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BWR Full Integral Simulation Test (FIST) Program TRAC-BWR Model Development Volume 2 — Models

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PREVIOUS REPORTS IN BWR FIST SERIES

BWR Full Integral Simulation Test (FIST) Program Test Plan, J. E. Thompson, General Electric Company, NUREG/CR-2575, September 1983.

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BWR FULL INTEGRAL SIMULATION TEST (FIST) PROGRAM

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TRAC-BWR MODEL DEVELOPMENT

VOLUME 2 - MODELS

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ABSTRACT

TRAC-BWR (Transient Reactor Analysis Code) is a computer code for best estimate analysis of the thermal hydraulic conditions in a Boiling Water Reactor system. In this report, the development of new models and the implementation of the balance of plant models leading to the creation of the TRACB04 version of the code, is described. The new models include an improved model for boron transport which accounts for non-uniform mixing and stratification, and a model for the interfacial heat transfer at two-phase levels. The balance of plant models (turbine, containment and heat exchanger) developed at INEL were evaluated, adapted, and implemented into TRACB04 to provide complete transient analysis capability. In addition, a model for air or a noncondensible gas as an additional field in the system of equations was adapted to the two step numerical method and incorporated into TRACB04.

TABLE OF CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

NOMENCLATURE

A	Flow Area (m^2)
$\underline{\underline{A}}$	Coefficient Matrix
C_p	Specific heat capacity (J/kg-K)
C_1, C_2, C_3, C_4, C_5	Correlation Constants for the enhanced boron transport model
C_k	Defined in Equation (3-2)
d_i^{-1}	Interfacial area per unit volume
d_{max}	Defined in Equation (3-4)
D	Hydraulic diameter (m)
Fr	Fronde number
G_{ROSEN}	Liquid entrainment mass flux from Rosen correlation (kg/m^2-sec)
g	gravitation constant (m/sec^2)
h	Heat transfer coefficient (W/m^2-K)
H_f	Defined in Equation (4-5)
h_{fg}	Heat of evaporization (J/kg)
j	Volumetric flux (m/sec)
k	Conductivity (W/m-K)
m	Boron density in subcell (kg/m^3)
$\langle m \rangle$	Average boron density (kg/m^3)
P	Pressure (Pa)
$p(\bar{x},m)$	Boron density probaiblity function. Defined in Equations (2-2) and (2-3)
R_e	Reynolds number
R_f	Defined in Equation (4-6)
T	Temperature
t	Time
Δt	Timestep size
V	Velocity (m/sec)
V_i	Volume of i^{th} cell
V_{crit}	Defined in Equation (3-3)
v	Subcell volume

X_f	Defined in Equation (4-4)
X_L	Level location measured from the bottom of the cell

Subscript

a	Air
B	Boron
C	Boron mass per unit liquid mass
i	i^{th} cell
i	Interfacial
L	Level
l	Liquid
max	Maximum
mix	Mixing
S	Saturation
t	Tube
v	Vapor

Superscript

n	n^{th} timestep
+	Above level
-	Below level

Greek

α	Void fraction
ρ	Density (kg/m^3)
$\Delta\rho$	Density difference between liquid and steam (kg/m^3)
σ	Mixing "ineffectiveness" (kg/m^3)
σ	Surface tension (N/m)
Γ	Source term
ψ	Defined in Equation (2-11)
μ	Viscosity (kg/m-s)

SUMMARY

TRAC-BWR (Transient Reactor Analysis Code) is a computer code for best-estimate analysis of the thermal hydraulic conditions in a reactor system. As part of the earlier BWR Refill Reflood Program, a version of TRAC-BWR (B02) was developed for Loss-of-Coolant Accident Analysis. The model development under the FIST program was primarily aimed at extending TRAC-BWR for the analysis of BWR transients. The main subtasks in this effort were to improve the numerical efficiency and computer execution time for long transients, to extend identified models to remove existing limitations, and to implement the models for balance of plant components developed at INEL. The end product from this effort is the TRACB04 version of the code. The development and implementation of an improved numerical method for the solution of the hydrodynamics equations in the three dimensional components is described in a companion report on model development (Volume 1). This report describes the improved boron tracking model and a two-phase level model. The balance of plant models are also briefly described for completeness.

The enhanced boron transport model which has the capability of simulating the boron stratification phenomenon is an extension of the boron transport model already implemented in TRACB02. In this model, boron travels with its own velocity which may be different from that of the liquid. An expression is formulated to calculate the boron velocity as a function of boron density, liquid velocity and mixing effectiveness. The transport equations for boron and mixing effectiveness are solved by a fully implicit numerical method to allow for large timestep size.

The two-phase level model improves the prediction of interfacial heat transfer when a level is predicted in a vertical pipe or vessel. This is accomplished by adding an additional flow regime to the current flow regime map in TRACB02. A set of criteria based on the void fraction profile and liquid entrainment are established to determine the formation of a level in a vertical pipe or vessel. Appropriate correlations are introduced to calculate the interfacial heat transfer coefficient and areas in this flow regime.

The balance of plant models include the turbine model, the heat exchanger model, the multiple channel model and the containment model. These models were developed by INEL and are documented in detail in References 3,4,5 and 6. Brief descriptions are included here for completeness. The implementation of these models and the results of testing are described. A model for air as an additional field in the system of equation has been incorporated. This was developed at INEL and adapted to the two-step numerical scheme in TRACB04.

SECTION 1
INTRODUCTION

TRAC (Transient Reactor Analysis Code) was originally developed by Los Alamos National Laboratory for the analysis of pressurized water reactors[1]. Development of a boiling water reactor version was initiated in 1979 as a collaborative effort between General Electric Company and Idaho National Engineering Laboratory (INEL). INEL is the prime contractor for the official NRC TRAC BD series of codes. The work performed by GE has been funded by the USNRC, EPRI and GE under the BWR Refill Reflood and FIST Programs and has been closely coordinated with INEL.

Key features of TRAC are a high degree of modularity and a stable numerical method. TRAC thus provides a framework where models for individual reactor components and physical phenomena can easily be interchanged. Furthermore, the free specification of the geometry allows the simulation of almost any geometry ranging from simple basic phenomena tests through system performance tests to complicated reactor systems. Consequently, the TRAC framework is a good base, around which a best estimate BWR code could be developed.

The major tasks in the development of a BWR version of TRAC, which have been addressed under the BWR Full Integral Simulation Test (FIST) Program are:

- Development of the fast numerical method.
- Development of the enhanced boron transport model and the two phase level model.
- Evaluation and implementation of models for the balance of plant components, such as the turbine, the heat exchanger, and the containment. The treatment of air as an additional field (needed for the containment component) and the generalized heat transfer between components have also been included.

In this report, the development of the enhanced boron transport model and the two phase level model, and the implementation of the balance of plant models and the air model are described. The development of the fast numerics is covered in a separate report[2]. While detailed descriptions of the balance of plant models and the air model can be found in the appropriate INEL reports[5,6,7,8,13], brief descriptions have been included for completeness.

Section 2 contains the development of the enhanced boron transport model and its verification. The two phase level model is described in Section 3. The implementation of the balance of plant models and the air field is presented in Section 4.

The models described in this report are included in the FIST Program working version of the designated code, TRACB04, and have been made available to Idaho National Engineering Laboratory (INEL) for inclusion in future TRAC-BD versions. The work on TRAC-BWR development has been split and interactively defined between GE and INEL. Figure 1-1 shows the relationship between the two parallel efforts and the interactions between the two series of codes.

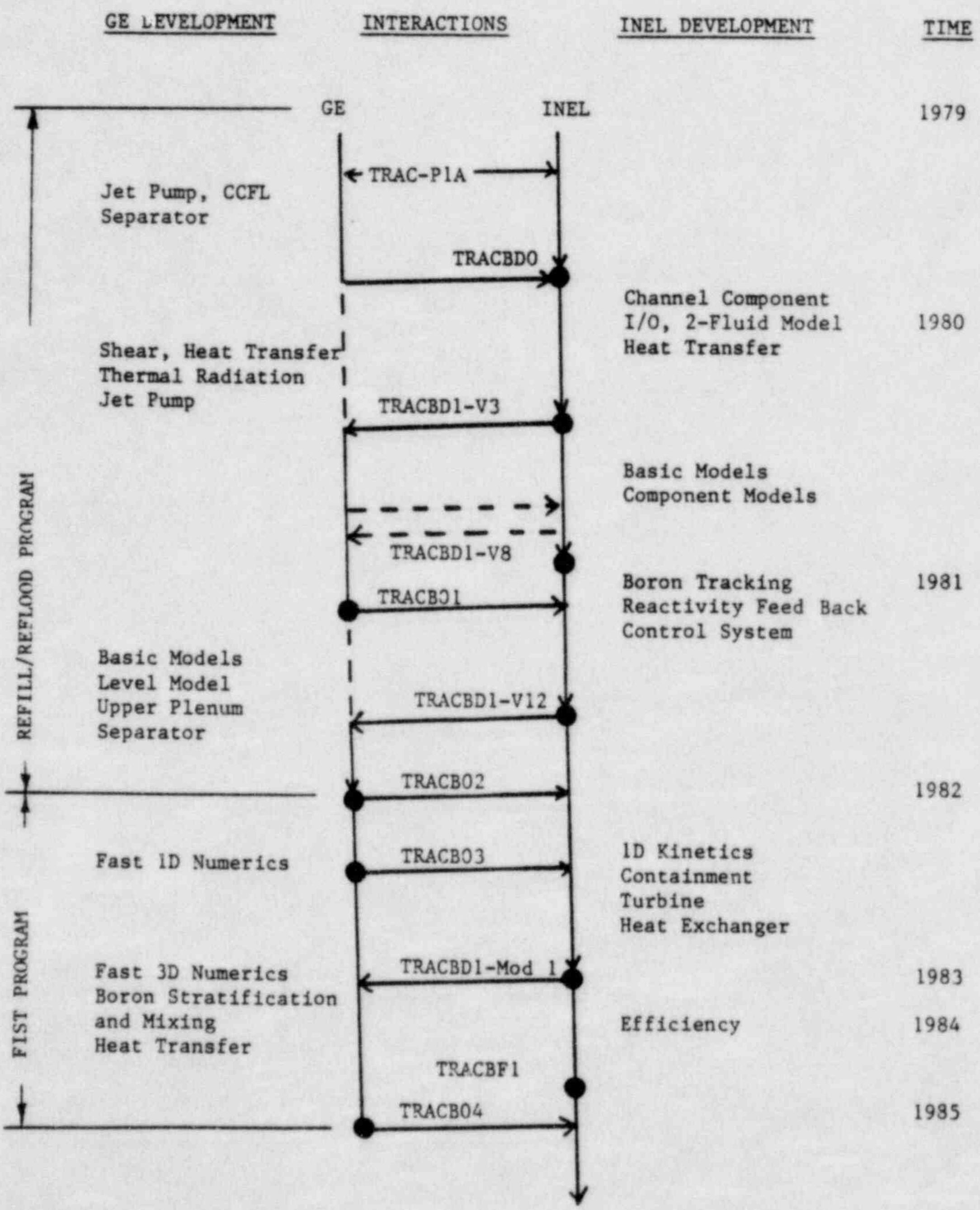


Figure 1-1. Major Milestones in TRAC-BWR Development

SECTION 2

ENHANCED BORON TRANSPORT MODEL

2.1 BACKGROUND AND OBJECTIVE OF THE MODEL

Boron injection into the vessel of a BWR is one of the methods used to shut down a BWR in the event of failure of the normal shutdown systems. In order to predict the power reduction in the core due to the negative reactivity feedback from the boron, a boron transport model is needed to calculate the boron distribution in the system after injection begins.

The boron transport model previously implemented in TRACB02 is based on the following assumptions(8):

a. Boron travels with the same velocity as that of the liquid

b. Boron exists in the liquid phase only

c. Boron has no effect on the hydrodynamics of the liquid

The boron is injected into the reactor vessel in the form of a dilute solution of sodium pentaborate in water. Because of the higher density of the borate solution, it may tend to settle in the water until it is mixed with the surrounding water. If such stratification were to take place in the lower plenum, for example at very low recirculation flow rates, the amount of boron transported to the core would be reduced and the shutdown of the reactor would not be correctly calculated. Thus, models for stratification (i.e. a relative velocity between the boron and water) and the governing phenomenon of mixing effectiveness of the injected solution with water have been developed. This relaxes assumptions a. and b. above.

The concentration of boron required to shut down the reactor is of the order of a few hundred parts per million. At these concentrations, properties of water are not appreciably affected. Thus, assumption c. has been retained. However, for numerical completeness, in order to conserve the amount of boron, the boron is allowed to precipitate out of solution and deposit on the fuel rods if the water in the core is boiled off to very low levels. It should be noted that even these concentrations corresponding to the maximum solubility of boron in water, are about 30,000 parts per million, which are not large enough to significantly affect water properties.

In addition, the model has been made compatible with the fast numerics with an implicit numerical solution. This ensures that the problem timestep will not be restricted by numerical instability in the boron transport solution.

2.2 FORMULATION OF THE BORON VELOCITY AND THE MIXING EFFECTIVENESS

The assumption that boron travels with the same velocity as that of the liquid breaks down when the boron is not perfectly mixed with the liquid. When a liquid with higher boron concentration is injected into one with lower concentration, the injected liquid due to its higher density will drift in the direction of gravity until it is perfectly mixed with its surrounding liquid. Modeling this stratification phenomenon requires that the assumption of boron traveling with the liquid velocity must be removed.

The boron stratification is modeled by inclusion of a buoyancy term in the boron transport equation to account for the relative motion due to density difference. Because TRAC is normally used to analyze a reactor system with cells of fairly large size, the concept of mixing effectiveness within a cell is also introduced.

The relative boron velocity is correlated with respect to the degree of mixing in the cell. Such a correlation should have the following limits:

a. The boron velocity approaches liquid velocity when boron in the cell approaches a perfectly mixed condition.

b. The relative boron velocity approaches a finite value given by the buoyancy when boron in the cell approaches a poorly mixed condition.

To quantify the degree of mixing, consider a cell of volume V with an average boron density of $\langle m \rangle$. Divide the cell into n subcells of volume dv_i each with a boron density of m_i and define the quantity "mixing ineffectiveness" as:

$$\sigma = \{\int_v \int_m p\,(\bar{x},m)\,(\langle m \rangle - m)^2 dm dv\}^{1/2} \qquad (2\text{-}1)$$

where $p\,(\bar{x},m)dmdv$ is the probability of having a boron density between m and m+dm in the volume dv at $\bar{x}$, and satisfies the following conditions:

$$\int_v \int_m p\,(\bar{x},m)dmdv = 1 \qquad (2\text{-}2)$$

$$\int_v \int_m m\ p\ (\bar{x},m)dmdv = \langle m \rangle \qquad (2-3)$$

For a perfectly mixed condition, the boron density in each subcell will be the same and equal to the average boron density and hence

σ = 0 for perfectly mixed condition

At the other extreme, the poorly mixed condition is achieved when all the boron mass aggregates into one subcell and leaves all the other subcells void of boron. Mathematically, σ will approach infinity as the subcell volume approaches zero. Physically, the maximum value of σ will be limited to $\sigma_{max} = \langle m \rangle \{\langle m \rangle_{max} - \langle m \rangle\}$ where $\langle m \rangle_{max}$ is the maximum boron density given by the solubility of the boron.

The relative velocity is formulated as a function of the mixing ineffectiveness σ and the boron concentration gradient.

$$V_{rB} = V_{\ell} - V_{Bo} = f(\sigma, \Delta\langle m \rangle)$$

where V_{rB} is the relative boron velocity and $\Delta\langle m \rangle$ is the boron density difference in the vertical direction.

Keeping in mind the limits a. and b., the following form has been chosen:

$$V_{rB} = V_{\ell} - V_{Bo}$$

$$= C_3\ [1-e^{-\sigma^2/C_1}) + (1-e^{-\Delta\langle m \rangle/C_2})] \qquad (2-4)$$

Here, the first term on the right hand side represents the effect of non-uniform mixing within a cell, while the second term characterizes the effect of boron density gradient. Both of these give rise to a relative boron velocity. The functional form for the boron relative velocity (Equation 2-4) has been chosen because it characterizes the asymptotic nature of the parameters and has the correct limits at perfectly mixed and poorly mixed conditions.

For the perfectly mixed condition, $\sigma = 0$ and $\Delta<m> = 0$, the boron velocity approaches the liquid velocity. For the poorly mixed condition, the boron relative velocity $V_{rB} = V_\ell - V_B$ approaches the finite value C_2. Equation 2-4 is also a monotonic increasing function for σ and $\Delta<m>$ indicating that V_{rB} will increase as σ or $\Delta<m>$ increases, which is physically reasonable.

2.3 CHOICE OF THE DEPENDENT VARIABLE

In TRACB02, boron concentration in the liquid phase was chosen to be the dependent variable in the boron transport equation. Under this formulation, the boron concentration will approach infinity as void fraction goes to one. Arbitrarily restricting the concentration introduces an error in the conservation of total boron mass in the system. Physically, as the void fraction approaches one, the boron density increases to a maximum value which is determined from the maximum solubility of the boron compound in liquid. The boron will then precipitate out of solution and will most likely start plating on the wall. The plated boron will later re-dissolve when liquid is available again.

In the enhanced boron transport model, the boron density, which is defined as the boron mass per unit volume, is chosen to be the dependent variable to avoid the above-mentioned numerical difficulties. Boron is not transported with the vapor phase. If the liquid content in a given region is depleted such that the boron concentration exceeds the maximum solubility of boron in water, boron will be precipitated. This is assumed to plate out on solid surfaces in the cell, by setting the boron velocity equal to zero. Boron dissolved in the liquid will still travel with the boron velocity V_{Bo} determined from Equation 2-4.

