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ABSTRACT

A preliminary model of the Steam Sector Test Facility was developed using the TRAC-BD1 computer program. The model is to be used for prediction and analysis of the hydrodynamic interactions between spray coolant injected by the emergency core cooling systems and coolant flows through the reactor core during a postulated LOCA. The test facility and test program are briefly described. The philosophy and assumptions necessary to represent the facility as a model are described. Deficiencies in the present computer program and the model are also listed. A transient blowdown and a steady state calculation were performed to check out the capability of the model to represent the behavior of test hardware. The results are described. The results of the steady state calculation are also compared to results of a spray distribution test previously conducted in the facility. Conclusions and recommendations concerning model and program improvements are made.

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SUMMARY

The CCFL/Refill System Effects Test Program to be accomplished in the Steam Sector Test Facility (a 30^{o} sector representation of a BWR/6 reactor vessel) is to provide data concerning the interaction of injected emergency core cooling spray with reactor coolant flows during a postulated LOCA. A preliminary analytical model of the facility was developed using the TRAC-BD1 computer program. This model is to be used in future applications to determine how well analytical techniques can predict the data and aid in the interpretation of the data collected at the test facility. It is expected that improvements in the modeling techniques, better knowledge of model input parameters, and computer program improvements will significantly improve the present analytical capability.

Two calculations were performed with the model for checkout purposes. The first was a transient blowdown beginning from about 1.0 MPa. Arbitrary initial fluid conditions as well as steam injection rates were input (steam injection simulates vapor generated by decay heat and stored energy within the vessel). The results were reasonable and explainable for the conditions imposed. The second calculation was performed at steady state with the fluid conditions approximating those of a spray distribution test previously conducted in the facility. The calculated results corresponded well with the data.

Several weaknesses exist in the TRAC program that affect its capability to predict the hydrodynamic behavior. The program lacks a model representing the injected spray distribution within the upper plenum. Also, it is not possible to explicitly model individual bundles that have measurements of liquid mass flow rates used to determine the occurrence and location of countercurrent flow and the spray distribution.

It was concluded that the model is capable of calculating the hydrodynamic interaction between injected emergency core cooling spray and reactor coolant flows providing that an explicit analytical model representing the injected spray is incorporated into the TRAC program. Development of such a model is in progress.

1. INTRODUCTION

The CCFL (Counter Current Flow Limiting)/Refill System Effects Test Program jointly sponsored by General Electric Co. (GE), the Electric Power Research Institute (EPRI) and Nuclear Regulatory Commission (NRC) has the primary purpose of providing data concerning the interaction of injected ECC spray with the coolant in a BWR reactor during a postulated LOCA (loss of coolant accident). The test program is to be accomplished in the SSTF, (Steam Sector Test Facility) a 30^{o} sector representation of a BWR/6 reactor vessel containing a simulated unheated core with important features maintained at full scale. The test conditions are limited to the later stage of blowdown and the refill and reflooding phases of a LOCA. The effect of stored energy in the structure and core decay heat is simulated by steam injection. The data are to be used for assessment of analytical models developed to predict the thermal-hydraulic behavior of a BWR during a LOCA.

This report describes a preliminary version of a computer model[a] of the SSTF developed using the TRAC-BD1 computer program. The model presented is not a complete representation of the facility as some details of the hardware design were not yet finalized. Also flow resistances for important flow paths were not known but only estimated to provide necessary program input. This model and its successors will be used to predict the behavior of designated tests and to analyze the experimental phenomena and evaluate the capabilities of the TRAC computer program in calculating the spray-coolant interactions. The model presented is a lumped representation of the facility and thus does not provide calculations for direct comparison with all of the measurements. Comparison of results with data from shakedown tests is necessary to obtain actual flow resistances of important system components. Also, it is expected that modifications and improvements will be incorporated into the model as better ways of representing the facility are determined. Future developments in the computer program will also require modeling changes.

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a. The model is contained in file SSTF1 with ID = MAB on the CDC 176 computer at the INEL.

The existing model was used to perform two calculations to determine if the computer program was capable of making the required calculations and find errors in the geometrical data comprising the input. The first was a transient blowdown performed with all steam injection systems operating; the second was a steady state calculation with the configuration and initial conditions of a spray distribution test run previously in the facility. Neither calculation was intended to predict or analyze phenomena that are expected to occur in the present or past test programs because of the missing design details and a lack of information concerning specific initial conditions.

A description of the experimental facility may be found in Section 2. Section 3 contains a discussion of the model and assumptions made in its development. Section 4 contains the results for the two checkout calculations and a brief discussion comparing the steady state calculation with the spray distribution test results. Section 5 contains the conclusions and recommendations resulting from the study. References are in Section 6. Appendix A contains a figure identifying the model components and junctions.

2. EXPERIMENT DESCRIPTION[1]

The Steam Sector Test Facility is a 30° segment representation of a BWR/6 reactor vessel containing an unheated simulated core. Its capabilities are currently being extended to accommodate the CCFL/Refill System Effects Test Program. The purpose of the facility is to study the hydrodynamic interaction between the spray coolant injected by the emergency core cooling systems and coolant flows through the reactor core during a postulated LOCA. The effect of core decay heat and stored energy in the vessel structure is simulated by injecting steam into the system. The following sections briefly describe the objectives of the experimental program and the facility design.

2.1 Experimental Objectives and Program

The general objectives of the experiments planned for the CCFL/Refill Program are to provide data for (a) developing a better understanding of the hydrodynamic phenomena controlling the refill and reflood phase of a postulated LOCA, (b) developing and qualifying analytical models used to predict reactor behavior during a LOCA, and (c) assessing assumptions used in establishing BWR LOCA safety margins.

Previous separate effects programs using the facility have determined the spray distribution during a steady state operating mode as a function of several parameters. The current program will attempt to couple all of the identified hydrodynamic variables together in a transient situation simulating the latter part of blowdown and the refill and reflood phases.

A number of parameters will be varied during testing to determine their effect on the hydrodynamic interactions. They are listed as follows:

1. Vessel pressure,
2. Break size,
3. Injection rate of simulated core generated steam,

4. Radial distribution of core generated steam,
5. Injection rate of simulated guide tube, core bypass, and lower plenum generated steam,
6. Spray system combinations, flow rate and temperature,
7. BWR/6 and BWR/4 ECC (emergency core cooling) configurations, and
8. Fluid inventory and distribution in the vessel at test initiation.

The results of several items will be of particular interest. The occurrence and location of CCFL is important as this factor will greatly influence the time of core reflooding. CCFL is expected to occur at the side entry orifice and/or the fuel bundle upper tie plate depending on the test flow conditions. The spray drainage through the top guide into the core bypass region and the flow split of steam entering the upper plenum from the jet pump and core are additional important factors.

2.2 Facility Description

The SSTF test section is a 30° segment representation of the BWR/6-218 (624 bundle) reactor design (Figure 1). The upper plenum is a full-scale mockup of a 30° sector of the reference reactor design, with the geometric shape, shroud head curvature, and height accurately simulated. Standpipes simulating the steam separators extend upward from the shroud head. The upper and lower core spray spargers are also full-scale mockups of the HPCS (High Pressure Core Spray) and LPCS (Low Pressure Core Spray) spargers with regard to size, curvature, location and nozzles. The core region is full-scale in cross-section, but is approximately 5 feet shorter than the reactor due to support facility height limitations. Fifty-eight simulated fuel bundles are used in the 30° sector, including 42 complete bundles and 16 partial bundles which have removable cover plates and baffles to simulate the 30° boundary within the partial bundle.

The individual simulated fuel bundles utilize production hardware for channels, channel fasteners, spacers, upper tie plates, and lower tie plates. Upper fuel rod simulation includes production expansion

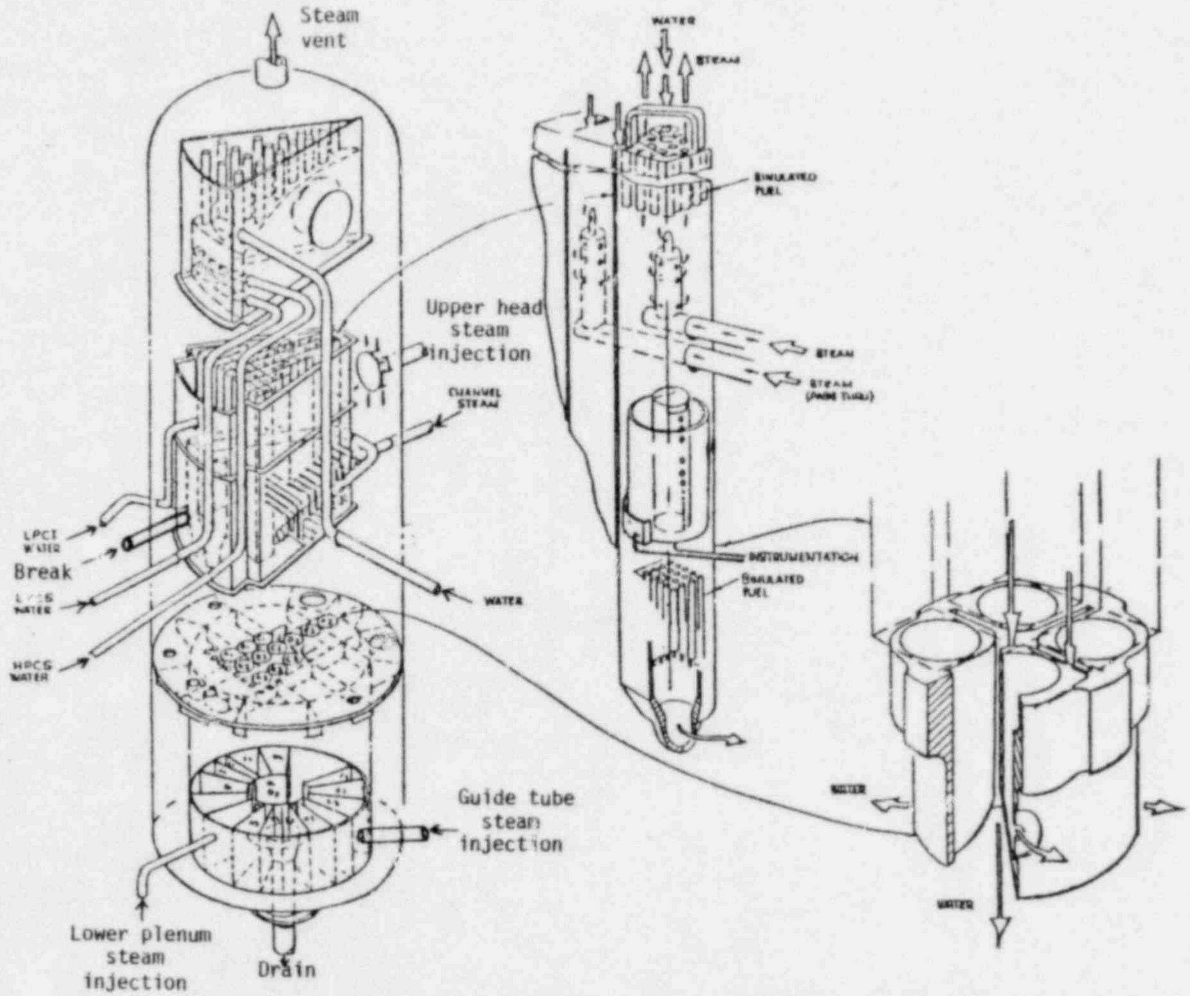

Figure 1. Steam sector test facility.

springs, end pins, locking tab washers, hexagon nuts, and one fuel rod spacer. A steam injector tube is provided in each bundle to deliver the channel steam from the distribution manifold outside the 30° sector wall. A weir tube measuring device for downward water flow is also provided in 6 selected bundles. The bypass region flow area between bundles is simulated and includes dummy control rods mounted on product hardware in conjunction with accurate representations of the top guide.

Twelve volume scaled guide tube regions are provided, one for each of the twelve centrally located side entry fuel supports. Steam is injected into each guide tube simulating the vapor generation within the guide tube and in the core bypass region. The lower plenum volume represents the scaled volume of the reference reactor lower plenum region outside the guide tubes, that is, four segments plus the center portion of the bottom tank which forms the major portion of the guide tube volume. The lower plenum volume above the jet pump discharge is also scaled. Steam simulating vapor generation within the lower plenum is injected into the lower plenum from a cross shaped sparger located horizontally within the bottom tank and below the jet pump discharge. The lower plenum and guide tubes are not contained within the sector but within a cylinder directly below the core support plate. The elevation of the jet pump inlet and outlet and the height of the steam separator above the shroud head in relation to the core height and the fuel support casting orifice location are matched to the reference reactor.

The test section has been designed with numerous instrument tap locations to derive quantities such as pressure, temperature, density, liquid levels, and flow rates. Transient programmed controls of the ECC injection rates, steam injection rates, steam superheat and for switching from steady state initial conditions to the transient are also provided.

3. MODEL DESCRIPTION

The following sections present a discussion of the computer program, the model, the computer program options selected and initial and boundary conditions.

3.1 Computer Program Description

TRAC-BD1 is a version of the TRAC family of computer programs developed to represent a BWR. Major differences between BD1 and other versions of TRAC are incorporation of components to represent the fuel rod bundles and jet pump and a two-fluid and critical flow hydrodynamics model. The program used in this report was TRAC-BD1 (INEL), MODA, Update 5 created on August 1, 1980. An additional update permitted the input of zero power into the CHAN component.

3.2 Model Basis and Nodalization

This section presents the basis for and a description of the model developed to represent the SSTF. The transient model consisted of 230 computational cells and the steady state model consisted of 237 cells.[a]

3.2.1 Model Basis

Several important areas of the experimental facility requiring modeling consideration are (a) the upper plenum where interaction between the injected spray and coolant exiting the core and the core bundles occurs, (b) the fuel rod bundles where measurements are made that will determine the spray distribution, the occurrence and location of CCFL, and refill/reflood of the core and (c) side wall effects on the spray distribution.

