A Study of Thermal Stratification in the Cold Legs During the Subcooled Blowdown Phase of a Loss of Coolant Accident in the OSU APEX Thermal Hydraulic Testing Facility

by

D. M. Wachs
Argonne National Laboratory - West
Engineering Division
Idaho Falls, ID 83403-2528 USA

J. N. Reyes, Jr.
Oregon State University
Corvallis, OR 97333

L. R. Davis
Oregon State University
Corvallis, OR 97333

Paper to be submitted for
American Nuclear Society Winter Meeting
November 15-19, 1998
Washington, D.C.

---

*Work supported by the U.S. Department of Energy, Materials/Chemistry, Materials Characterization, under Contract W-31-109-ENG-38.

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

A Study of Thermal Stratification in the Cold Legs During the Subcooled Blowdown Phase of a Loss of Coolant Accident in the OSU APEX Thermal Hydraulic Testing Facility

Daniel M. Wachs
P. O. Box 2528 – Engineering Division
Argonne National Laboratory - West
Idaho Falls, Idaho 83403-2528

Jose N. Reyes, Jr.
100 Radiation Center
Oregon State University
Corvallis, Oregon 97333

Lorin R. Davis
Rogers Hall
Oregon State University
Corvallis, Oregon 97333

ABSTRACT

Thermal stratification, which has been linked to the occurrence of pressurized thermal shock (PTS), is observed to occur during the early stages of simulated loss of coolant accidents (LOCAs) in the Oregon State University Advanced Plant Experiment (OSU APEX) Thermal Hydraulic Test Facility. The OSU APEX Test Facility is a scaled model of the Westinghouse AP600 nuclear power plant. Analysis of the OSU APEX facility data has allowed the determination of an onset criteria for thermal stratification and has provided support for the postulated mechanisms leading to thermal stratification. CFX 4.1, a computational fluid dynamics code, was used to generate a model of the cold legs and the downcomer that described the phenomena occurring within them. Some mixing phenomena were predicted that lead to non-uniformity between the two cold legs attached to the steam generator on the side of the facility containing the Passive Residual Heat Removal (PRHR) injection system. The stratification was found to be two phase and unlikely to be a factor in PTS.

1. INTRODUCTION

The OSU APEX Test Facility is a ¼ height scale, ½ time scale, reduced pressure integral systems test facility constructed to model the Westinghouse AP600 (13). The model includes the entire primary system, the passive safety systems and parts of the non-safety grade chemical and volume control systems (CVCS) and residual natural circulation systems (RNCS). The interconnecting pipe routings are also duplicated in the model. The facility contains a wide range of instruments in a variety of locations. A schematic of the facility is shown in figure 1. A computer operated data acquisition system (DAS) is included to collect and store the instrument readings during the tests. Review of this data revealed that during parts of the test the temperature of the fluid in the cold legs was not always uniform and well mixed (i.e. the cold leg was thermally stratified). Periods of thermal stratification were observed throughout each test.

Figure 1 – Schematic of the OSU APEX Facility (1)

In past studies by the Nuclear Regulatory Commission and EPRI (5) it was concluded that a pressurized thermal shock (PTS) event can only occur if all of the following conditions exist simultaneously in the reactor vessel;

I. The reactor pressure vessel has incurred radiation embrittlement,

II. A flaw exists in the vessel material and is large enough to propagate,

III. The reactor coolant near the pressure vessel flaw cools rapidly,

IV. Heat is transferred quickly from the vessel wall to the fluid,

V. The primary system is at high pressure.

The observation of thermal stratification therefore demonstrates that condition (III) above is possible, which necessitates the evaluation of this reactor geometry. Many of the tools necessary to analyze the risk of PTS, including vessel embrittlement and non-destructive testing for material flaws, have been developed and are directly applicable to the Westinghouse AP600 (9-12). New thermal hydraulic analysis must be done though, - because it is very dependent upon the system of interest.

The injection of cold safety injection water is the primary requirement for the occurrence of thermal stratification. The safety injection for most of the plants previously analyzed occurred within the cold legs. In the APEX facility, emergency reactor cooling is provided by the Passive Residual Heat Removal (PRHR) system and the Direct Vessel Injection (DVI) system. The injection of cooling water occurs within the steam generator lower plenum (PRHR injection) and the reactor pressure vessel (DVI). Direct vessel injection has already been examined for the Westinghouse two-loop plants and the downcomer behaves very similarly to the plants previously modeled (2). The study can be limited to the initial stages of the LOCA (by condition (IV)) because the system pressure drops rapidly. This leaves the mixing behavior within the cold leg as the only unsettled PTS issue.