Thus, the boron velocity is modified at high void fractions as follows:

$$V_B = 0 \qquad \text{when} \quad \alpha = 1$$

$$V_B = V_{Bo} \left(\frac{1 - \alpha}{1 - \alpha'}\right) \qquad \text{when} \quad \alpha' < \alpha < 1 \qquad (2\text{-}5)$$

$$V_B = V_{Bo} \qquad \text{when} \quad \alpha \leq \alpha'$$

where V_{Bo} is the correlated boron velocity defined in Equation 2-4 and α' is a critical liquid fraction determined from

$$1 - \alpha' = \frac{<m>}{\rho_\ell C} \qquad (2\text{-}6)$$

$<m>$ = boron density

C = maximum soluble boron mass per unit liquid mass[15]

$$= \begin{cases} 50.3 & \text{for } T \geq 373°K \\ 26.9 + (50.3-26.9)(T-323)/50 & \\ 26.9 & \text{for } T \leq 323°K \end{cases}$$

ρ_ℓ = liquid density

2.4 THE GOVERNING EQUATIONS

The governing equation for the enhanced boron transport model is the same as that in TRACB02, except that the dependent variable is changed from boron concentration in liquid to boron mass per unit volume and the boron convection velocity changed from liquid velocity to its own velocity. The continuity equation has the following form:

$$\frac{\partial <m>}{\partial t} = - \nabla \cdot (\bar{V}_B <m>) + \Gamma_{<m>} \qquad (2\text{-}7)$$

where

$<m>$: boron mass per unit volume

V_B: boron velocity

$\Gamma_{<m>}$: boron source term

From Equation 2-1, the value of mixing ineffectiveness, σ depends on the probability function $p(\bar{x},m)$ and the average boron density $<m>$. Therefore, changes in either $p(\bar{x},m)$ or $<m>$ will contribute to the change in σ. By assuming the probability function varies only from cell to cell but remains unchanged within a cell, the following equation can be obtained by performing a control volume analysis on $<m^2>$.

$$\frac{\partial}{\partial t} (<m^2>) = - \nabla \cdot (V_B <m^2>) \tag{2-8a}$$

where

$$<m^2> = {}_v\int_m\int m^2 p\ (\bar{x},m)\ dmdv$$

Equation 2-8a represents a conservation equation in $<m^2>$. Source term can be added to Equation 2-8a to account for sources and sinks for $<m^2>$, and a mixing term can be added to account for the mixing of boron with the surrounding liquid. From the statistical relationship that $\sigma^2+<m>^2 = <m^2>$, Equation 2-8a can be rewritten as

$$\frac{\partial}{\partial t} (\sigma^2 + <m>^2) = - \nabla \cdot (\bar{V}_B (\sigma^2 + <m>^2)) \tag{2-8}$$

$$+ \quad \Gamma_{\sigma^2+<m>^2} - \Gamma_{mix}$$

where

V_B: Boron velocity

$\Gamma_{\sigma^2+<m>^2}$: source term for $\sigma^2 + <m>^2$

σ: mixing ineffectiveness

Γ_{mix}: source term for σ due to local mixing

The term Γ_{mix} is included to simulate the enhancement of mixing due to local turbulence. Since the Reynolds Number is a parameter associated with turbulence and gross motion of the fluid, the mixing should increase as Re increases. Furthermore the mixing should be proportional to σ^2. Consequently Γ_{mix} is correlated as the following:

$$\Gamma_{mix} = C_4 \sigma^2 Re_\ell \tag{2-9}$$

$$Re_\ell = \text{Max } \{\text{local liquid Reynolds Number, } C_5\}$$

where C_4 and C_5 are constants to be determined from experiments.

Since the boron velocity is a function of $<m>$ and σ, the two equations form a closed system which can be solved for $<m>$ and σ.

2.5 THE NUMERICAL METHOD

The numerical scheme used in TRACB02 to solve the boron transport equation is formulated based on an explicit method[8]. This is not compatible with the fast numeric method currently implemented in TRAC(2). The solution will become unstable when the Courant limit based on boron velocity is exceeded. The two governing equations for the enhanced boron transport model are solved based on an implicit numerical algorithm to avoid this restriction on time step size.

The governing equations of the model are discretized using a semi-implicit donor cell method. For one dimensional components, the discretized equations possess the following form:

$$V_i \left[\psi_i^{n+1} - \psi_i^n\right] = A_{i-\frac{1}{2}} V^n_{B,i-\frac{1}{2}} \psi^{n+1}_{i-\frac{1}{2}} \Delta t - A_{i+\frac{1}{2}} V^n_{B,i+\frac{1}{2}} \psi^{n+1}_{i+\frac{1}{2}} \Delta t + V_i \Gamma_{\psi,i} \Delta t \qquad (2\text{-}10)$$

where $\psi^{n+1}_{i-\frac{1}{2}}$ and $\psi^{n+1}_{i+\frac{1}{2}}$ are the donor celled property

$$\psi^{n+1}_{i-\frac{1}{2}} = \begin{cases} \psi^{n+1}_{i-1} & \text{for} \quad V^n_{B,i-\frac{1}{2}} \geq 0 \\ \psi^{n+1}_{i} & \text{for} \quad V^n_{B,i-\frac{1}{2}} < 0 \end{cases}$$

$$\psi^{n+1}_{i+\frac{1}{2}} = \begin{cases} \psi^{n+1}_{i} & \text{for} \quad V^n_{B,i+\frac{1}{2}} \geq 0 \\ \psi^{n+1}_{i+1} & \text{for} \quad V^n_{B,i+\frac{1}{2}} < 0 \end{cases}$$

$$\Gamma^n_{\psi,i} = \begin{cases} \Gamma_{\langle m\rangle} & \text{for boron equation } (\psi = \langle m\rangle) \\ \Gamma_{\sigma^2+\langle m\rangle^2} - \Gamma_{mix} & \text{for mixing equation } (\psi = \sigma^2 + \langle m\rangle^2) \end{cases}$$

and

$$\psi = \begin{cases} \langle m\rangle & \text{for boron equation} \\ \sigma^2 + \langle m\rangle^2 & \text{for mixing equation} \end{cases} \qquad (2\text{-}11)$$

The three dimensional discretized equation for the vessel can be formulated in a similar manner by including all six faces of a cell.

Two sets of linear equations of the form

$$\underline{A} \cdot \langle \bar{m} \rangle = b_{\langle m \rangle}$$

and

$$\underline{A} \cdot \overline{(\sigma^2 + \langle m \rangle^2)} = b_{\sigma^2 + \langle m \rangle^2}$$

can be formed and solved for $\langle m \rangle$ and $(\sigma^2 + \langle m \rangle^2)$.

2.6 VERIFICATION

To verify the proper implementation of the enhanced boron transport model, the following test cases were performed:

2.6.1 Injection of Boron into a Pipe

The objective of this test is twofold: to verify the performance of the model; and to check out the implicit numerical algorithm.

A one meter long pipe with liquid initially running at a velocity of 10 m/sec, was injected with boron from below for 0.4 seconds. The system was simulated by TRAC with two pipe components each consisting of five cells, a break component and a fill component, (see Figure 2-1).

The boron concentrations of each cell are plotted in Figures 2-2 and 2-3, and the results show the boron is transported at the right velocity through the pipe. The timestep was 1 second, giving a Courant number of 10. This shows the implicit algorithm performs properly.

2.6.2 Stratification of Boron

The objective of this test is to show the ability of the model in predicting the stratification phenomenon.

A vertical pipe one meter long is simulated by TRAC as illustrated in Figure 2-4. Initially the pipe is filled with stagnant liquid with zero boron concentration except in the 8th cell. Physically the boron in cell 8 will start drifting downward

due to difference in density. Results from the model are shown in Figure 2-4. The boron density in cell 8 reduces as the boron densities in the cells below increase, indicating that the boron is slowly drifting downward.

At first glance, it might seen that the boron should eventually collect in the bottom cell. However, as the borate solution mixes with the water in each cell, concentration differences between cells are reduced. A uniform solution will not have a tendency to stratify. The TRACB04 calculation shows that eventually a uniform boron concentration is achieved in cells 1 through 8. Cells 9 and 10 being above the injection location are not affected by the settling process.

In contrast, the original boron model would not predict this sequence of events. As the water is stagnant, the injected boron would also have no downward velocity and remain in the injected cell. This result with the previous model is also shown in Figure 2-4.

2.6.3 Boron Injection in BWR/6 System

The purpose of this test is to check the performance of the model in a large system. A BWR/6 system is simulated by TRAC as illustrated in Figure 2-5. Initially the system is at steady state. At t=0, boron is injected into the system through the feedwater line. Boron concentrations at various locations are shown in Figures 2-6 thru 2-13. From these diagrams, the path which the boron travels in the system can be observed. After leaving the feedwater pipe, the boron travels down the downcomer, through the jet pump standpipe and enters the lower plenum. Then it travels upward to the upper plenum through the bundles and bypass. When it goes through the separators, most of the boron is carried out in the separated liquid and then combines with the feedwater flow. From Figure 2-8, a rough estimate on the time for the injected boron to completely circulate the system can be obtained. The boron concentration in the downcomer region above the feedwater level remains zero until around six seconds when boron is being transported in the liquid separated by the separators. This indicates that it takes approximately six seconds for the boron to travel down the downcomer, through the core and separators and back to the downcomer region.

2.7 Correlation of Stratification and Mixing Parameters

The boron transport model developed for TRAC gives the framework for simulating the boron injection and transport in a BWR system including the effect of stratification and mixing. The testing of the model has demonstrated that the code

performs as intended. The main effect of stratification and mixing is to alter the transport time for boron in a BWR system. The degree that the transport times are affected depends on the numerical values for V_{rB} and Γ_{mix}.

The expressions for the relative boron velocity (Equation 2-4) and local mixing (Equation 2-9) must be correlated from available data. Ideally the constants in V_{rB} and Γ_{mix}, C_1 through C_5 should be determined from separate effects tests where stratification and mixing are performed under well controlled conditions. They should then be qualified by comparison to system effects tests e.g., a scaled mock up of a BWR system. This qualification task was not included in the FIST program, but it is highly recommended that such a program be undertaken.

2.8 CONCLUSIONS

An enhanced boron transport model has been developed and implemented in TRAC. Results from tests show that the model is performing properly. However in order to fully utilize the model the constants in the stratification (Equation 2-4) and mixing model (Equation 2-9) must be correlated from data.