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a. A full scale BWR plant was modeled at INEL using the TRAC-BD1 computer program. For computational comparison this model has 164 computational cells.

The computer program is currently limited to a choice between two coordinate systems to represent the experiment, i.e., r, θ, Z coordinates (a right circular cylinder) or X, Z coordinates (a slab). Neither system permits explicit representation of the SSTF components as they actually exist.

The upper plenum is basically a sector of a circle (r, θ geometry), but has a dome shaped top difficult to represent with the Z coordinate. Nodalization of the upper plenum is necessary to compute any flow circulation patterns. The core is basically an array of rectangular blocks best represented by cartesian coordinates. A model of the core in r, θ coordinates would be difficult to formulate and it would also be difficult to relate the analytical results back to the measurements. Subdividing the core region is necessary to compare measured spray distributions with the calculations.

The necessity to compare measured spray distributions with the calculations outweighed the importance of modeling the upper plenum with r, θ coordinates, therefore, the X, Z coordinates (slab geometry) were selected to represent the test facility. The upper plenum can be adequately represented in the X, Z coordinate system, however, a transverse spray distribution cannot be calculated by the slab geometry. Incorporation of a cartesian (X, Y, Z) system within the TRAC program would be highly desirable to better calculate the distribution if the slab is found to be deficient.

The effect of the side walls of the sector on the radial spray distribution (average around sector midplane) has been determined to be limited to the center 0.5 m of the core section.[2] Nonuniform transverse distributions were also noted with either or both spray systems operating together. In the model described herein the effect of the side walls on spray distribution is treated by inputting the distributions as stated in Section 3.2.10. Incorporation of a spray model in the program (expected in 1981) will make the calculation of wall effects more important.

3.2.2 Vessel

Figure 2 is a cross section of the facility showing the annulus, jet pumps, fuel rod bundles and guide tube locations for the quadrant fuel support pieces. The cell structure for the slab geometry representation is also shown. The flow areas and volumes of the cells were adjusted to correspond to the portion of the facility encompassed by the cell. Seven cells represented the core and the eighth cell represented the annulus. The first 6 cells were two bundles wide and corresponded to the rows of quadrant fuel support pieces. The seventh cell contained the peripheral bundles. The cells were eight bundles thick corresponding to the number of bundles in cell 7. This thickness was fixed for all cells.

Figure 3 shows the axial levels selected to represent the vessel and the locations of the components necessary to complete the model. Guide tubes were located in cells 1 through 6 in the lower plenum. Standpipes were located in cells 1 through 7.

Level 3 corresponded to the top of the cylindrical tank (see Figure 1) divided into segments which simulated the guide tube volume. Levels 2 and 3 provide a finer axial node spacing around the jet pump extension to better determine the time when the end becomes covered, stopping steam flow from the lower plenum to the upper plenum through the jet pump.

The remaining levels were selected as follows. The top of level 4 corresponded to the top of the core support plate. It corresponded to the volume above the cylindrical tank from which flow can enter the rod bundles through the side entry orifices. Level 5 was located at the bottom of the break piping and permits liquid accumulation in the bottom of the annulus. Level 6 located the top of the jet pump. The top of the top guide and core was fixed by Level 7.

Level 8 was located at the axial midplane of the HPCS piping. Level 9 corresponded to the elevation in the upper plenum where the curved dome

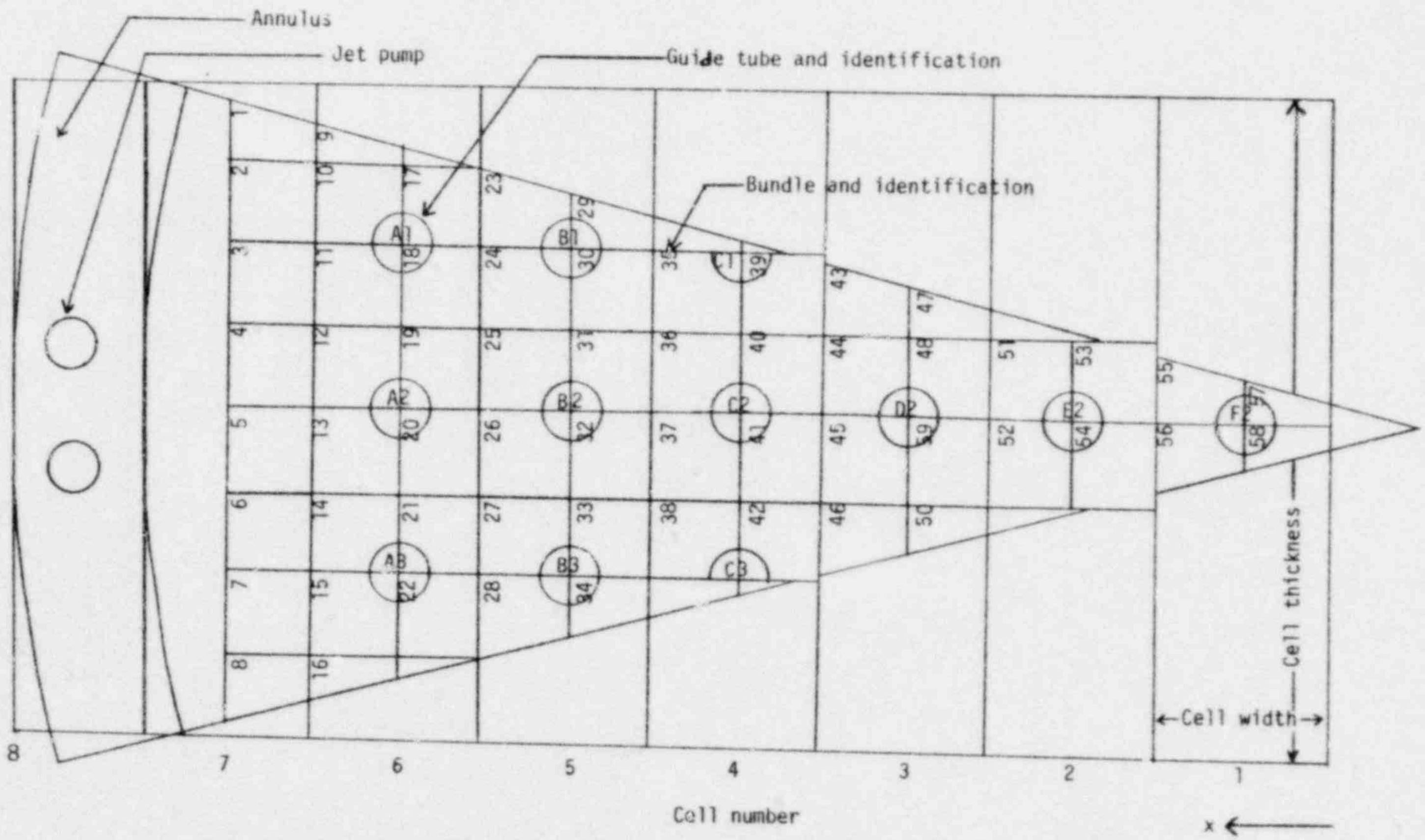

Figure 2. Cross section of model and test facility showing bundles, guide tubes, jet pumps and slab noding.

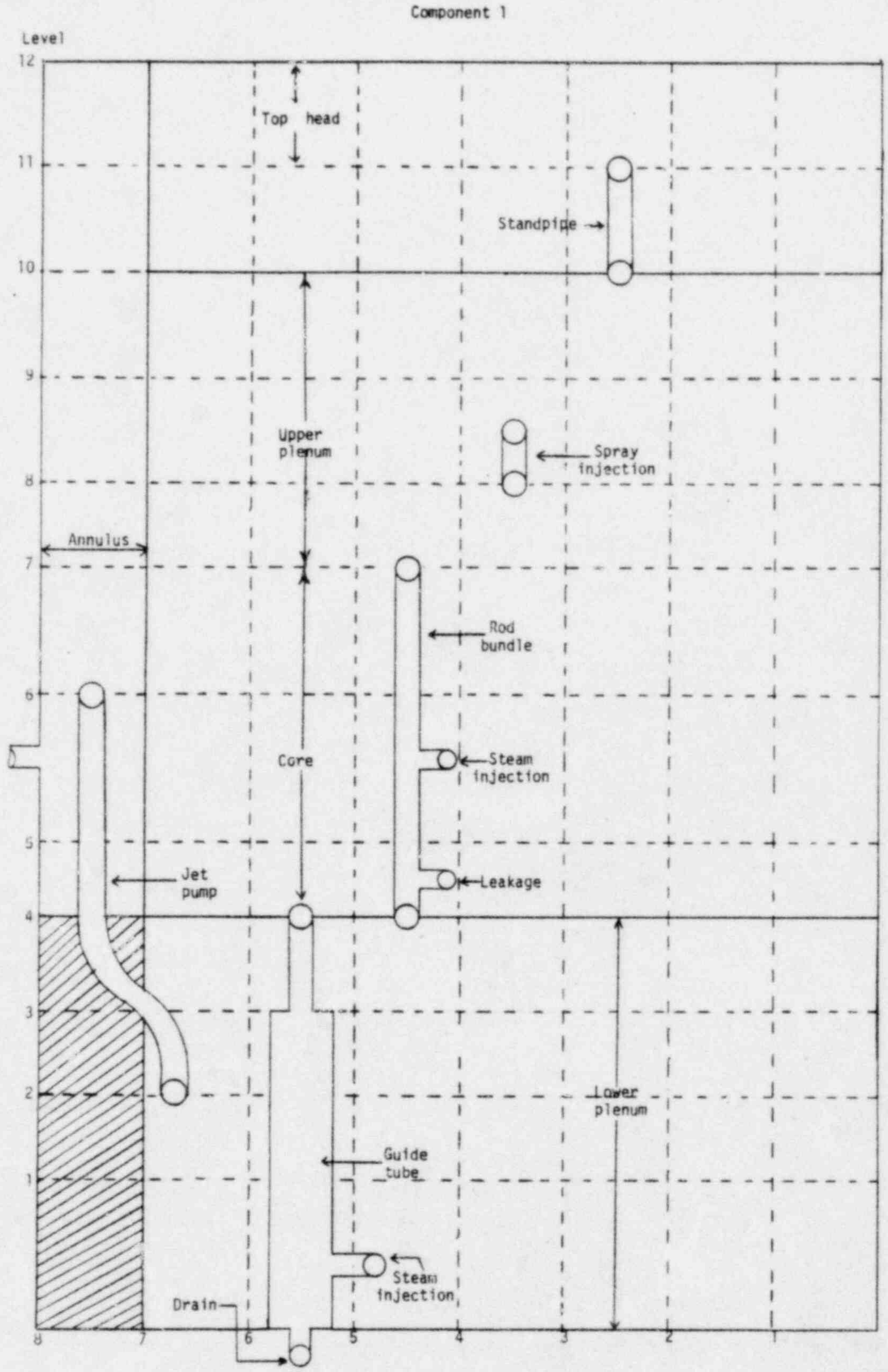

Figure 3. Vessel nodalization showing location of components.

begins and Level 10 located the top of the upper plenum. The top of the standpipes was located by Level 11 and the top elevation of the steam dome in the top head was fixed by Level 12.

3.2.3 Lower Plenum

The lower plenum consisted of the volume in the cylinder under the core excluding the guide tubes. The volume was distributed among cells 1 through 7 in proportion to the volume of the sector falling within the model cell. The lateral flow area connecting the cells was restricted in levels 1 and 2 corresponding to flow path through the tank connecting the segments forming the lower plenum volume. One PIPE and FILL injected the steam representing the vapor generated within the lower plenum. The PIPE was connected to the side of cell 4.

3.2.4 Guide Tubes

The facility guide tubes in the A, B and C rows were lumped into one equivalent tube in the model. The guide tubes consisted of TEE components. The secondary side of the TEE was provided for steam injection representing the vapor generated in the guide tube and in the core bypass region. (No steam was injected into the bypass). This steam has a flow path through the bypass region to the upper plenum. The lower end connection of the guide tube TEE can be connected to a BREAK when draining of the collected liquid is necessary to simulate a separate effects type test or to a zero velocity FILL for transient simulation.

3.2.5 Fuel Rod Bundles

The bundles within a cell were lumped together and represented by a TEE and CHAN connected in series. The TRAC-BD1 CHAN component has been developed to represent a fuel rod bundle of a BWR. However, it has no provision for supplying fluid through the channel wall as required by the SSTF design which supplies steam to each individual fuel rod bundle. The fuel rod bundle flow area, flow resistance and the heat transfer from the channel to the bypass fluid can be represented by the TEE; however rod heat transfer cannot be included. As the SSTF rods are unheated the loss in heat transfer capability does not seem important. The CHAN component represented that section of the bundle below the steam injection point and provided for the leakage path from the bundle to the bypass channel. The resistance and flow area used for the leakage path was determined from a TRAC-BD1 model of a BWR/6 and was scaled to the number of bundles represented by the CHAN component per VESSEL cell. The leakage hole in the CHAN represented all flow paths between the bundle and the core bypass. An update to the TRAC-BD1 computer program was used to allow zero power in the CHAN component. Initially the lower section of the bundle was modeled by a TEE, however computation could not be achieved even after several modifications to the component noding. Thus the CHAN component was modified to provide zero power and substituted. The bundles were slightly shortened so the tie plate elevation corresponded to the top guide and the side entry orifices to the elevation of the core support plate.

3.2.6 Core Bypass Region

The core bypass region was a lumped volume in each cell. The volume in cells 1 through 6 was connected to the guide tube at the core support plate, the upper plenum through the flow area restriction representing the top guide, the leakage path from the bundle within the cell and adjacent cell bypass volumes. It was not connected to the lower plenum. That is, the leakage flow paths formed by the actual hardware connections were not modeled. It was divided into three levels as a consequence of locating the jet pump entrance and recirculation line with the simulated break.

3.2.7 Jet Pumps

The two inactive jet pumps were represented by a single PIPE component.

3.2.8 Standpipes

The standpipes were lumped together by cell with one in cells 1 and 2, two in cell 3, three in cells 5 and 7 and four in cells 4 and 6. The length of the PIPE component representing the standpipes corresponded to the average of the standpipes lumped into each cell.