2. REVIEW OF LITERATURE

Examination of the available literature revealed the development of several models to describe the fluid mixing within the cold legs. An onset criterion for thermal stratification in a plant cold leg experiencing high-pressure safety injection (HPSI) was also previously developed.

Well-Mixed Model

The well-mixed model (14-19) assumes complete mixing between the loop and HPSI flow. This method is not applicable to a stagnant loop condition (i.e. no loop flow) because the well-mixed assumption ignores the transient cool-down behavior and would predict a cold leg filled entirely with water at the HPI inlet temperature. This condition is far too conservative for accurate, realistic analysis. While at the opposite extreme, a well-mixed cold leg with moderate loop flows may not be conservative enough. It has been observed that small loop flows may not be sufficient to generate complete mixing and thermal stratification may occur. If the cold leg is stratified, the cold stream falling into the downcomer may be significantly colder than the fluid temperature predicted by the well-mixed model. This would subject the vessel wall to a cool-down transient much more severe than anticipated. The well-mixed model is still useful, though, when the cold leg is actually well mixed.

Regional Mixing Model

Theofanous (16-19) recognized that very small loop flows were sufficient to break up any injection plume that might exist therefore generating a well-mixed condition in the cold leg. This led to the creation of the Regional Mixing Model (RMM) which allowed the quantitative description of thermal stratification in a stagnant loop. The RMM treated the hot and cold streams of the cold leg as stabily stratified and solved the continuity, momentum and energy equations for each region. The RMM modeled mixing at the HPSI point and at the cold leg and downcomer junction. The amount of mixing that occurred in these regions was calculated using empirical correlations. To modify the RMM for the OSU APEX facility would therefore require the replication of the mixing experiments for the new geometry.

Three-Dimensional Computer Codes

The mixing behavior in the cold legs has also been modeled using a computer program called COMMIX (3,4,7,8). COMMIX is a general purpose, three-dimensional single-phase steady-state/transient computer program for thermal hydraulic analysis of single and multi-component systems which uses a porous media formulation.

Onset Criteria

It has been repeatedly recognized that a well-mixed cold leg (i.e. non-stratified) is unlikely to lead to a PTS event (3,6,8,10-12,16-19). Theofanous therefore generated an onset criterion to quickly determine if a particular combination of loop flow (be it forced or natural circulation) and safety injection flow could potentially be stratified at the cold leg exit. Theofanous pointed out that for the cold leg flow to be well-mixed there must be sufficient loop flow to break up the HPI plume (or PRHR injection plume in this case) and to produce a stable exit of flow into the downcomer. Expressing the stationarity of long waves at the interface of two parallel flowing liquid layers of different density with the superficial Froude number leads to an equation describing the boundary of stability (26).

$$Fr_{HPI,CL} \cong \left\{1+\frac{Q_{loop}}{Q_{HPI}}\right\}^{-7/5}$$

where the superficial Froude number is defined as,

$$Fr_{HPI,CL} = \frac{Q_{HPI}}{A_{CL}}\left\{gD_{CL}\frac{\rho_{HPI}-\rho_{h}}{\rho_{HPI}}\right\}^{-1/2}$$

This condition is analogous to flow choking (or flooding) in the sense that the two-layer flow cannot be changed gradually without leading to a violent disruption of the flow by internal discontinuities (i.e. hydraulic jump).

Figure 2- Comparison of theoretical stratification criteria with the CREARE 1/5-scale test results (16).

Theofanous compared the stratification/mixing boundaries expressed by this equation to the experimental data collected from the CREARE 1/5 scale mixing facility in figure 2. Excellent agreement is noted. The equation does not predict the degree of stratification. It simply provides an uncomplicated tool for establishing an estimate of loop flow for which stratification can be ignored and a well-mixed condition can be assumed to exist.

3. DESCRIPTION OF THERMAL STRATIFICATION

To reasonably predict thermal stratification and to reduce the amount of modeling necessary the problem must be simplified. To do this a qualitative analysis was performed initially to establish which components were significant to the study of thermal stratification as it affected PTS. Data from the OSU APEX facility was used to generate and support assumptions regarding the conditions within the cold leg, downcomer, core makeup tanks (CMTs) and steam generators and to explain the interactions between them. The reactor is symmetric and may therefore be broken into two distinct halves, the CMT-side of the facility that is affected by the presence of the CMT-Pressure Balance Lines (PBLs) and the PRHR-side of the facility which contains the PRHR injection line at the base of the steam generator.