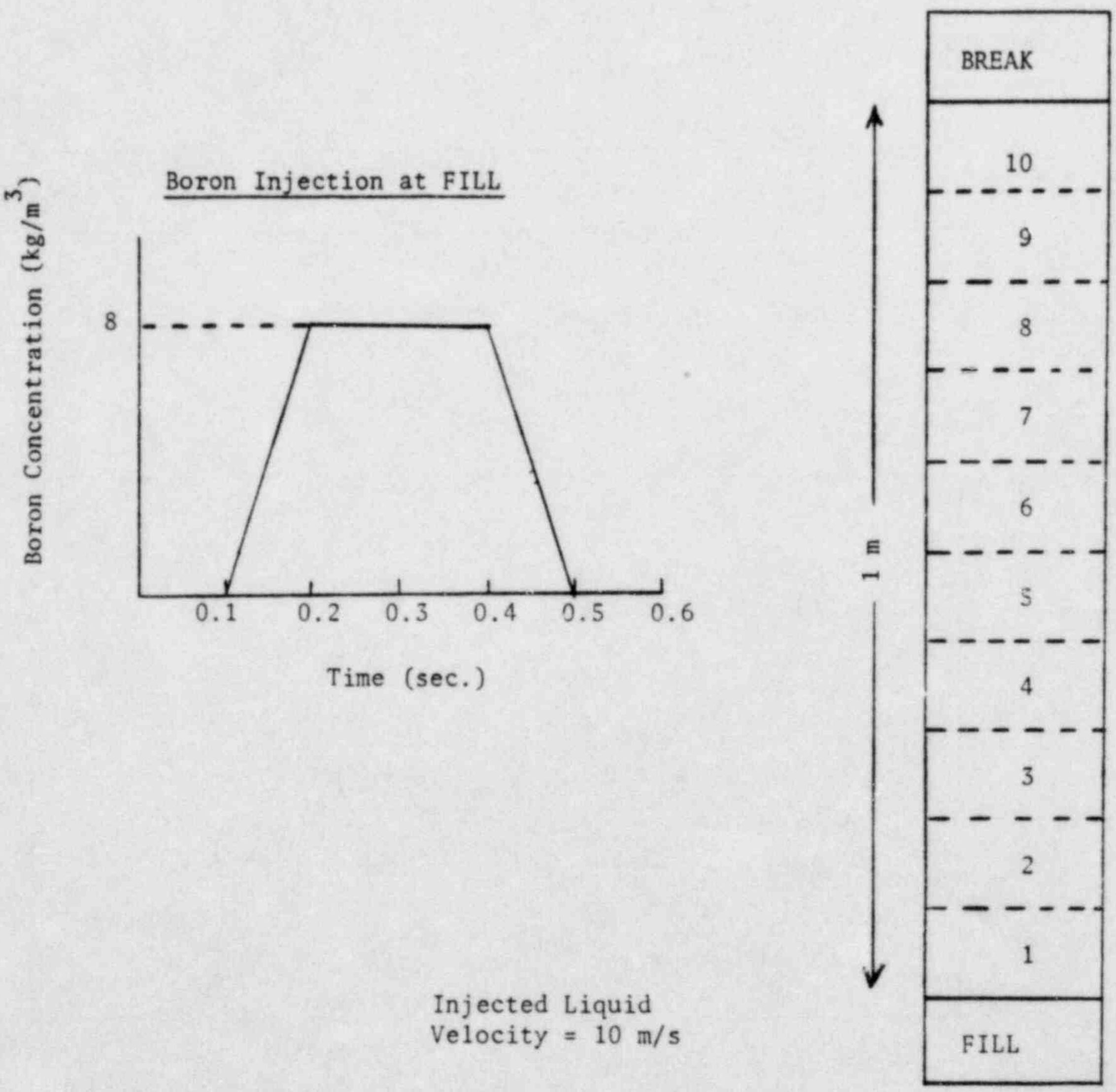


Figure 2-1 Nodalization of Boron Test Case 1 - Injection of Boron Into a Pipe

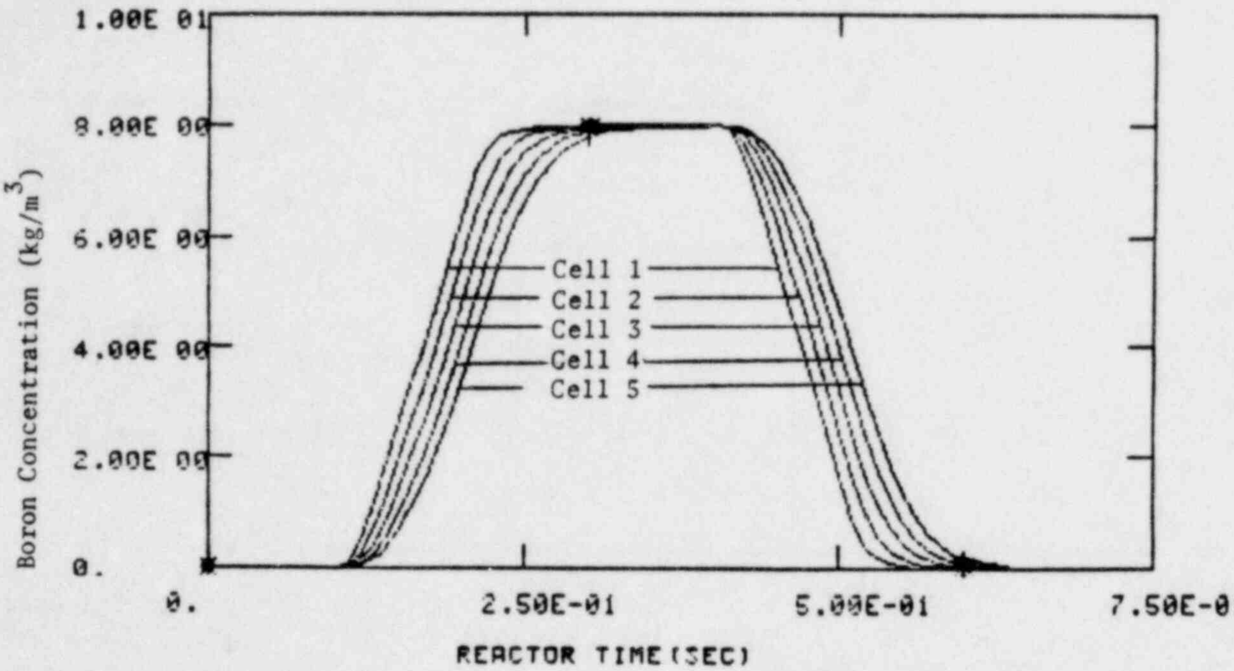


Figure 2-2. Results from Boron Test Case 1 - Cells 1 thru 5

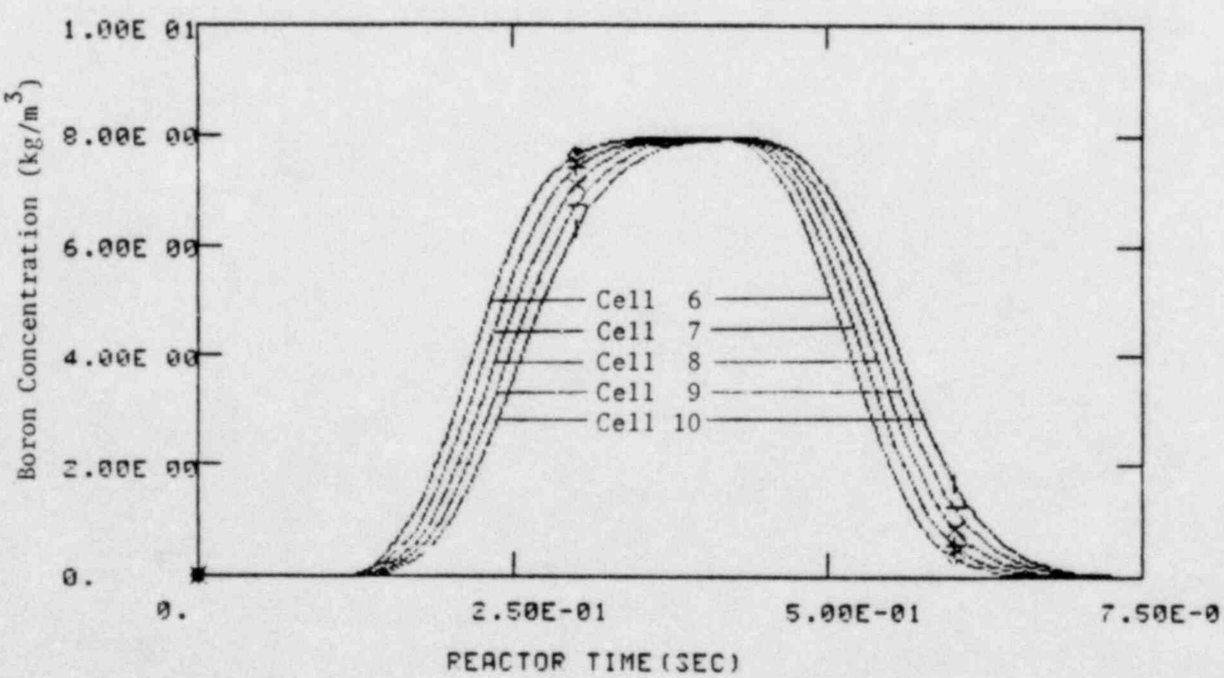


Figure 2-3. Results from Boron Test Case 1 - Cells 6 thru 10

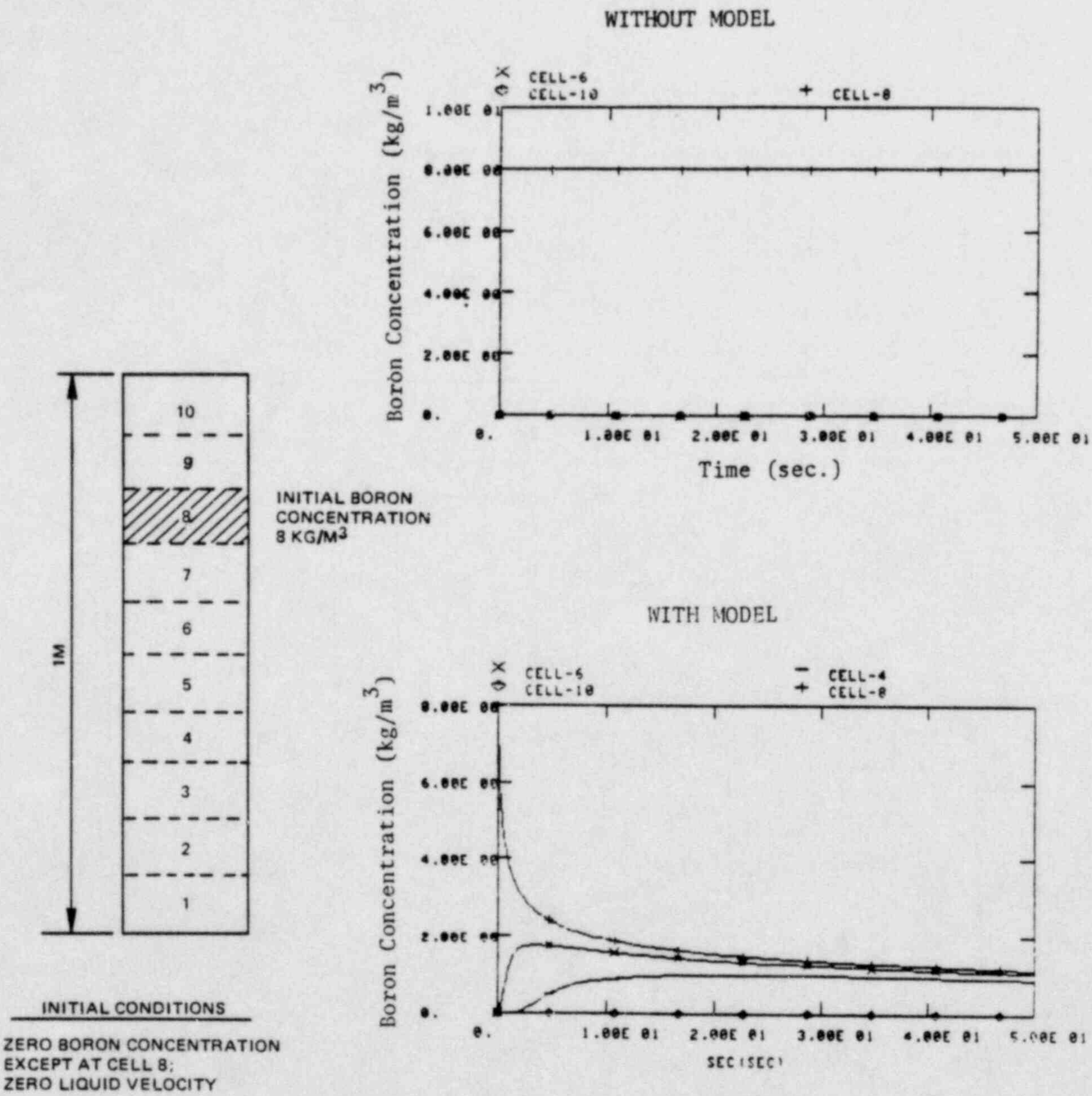


Figure 2-4. Nodalization and Results for Boron Test Case 2

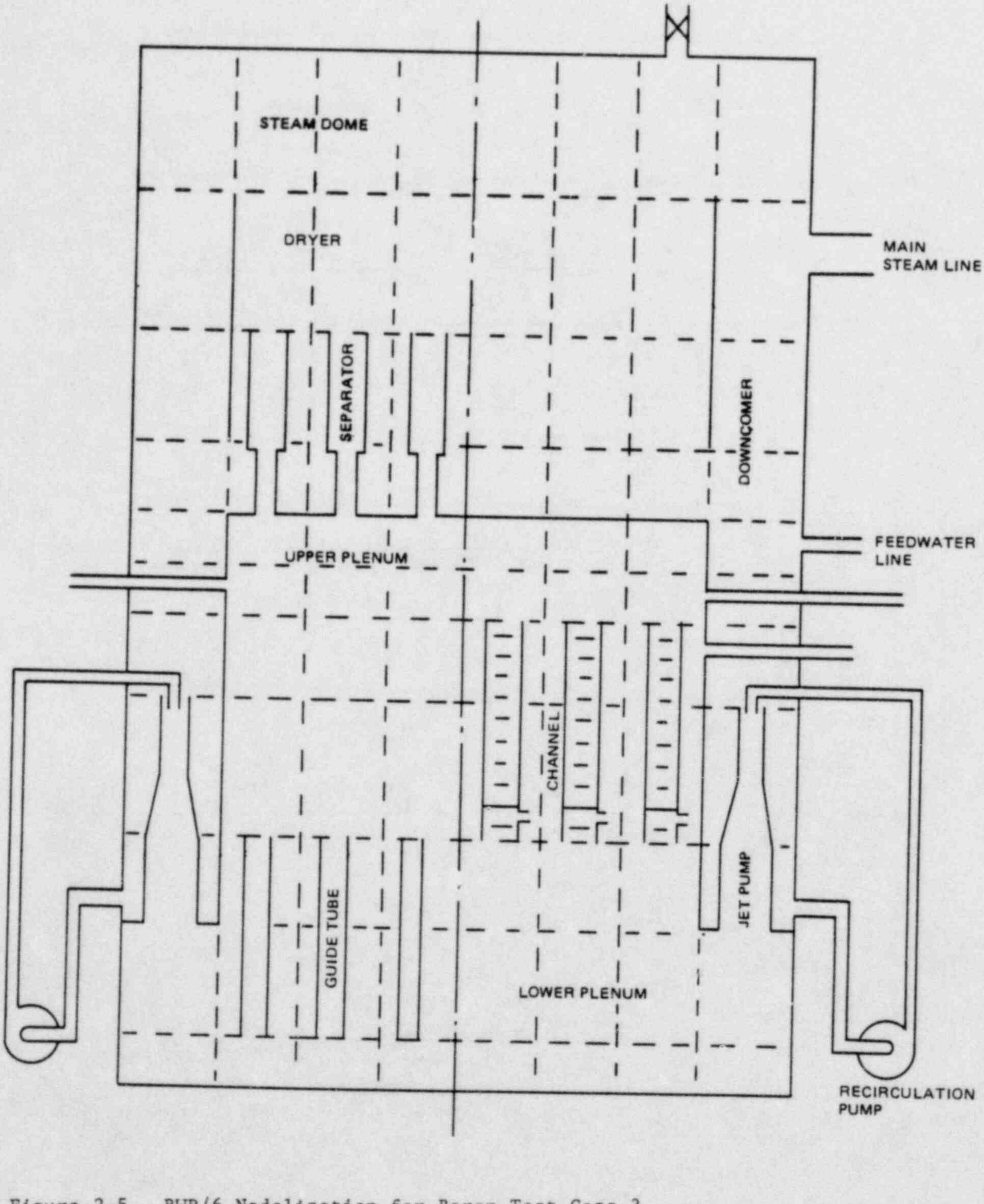


Figure 2-5. BWR/6 Nodalization for Boron Test Case 3

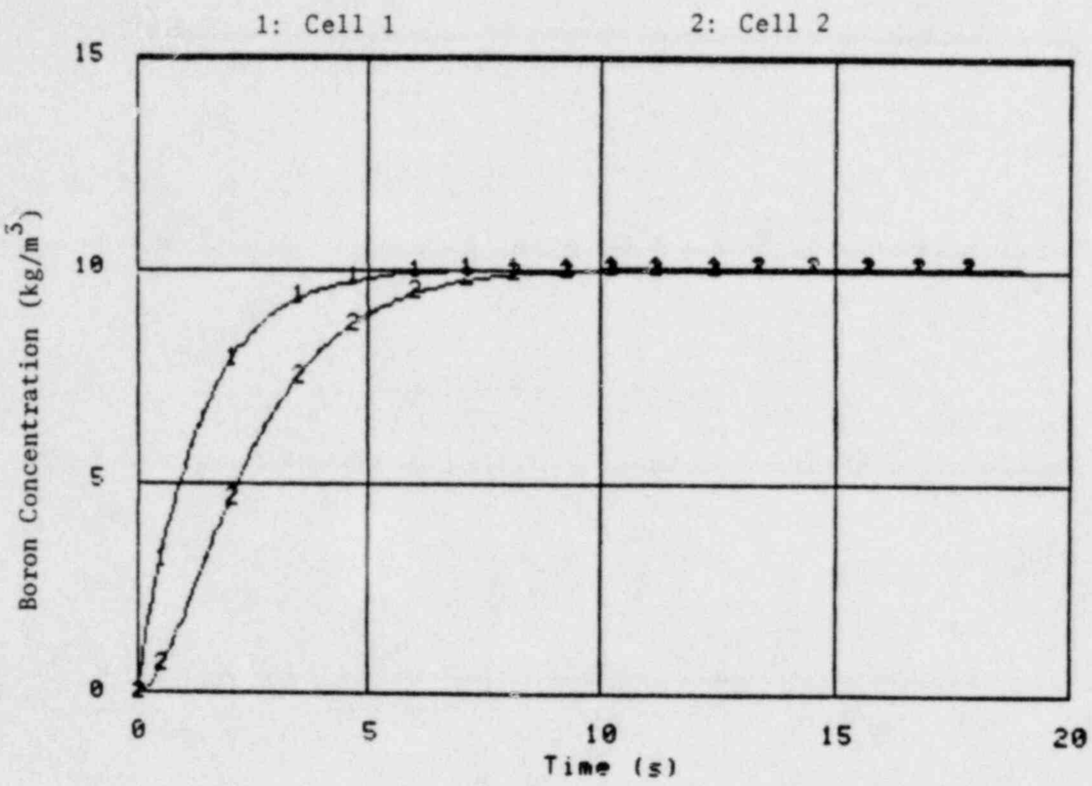


Figure 2-6. Boron Concentration in Feedwater Pipe

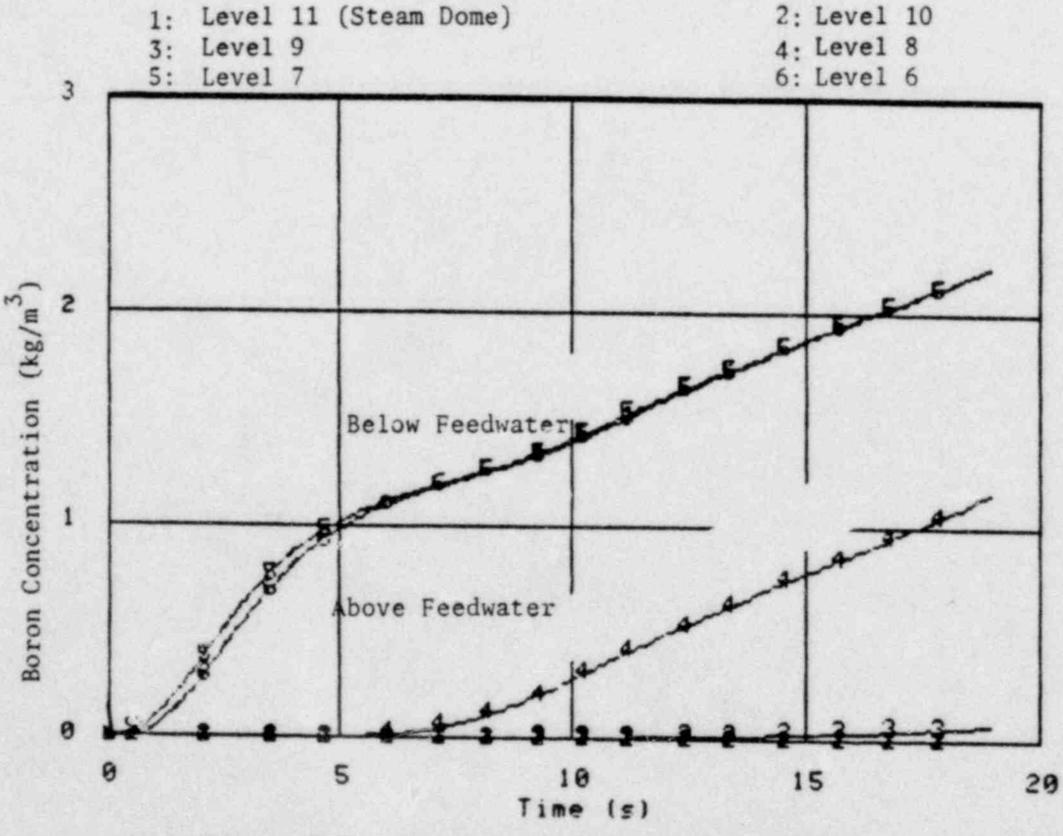


Figure 2-7. Boron Concentration in Downcomer Region

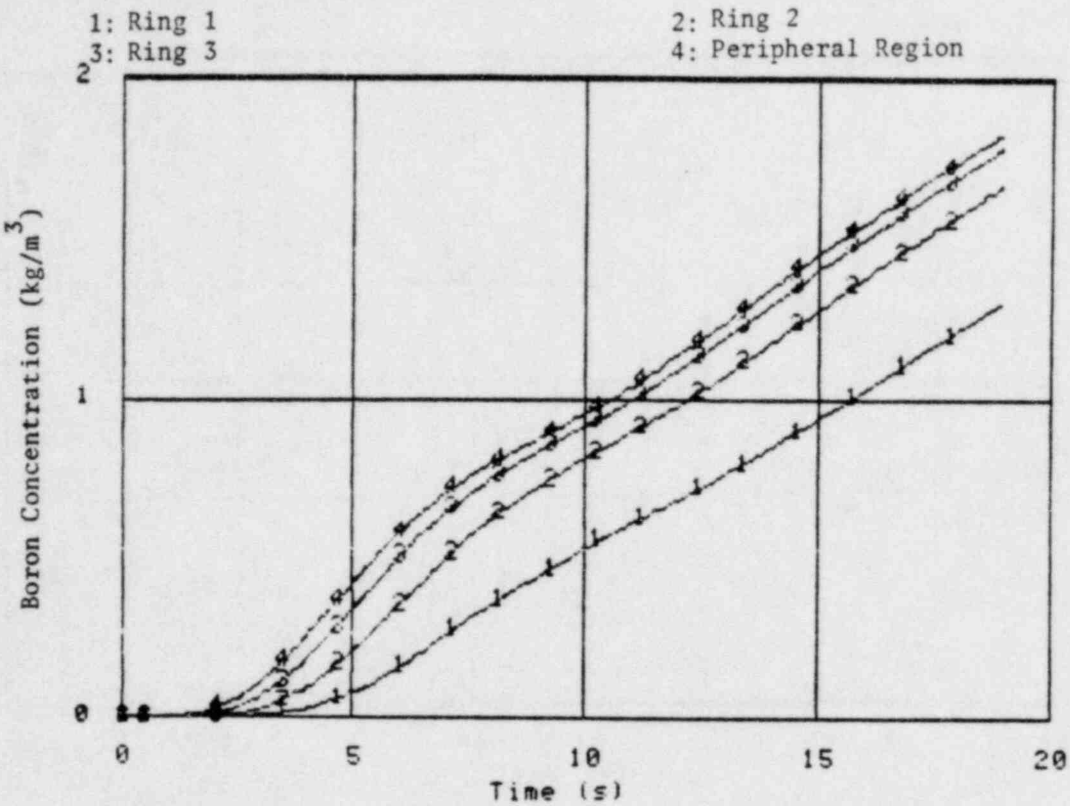


Figure 2-8. Boron Concentration in Lower Plenum

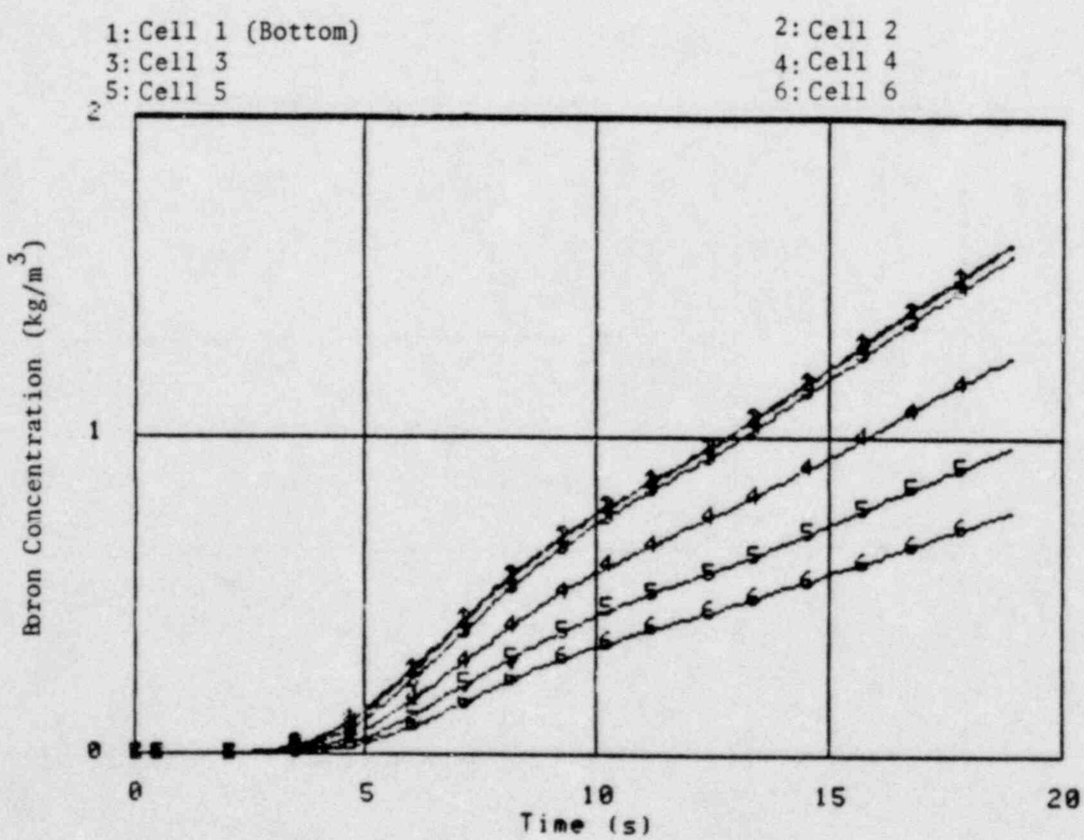


Figure 2-9. Boron Concentration in Lower Half of Average Power Bundle

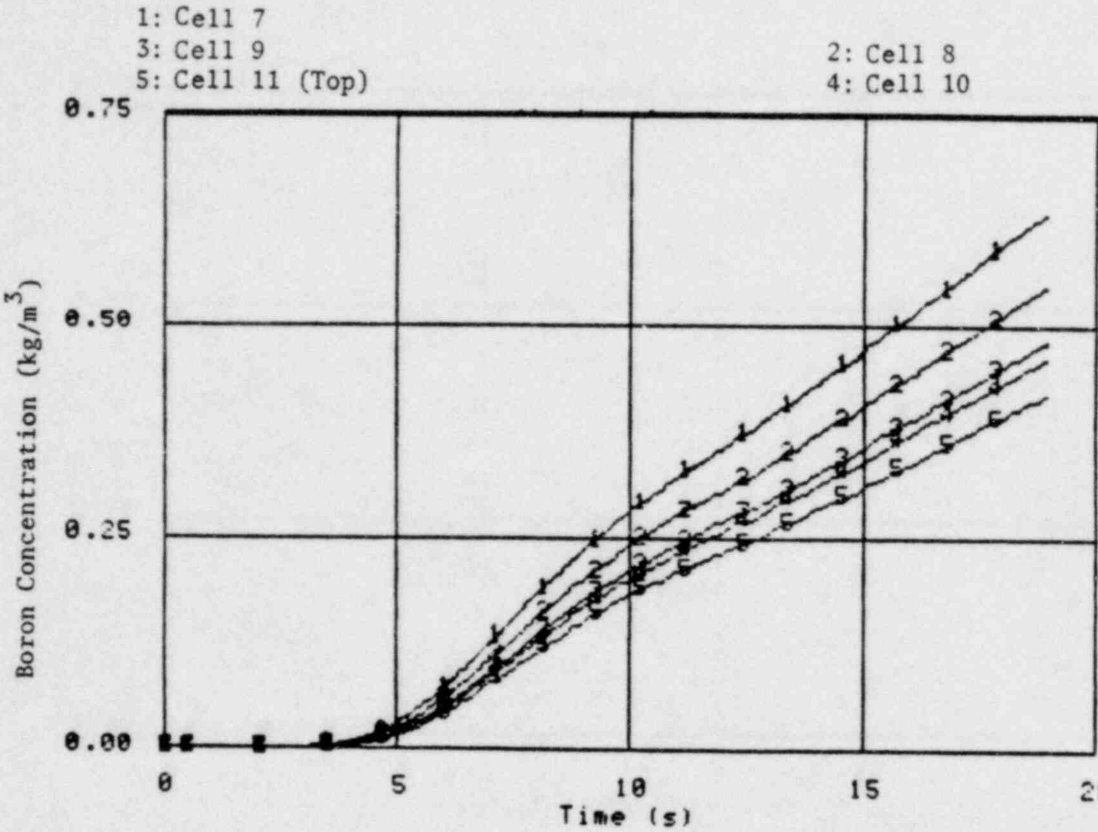


Figure 2-10. Boron Concentration in Upper Half of Average Power Bundle

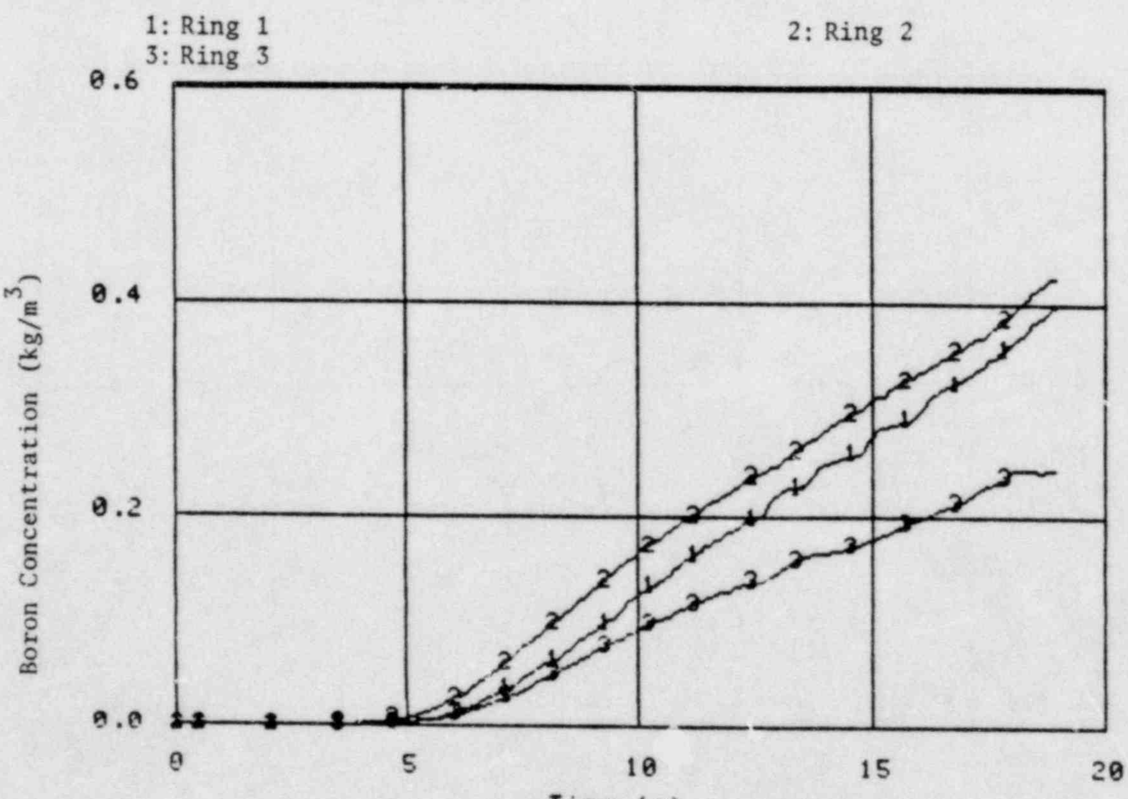


Figure 2-11. Boron Concentration in Upper Plenum

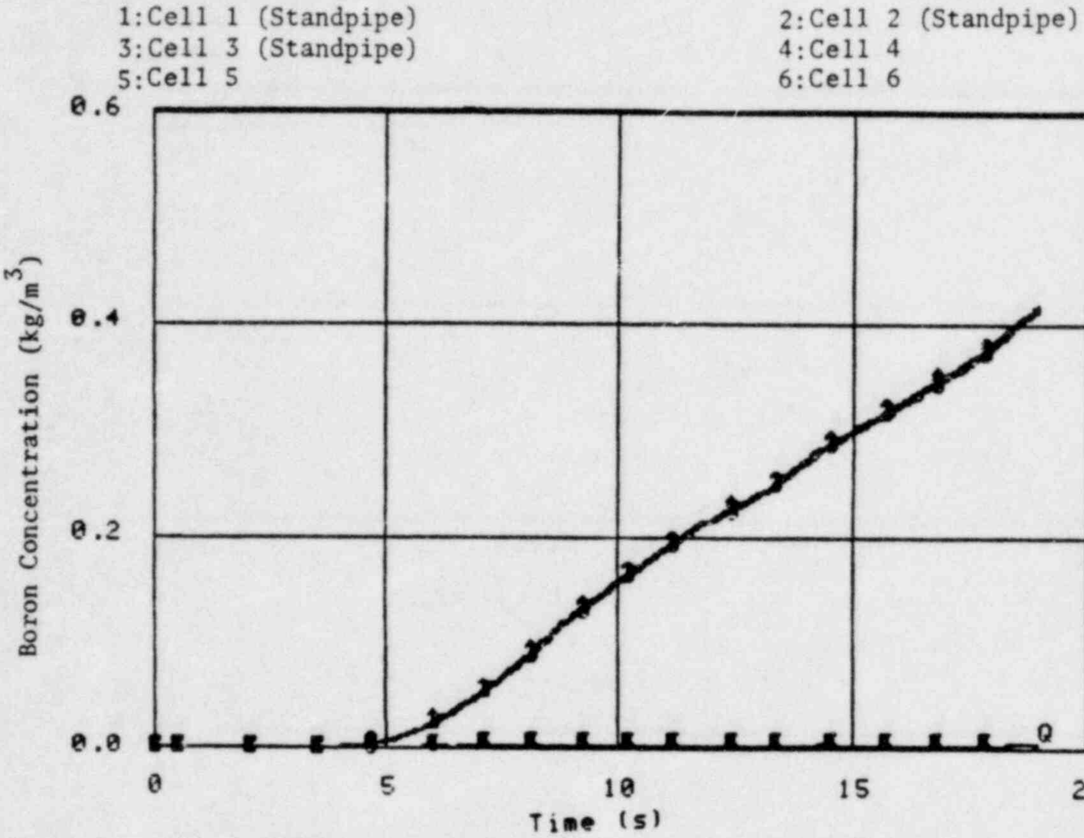


Figure 2-12. Boron Concentration in Separator

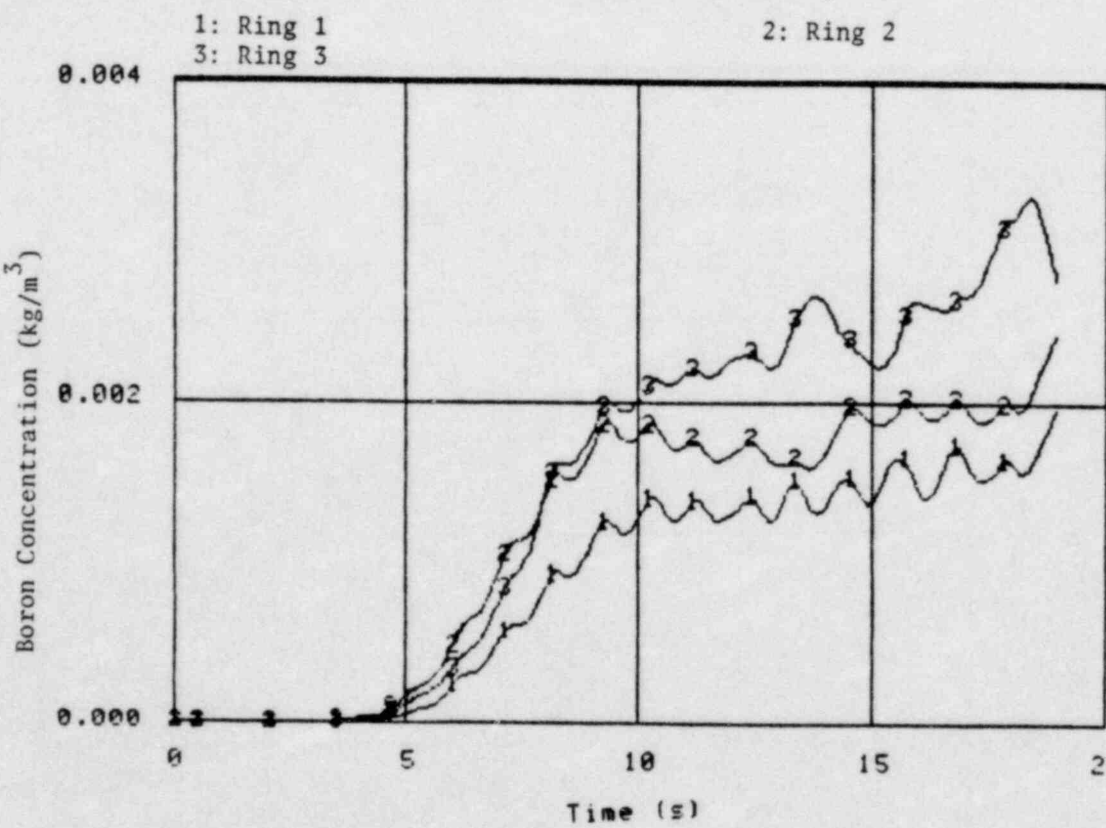


Figure 2-13. Boron Concentration in Dryer Region

SECTION 3

THE TWO-PHASE LEVEL MODEL

3.1 BACKGROUND AND OBJECTIVES OF THE MODEL

The interfacial heat transfer in TRAC is tied to the flow regime map through the void fraction of the cell[9]. However the flow regime map in TRACB02 cannot distinguish between the flow regimes shown in Figure 3-1. For the partially filled cell situation illustrated in Figure 3-1, the interfacial heat transfer coefficient is incorrectly calculated based on the dispersed flow regime. The difference between the interfacial areas and heat transfer coefficients is quite significant and may produce unreasonable results. The objective of the two-phase level model is to modify the flow regime map such that it can distinguish the situations in Figure 3-1 and calculate the interfacial heat transfer appropriately. These discontinuities are already tracked in the three dimensional regions. The emphasis in the present model development is to define criteria for levels in one dimensional regions and appropriate interfacial areas and heat transfer.

3.2 DESCRIPTION OF THE MODEL

3.2.1 1D levels

In order to establish a level in a cell in a one-dimensional region as shown in Figure 3-1, the following condition has to be met:

1. The cell above the level has to be in annular/drop flow.
2. The cell below the level has to be in bubbly/churn flow.
3. The entrainment predicted by the Rosen entrainment correlation [10] has to be smaller than the liquid flux leaving the top of the cell. The Rosen entrainment correlation is given by:

$$G_{ROSEN} = 3\times10^{5}\,(C_k^{0.5} + 530\,C_k^{2.1})\,\left(\frac{\Delta\rho}{\rho_g}\right)^{1/2}\rho_g j_g \qquad (3\text{-}1)$$

where

$$C_k = \frac{2d_{max}\ j_g}{V_{crit}\ (\frac{\sigma}{g\Delta p})^{1/2}} \qquad (3-2)$$

$$V_{crit} = 2\ (\frac{\Delta\rho g\sigma}{\rho_g^2})^{1/2} \qquad (3-3)$$

$$d_{max} = 0.3375\ \rho_g j_g^2/g\Delta\rho\alpha^2 \qquad (3-4)$$

The cell void fraction above and below the level is assumed to be the same as that in the cells above and below respectively. The level location in the cell is determined from