3.2.9 Spray Model

An explicit spray distribution representation is currently not available in the TRAC computer program. Spray injection was limited to treatment by means of a PIPE and FILL connected to a vessel cell. Location of the PIPE junction at the radial edge of the upper plenum would likely result in preferential flow through a single cell, i.e., cell 1, instead of a distribution because of the radial momentum factor. To obtain a distribution across the core, it was necessary to include a vertical FILL at the top of each cell above the core at level 8. The distribution was thus specified as an input. The spray junction flow area was made sufficiently large so the downward velocity of the entering spray was about 0.2 m/s.

3.2.10 Break

A BREAK component simulating the break plane of the nozzle was attached to a PIPE component to form the break. Special noding of the PIPE was not necessary as the mass flow rate is determined by a correlation.

3.3 Computer Program Options

Few options exist within the program. The friction factor correlation selected for components other than for the vessel proper was for annular flow (NFF = 4). The water packing option was not used (IPAK = 0).

3.4 Initial and Boundary Conditions

This section describes the initial and boundary conditions used in the two calculations. As stated before, neither calculation was intended to predict or analyze phenomena that are expected to occur in the present or past test programs, but rather they were made for checkout purposes. Some inconsistency may be imbedded in the initial conditions. Future calculations can guard against this potential condition by using the results from a TRAC-BD1 BWR-6 model developed by EG&G to identify and resolve any such inconsistency when performing double blind calculations. Table 1 presents the initial and boundary conditions for the two calculations. The mass flows presented in the table are total mass flow rates for each particular place of injection. Table 2 is a breakdown of the individual mass flow rates injected per VESSEL cell or component within the cell. This distribution was based upon the literature of Reference 2. All system drains were closed for both calculations. The steam vent was open for the steady state calculation and closed for the transient calculation.

3.5 Model Deficiencies

Deficiencies in the current model are listed as obvious TRAC computer program deficiencies and geometrical data lacking at the time the model was assembled.

3.5.1 TRAC Computer Program Deficiencies

Major program deficiencies noted are:

1. Spray injection model or correlation to represent the spray, and

2. A cartesian coordinate system to represent the fuel rod bundles.

TABLE 1. INITIAL AND BOUNDARY CONDITIONS FOR SSTF CHECKOUT CALCULATIONS

Parameter	Transient	Steady State
Initial system pressure (MPa)	1.034	0.203
Steam temperature (K)	454.0	410.4
ECC spray temperature (K)	308.3	335.78
Break Pressure[a] (MPa)	0.0965	0.203
Lower plenum steam injection (kg/s)	3.050	0.0
Guide tube steam injection (kg/s)	3.240	0.0
Core steam injection (kg/s)	4.448	1.719
Upper head steam injection (kg/s)	0.0	1.721
ECC spray injection (kg/s)	65.681[b]	32.829

a. In the steady state calculation there was no break. The break pressure for the steady state is a boundary condition imposed at the steam vent to maintain a constant system pressure.

b. Represents two ECC spray headers (LPCI and HPCI).

TABLE 2. DISTRIBUTION OF STEAM AND ECC INJECTION FLOWS FOR CHECKOUT CALCULATIONS

Injection Source	Calculation	Cell 7	Cell 6	Cell 5	Cell 4	Cell 3	Cell 2	Cell 1
Lower Plenum Steam Injection (kg/s)	Transient	0.0	0.0	3.0507	0.0	0.0	0.0	0.0
	Steady State	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Guide Tube Steam Injection (kg/s)	Transient	--	0.884	0.884	0.589	0.294	0.294	0.294
	Steady State	--	0.0	0.0	0.0	0.0	0.0	0.0
Core Steam Injection (kg/s)	Transient	0.438	1.072	1.005	0.759	0.617	0.376	0.181
	Steady State	0.169	0.414	0.388	0.293	0.238	0.145	0.070
Upper Head Steam Injection (kg/s)	Transient	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Steady State	0.0	0.0	1.7219	0.0	0.0	0.0	0.0
ECC Spray Injection (kg/s)	Transient	20.437	14.23	11.683	7.686	7.454	2.720	1.470
	Steady State	10.215	7.112	5.839	3.841	3.725	1.359	0.734

3.5.2 Unavailable Geometrical Data

The following data were missing, therefore assumptions were made to provide the necesary input:

1. Flow area, path length and/or flow resistance of leakage holes in fuel support casting,

2. Fuel rod bundle tie plate flow area, hydraulic diameter, and/or flow resistance,

3. Break piping design,

4. Steam injection piping design in lower plenum, and

5. Top steam dome volume and bellows location.

4. CALCULATION RESULTS

Two calculations were made with the model to check out the program input and to determine if the network representation developed was practical and would yield reasonable results. A transient blowdown calculation was made first with all steam and spray injections operating as they would during simulation of a postulated LOCA. The second calculation more closely approximated a spray distribution test previously conducted in the facility.

4.1 Transient Calculation

The specific initial conditions selected for the calculation were described in Section 3.4. The initial fluid inventory and steam injection rates do not represent specific test conditions but were abitrarily selected to fall within the range of the parameters to be varied during actual testing.

The calculation was executed to approximately 38 seconds at which time the lower plenum pressure and break mass flow rate (Figures 4 and 5) achieved near constant values. A pressure of 0.25 MPa indicated that too much steam was being injected into the system preventing further decompression. The first 20 seconds were transient in nature with the remainder of the calculation being of a quasi-steady state nature. Throughout the calculation the parameters of liquid and vapor velocities and void fractions were highly oscillatory indicating system instability, perhaps partially because of the multiple parallel flow paths. Incorrect modeling of components which are controlling flow resistance, i.e., bundle tie plates, leakage hole, and top guide, and unmatched initial conditions were likely additional causes. Before making predictions of transient test behavior, the flow resistances within the system should be verified by checking the model output against shakedown test data (to be available at a future date). The oscillations were generally not coincident in magnitude or frequency except in the jet pump and lower plenum directly below. This behavior is illustrated and explained later.

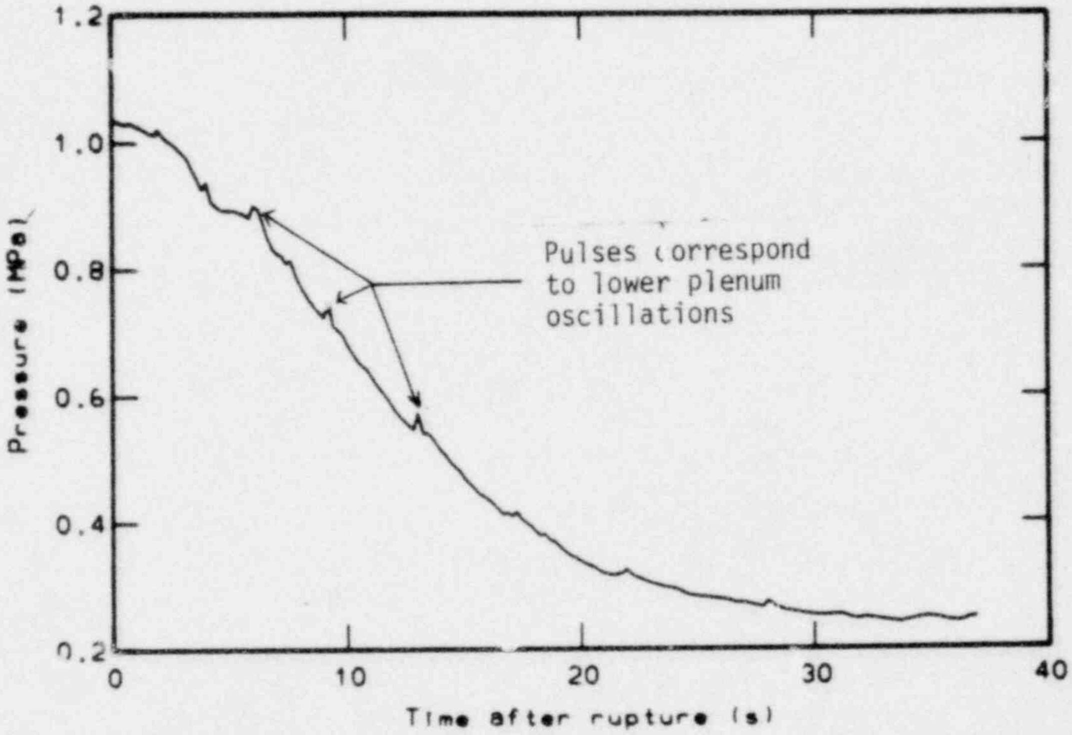

Figure 4. Lower plenum pressure versus time during the transient calculation.

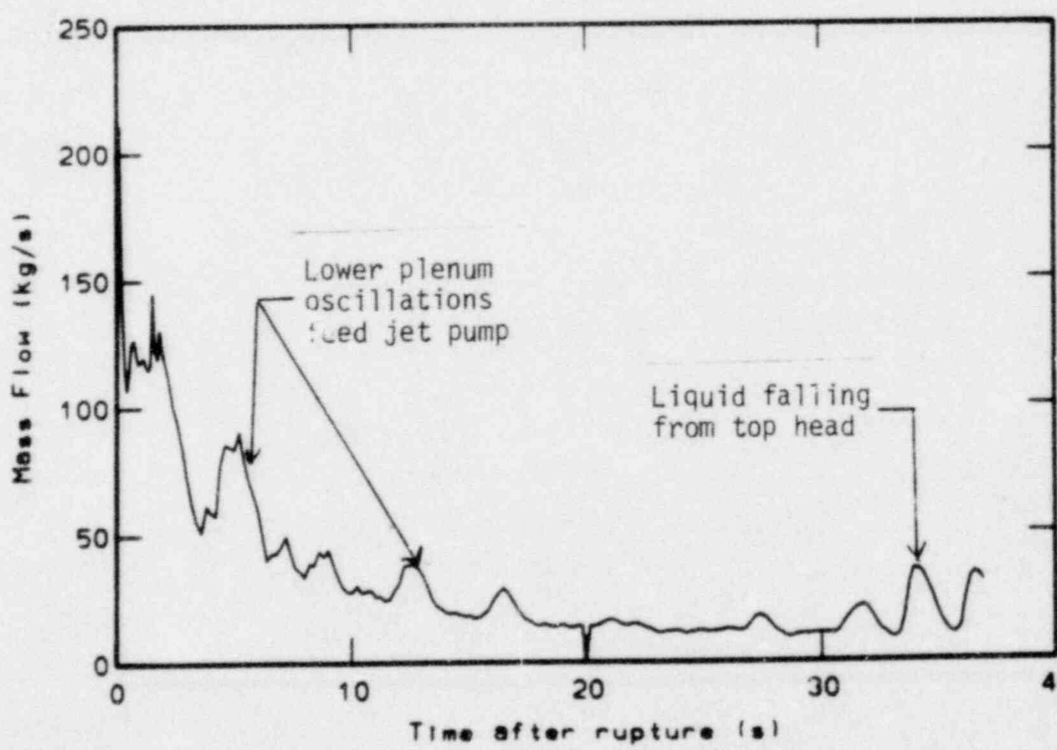

Figure 5. Break mass flow rate versus time during the transient calculation.

A number of observations were drawn from a study of the system hydraulic behavior. These are briefly presented below and may be helpful in future analysis of the model predictions. The liquid spray entering vessel level 8 in the upper plenum (levels 8, 9 and 10) accumulated in level 8 until a void fraction of 0.75 was attained. (A void fraction of 0.75 is a boundary for a transition in flow mechanism and interfacial friction from dropwise annular to slug flow. The transition has been smoothed in later computer program versions.) Then liquid was carried up into level 9. With level 9 reaching the same value of void fraction, liquid was again carried up into level 10. As level 10 reached a void fraction near 0.75 liquid was carried up through the standpipes and settled in level 11 on top of the upper phenum shroud surrounding the standpipes. This behavior is illustrated in Figures 6 through 8 which show the time dependent void fraction in cells 1 and 7 for the three levels and Figure 9 for the standpipes located in the same cells. Cell 1 was at the apex of the sector and cell 7 was at the outside edge of the core. Cell 7 collected more liquid than cells 1 through 6 which more closely approximated behavior shown for cell 1. The upper plenum continued to collect liquid from the spray with the additional storage occurring in level 11 until near 30 s when level 10 began filling and then at 32 s when the sector apex of level 8 began filling.

At the interface between the core bypass region and the upper plenum, vapor continuously entered the upper plenum. Liquid in the upper plenum penetrated into the bypass region for only short time periods in the cells located in the sector apex. This is illustrated in Figures 10 through 13 which show the liquid and vapor velocity at the top guide for cells 1 and 7. Liquid first penetrated in cell 1 when the vapor velocity dropped below 5 m/s at about 4.5 s shortly after the void fraction of the cell above (level 8) decreased to 0.75. Thereafter liquid penetrated into the bypass region several times when the upward vapor velocity decreased to 2 or 3 m/s. In cell 7 the vapor velocity was always larger than 5 m/s and no liquid penetration was calculated. Cells 2 and 3 also showed some penetration while cells 4, 5 and 6 did not show penetration until the end of the calculation.

