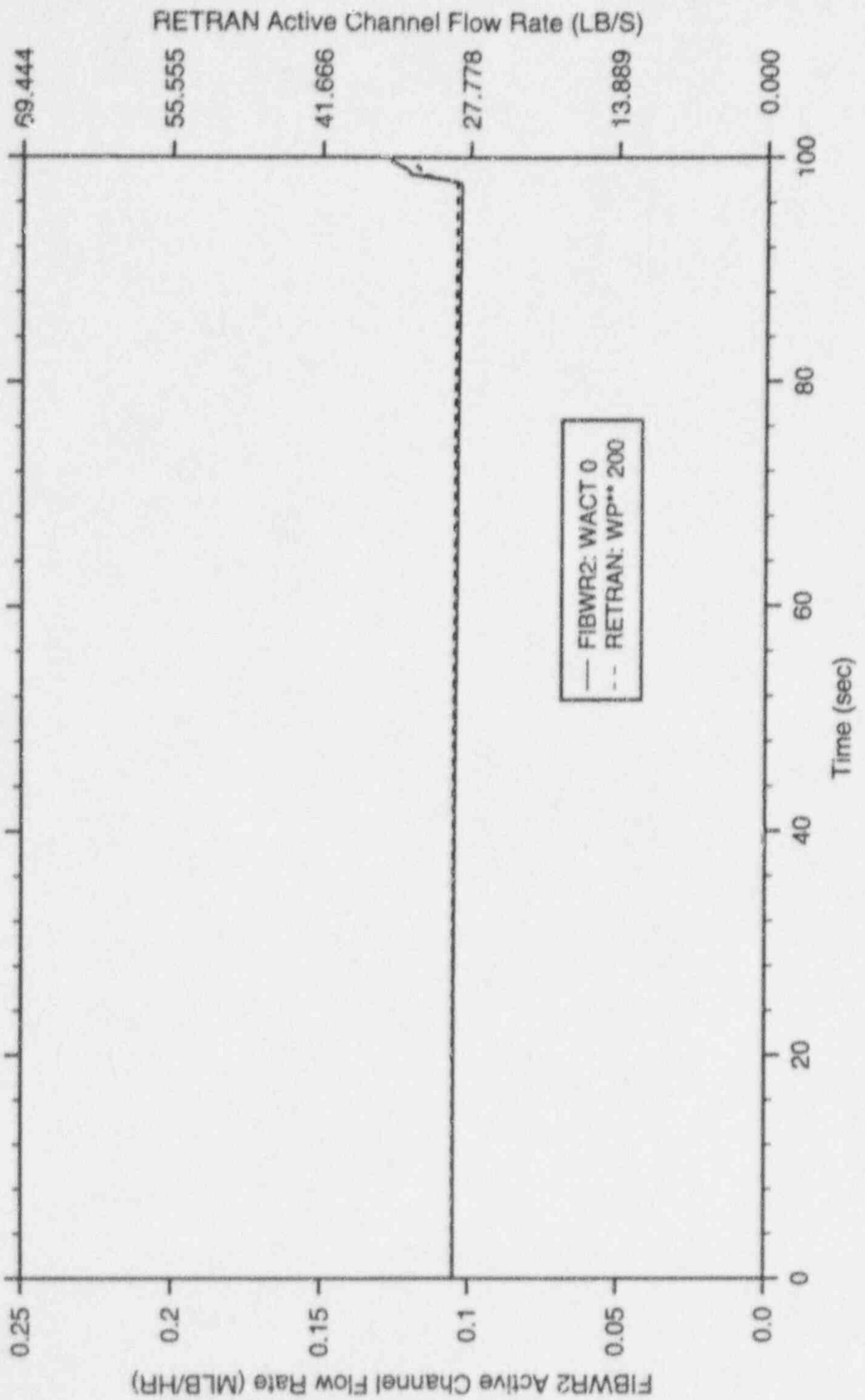

FIGURE 5-7

LOSC Results - Active Channel Flow Rate

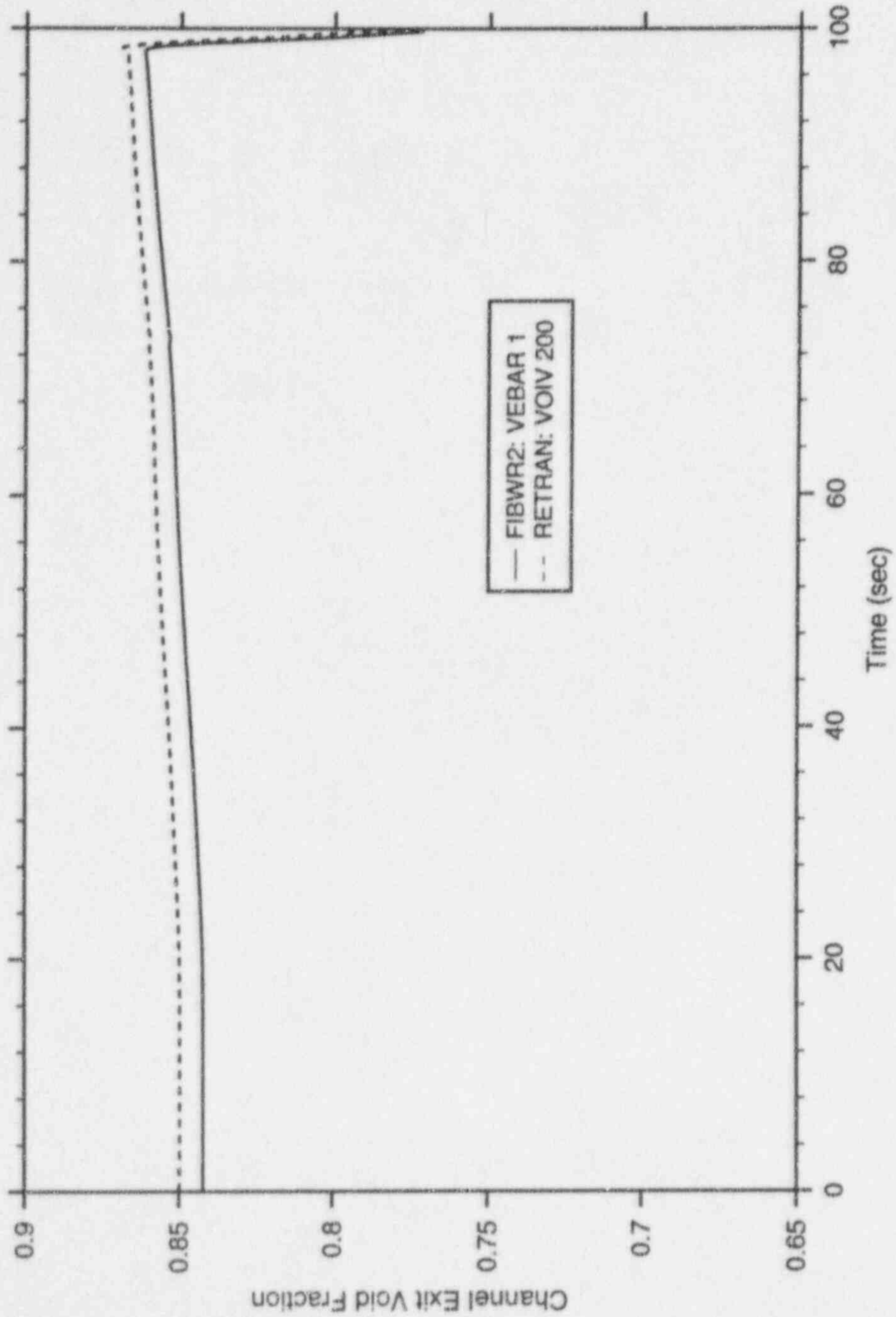

FIGURE 5-8

LOSC Results - Channel Exit Void Fraction

6.0 CONCLUSIONS

The FIBWR2 code extends the BWR specific models used in the FIBWR code for use in the evaluation of transient thermal hydraulic conditions. FIBWR2 includes the capability to explicitly model features of advanced BWR fuel designs such as axially variable flow areas and alternative water tube designs and the FIBWR2 program structure allows the implementation of CPR correlations within the code. The applicability of the FIBWR2 models and equations and application of FIBWR2 within the YAEC BWR transient analysis methodology for evaluation of transient hot channel CPR performance has been demonstrated by:

- Comparison of FIBWR2 solutions to two thermal hydraulic problems (exponential flow decay and sinusoidal flow variation) and their analytical solutions to demonstrate the basic transient hydraulic equations and solution techniques have been correctly applied.

- Comparison to steady state and transient experimental test results for a 16 rod test assembly configuration and to the results of similar simulations performed using the RETRAN/TCPYA01 models. These comparisons demonstrate both the applicability of the FIBWR2 thermal hydraulic models to be used for the evaluation of transient thermal hydraulic conditions and the proper implementation of the vendor proprietary CPR correlation within the FIBWR program structure. Furthermore, sensitivity studies performed for selected transient tests demonstrate the applicability of alternate modeling choices available with FIBWR2 relative to the specification of nodalization, void model and time step sizes.

- Comparison with RETRAN/TCPYA01 results for several characteristic limiting BWR reload transients. Relative to the RETRAN/TCPYA01 results, the FIBWR2 results produce a smaller change (0.02 to 0.05) in the CPR for pressurization events (e.g. turbine trip) and a larger change (0.01) in CPR for increased subcooling events. These differences in the CPR results are due to the more accurate modeling of the two phase form loss multiplier in FIBWR2 and the resulting changes in active coolant flow.

These comparisons demonstrate the applicability of the FIBWR2 code to the analysis of transient thermal hydraulic conditions during Abnormal Operational Transients. In addition, the comparison of FIBWR2 results with RETRAN/TCPYA01 for both the Vermont Yankee limiting reload transients and the 16 rod test assembly data specifically demonstrates the applicability of FIBWR2 based models as a revised approach in the YAEC BWR reload analysis methodology for hot channel CPR evaluation.

7.0 REFERENCES

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