$$X_L = \frac{\alpha^+ - \alpha}{\alpha^+ - \alpha^-}$$

where

X_L: Level location measured from the bottom of the cell

α: Void fraction

α^+: Void fraction above the level

α^-: Void fraction below the level

3.2.2 Interfacial Heat Transfer at Levels

The total interfacial heat transfer per unit volume for this flow regime consists of three components: one above the level, one below the level and one at the free surface.

Below the level the interfacial heat transfer is calculated corresponding to bubbly/churn flow.

$$(Ah)^-_{i\ell} = X_L\ V \frac{1}{d^-_i}\ h^-_{i\ell}$$

$$(Ah)^-_{ig} = X_L\ V \frac{1}{d^-_i}\ h^-_{ig}$$

Above the level the interfacial heat transfer is calculated corresponding to

annular/drop flow

$$(Ah)^+_{i\ell} = (1-X_L) \; V \frac{1}{d_i^+} \; h^+_{i\ell}$$

$$(Ah)^+_{ig} = (1-X_L) \; V \frac{1}{d_i^+} \; h^+_{ig}$$

At the level the interfacial heat transfer is calculated from

$$(Ah)^L_{i\ell} = Ah^L_{i\ell}$$

$$(Ah)^L_{ig} = Ah^L_{ig}$$

The interfacial heat transfer coefficients at the level are given by(11)

$$h^L_{i\ell} = \frac{k_\ell}{k_a} \; 1.027 \; (\Delta T_\ell)^{1/3}$$

$$h^L_{ig} = \frac{k_\ell}{k_a} \; 1.027 \; (\Delta T_g)^{1/3}$$

where

$$\Delta T_\ell = | T_\ell - T_s |$$

$$\Delta T_g = | T_g - T_s |$$

The total interfacial heat transfer is thus given by

$$(Ah)_{i\ell} = (Ah)^-_{i\ell} + (Ah)^+_{i\ell} + (Ah)^L_{i\ell}$$

$$(Ah)_{ig} = (Ah)^-_{ig} + (Ah)^+_{ig} + (Ah)^L_{i\ell}$$

3.3 VERIFICATION

The two-phase level model has been verified by demonstrating its ability to simulate the condensation phenomenon at the free surface of a rising water level.

A vertical pipe initially filled with saturated steam is injected from below with a highly subcooled liquid at the rate of 70 kilograms per second. The top of the pipe is connected to a steam reservoir to replenish the steam condensed at the

free surface. Nodalization of this system for TRAC is shown in Figure 3-2. Simulations were performed both with and without the model. The results are presented in Figure 3-3. For the case without the model, a large steam flow into the pipe was predicted (steam velocities corresponding to choked flow were observed). This indicates a large amount of steam is condensed in the pipe. The result also showed periodic oscillation of the steam flow as the water level passed through cells. This is caused by the cell going through all the flow regimes as the void fraction in the cell changes from 1.0 to 0.0 and the interfacial area and heat transfer coefficients change their values accordingly. The large condensation rates are clearly not realistic and are only due to the heat transfer logic in TRAC. For the case with the improved model, steam flow into the pipe is much smaller because the condensation is limited to the two-phase level surface. In fact, these flows are smaller than the rate of steam being displaced by the rising level. The steam flowrate also maintains a constant value indicating that the cells remain in one flow regime as the water level passes through each cell.

3.4 CONCLUSION

A vertical two-phase level model has been developed and implemented in TRAC. Results of testing showed that the model is performing properly.