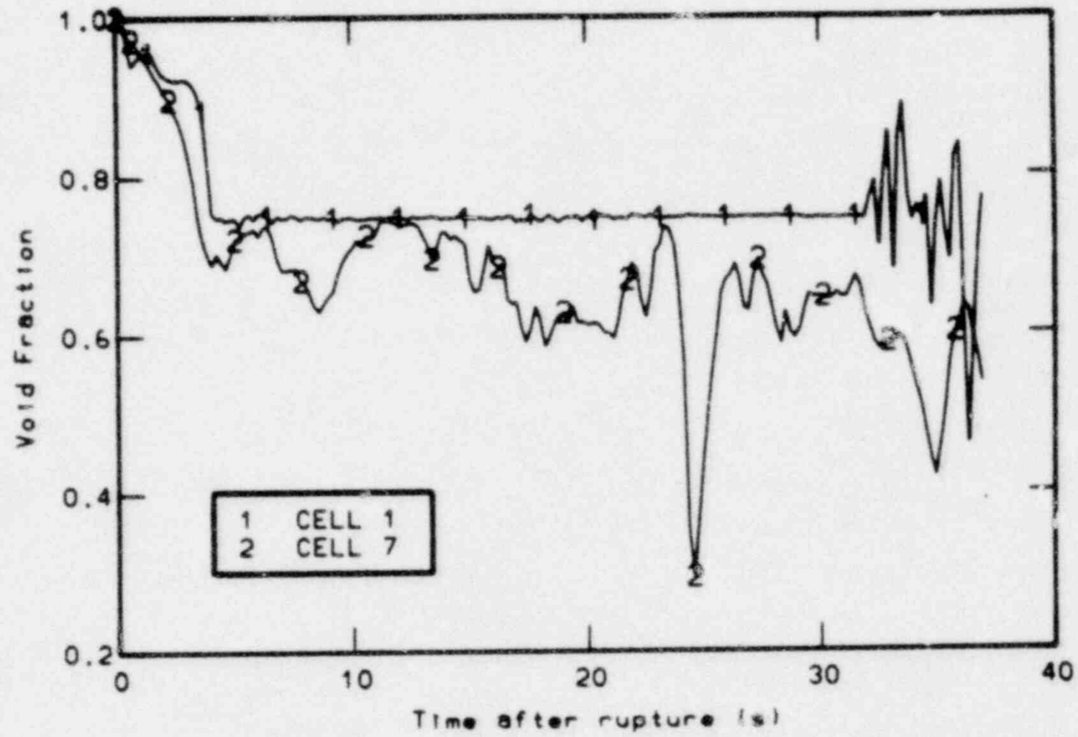

Figure 6. Void fraction versus time for cells 1 and 7 of upper plenum level 8 during the transient calculation.

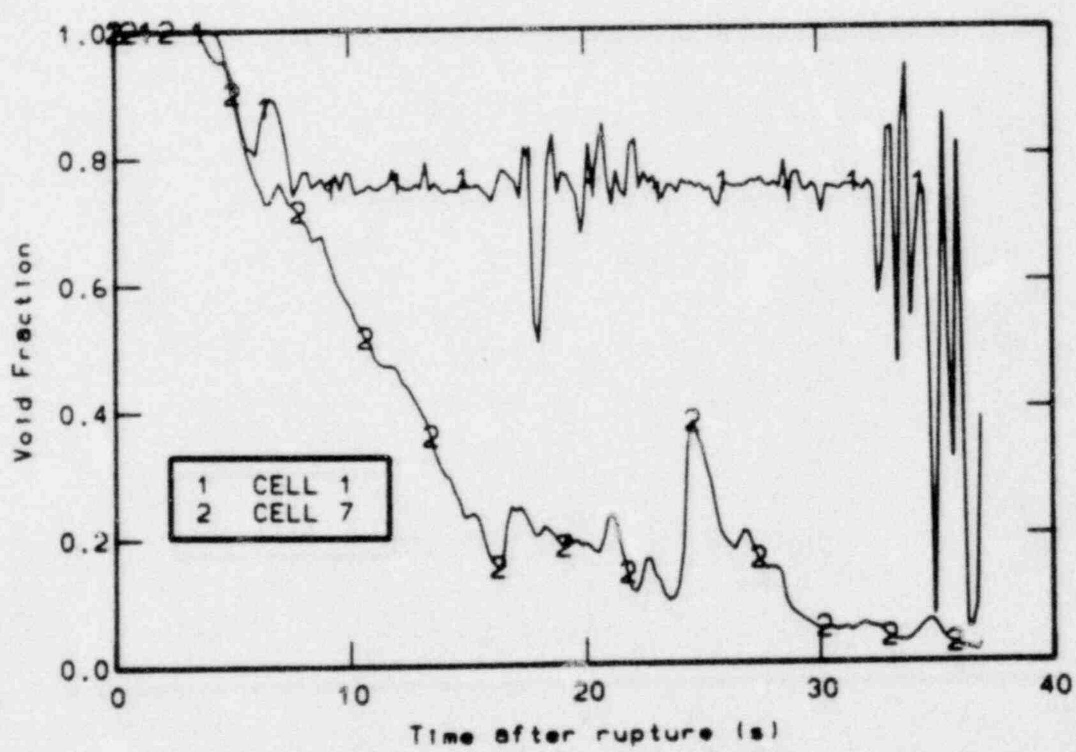

Figure 7. Void fraction versus time for cells 1 and 7 of upper plenum level 9 during the transient calculation.

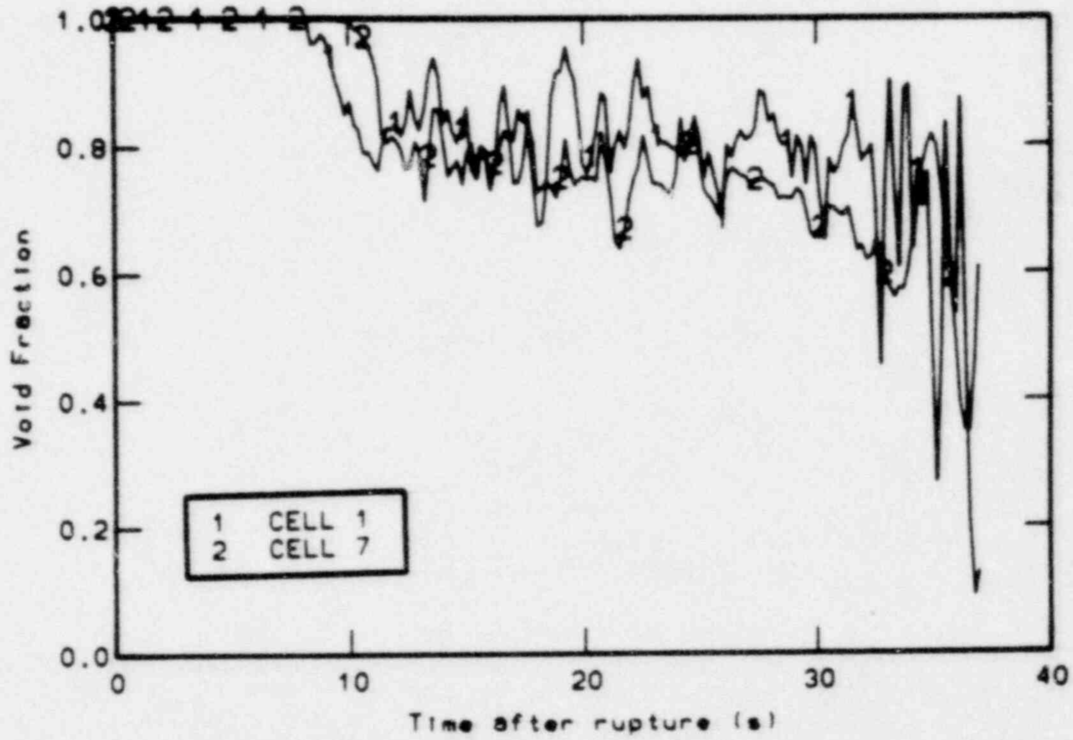

Figure 8. Void fraction versus time for cells 1 and 7 of upper plenum level 10 during the transient calculation.

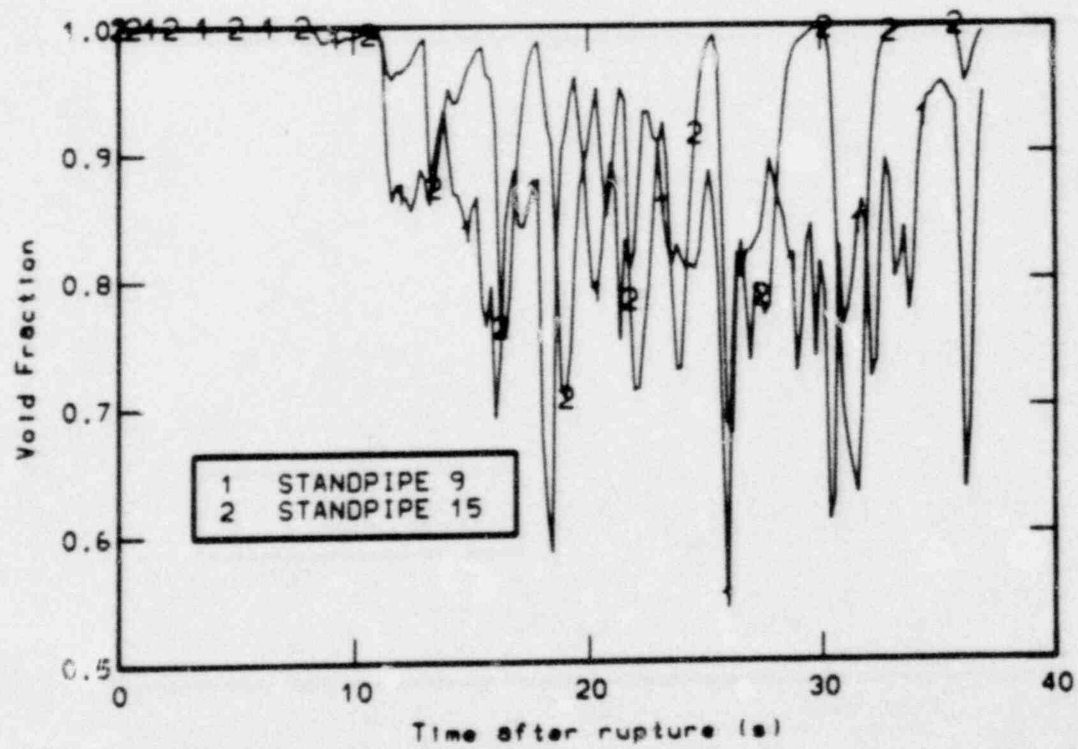

Figure 9. Void fraction versus time for the stand pipes located in cells 1 and 7 (components 9 and 15 during the transient calculations.

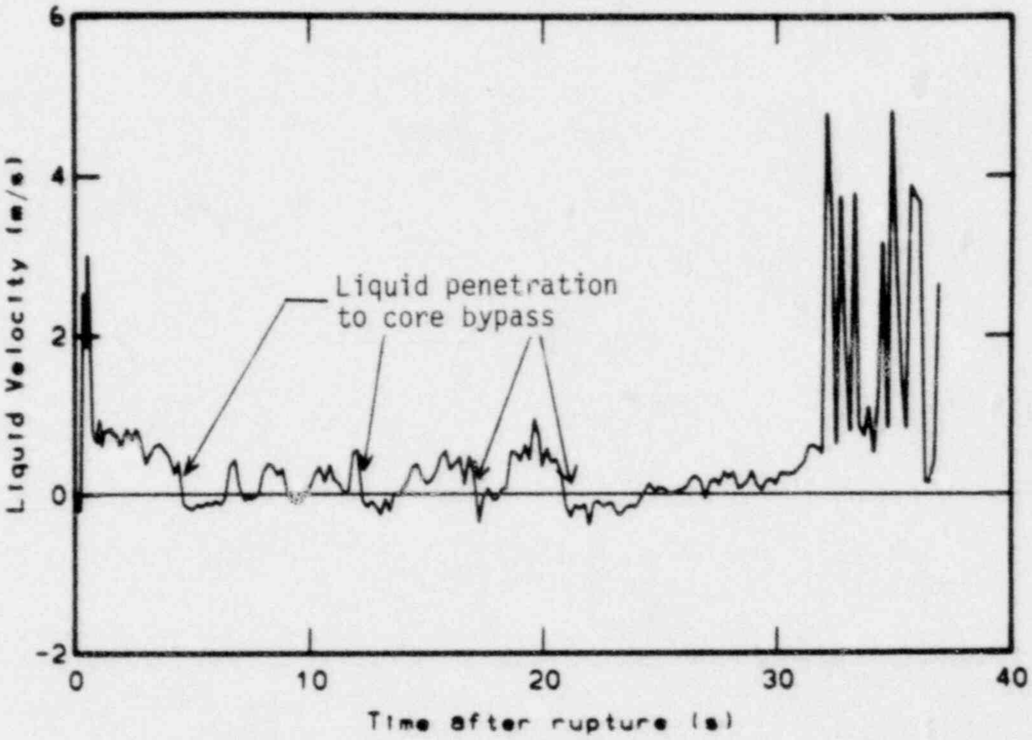

Figure 10. Liquid velocity versus time at the upper plenum-core bypass interface in cell 1 during the transient calculation.

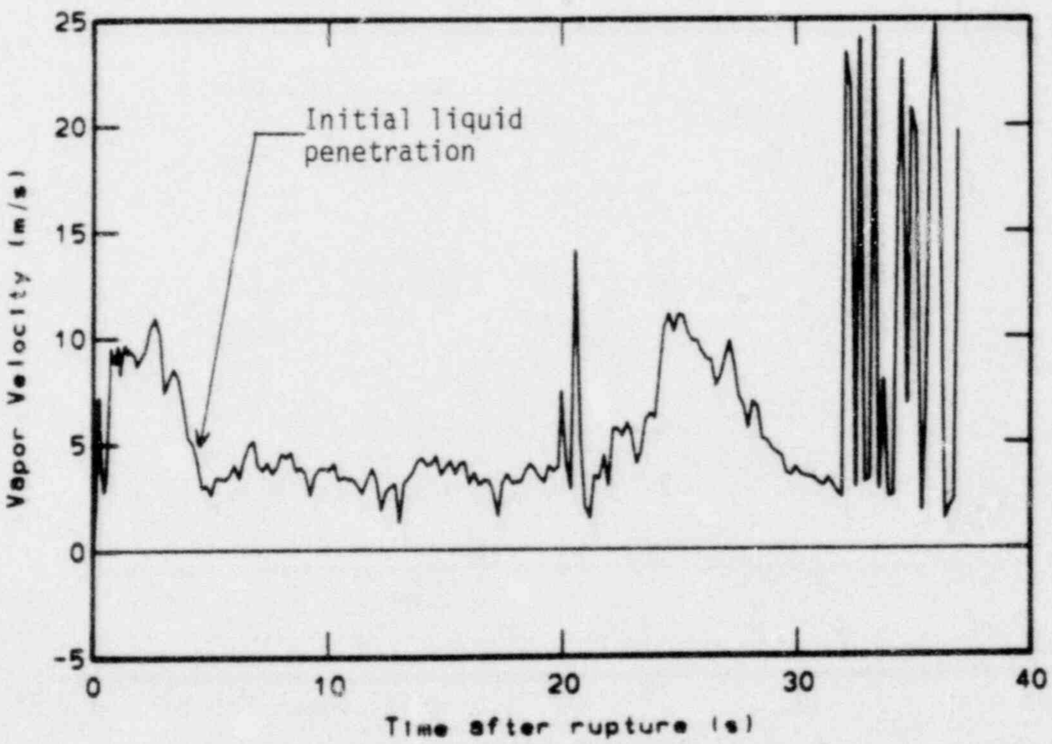

Figure 11. Vapor velocity versus time at the upper plenum-core bypass interface in cell 1 during the transient calculation.