Thermal Stratification on the CMT-Side

During the high-pressure stage of the LOCA the fluid in the CMT-side cold legs transitions between four conditions. A plot of the vertical temperature profile in cold leg #3 is shown in figure 3. This cold leg is located on the CMT-side of the facility and is the cold leg containing the break.

Figure 3 - Cold leg temperature profile as measured by the thermocouple rake in cold leg #3.

Figure 4- Schematic of normal operation.

Figure 5 - Schematic of loop stagnation.

Figure 6 - Schematic of two-phase stratification.

The events leading to thermal stratification in the CMT-side cold legs can be broken down into the following four stages:

1. natural circulation
2. cold leg stagnation
3. two-phase stratification
4. vapor filled ("empty") cold legs

The beginning of the third stage (two-phase stratification) is chosen as the time of onset for thermal stratification. A description of the events leading up to the onset of thermal stratification in the CMT-side cold legs follows.

Prior to the beginning of the LOCA, the reactor is operating under normal conditions. Water is circulating through the reactor primary loop, driven by the reactor coolant pumps and, to a lesser extent, by buoyancy forces. A schematic of normal operation is shown in Figure 4.

Stage 1 - Natural Circulation

When the simulated break occurs, the safety systems are actuated and the reactor trips. Even though the pumps have tripped, natural convection continues to drive the flow of the coolant through the reactor. The flow patterns are similar to normal operation, but with significantly lower flow rates. On the CMT-side of the facility, cold water is not injected into the cold legs at any point during the transient. During this stage there is no mixing occurring and the cold leg temperature is therefore the same as the steam generator temperature, resulting in a uniform temperature profile.

As the reactor pressure drops, steam bubbles begin to form within the vessel head, pressurizer and steam generator U-tubes. Eventually, the bubbles in the steam generators grow large enough that they interrupt natural circulation through the reactor. When the steam generator steam bubble stops natural circulation, the primary loop is considered "stagnant." The break, though, still draws fluid into the cold leg. The CMT is still in a natural circulation mode and is also drawing fluid into the cold leg. This flow must come from the downcomer. Thus beginning stage 2.

Stage 2 - Loop Stagnation

A schematic of loop stagnation is shown in figure 5. The lower downcomer temperature steadily drops throughout the LOCA transient while the upper downcomer temperature quickly becomes saturated. The high temperature of the upper downcomer is caused by the flow of vapor through the downcomer bypass holes in the top of the downcomer. Eventually the vapor fills the upper downcomer and saturated steam begins to be drawn into the cold leg. This marks the onset of thermal stratification in the cold legs and the beginning of stage 3.

Stage 3 - Two-Phase Stratification in the Cold Legs

A schematic of two-phase stratified condition is shown in figure 6. The entrance of vapor through the bypass holes allows steam to flow into the upper downcomer and form an annular region of steam. Steam is then drawn into the cold leg and flows along the top of the cold leg and into the CMT-PBL where it is either condensed or coalesces to form a vapor bubble allowing the CMT to begin draining.

The lower stream in the cold leg also comes from the downcomer. It consists of subcooled liquid and runs along the bottom of the cold leg. The top stream will always be at the system saturation temperature and the bottom stream will control the degree of stratification.

The purpose of this study was to provide a description of the cold leg temperature profile at the exit of the cold legs so that their contribution to a potential PTS event can be evaluated. It is therefore important to note that flow is going from the downcomer into the cold leg and not from the cold leg into the downcomer. This means that there is no cold plume falling into the downcomer and no vessel cool-down transient below the CMT-side cold legs that is more severe than the overall vessel cool-down rate. The cold legs on the CMT-side of the facility therefore can not cause PTS.

Stage 4 - Vapor Filled Cold Legs

The vapor bubble in the reactor pressure vessel continues to grow. When the Automatic Depressurization System (ADS) valves open the reactor pressure drops rapidly and much of the primary system liquid volume flashes to steam. This quickly lowers the reactor liquid level and causes the cold legs to fill with steam. The cold legs will refill with water later in the test, but PTS will not be a danger because the reactor pressure is relatively low.

Figure 7 - Cold leg #4 temperature profile as measured by the thermocouple rake within the cold leg.

Figure 8 - Schematic of natural circulation on the PRHR-side of the facility.

Figure 9 - Schematic of two-phase stratification in cold leg #4 (PRHR-side).

Thermal Stratification on the PRHR-Side

There is an observed difference between the magnitude of thermal stratification on the PRHR- and CMT-sides of the facility. Thermal Stratification of the PRHR-side of the facility can be as much as 100° F larger. This greater stratification is directly related to the injection of cold water from the PRHR into the steam generator, whereas the CMT-side of the facility does not have any sources of water colder than the downcomer fluid. Figure 7 shows a plot of the vertical thermocouple rake in cold leg #4 on the PRHR-side of the facility.