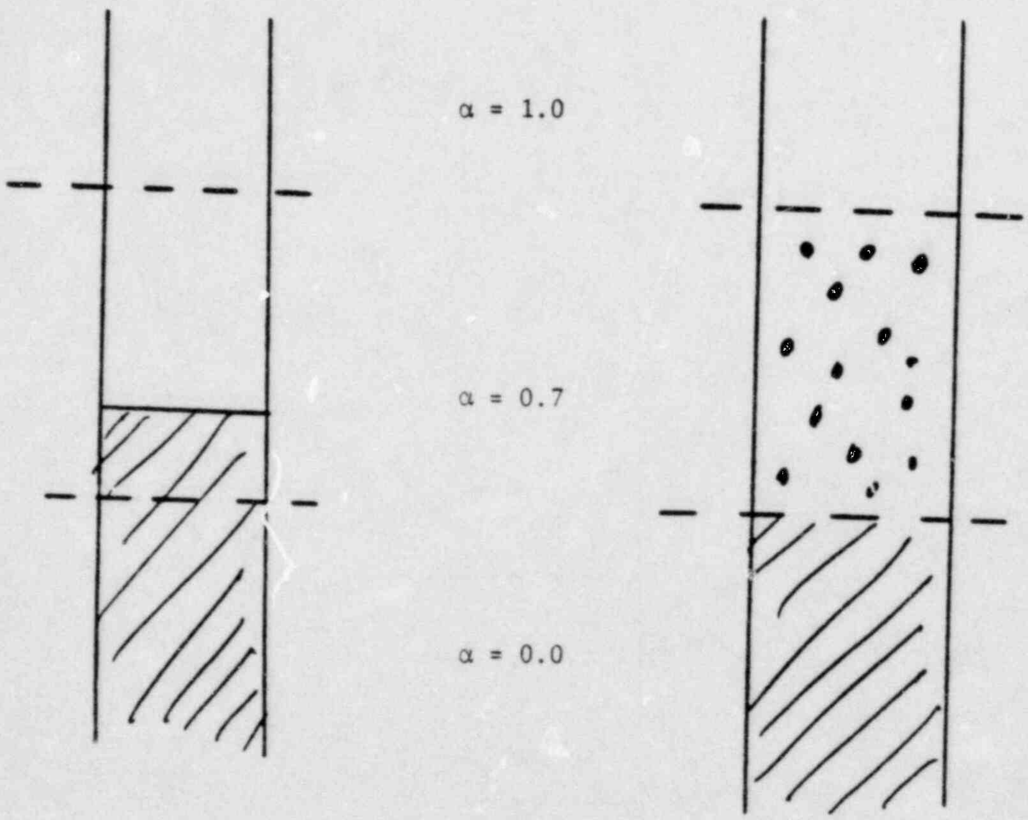


Figure 3-1 Flow Regime Dilemma

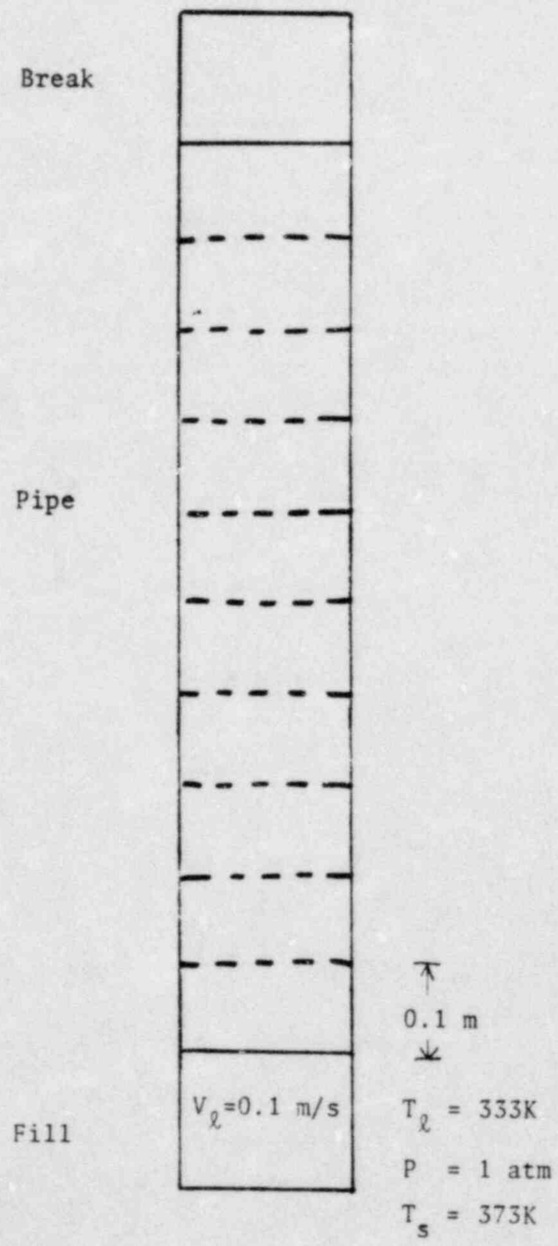


Figure 3-2. Nodalization of the Stratified Flow Test Case

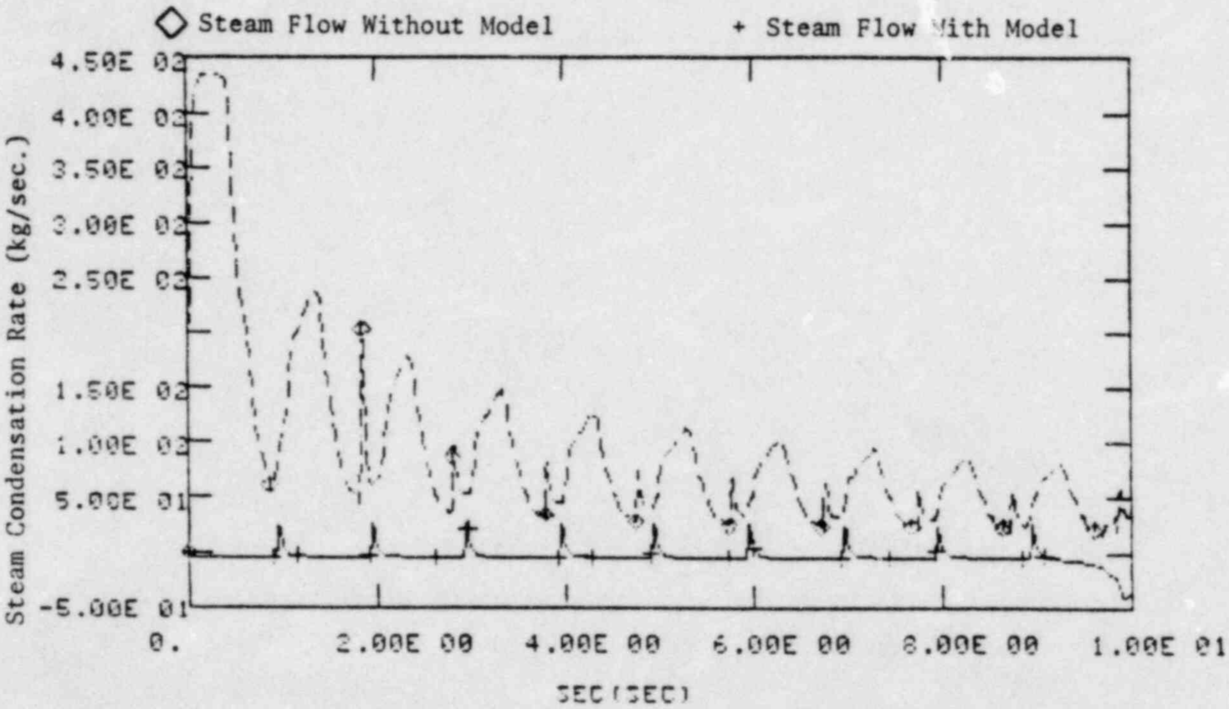


Figure 3-3. Results from Stratified Flow Tests

SECTION 4

BALANCE OF PLANT MODELS

The Balance of Plant Models implemented into TRACB04 are the turbine model, heat exchanger model, and containment model. These models were developed at INEL and details of these models are documented in References 3, 4, 5, and 6. Under the FIST program, these models were evaluated and adapted to the TRACB04 version.

4.1 TURBINE MODEL

The turbine model provides a basic capability in the TRAC code for modeling BWR main steam turbines and for modeling smaller turbines such as those used for driving feedwater pumps. This model is implemented into the TRAC code as a new component type, the TURB component.

The TURB component contains two fluid cells in the configuration as shown in Figure 4-1. In normal use, turbine stages will be lumped together into several groups, with a TURB component to represent each group of stages. The grouping will be dictated by the location of desired steam extraction points or separator drains along the turbine. The TURB component includes the following features for modeling turbine behavior:

1. An isentropic flow equation is used to determine turbine nozzle velocity.

2. A term is included in the fluid energy equation to account for energy removal from the fluid stream by the turbine blade assembly.

3. An optional steam/water separator is implemented to remove liquid from the main turbine flow stream and divert it to the side arm drain of the turbine.

4. A model is included to simulate the dynamics of the turbine rotor assembly. This calculation tracks the turbine rotor speed, which is required for calculation of turbine efficiency and for detection of turbine overspeed conditions.

Detailed descriptions of the governing equations and solution strategy are given in Reference [illegible].

A test case (sample problem TUR3 in Reference 3) was executed to verify that the turbine model was correctly implemented into TRACB04. This sample problem models an isolated turbine with boundary conditions specified by BREAK components as shown in Figure 4-2. The three TURB components in the model are used to model the high and low pressure sections of a BWR main steam turbine, with an intermediate section representing the moisture separator. Boundary conditions were chosen to be roughly representative of conditions for a BWR/6 main turbine. A brief transient was run with trips set to simulate a hypothetical generator load rejection incident. During the first 5 seconds of the transient, the model runs from its unsteady initial state to a well-converged steady state. At 5 sec the turbine trip is activated to simulate a generator load rejection. During the next 3 sec, the turbine rotor accelerates since it has lost its load but is still receiving nearly full power from the turbine steam flow. At 8 seconds the inlet BREAK pressure is reduced, simulating a closure of the turbine stop valve due to a turbine overspeed trip.

The turbine rotor speed, turbine rotor torque, and high pressure turbine mass flow rate calculated by TRACB04 are compared with those calculated by TRACBD1-MOD1 (INEL version) and shown in Figures 4-3 to 4-5. The good agreement of results verifies that the turbine model was correctly implemented into TRACB04.

4.2 HEAT EXCHANGER MODEL

The heat exchanger model provides a basic capability in the TRACB04 code for modeling typical heat exchangers such as feedwater heaters and steam condensers found in BWRs.

The heat exchanger shell is modeled by a TRAC TEE component. The tube bank is modeled by a single pipe component. A typical heater model consisting of shell, drain cooler and tube bank is shown in Figure 4-6. Heat transfer between tube and shell is calculated by using the generalized component-to-component heat transfer logic described in the multiple channel model[5].

Correlations appropriate to condensation on horizontal and vertical tube banks[12] have been introduced. In addition, a correlation for single-phase (liquid) convection across tube banks[13] has been implemented in order to better describe the behavior in the liquid-filled regions of the heat exchanger. These correlations are available in the code for use in the heat exchanger component only. The previous models for convection and condensation are still used for other components. The correlations used are:

For condensing flow on horizontal tube banks

$$h_v = X_f \frac{k_\ell}{D_t} Re_\ell^{1/2} \quad (1.0 + \frac{0.276}{X_f^4 \; FrH_f})^{1/4} \tag{4-1}$$

For condensing flow on vertical tube banks

$$h_v = 0.943 \left[\frac{h_{fg} k_\ell^3 \rho_\ell^2 g}{\mu_\ell D_B (T_s - T_w)}\right]^{1/4} + X_f \frac{k_\ell Re_\ell^{1/2}}{D_t} \tag{4-2}$$

For liquid crossflow across tube banks

$$h_v = 0.36 \left(\frac{k_\ell}{D_t} \frac{D_h \rho_\ell V_\ell}{\mu_\ell}\right)^{0.55} \left(\frac{C_{p_\ell} \mu_\ell}{k_\ell}\right)^{1/3} \tag{4-3}$$

X_f, H_f, R_f, Re_ℓ (liquid film Reynolds number) and Fr (Froude number) a... dimensionless quantities defined as

$$X_f = 0.9 \left(1 + \frac{1}{R_f + H_f}\right) \tag{4-4}$$

$$H_f = \frac{k_\ell (T_s - t_w)}{\mu_\ell \; h_{fg}} \tag{4-5}$$

$$R_f = \left(\frac{\rho_\ell \mu_\ell}{\rho_g \mu_g}\right)^{1/2} \tag{4-6}$$

$$Re_\ell = \rho_\ell V_g \; D_t / \mu_\ell \tag{4-7}$$

$$Fr = V_g^2 / g D_t \tag{4-8}$$

4.3 MULTIPLE CHANNEL MODEL

In the TRACB02 code, only one CHAN component with proper heat transfer and leakage connection to the bypass region is allowed in a vertical stack of VESSEL cells. In TRACB04, the multiple channel model is implemented to generalize the heat transfer calculations and extend the capability to allow:

1. More than one CHAN component with proper heat transfer in a vertical stack of VESSEL cells and;

2. Heat transfer from the walls of any 1-D component to the fluid in any other 1-D component.

Detailed descriptions of this model are given in Reference 5.

The multiple channel model as implemented in TRACB04 makes no changes to the heat transfer correlations used in TRAC. The impact of this model is to replace the specialized coding logic for treating heat transfer from the channel outside surface with the general component-to-component heat transfer logic. To verify that this change had been implemented correctly, a typical BWR/6 simulation, as shown in Figure 4-7, was executed with and without this model. An examination of the detailed heat transfer output for the channel wall verified that the current capability had been maintained.

To verify that multiple channels could transfer heat to a single vessel cell, the BWR nodalization was modified to include only 2 vessel rings. As Figure 4-8 shows, this nodalization has all three channels placed in the central ring. This nodalization was executed and examination of the detailed heat transfer edits verified that the calculation was performing properly.

As indicated above, this model allows heat transfer from the surface of a 1-D component to the fluid in other 1-D components. This capability is required by the heat exchanger model in which heat is transferred between the fluid in the shell component and the surface of the tube bank component. The test performed for the heat exchanger verified that this capability was performing properly.

4.4 CONTAINMENT MODEL

The containment model provides a capability in the TRACB04 code to calculate the temperatures, pressures, mass, and energy inventories in the drywell, wetwell, and suppression pool regions of the containment of a BWR during accident or transient conditions. The principal regions of a BWR containment to be modeled are the drywell and wetwell (including the suppression pool). Lumped parameter models for each separate containment region (or compartment) are used to calculate mass and energy inventories in the same manner as in existing containment codes such as CONTEMPT-LT[14]. Coupling between nodes occurs via intercompartmental flows and via heat transfer to the surfaces of common heat-structures (walls).

Each node in the calculation is assumed to consist of a vapor region, composed of steam and a non-condensible gas (air), and a liquid or pool region. Mass and energy flows to the two regions for a given compartment are computed. The resulting mass and energy addition rates are integrated in time and thermodynamic calculations are performed at each time step to determine pressures and temperatures in each region, and to transfer condensed steam from the vapor to the pool region.

BREAK, FILL and VESSEL components may be coupled to the containment at the option of the user. BREAK components so coupled will have fluid conditions (pressure, temperature, and void fractions) corresponding with those at the containment location specified by the user. FILL components drawing liquid from containment sources (such as the pressure suppression pool in the BWR wetwell) will similarly have fluid conditions that are periodically updated by the containment model. The VESSEL component may be thermally coupled to a containment compartment by the user. The containment module will periodically update the vessel exterior heat transfer coefficients and fluid temperatures that provide the outside boundary condition for the temperature calculation in the vessel wall.

The containment calculation is coupled to the normal TRAC simulation of the reactor vessel and the primary coolant loop via the boundary conditions at the point of primary coolant discharge into the containment, and at the supply points for ECC systems. The containment model is implemented such that the calculation is independent of that for the primary loop. The only coupling between the two is through the vessel outside surface heat transfer and through the boundary flow conditions at BREAK and FILL components in the primary loop, which act as mass and energy sources for the containment. The transient containment calculation is performed in a separate subprogram which is called at fixed time intervals (specified by the user) during the transient calculation.

A detailed descriptions of the containment model is given in Reference 6.

The sample problem in Reference 6 was executed to verify that the containment model was correctly implemented into TRACB04. This sample problem incorporates all systems and options available in the TRAC containment model. A schematic of the containment nodalization used for the sample problem is shown in Figure 4-9. A three-cell VESSEL was used in the primary loop calculation in order to test the vessel exterior surface heating option in the containment model, and to allow the connection of multiple BREAK and FILL components to the containment in a single run.

Six compartments were used in the model to facilitate demonstration of the effects of various options. Table 4-1 summarizes the sequence of events during the 1.0 second containment transient simulated in the sample problem.

Detailed results of this sample problem were documented in Reference 6. These results were compared with those calculated by TRACB04 and found to be in good agreement. Figure 4-10 to 4-12 show the compared liquid mass, steam mass and total pressure in Compartment 10, and Figure 4-13 shows the compared liquid mass in Compartment 20. The good agreement of results verifies that the containment nodal was correctly implemented into TRACB04.

4.5 AIR FIELD

The air field provides the TRACB04 code with the capability to model the presence of air within the reactor system. This capability is essential for modeling the BWR containment and allows the simulation of air entering the reactor vessel during postulated accident conditions. The presence of air will greatly impact the hydrodynamic behavior of the system by altering the physical properties of the vapor mixture.

The governing equations for the air field are described in Reference 7. The following is a brief summary of the model features. The air is assumed to be perfectly mixed with the steam phase. Since this steam and air mixture is at a single temperature and moves at a single velocity, the current TRAC equations for continuity, energy and momentum of the vapor phase can be utilized for the vapor mixture. The thermodynamic properties of the mixture are determined by mixing the properties of the steam and air calculated using the appropriate partial pressures. The mixture transport properties are partial pressure weighted averages of the steam and air properties at their respective partial pressures.

The proportion of air within the vapor mixture is determined by solving an additional continuity equation for the air. The discretization of the air continuity equation is consistent with that of the existing vapor and liquid equations. The independent variable for the air is converted from density to partial air pressure by treating the air as a perfect gas. The resulting air equation is solved simultaneously with the vapor mixture and liquid conservation equations in the predictor step of the TRAC numerics. The air continuity equation is added to the correction step to assure air mass conservation when using the Courant violating numerics. A detailed description of the numerical method is given in Volume 1 of this report.

The presence of air affects the TRAC heat transfer calculations as a result of the changes in the thermodynamic and transport properties. In addition, the condensation heat transfer is reduced with a factor f to account for diffusion of steam through an air boundary layer at the interface[7].

$$f = 0.163 \left[\frac{\alpha \rho_v^2}{\rho_{NC}(1-\alpha)\rho_\ell}\right]^{0.1}$$

Several test cases were executed to verify that the air model performs correctly. In each case the results were examined and found to be acceptable.

Figure 4-14 shows the system configuration used for the tests. A sample of the results of two of the tests cases are given here. For the first test the system is initially filled with steam. At t=0 air is injected through FILL No. 1. Figure 4-15 shows the air pressure in various cells as a function of time. Figure 4-16 shows that the time step used during this calculation exceeded the Courant limit. Examination of the output verified that mass was conserved. In the second test, the system is initially filled with air. At t=0 liquid is injected through FILL No. 1. Figure 4-17 shows the mass flow rate at various cell boundaries as the liquid fills the system. This calculation was also run at time steps larger than the Courant limit as shown in Figure 4-18. The time step size is limited in the period from 0 to 8 seconds by the allowable rate of change of void fraction.