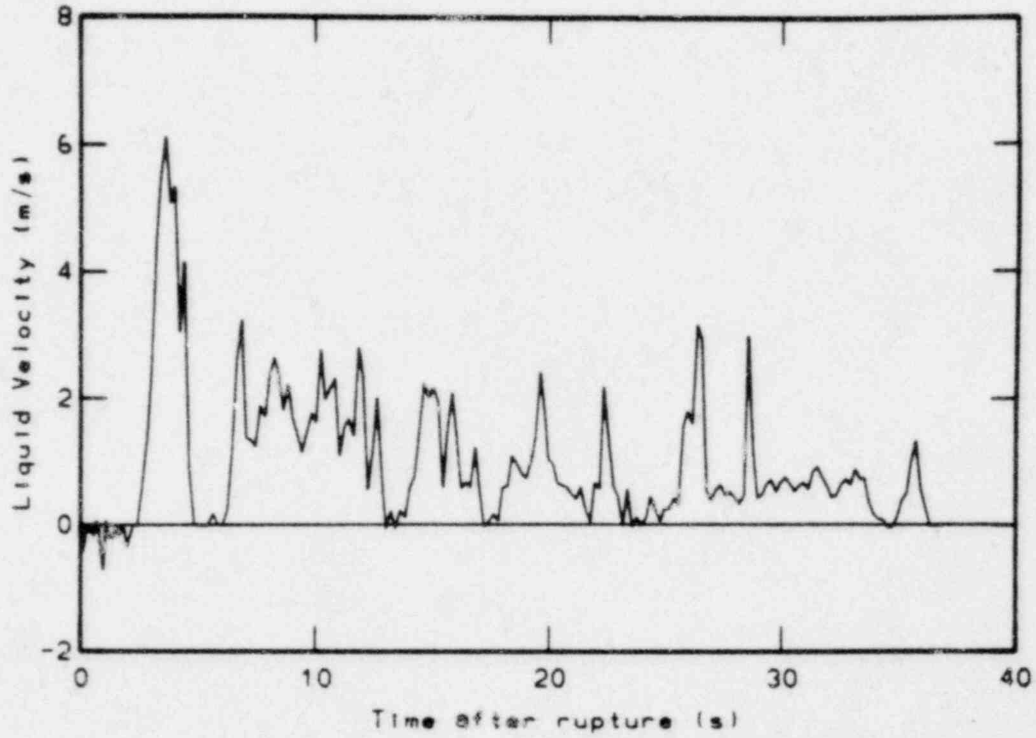

Figure 12. Liquid velocity versus time at the upper plenum-core bypass interface in cell 7 during the transient calculation.

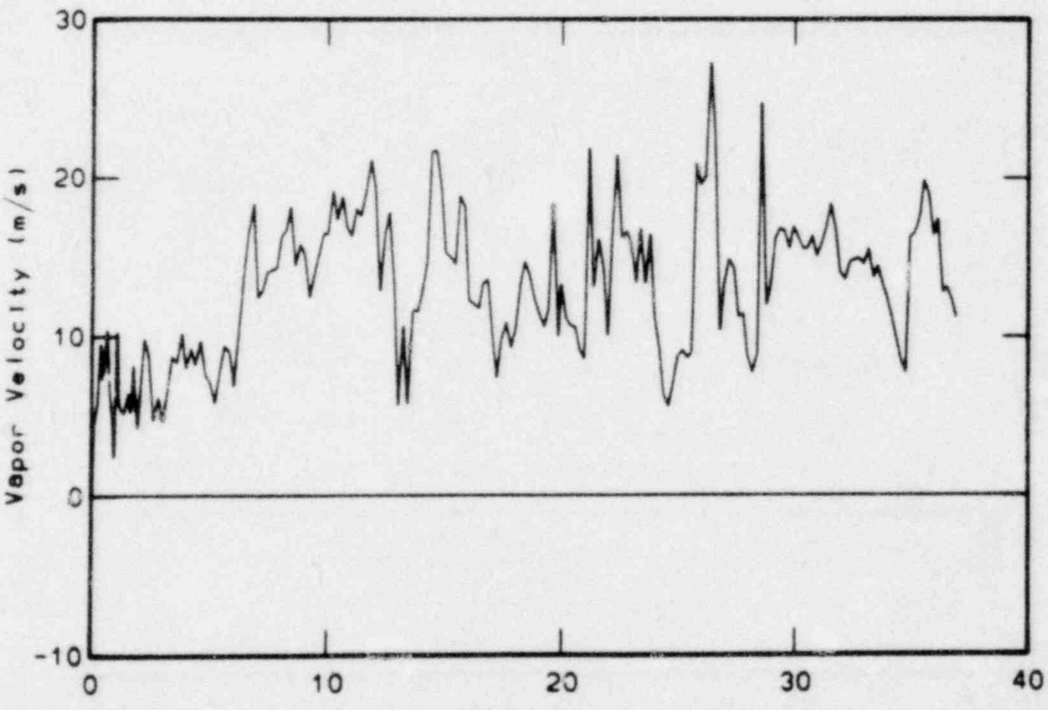

Figure 13. Vapor velocity versus time at the upper plenum-core bypass interface in cell 7 during the transient calculation.

At the top tie plate of the fuel rod bundles liquid penetration was calculated to occur in the bundles of cells 5, 6 and 7 throughout the transient except for sharply peaked flow reversals. The flow reversals did not seem to correspond with large upward vapor velocities and may have been an indication of numerical instabilities. Cells 2, 3 and 4 indicated penetration after 20 s when the upward vapor velocities decreased in magnitude. Cell 1 did not indicate penetration until about 34 s when the vapor velocity decreased to about 5 m/s. Figures 14 through 17 show the liquid and vapor velocities at the bundle tie plates located in cells 1 and 7.

Steam injected into the rod bundles traveled upward into the upper plenum if no penetration had occurred at the bundle upper tie plate or downward into the lower plenum if penetration had occurred. For the bundles in cell 1, all the injected steam flowed to the upper plenum until about 34 s. For the bundles in cells 2, 3 and 4 the flow was upward until near 20 s when liquid penetration occurred. For the bundles in cells 5, 6 and 7 the flow early in the transient split with a significant fraction exiting the bundle through the side entry orifice to the lower plenum. Flow through the bundle leakage flow path was always into the bundle from the bypass region. (This behavior was noted in the TRAC system model of a BWR-6 during steady state as well as during the blowdown).

The vapor velocity at the side entry orifice is shown for the bundles of cells 1 and 7 in Figures 18 and 19. The vapor entering the bundles of cell 7 was furnished by the lower plenum steam injection.

Examination of the lower plenum indicated significant oscillations in velocity and void fraction. Cell 7 of level 1 showed a smooth periodic behavior in void fraction throughout most of the transient as shown in Figure 20. Behavior was more random in cells further removed from the one illustrated. Cell 7 of level 1 was the closest cell to the jet pump that was initially full of saturated water. Examination of the liquid and vapor temperatures of the cell indicated that as the cell depressurized the

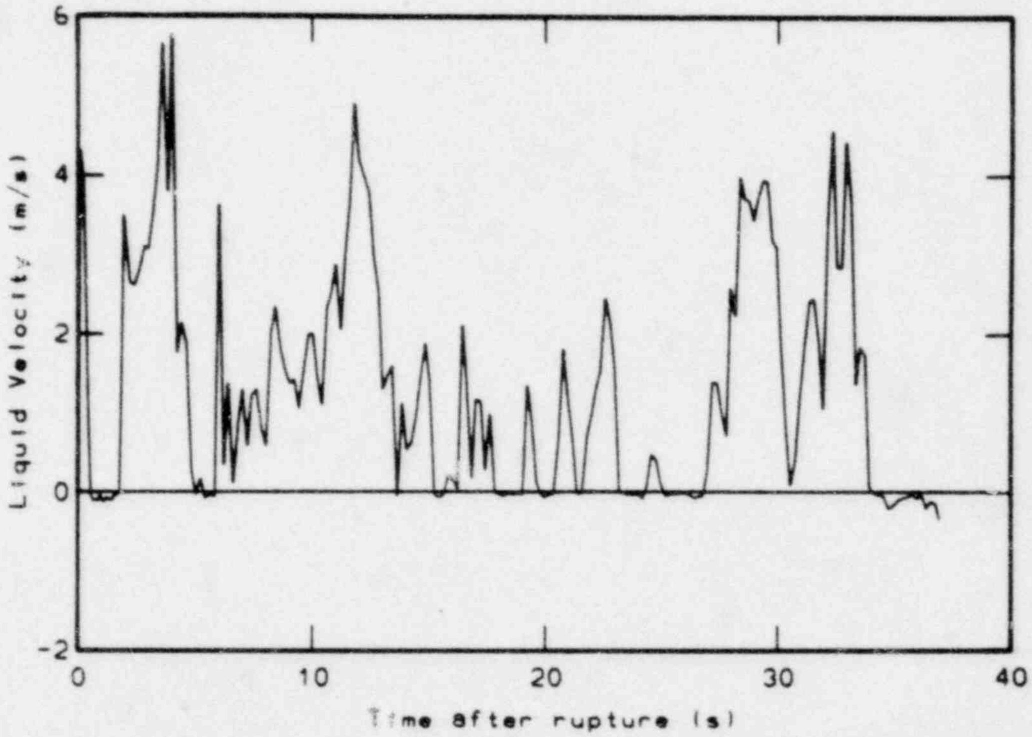

Figure 14. Liquid velocity versus time at the upper tie plate of the fuel rod bundle in cell 1 (component 23) during the transient calculation.

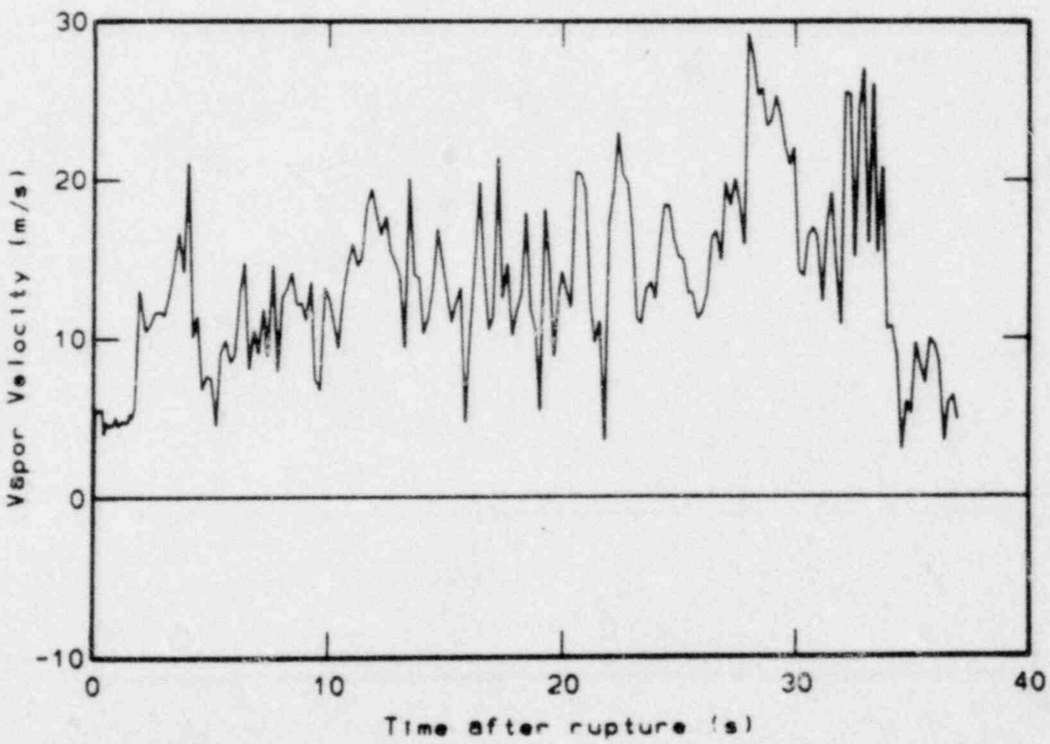

Figure 15. Vapor velocity versus time at the upper tie plate of the fuel rod bundle in cell 1 (component 23) during the transient calculation.