The PRHR-side cold legs go through three stages early in the LOCA. These stages are similar to those experienced by the CMT-side but with different bulk flow direction. The stages are as follows:

1. natural circulation
2. two-phase cold leg "stagnation"
3. vapor filled cold legs

Stage 1 - Natural Circulation

The natural circulation stage is very similar to the natural circulation stage of the CMT-side. A schematic of this condition is shown in figure 8. Natural circulation flow, which is large compared to the PRHR flow, dominates the cold leg. Because the natural circulation flow is so much larger than the PRHR flow the PRHR injection plume is thoroughly broken up and completely mixed, therefore a uniform cold leg temperature is obtained. The bulk cold leg flow, though, is still cooled noticeably by the PRHR operation. This stage will continue until the steam generator void becomes large enough that it interrupts natural circulation.

Stage 2 - Two-Phase Loop Stagnation

When natural circulation stops the primary loop is considered stagnant where stagnation is defined in the same manner as in stage 2 of the CMT-side discussion. The only activity on the PRHR-side of the facility at this point is generated by the PRHR injection. The PRHR flow is much colder than the ambient primary fluid. Buoyancy forces therefore drive flow down into the cold leg and towards the downcomer. Incomplete mixing of the PRHR injection stream may result in the formation of a single-phase counter-current flow condition, where the bottom of the cold leg is colder than the top. This condition would result in a colder plume of water exiting the cold leg into the downcomer than if the cold leg was well mixed. Figure 7 does not conclusively show the existence of a counter-current condition. Other methods must be employed to determine if this condition exists. At this point the PRHR is analogous to the high-pressure safety injection (HPSI) systems of common reactors currently in operation and some analysis tools generated for this problem may therefore be used (including the onset criterion of Theofanous).

The thermal stratification observed in this plot is significant, but it can be credited to the presence of a thin layer of vapor near the top of the cold leg pipe. This suggests that because the remainder of the cold leg is of uniform temperature that the PRHR injection plume is becoming well mixed with the ambient fluid in the steam generator lower plenum and the reactor coolant pump prior to entering the cold leg. Therefore, if thermal stratification due to counter-current flow is occurring, the magnitude of the temperature difference is small. A schematic of the natural circulation phase is shown in figure 8.

As previously observed on the CMT-side of the facility, the vapor bubble in the reactor pressure vessel grows and eventually fills the upper downcomer with steam. Because the top of the steam generator is at a much higher elevation than the top of reactor vessel the steam is driven by buoyancy toward the steam generator. For the steam to reach the steam generator a counter-current flow condition in the cold leg must develop. When this counter-current flow condition develops to the cold leg stratifies.

Stage 3 - Empty Cold Legs

As the primary system pressure drops the vapor bubble in the reactor vessel grows and eventually the cold legs fill with vapor and the PRHR natural circulation loop is interrupted.

Comparison with ROSA Facility Data

The Large Scale Test Facility (LSTF) of the Japan Atomic Energy Research Institute was modified to simulate the Westinghouse AP600 and to provide data for comparison to the OSU APEX test facility. When in the AP600 configuration the LSTF is more commonly known as the ROSA facility. The data generated by the ROSA facility was compared to that generated by the OSU APEX facility and very similar phenomena were observed.

4. DESCRIPTION OF CFX MODEL

It was determined that the use of a three-dimensional computational fluid dynamics (CFD) code would be best suited for generating a model of this system. CFX 4.1 by AEA technologies was selected for the task.

CFX 4.1 is a general purpose CFD package that can be used to simulate a wide range of fluid flow and heat transfer processes. The package is comprehensive and includes software to generate the problem geometry, setup the flow solver, and analyze the results with flow visualization tools.

Description of Model

The model was intended to predict the onset and severity of thermal stratification in the cold legs for a variety of circumstances. The CMT-side cold legs were not included because they did not affect the downcomer. It was soon found that the cold leg behavior was extremely dependent on the phenomena occurring in its neighboring equipment, including the steam generator lower plenum and the downcomer. An accurate model of the cold leg phenomena would therefore require the inclusion of these components. The system was constructed by attaching many blocks together and then subdividing the blocks into cells. The final model contained 38 blocks and 55,772 cells.

Summary of Model Output

The CFD model was setup to simulate three system conditions on the PRHR side of the OSU APEX facility including:

- the full natural circulation phase
- a reduced natural circulation phase

- the loop stagnation phase

The first and last phases are described in the description of phenomena section and the third phase is included to illustrate the transition between the other two. Boundary conditions at the steam generator inlet were the only difference between these cases. In all three cases, the PRHR inlet flow is the same and there is a moderate flow of water through the bypass holes located at the top of the downcomer. The temperature and flow rate for each of these inlet streams is tabulated in the following table.