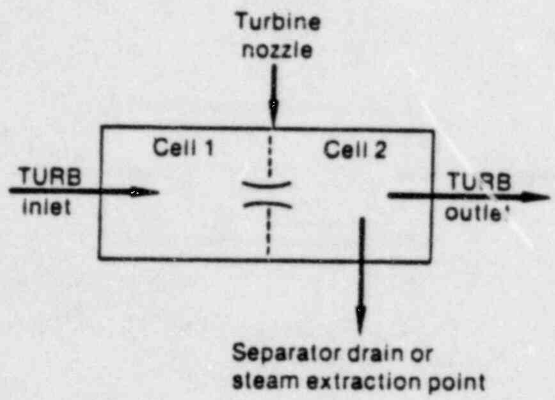


Figure 4-1. Configuration of TURB Component

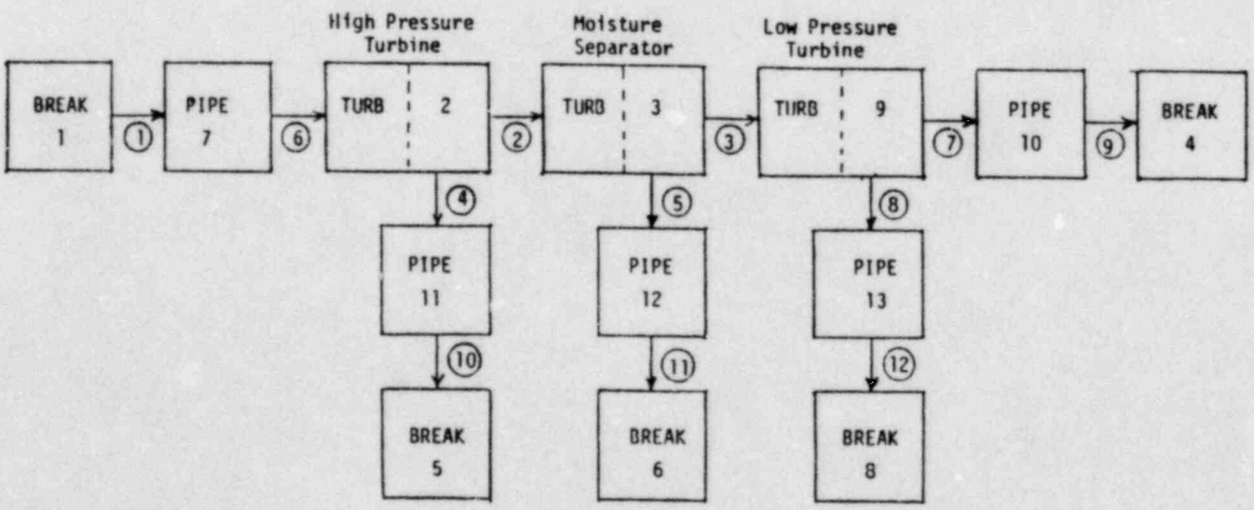


Figure 4-2. Test Case TURB

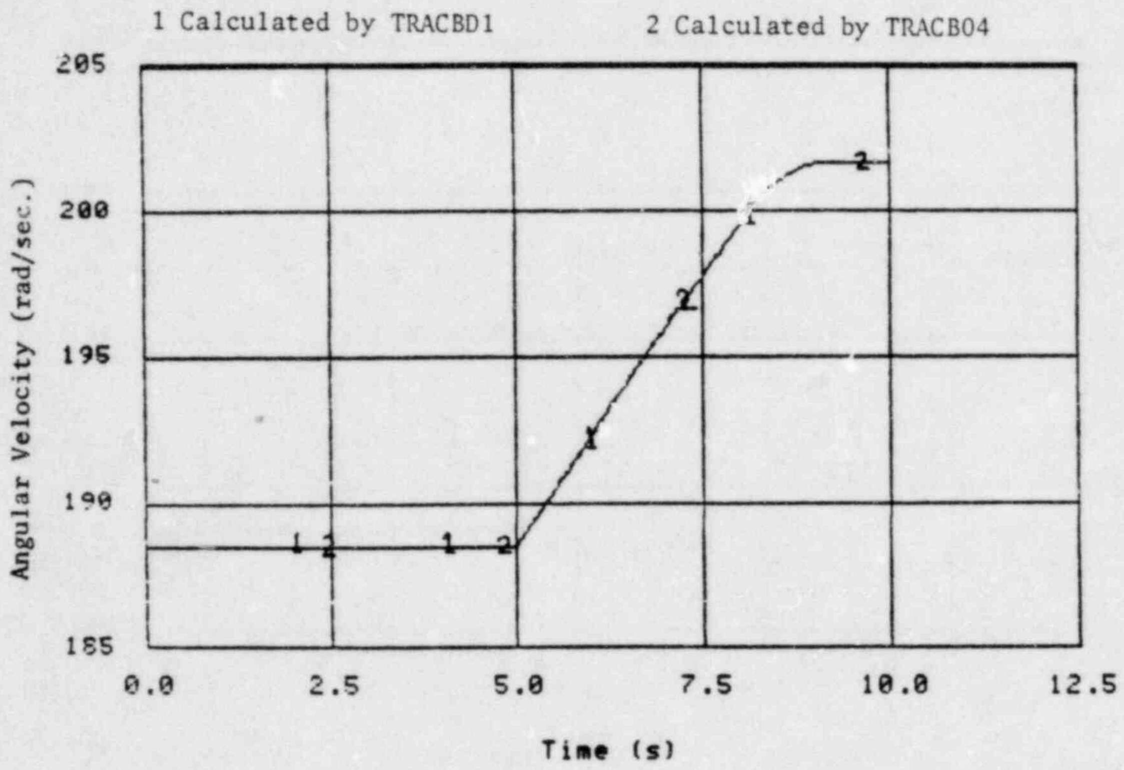


Figure 4-3. Comparison of Calculated Turbine Rotor Speed

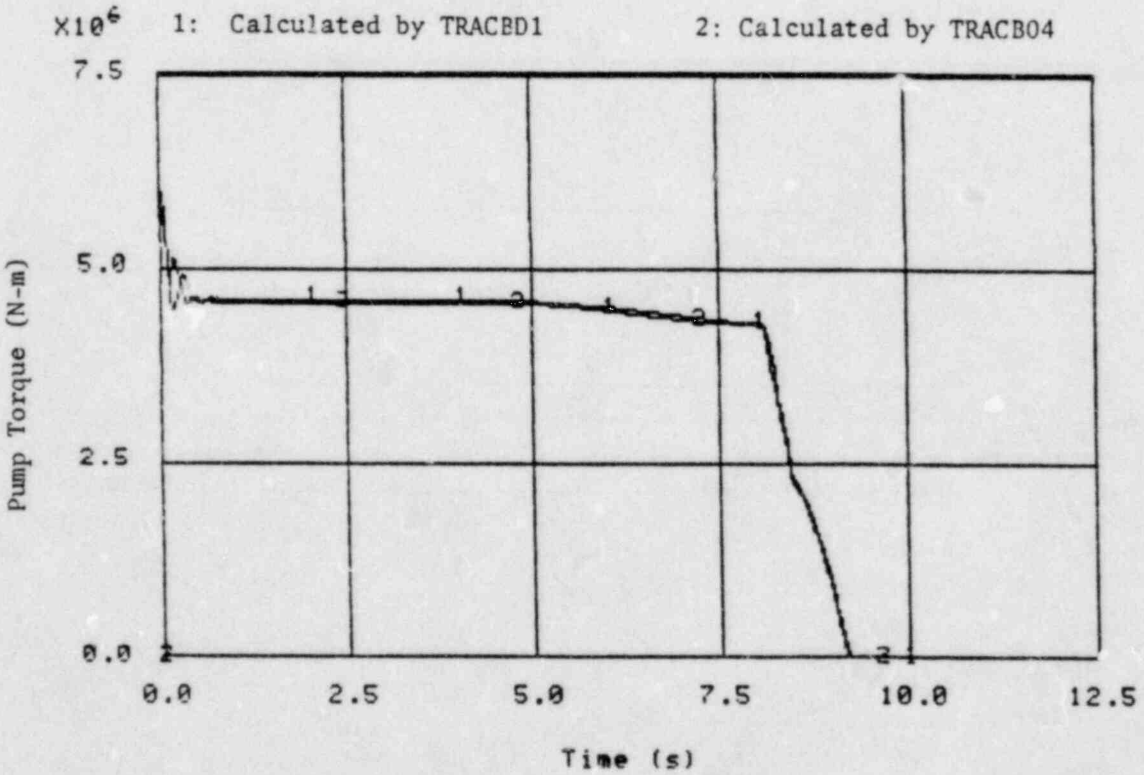


Figure 4-4. Comparison of Calculated Turbine Rotor Torque

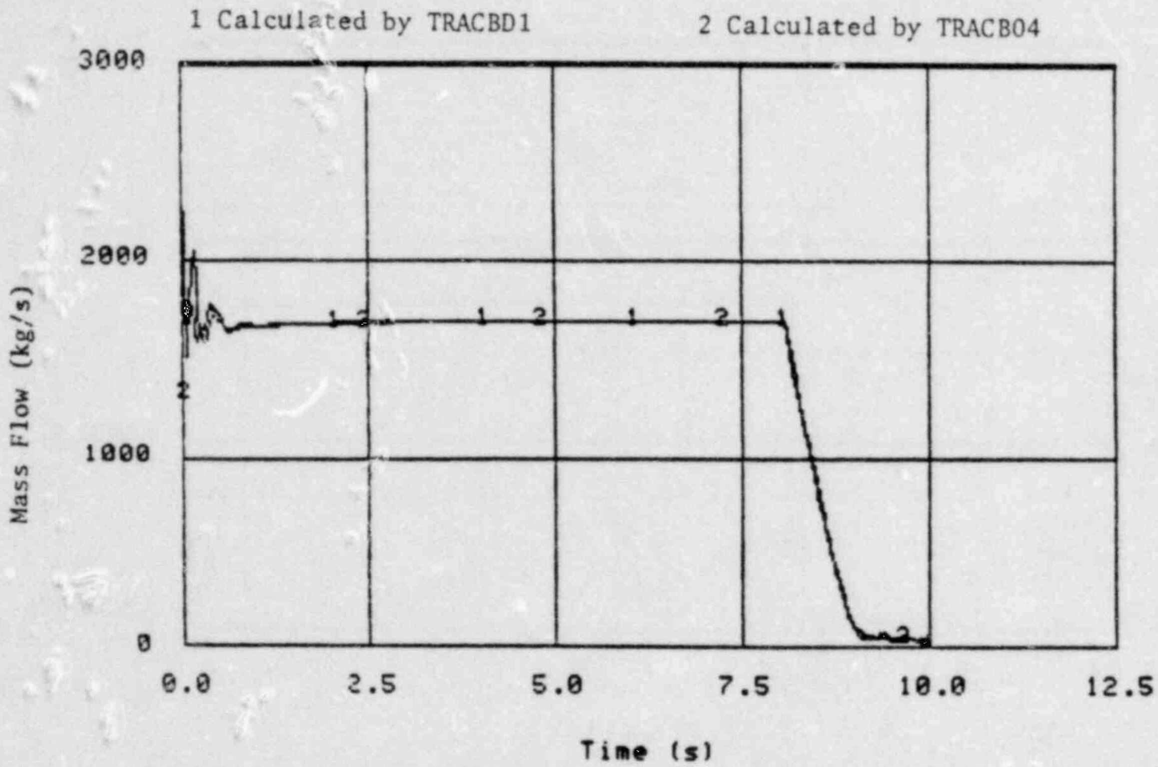


Figure 4-5. Comparison of Calculated High Pressure Turbine Mass Flow Rate

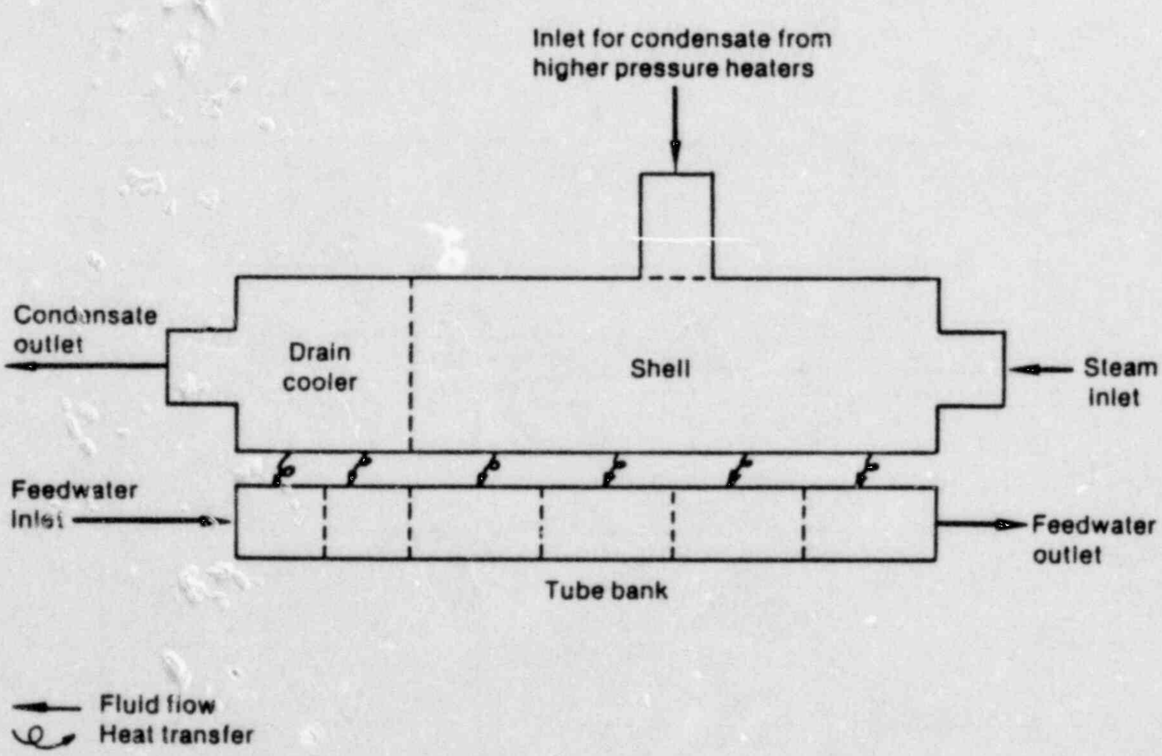


Figure 4-6. TRAC Model of Feedwater Heater Using a HEATR Component (Modified TEE) and PIPE Component for the Tube Bank