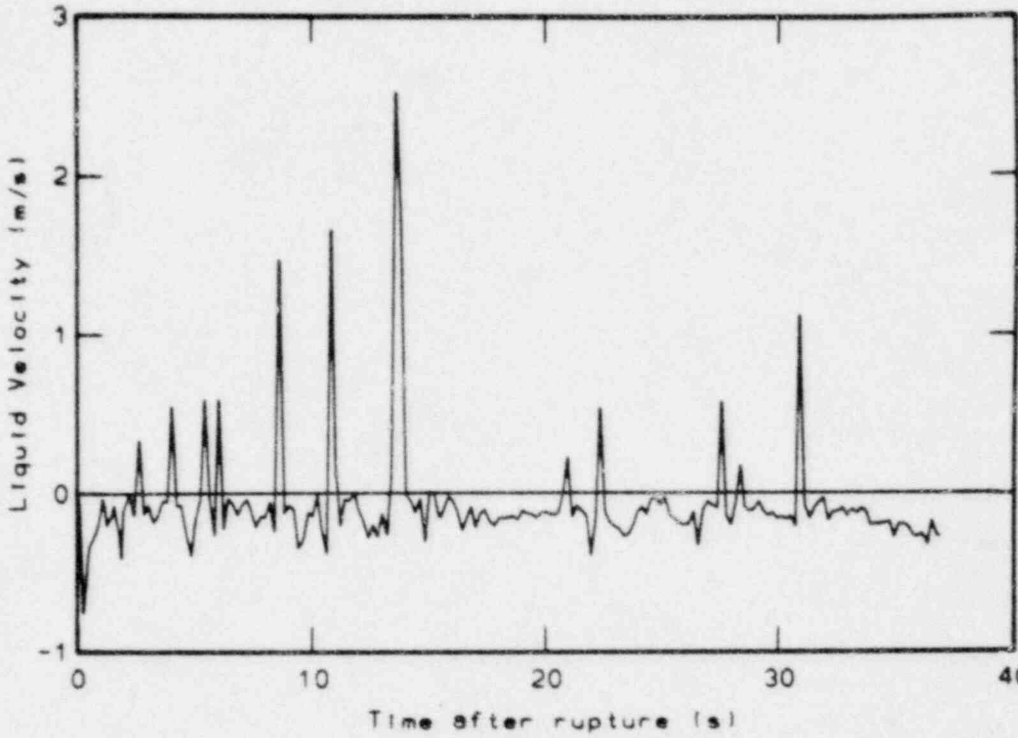

Figure 16. Liquid velocity versus time at the upper tie plate of the fuel rod bundle in cell 7 (component 29) during the transient calculation.

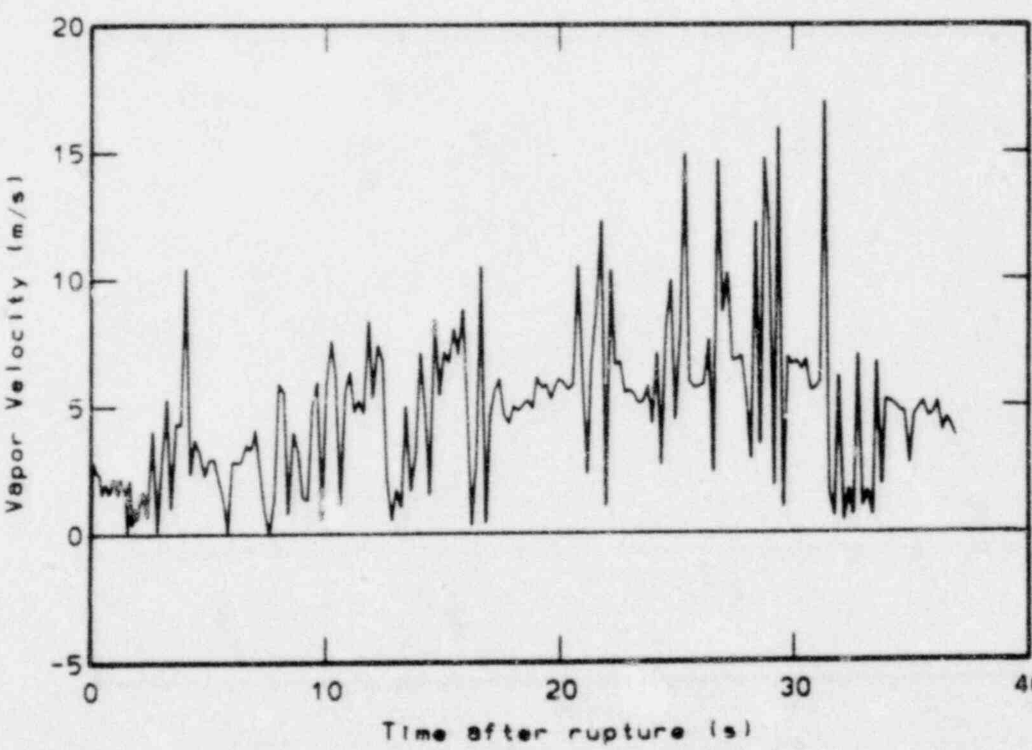

Figure 17. Vapor velocity versus time at the upper tie plate of the fuel rod bundle in cell 7 (component 29) during the transient calculation.

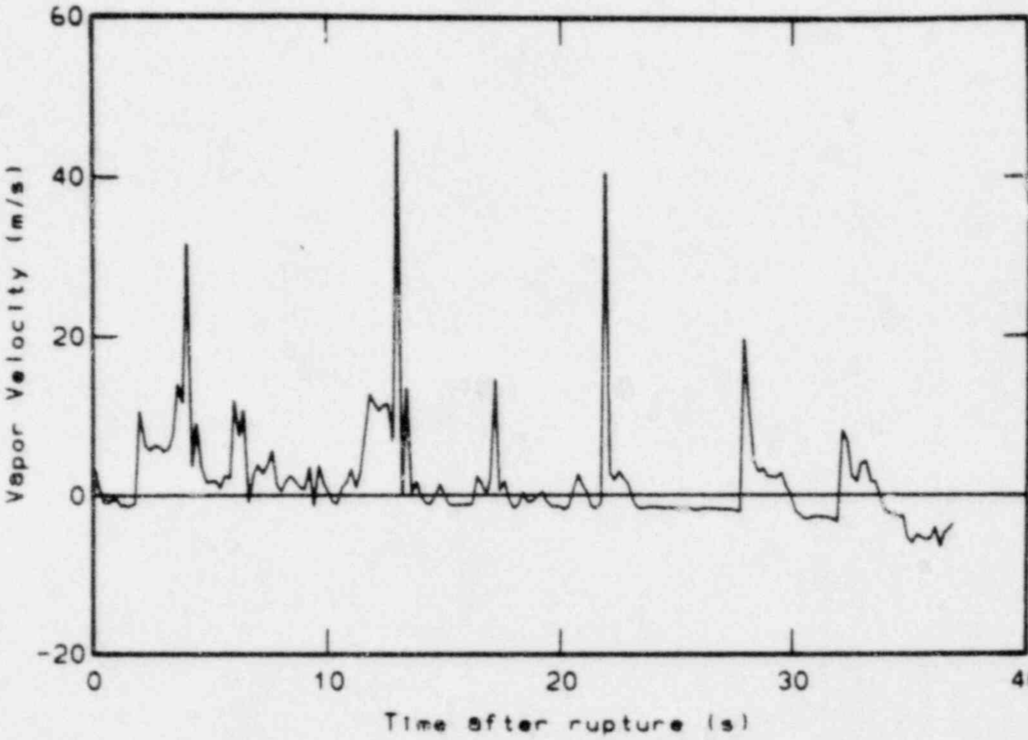

Figure 18. Vapor velocity versus time at the side entry orifice of the fuel rod bundle in cell 1 (component 16) during the transient calculation.

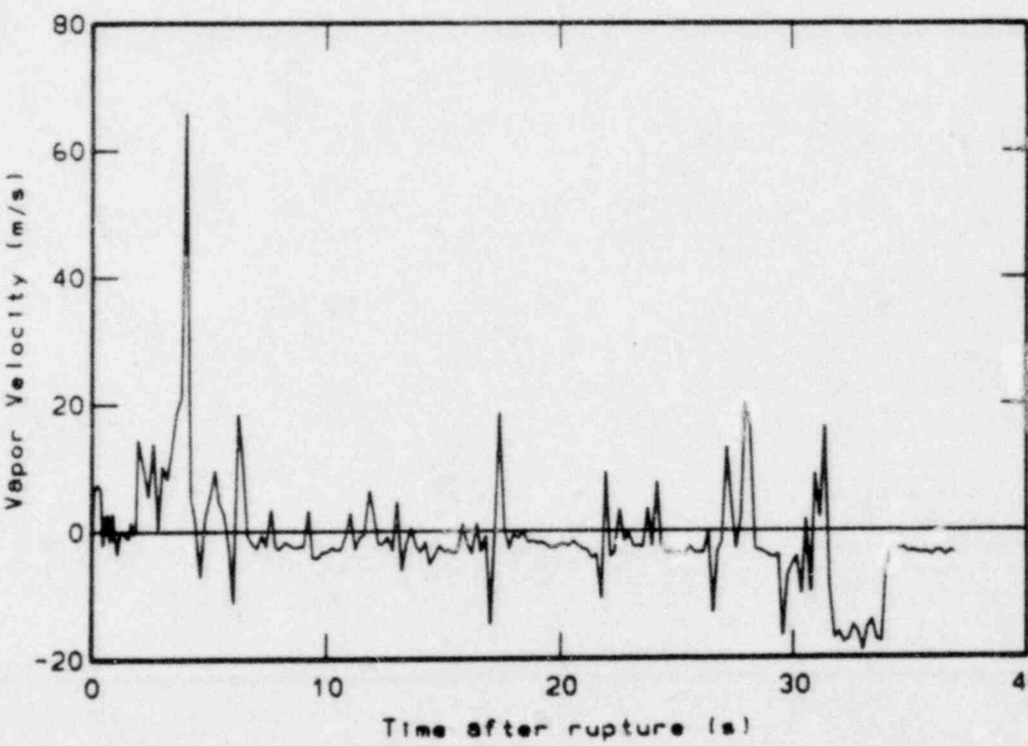

Figure 19. Vapor velocity versus time at the side entry orifice of the fuel rod bundle in cell 7 (component 22) during the transient calculation.

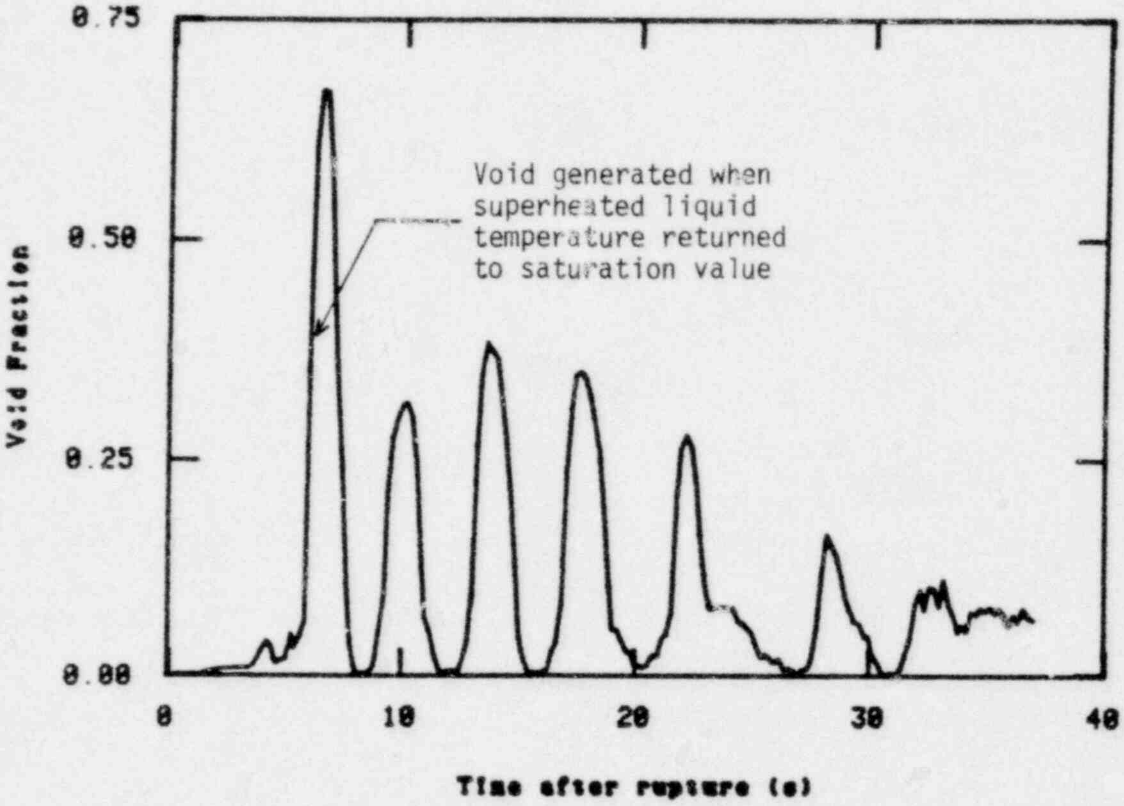

Figure 20. Void fraction versus time in cell 7 of lower plenum level 1 during the transient calculation.

liquid temperature remained nearly constant (except for the first deviation between the two temperatures) while the vapor temperature decreased following the saturation temperature, (Figure 21). Finally, the liquid temperature sharply decreased to the vapor temperature. The energy lost by the liquid as its temperature decreased generated vapor which caused the void fraction oscillation. This behavior resulted from the value of the interfacial heat transfer coefficient from the liquid to the vapor being too small at a low void fraction. As the void fraction in the cell increased the coefficient jumped to a large value sharply increasing the heat transfer rate to the vapor phase and increasing the total void.

The large increase in void in cell 7 of level 1 pushed liquid into the cell above and into the jet pump exit. The mass flow through the jet pump is shown in Figure 22. The mass flow through the jet pump furnished the mass that was ejected through the break (Figure 5) which showed peaks corresponding to the jet pump flow until 30 s. After 30 s the break flow responded to the liquid falling down the annulus from the pool that had collected around the standpipes.

An updated version of the code (Update 6) was used to recalculate the first 10 s of the transient. The updates included better representations of the interfacial shear and heat transfer between the phases. The oscillatory behavior in the lower plenum was considerably smoothed and the liquid levitation in the upper plenum was considerably reduced.

Figure 23 shows the predominant fluid circulation patterns throughout the vessel during the period 10-20 s. The upper plenum had a definite circulation pattern but it did not seem to have much effect on liquid accumulation within the upper plenum.

The lower plenum flow pattern was primarily affected by the jet pump location. Injection of the lower plenum steam into one cell instead of distributing it in several, probably had no effect on the behavior within the lower plenum.