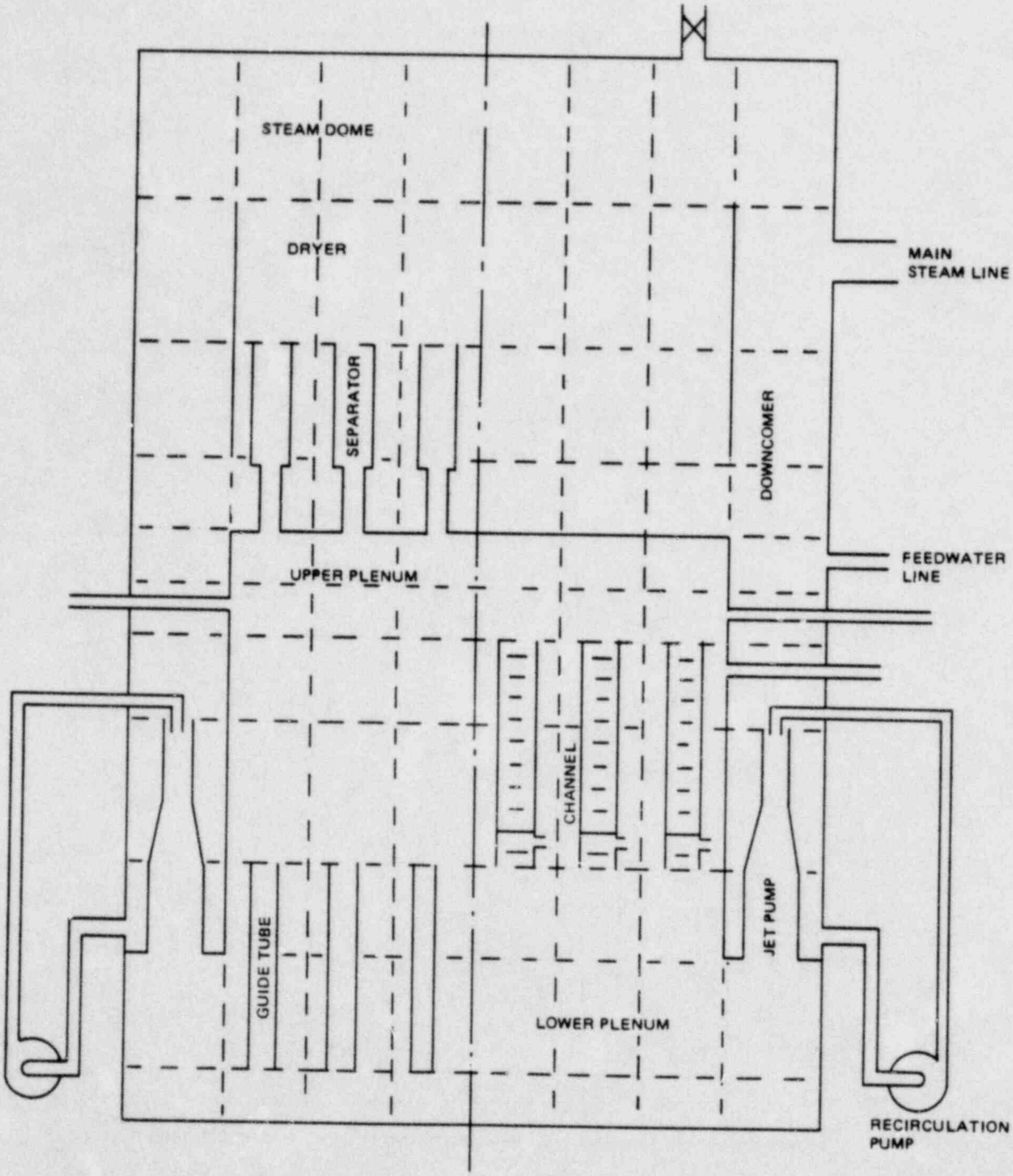


Figure 4-7. BWR/6 Nodalization with Single Channel per Vessel Cell

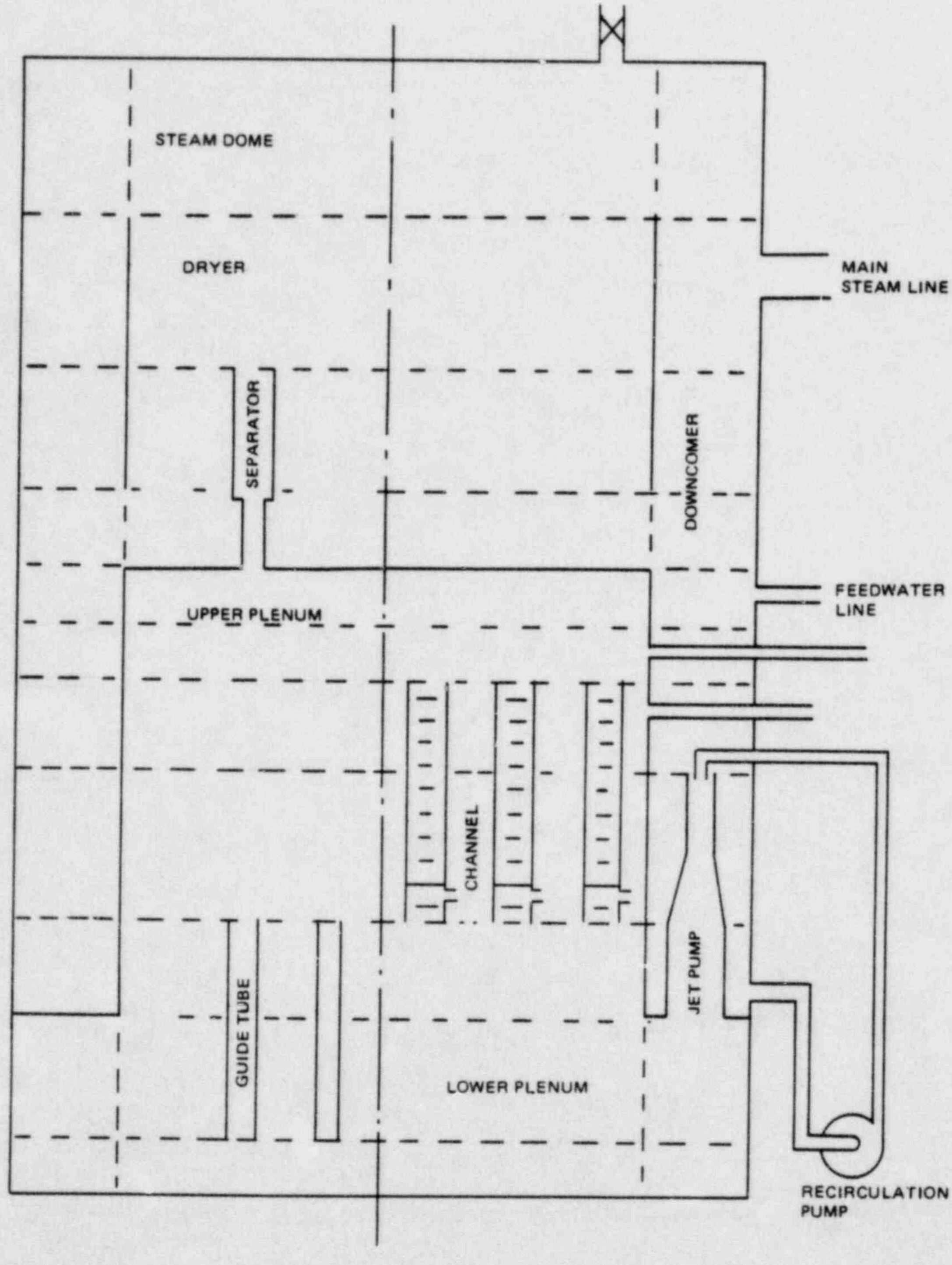
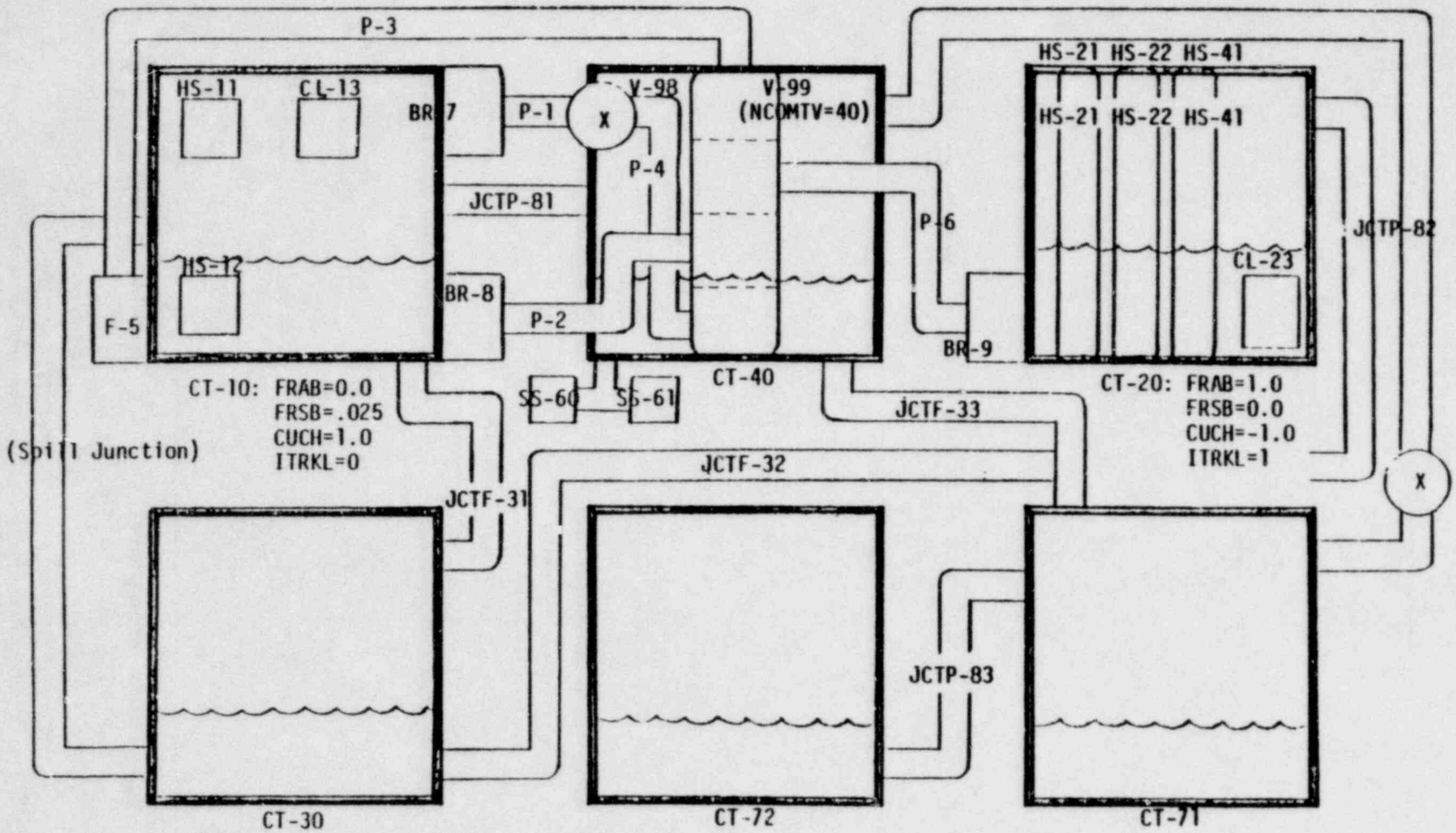


Figure 4-8. BWR/6 Nodalization Utilizing Multiple Channel Model



Abbreviations:

CT-10 = COMPARTMENT 10		V-99 = VESSEL 99
HS-11 = HEAT STRUCTURE 11		P-1 = PIPE 1
CL-13 = COOLER 13		BR-7 = BREAK 7
JCTP-82 = PASSIVE FLOW JUNCTION 82		F-1 = FILL 1
JCTF-33 = FORCED FLOW JUNCTION 33		V-98 = VALVE 98
JCTS-60 = SOURCE/SINK JUNCTION 60		