The calculation presented took 69,892 system seconds on the CDC 176 computer at the INEL.

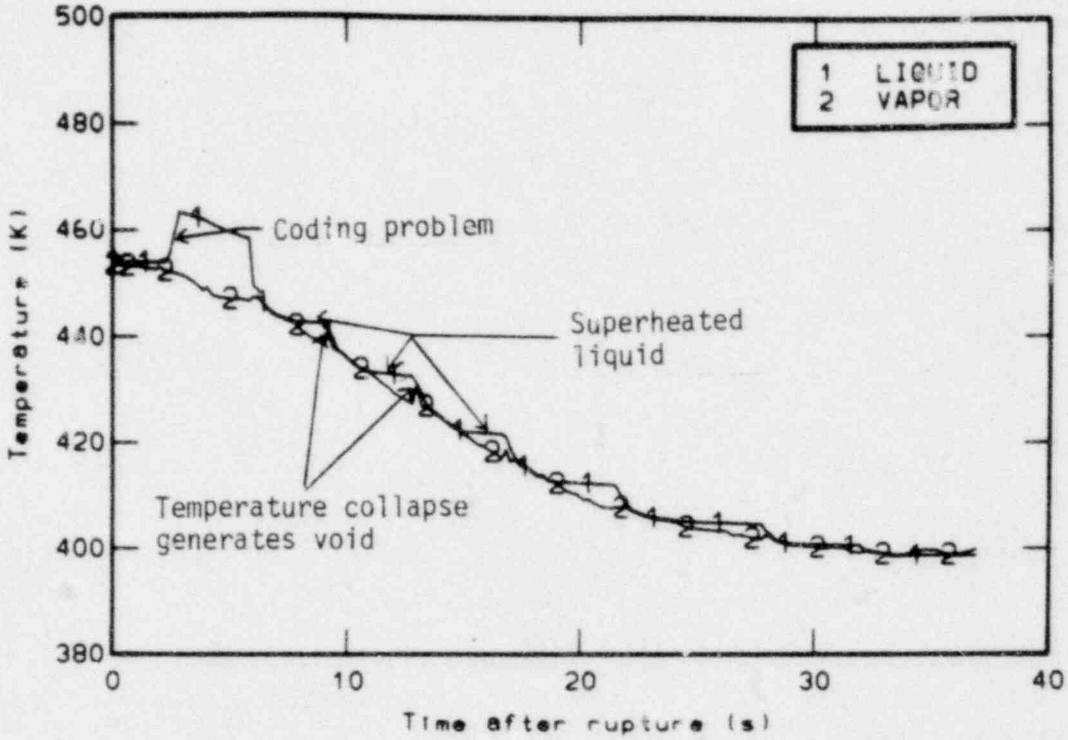

Figure 21. Temperature of liquid and vapor phases versus time in cell 7 of lower plenum level 1 during the transient calculation.

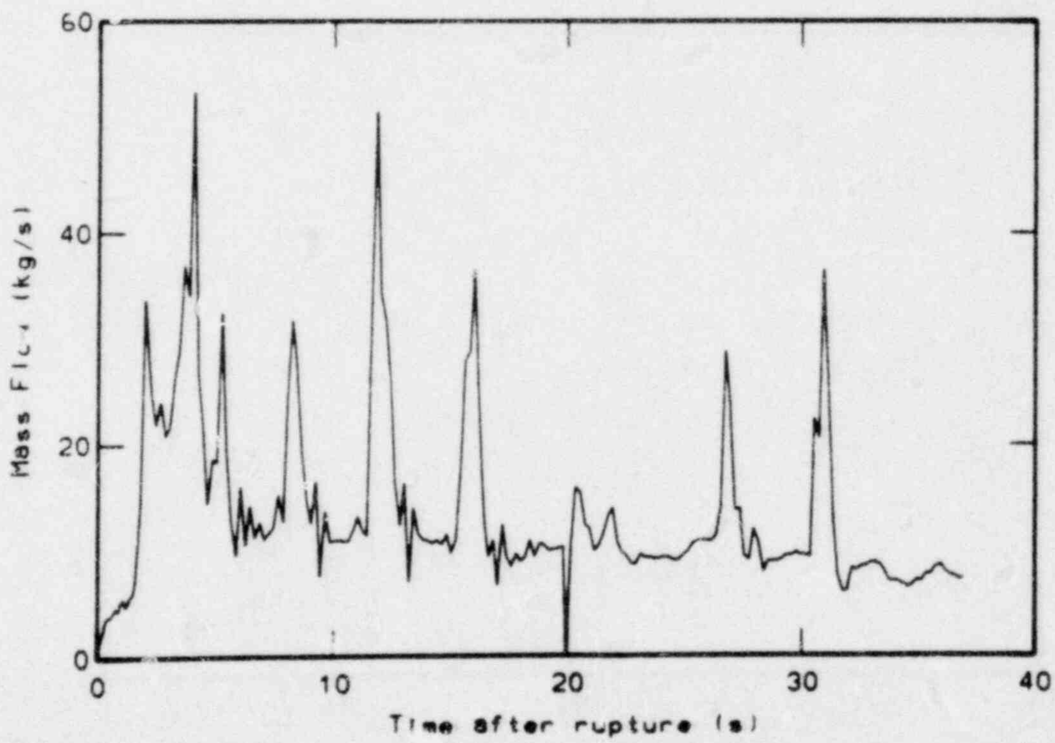

Figure 22. Mass flow rate versus time at the exit of jet pump in lower plenum during the transient calculation.

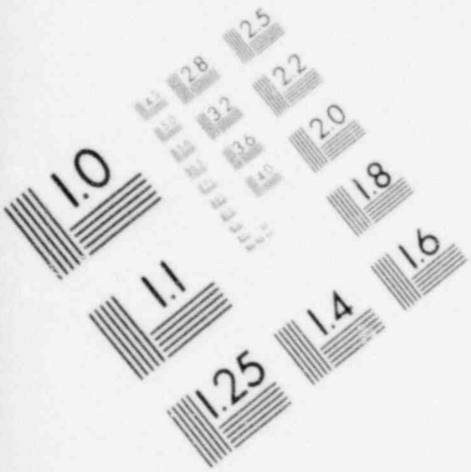
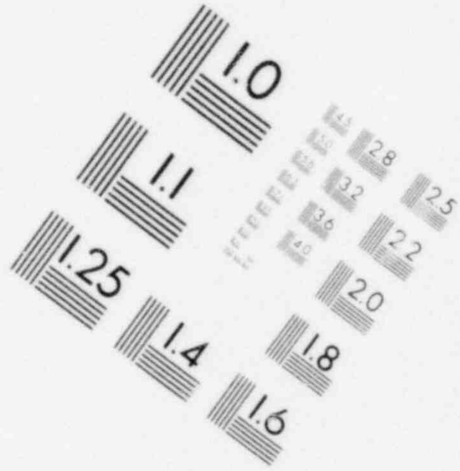

IMAGE EVALUATION
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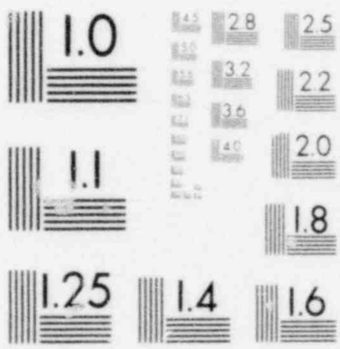

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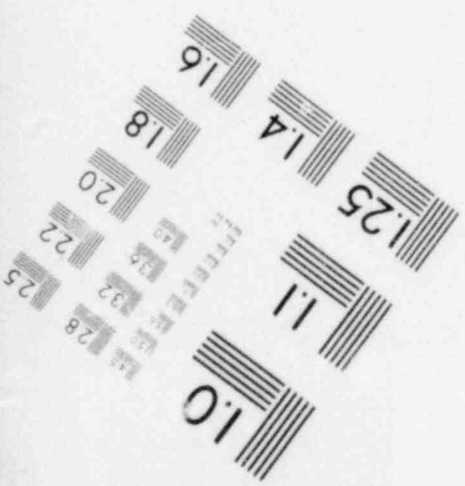
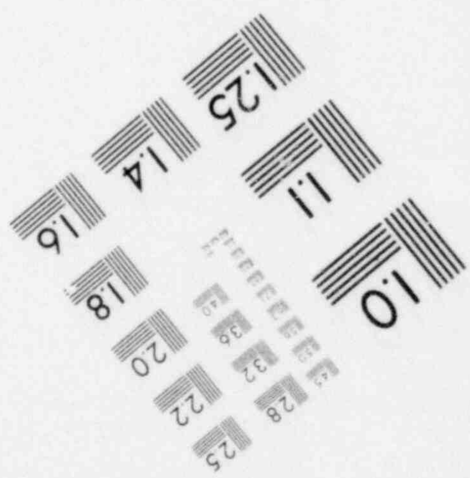



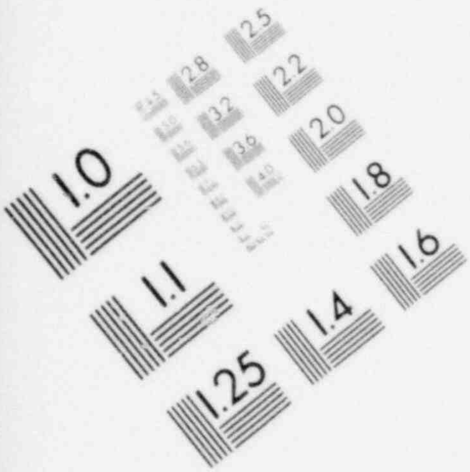
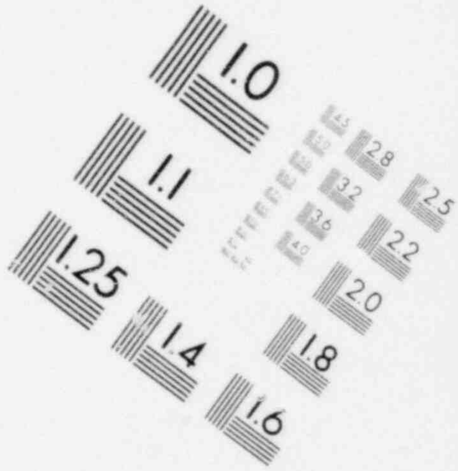
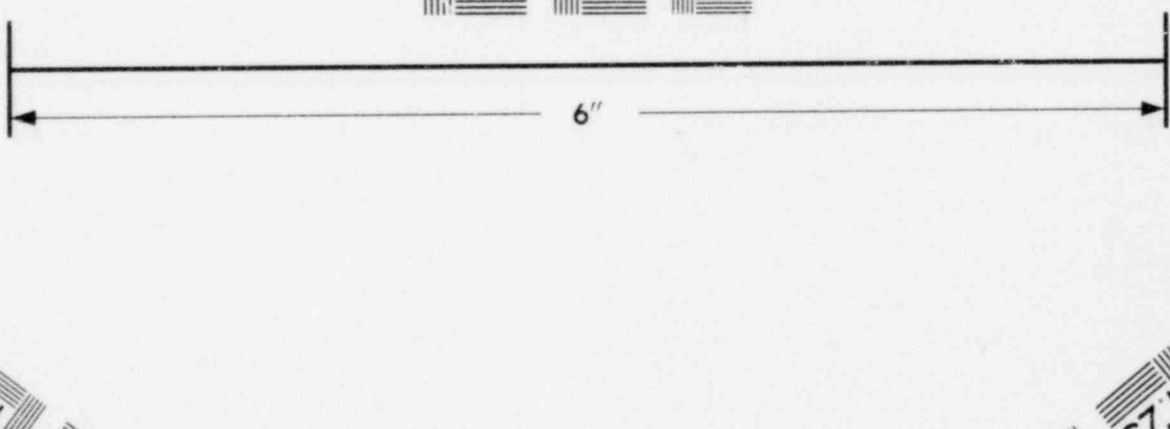
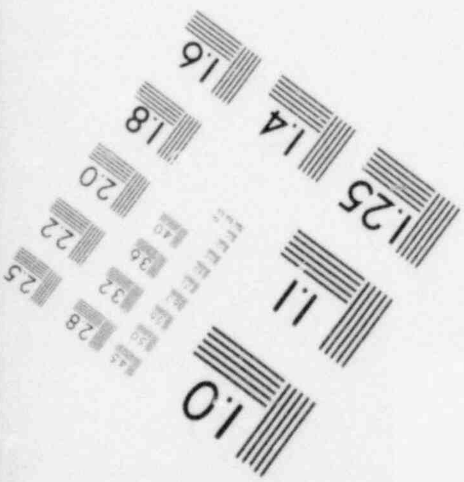
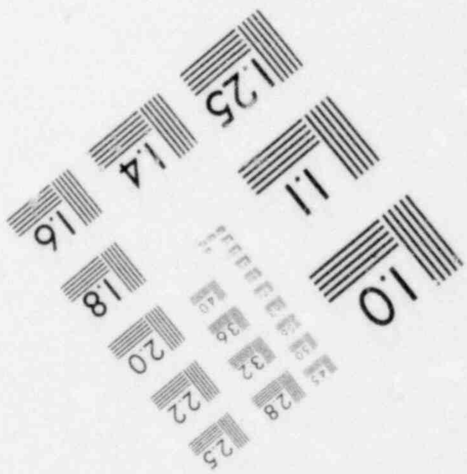
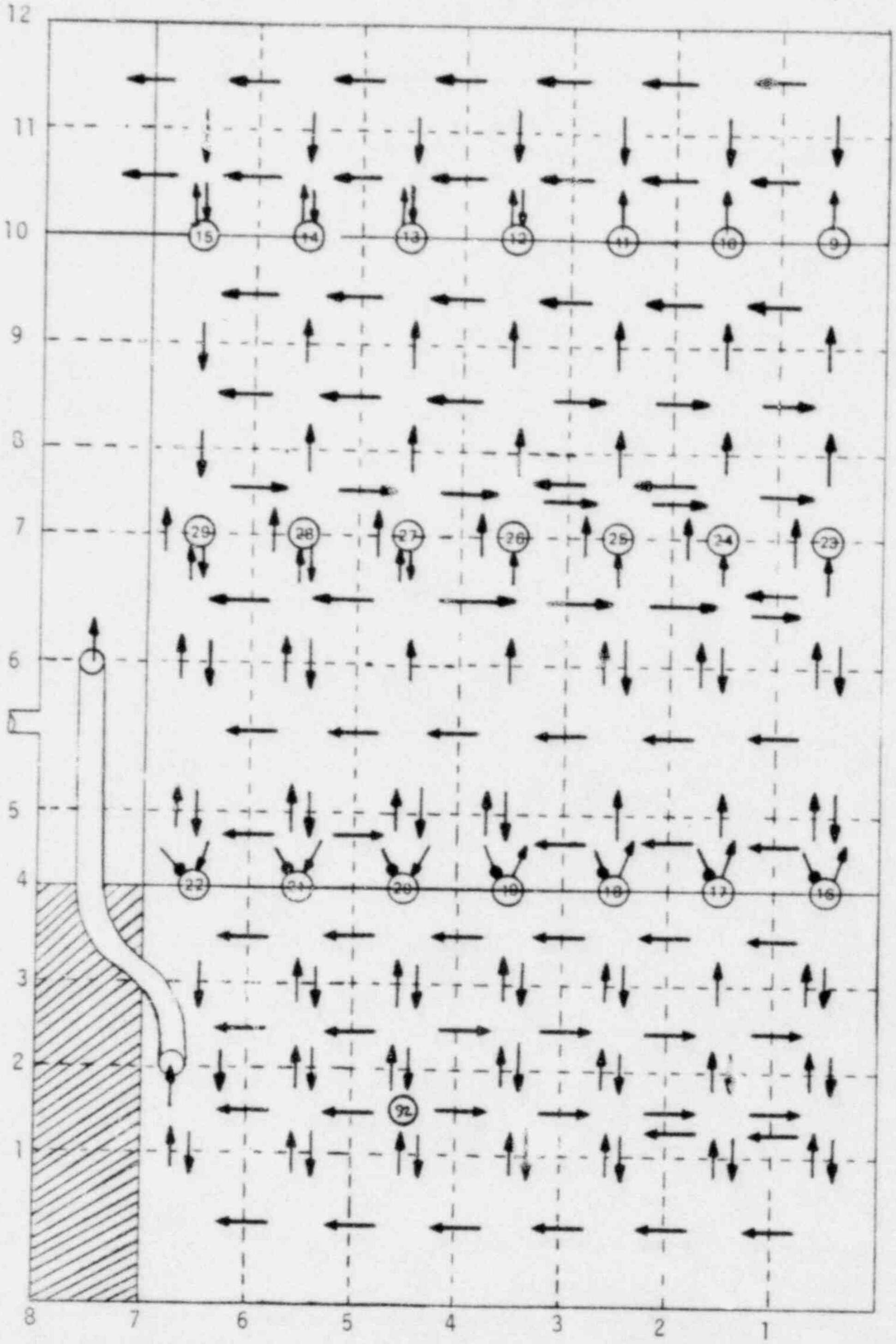