Figure 4-9. Schematic of Sample Problem Containment

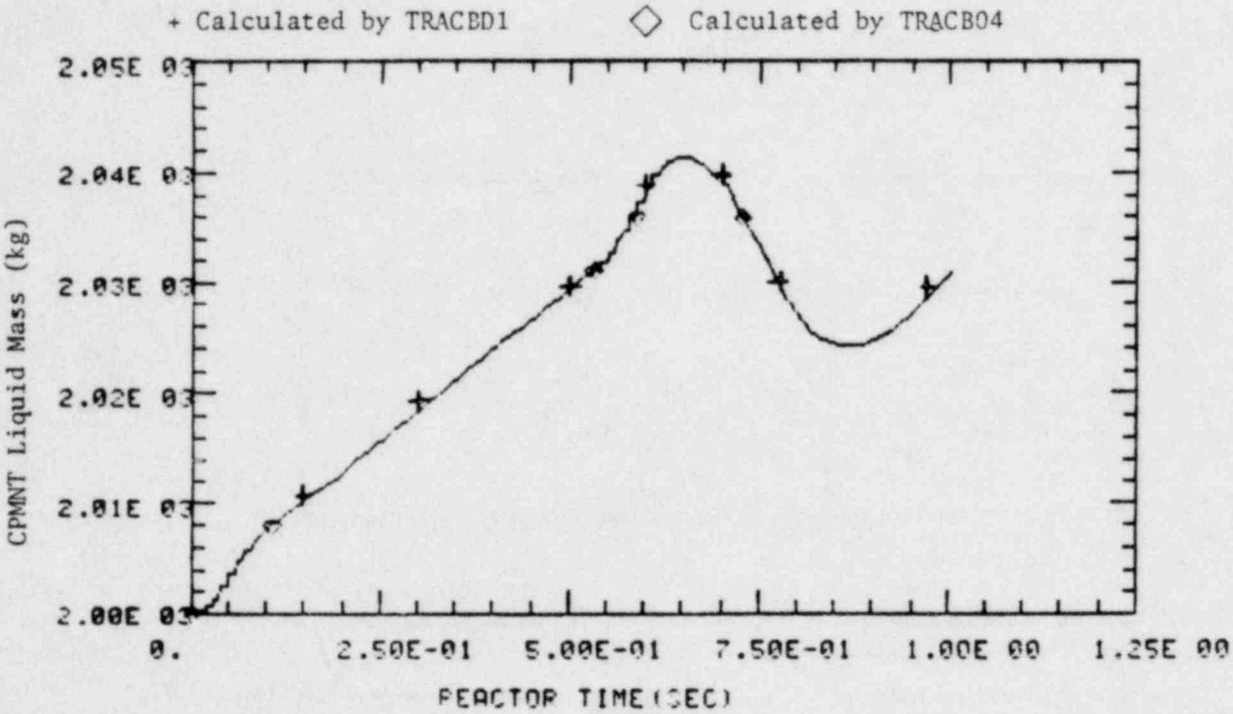


Figure 4-10. Comparison of Calculated Liquid Mass in Compartment #10

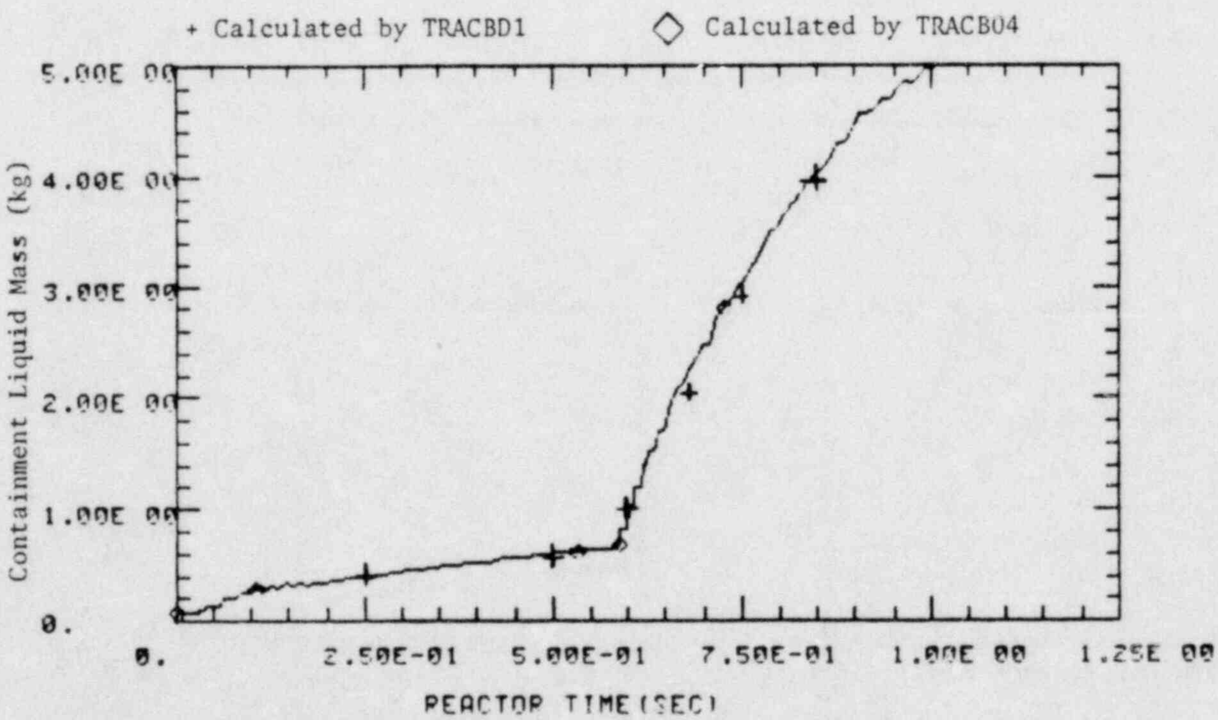


Figure 4-11. Comparison of Calculated Steam Mass in Compartment #10

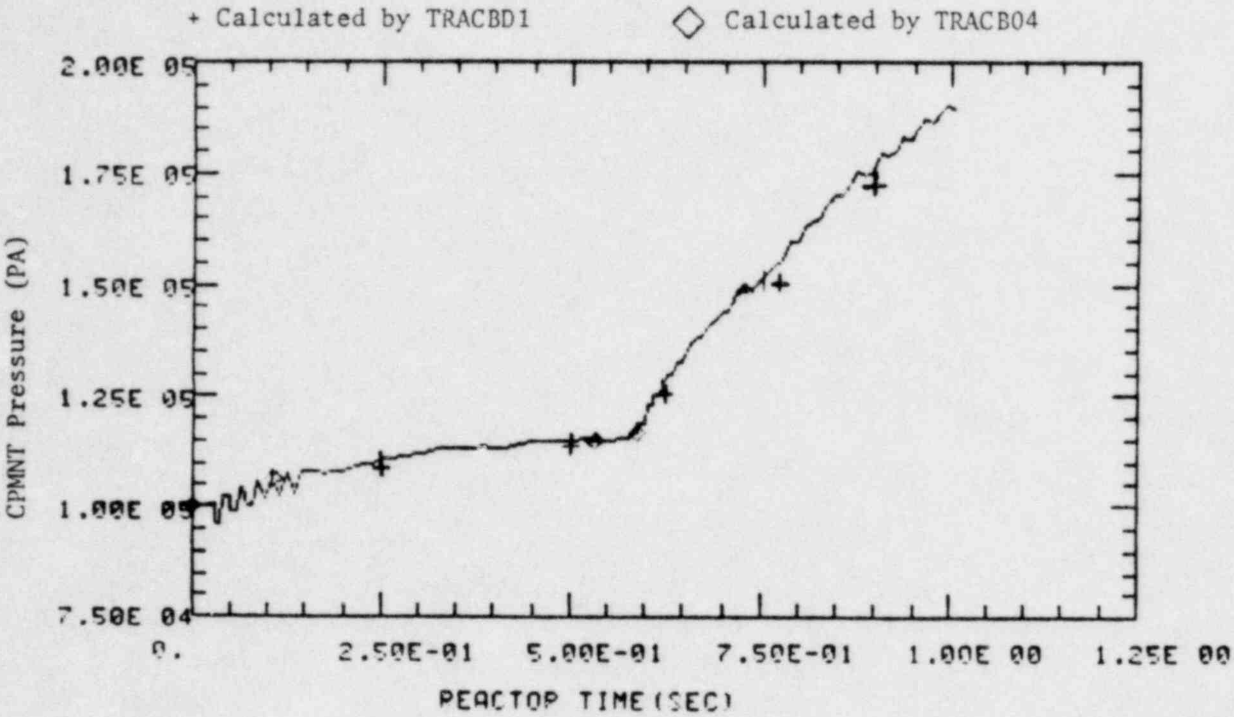


Figure 4-12. Comparison of Calculated Total Pressure in Compartment #10

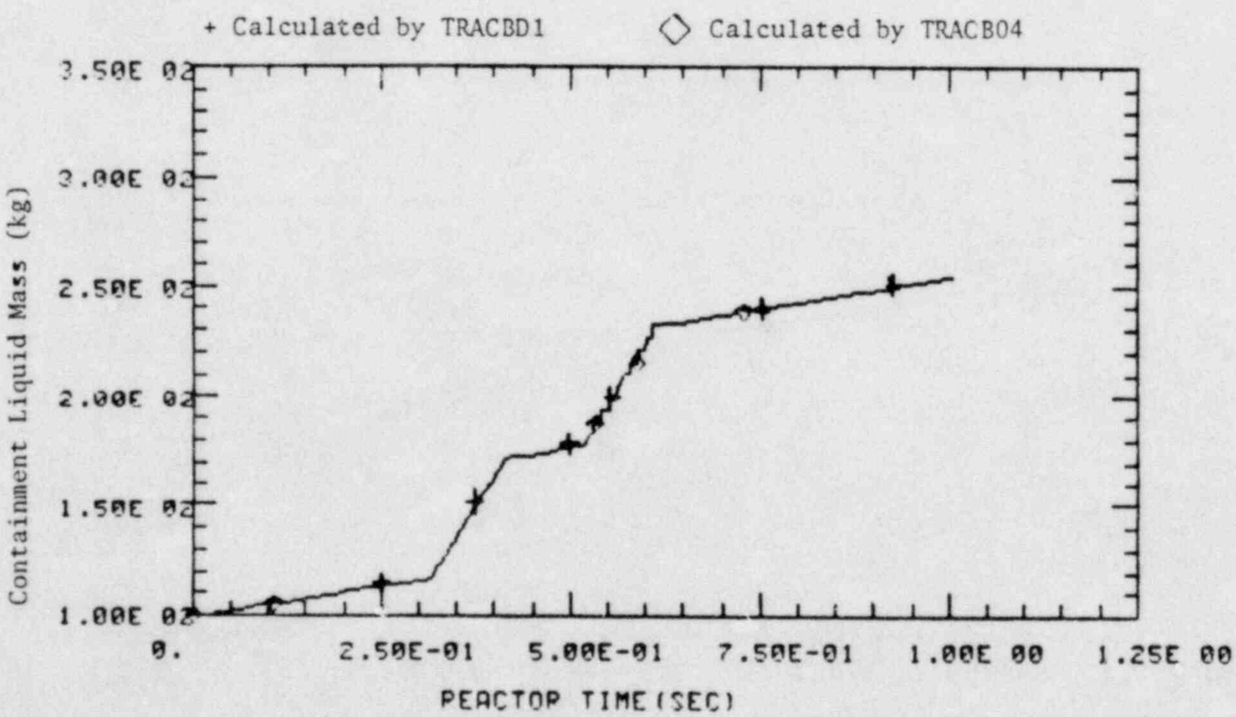


Figure 4-13. Comparison of Calculated Liquid Mass in Compartment #20

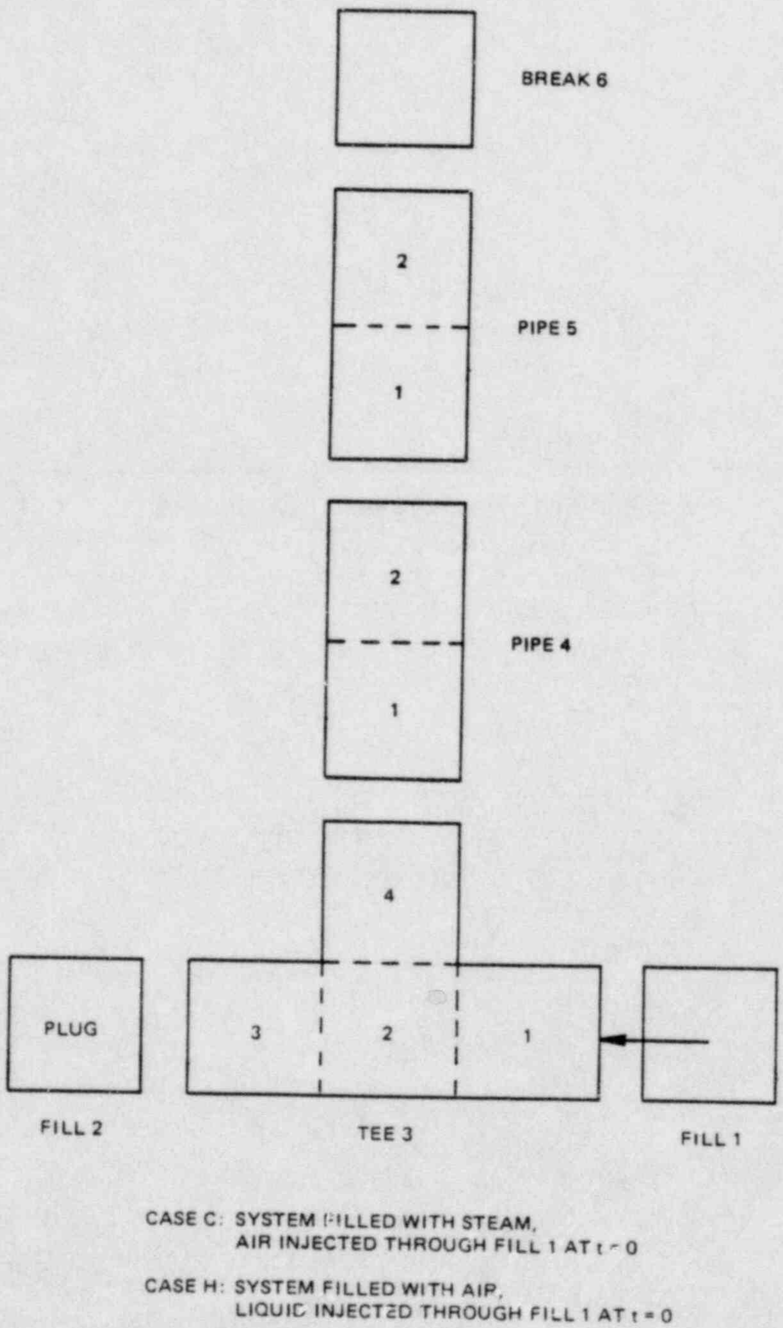


Figure 4-14. Air Model Test Case Configuration

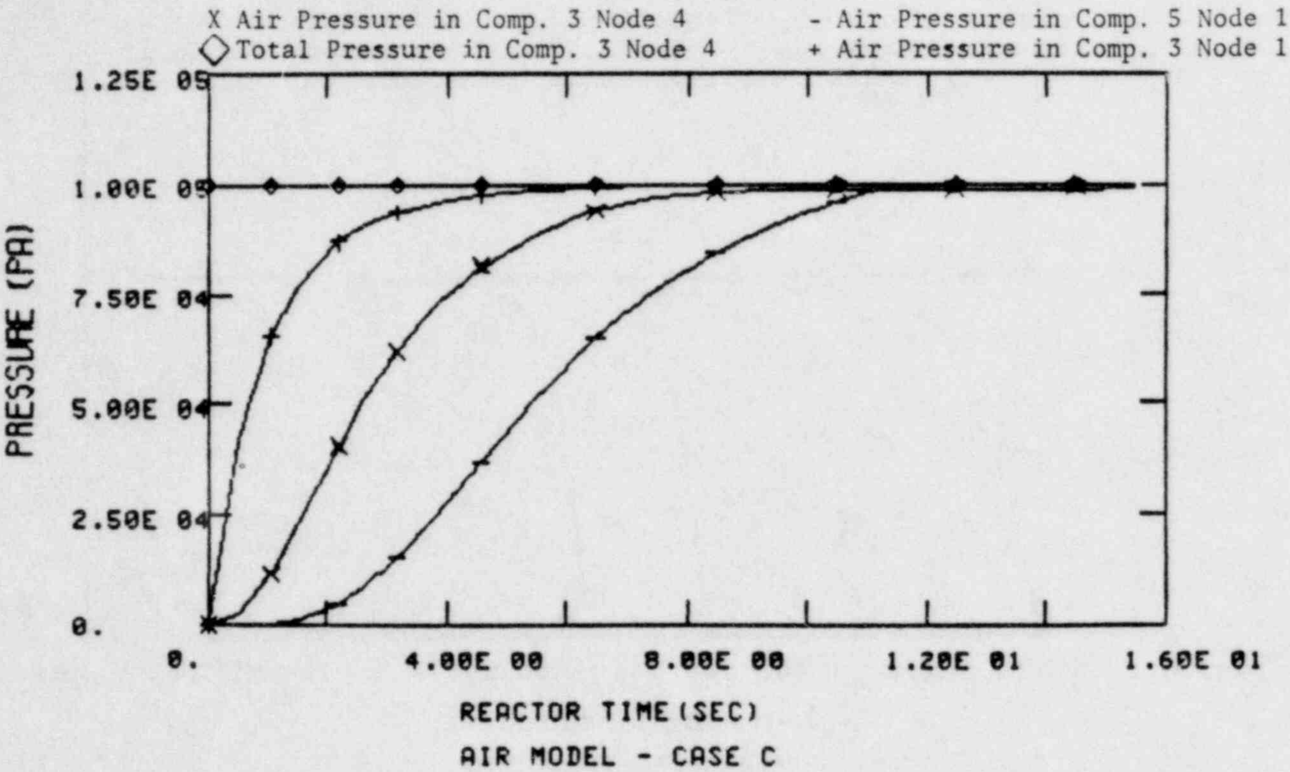


Figure 4-15. Air Pressure (Air Model Test 1)

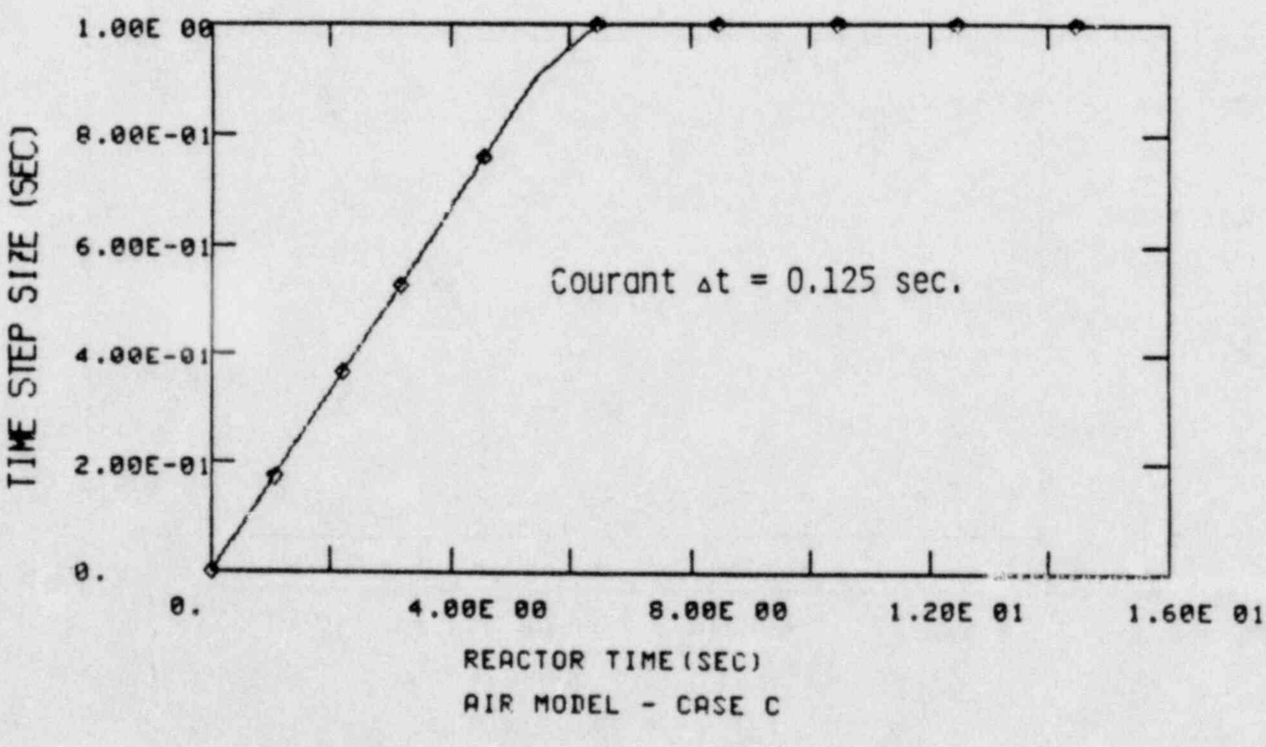


Figure 4-16. Time Step Size (Air Model Test 1)

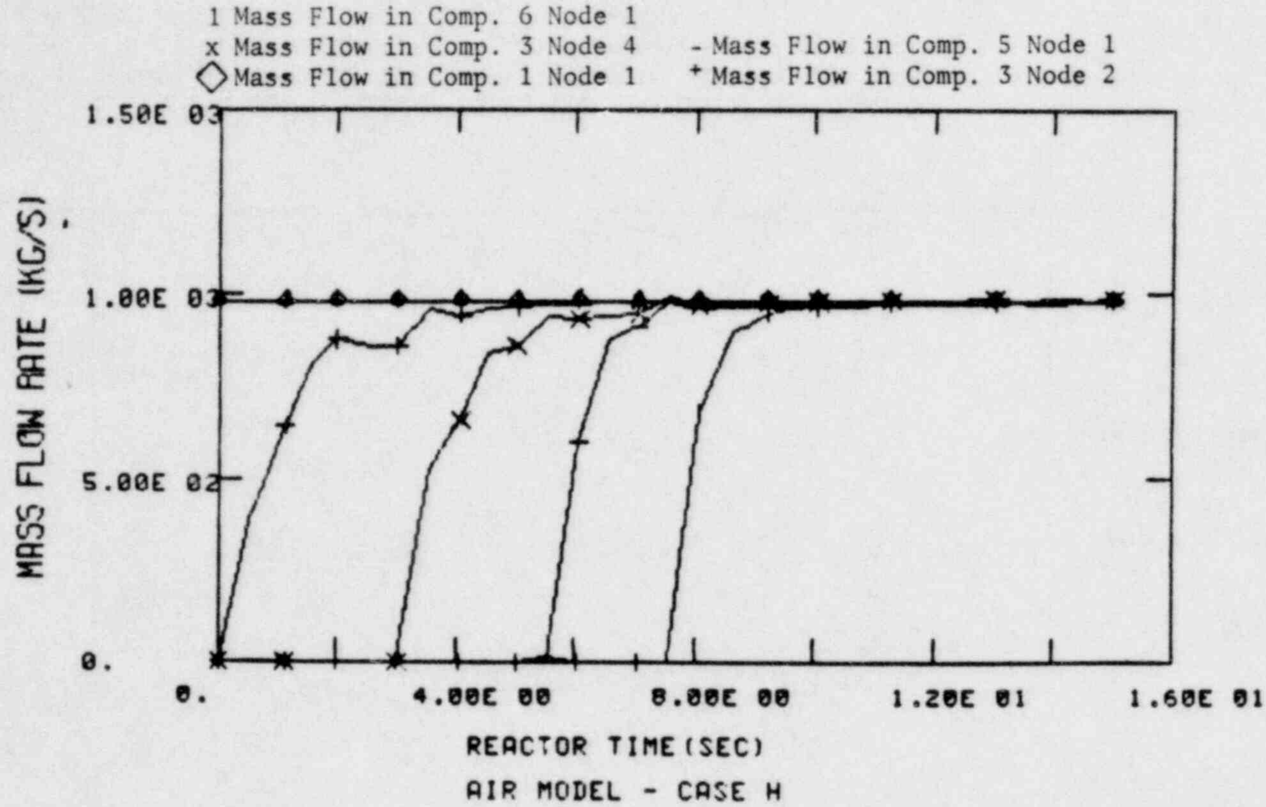


Figure 4-17. Mass Flow Rate (Air Model Test 2)

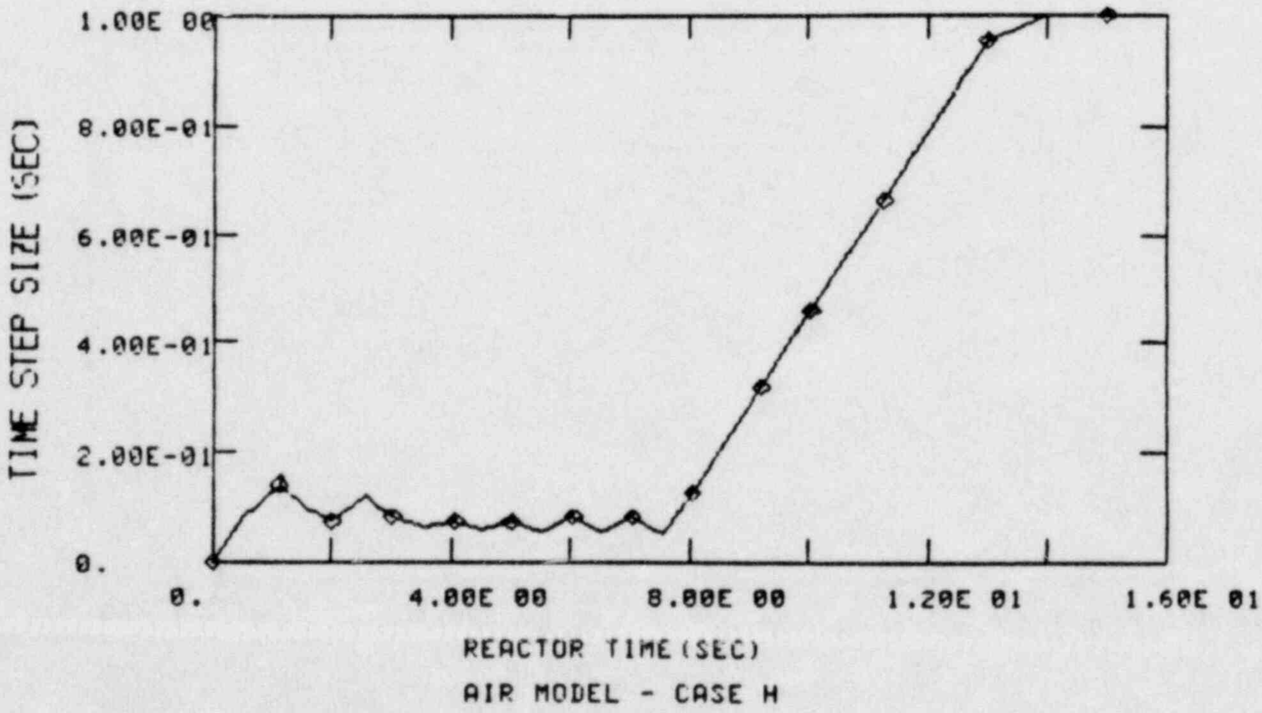


Figure 4-18. Time Step Size (Air Model Test 2)

Table 4.1. Major Events During Sample Containment Problem Transient

Time (s)	Description of Major Events
	Flow begins from BREAK 8 to compartment 10 (liquid region)
	FLow begins from BREAK 9 to compartment 20 (liquid region)
	Flow from source junction 60 to compartment 40 is active
0.1-0.2	Forced flow junction 33 from compartment 40 to compartment 71 is active
0.2-0.3	Cooler 23 in liquid region of compartment 20 is active
0.3-0.4	Forced flow junction 32 from compartment 30 to compartment 20 is active (spray efficienty = 0.0)
0.4-0.5	Forced flow junction 31 from compartment 10 to compartment 30 is active
0.5-0.6	Flow to sink junction 61 from compartment 40 is active
	Forced flow junction 32 from compartment 30 to compartment 20 is active (spray efficienty = 1.0)
0.6-0.8	FILL 5 from compartment 10 (liquid region) to VESSEL 99 is active
0.8-0.9	VALVE 98 open BREAK 7 to compartment 10 (vapor region) becomes active
0.9-1.0	Coolant temperature of COOLER 13 in compartment 10 (vapor region) drops significantly

SECTION 5

CONCLUSION

An enhanced boron transport model which is capable of simulating the boron stratification phenomenon has been developed. The implicit numerical method used to solve the governing equations of the new method works properly with the fast numerics. Reasonable results were obtained from the tests performed to verify the enhanced boron transport model. However it should be noted, that in order to properly benefit from the model the constants in the stratification and mixing model must be correlated from boron mixing data. It is highly recommended that such a task be undertaken.

The ability to distinguish a partially filled cell has been added to the existing flow regime map to cover the situation of a rising or falling level in the vertical pipe or vessel. Interfacial areas and heat transfer coefficients for this flow regime were also introduced. Two tests one with the new model and the other without were performed. Comparison of the two results showed the two-phase level model captures the physical phenomena better.

The balance of plant models and the air field model developed by INEL were implemented into the FIST program version of TRAC (TRACB04). These models include the turbine model, the heat exchanger model and the containment model, and enhance the TRAC capability for realistic simulation of the complete BWR plant.

SECTION 6

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TRAC-BWR (Transient Reactor Analysis Code) is a computer code for best estimate analysis of the thermal hydraulic conditions in a Boiling Water Reactor system. In this report, the development of new models and the implementation of the balance of plant models leading to the creation of the TRACB04 version of the code, is described. The new models include an improved model for boron transport which accounts for non-uniform mixing and stratification, and a model for the interfacial heat transfer at two-phase levels. The balance of plant models (turbine, containment and heat exchanger) developed at INEL were evaluated, adapted, and implemented into TRACB04 to provide complete transient analysis capability. In addition, a model for air or a noncondensible gas as an additional field in the system of equations was adapted to the two step numerical method and incorporated into TRACB04.

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