IMAGE EVALUATION TEST TARGET (MT-3)



NOTE: Single arrows: liquid and vapor velocities are in the same direction.
Double arrows: vapor velocities on the left and liquid velocities on the right.
Dot arrows: leakage velocity of CHAN component.

Figure 23. Flow pattern between 10-20 seconds of the transient calculation.

4.2 Steady State Calculation

The steady state calculation simulated the imposed conditions of a spray distribution test previously conducted. A brief description of the experiment is presented first, followed by a discussion of the calculated results.

The experiment, Test CS-3.1, is described in Reference 2. ECC spray, representing one header (LPCS), was injected into the upper plenum. Steam was injected in two places, the fuel bundles and the top head. Half of the steam flow was injected into the fuel bundles with the other half injected into the top head. The steam flow in the bundles was individually set for each bundle. The steam flow through the simulated steam separators was supplied as demanded by condensation on the ECC spray to maintain steady state pressure in the upper plenum. The remainder of the steam exited through the steam vent. The jet pump flow path, which allowed steam to flow from the lower plenum to the annulus and then to the upper head, was blocked off by raising the liquid level in the lower plenum to cover the jet pump exit.

The initial and boundary conditions of the test were used as initial and boundary conditions of the calculation as described in Section 3.4. The calculation was run until approximate steady state conditions were met. Transient oscillations occurred the first 10 seconds as the steam flows and ECC spray were ramped on. At approximately 16 seconds the system had reached a steady state condition.

An examination of the upper plenum at the steady state condition shows that the injected super heated[a] steam entered the upper plenum from the core and from the top head through the standpipes and condensed on the subcooled ECC spray similar to the test behavior. Not all of the steam

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a. Information obtained after the calculation had shown that the test was run with saturated steam.

injected into the upper head migrated through the standpipes and into the upper plenum, a small fraction escaped through the steam vent. Not all of the steam that entered the upper plenum condensed on the ECC spray; some was carried with the liquid into the core bypass region. Neither the steam nor the liquid reached a saturated condition in the upper plenum. At steady state there was an accumulation of between 5 and 10 percent liquid by volume in the lower section of the upper plenum represented by level 8, the remainder of the liquid dropped into the core region.

The liquid which entered the core region either penetrated the fuel bundles or the core bypass region. As the slightly subcooled liquid penetrated the fuel bundles it interacted with the upward flow of injected steam. This interaction increased the temperature of the liquid to saturation. Also as the liquid penetrated the core bypass region from the upper plenum it carried with it the noncondensed steam. With the interaction of the two phases both the liquid and steam had become saturated by the time the flow reached the bottom of the core bypass region. Table 3 compares the measured value of liquid mass flow through the fuel bundles of Test CS-3.1 to the calculated values. Close agreement exists between calculated and measured values of mass flow rates in a majority of the cells indicating that modeling of the fuel bundles and upper tie plates and code calculated resistances were reasonable. Additive loss coefficients in conjunction with the code calculated resitances may give a closer agreement between the calculated and measured bundle flows.

The steam injected into the fuel bundle slightly increased the pressure of the bundle which resulted in a positive leakage from the bundle to the core bypass, except in cell 7 where a negative leakage rate was calculated. The negative leak rate was due to a higher pressure in VESSEL level 5, cell 7 than in the CHAN component associated with that cell. The higher pressure in the VESSEL cell was a result of a static head buildup due to liquid accumulation in the cell. Unlike the other cells on that level, there was no guide tube connection in cell 7 for the liquid to drop

TABLE 3. MASS FLOW OF LIQUID DOWN BUNDLES FOR MEASURED AND CALCULATED RESULTS

Cell No.	Measured (kg/s)	Calculated (kg/s)
1	0.474	0.409
2	0.977	1.163
3	2.677	2.156
4	2.761	2.667
5	4.197	3.403
6	5.113	4.003
7	7.339	2.173

down; therefore, the only way the liquid could drain out of the cell was in the radial direction or through the leakage path of the CHAN component. Because of the assumption of dispersed flow in the TRAC computer program, radial phase separation due to gravitational effects occur slowly unless a large number of computational levels are used.The liquid accumulated in cell 7 of level 5 until a pressure difference was enough to cause a flow of liquid in the radial direction. The pressure in cell 7 was also greater than that in the CHAN component, thus the negative leakage flow in that component.

Liquid in the core bypass region entered the lower plenum either through the bundles or the guide tubes via the leakage path. As the liquid filled the bottom cells of the guide tubes, inner iteration failures and vapor temperature limit warnings occurred, possibly indicating water packing problems. These problems may have been eliminated had the water packing option been turned on or the guide tube drains opened or both. The liquid which entered the lower plenum continued to fill up the lower plenum levels keeping the jet pump exit covered. Liquid from the lower plenum oscillated in the jet pump piping with small amounts spilling over the top of the jet pump filling the lower part of the vessel annulus (level 5, cell 8).

The conditions in the vessel annulus (levels 5-12, cell 8) at steady state were esstentially stagnant.

The calculation took 69,990 system seconds on the CDC 176 at the INEL. The time may have been reduced if the water packing option had been turned on to reduce the inner iteration failures. The optimum use of the water packing option will be determined in future planned studies. Other optimization studies relative to the noding of the standpipes should also be performed to possibly reduce running time and costs.

5. CONCLUSIONS AND RECOMMENDATIONS

The calculated results of the transient test appeared to be reasonable and explainable. The calculated results of the steady state test compared favorably with actual test data. Thus, with the incorporation of an explicit model to represent spray coolant in the computer program, the model of the SSTF appears capable of making the calculation to determine the hydrodynamic interaction between the spray liquid and the coolant flows generated within the BWR system by surface heat transfer (simulated by steam injection) and depressurization.

Before making predictions of transient test behavior, the flow resistances within the system should be verified by checking the model output against shakedown test data. The major controlling resistances are likely to be the fuel rod bundle tie plates, top guide, leakage paths and side entry orifice.

The model geometric data (volumes, flow areas) should be compared to the information to be provided in the future by General Electric Company.

A more representative calculation to determine the adequacy of the model could be accomplished by using conditions calculated by a TRAC-BD1 BWR-6 model developed by EG&G as initial conditions for the transient started at 1.03 MPa.

The model should be optimized for computer running time. Elimination of the standpipes by including the flow area and volume in a vessel level and placing two cells in the secondary side of TEEs are examples where optimization might be considered. Optimum use of the water packing option should also be determined.

6. REFERENCES

1. D. G. Schumacher, Experimental Task Plan, Task 44-CCFL/Refill System Effects Test (30^{o} sector), BWR Refill-Reflood Program, General Electric Company, ETP 514.8011, Attached to letter G. W. Burnette (GE) to Merilo (EPRI) and Beckner (NRC), March 14, 1980.

2. S. A. Sandoz et al., Core Spray Design Methodology Confirmation Tests, General Electric Company, NEDO-24712, August 1979.

APPENDIX A

IDENTIFICATION OF MODEL COMPONENTS AND JUNCTIONS

Figure A-1 describes the TRAC-BD1 model of the Steam Sector Facility.

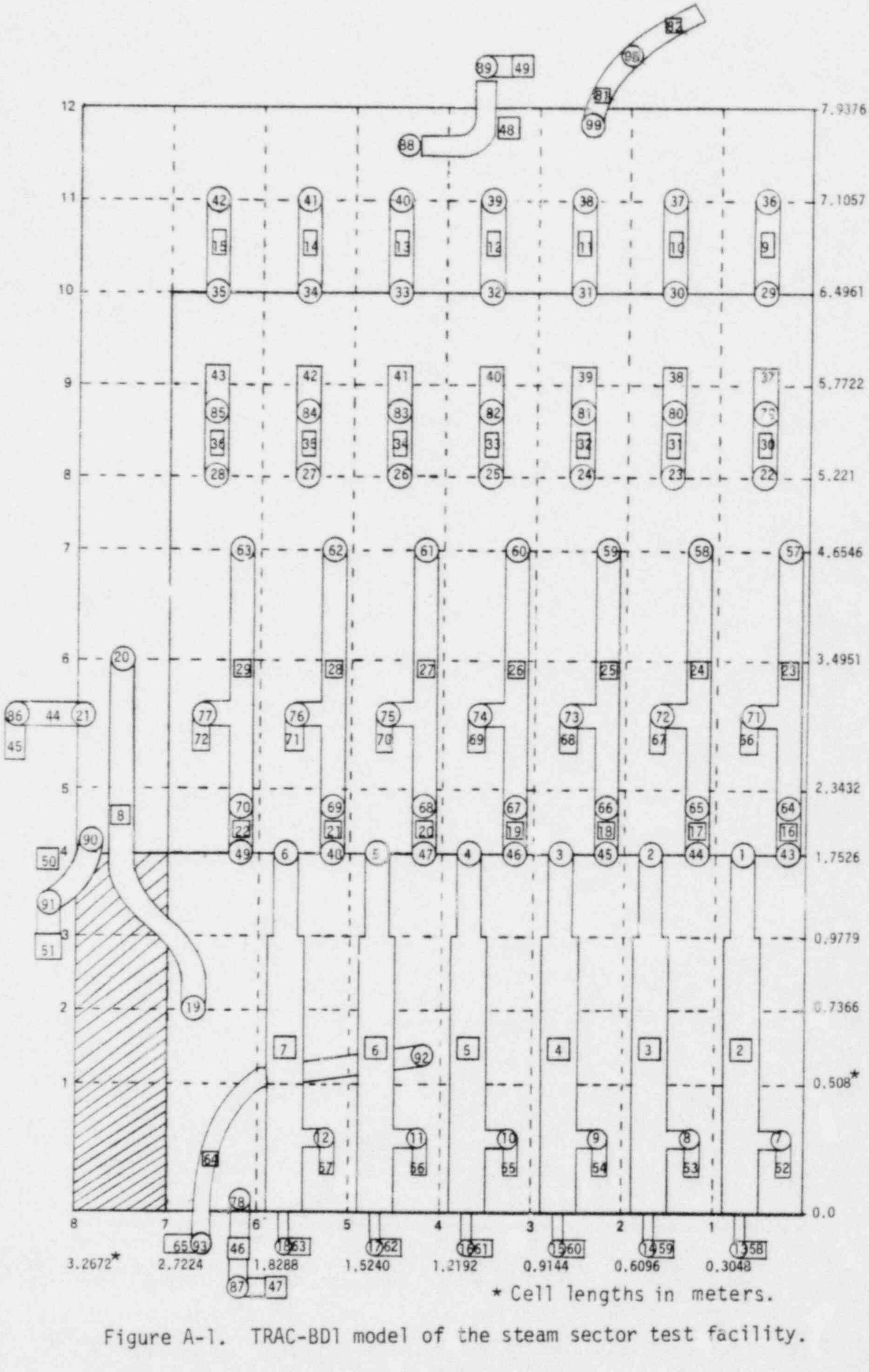

Figure A-1. TRAC-BD1 model of the steam sector test facility.