		Temp. (K)	Flow Rate (GPM)
Full Natural Circulation	PRHR inlet	295	5
	SG flow	477	50
	Bypass Flow	477	2.5
Reduced Natural Circulation	PRHR inlet	295	5
	SG flow	477	20
	Bypass Flow	477	2.5
Loop Stagnation	PRHR inlet	295	5
	SG flow	-N/A-	0
	Bypass flow	477	2.5

Table 4-1 - Boundary conditions for CFX 4.1 models.

A significant simplification to the system was made by assuming that flow through the bypass holes was water instead of steam. This assumption greatly reduces the difficulty of the problem. The assumption undoubtedly reduces the magnitude of the buoyancy forces but it does not eliminate them. The phenomena observed in the models can therefore still be extrapolated to the actual system.

Figure 10 – The surface temperatures for the full natural circulation case as predicted by CFX 4.1.

Figure 11 – The cold leg temperature profiles for the full natural circulation case as predicted by CFX 4.1.

Figure 12 – The cold leg velocity profiles for the full natural circulation case as predicted by CFX 4.1.

Figure 13 – The steam generator lower plenum temperature profile for the full natural circulation case as predicted by CFX 4.1.

Figure 14 – The steam generator lower plenum velocity profile and velocity vectors for the full natural circulation case as predicted by CFX 4.1.

Full Natural Circulation

CFX 4.1 was used to calculate the velocity and temperature of the fluid at every node of the problem. Figure 10 shows the temperature at the system surfaces. A few phenomena are of particular interest in this plot, including the pool of cold water at the base of the steam generator and the lack of thermal stratification in the cold legs.

Figures 11 and 12 consist of several vertical slices in the cold leg. These slices show cross sectional views of the temperature and velocity of fluid in the cold legs. It is important to note that the flow is one directional and is moving toward the downcomer.

Another area of interest is the steam generator lower plenum and cold leg penetrations (the connective piping between the steam generator lower plenum and the reactor coolant pumps). Figure 13 shows the temperature field in a vertical slice of this region. The cold pool above the PRHR injection nozzle is apparent. Figure 14 shows a velocity vector plot of this region. It clearly shows that the all the fluid is moving downward into the reactor coolant pumps.

Figure 15 – The surface temperatures for the reduced natural circulation case as predicted by CFX 4.1.

Figure 16 – The cold leg temperature profiles for the reduced natural circulation case as predicted by CFX 4.1.

Figure 17 – The cold leg velocity profiles for the reduced natural circulation case as predicted by CFX 4.1.

Figure 18 – The steam generator lower plenum temperature profile for the reduced natural circulation case as predicted by CFX 4.1.

Figure 19 – The steam generator lower plenum velocity profile and velocity vectors for the reduced natural circulation case as predicted by CFX 4.1.

Reduced Natural Circulation

Again, CFX 4.1 was used to calculate the velocity and temperature of the fluid at every node of the problem. Figure 15 shows the temperature at the system surfaces. The pool of cold water at the base of the steam generator is present once again and the cold legs are thermally stratified. The magnitude of stratification is approximately 30° Celsius.

Figures 16 and 17 show cross section views of the temperature and velocity of fluid in the cold legs. It is important to note that there is a counter-current flow condition occurring and that the hot fluid on top is moving toward the steam generator and the cold fluid on bottom is moving toward the downcomer.

Figure 18 shows the temperature field in a vertical slice of this region. The cold pool above the PRHR injection nozzle is apparent. Figure 19 shows a velocity vector plot of this same region. The counter-current flow condition in this region is evident.

Figure 20 – The surface temperatures for the stagnant loop case as predicted by CFX 4.1.

Figure 21 – The cold leg temperature profiles for the stagnant loop case as predicted by CFX 4.1.

Figure 22 – The cold leg velocity profiles for the stagnant loop case as predicted by CFX 4.1.

Figure 23 – The steam generator lower plenum temperature profile for the stagnant loop case as predicted by CFX 4.1.

Figure 24 – The steam generator lower plenum velocity profile and velocity vectors for the stagnant loop case as predicted by CFX 4.1. surface temp

Loop Stagnation

Figures 20 through 24 describe the CFX 4.1 output for the case where there is no natural circulation and the primary system is therefore considered stagnant. For this case there is still PRHR injection and downcomer bypass flow. The predicted phenomena are very similar to the reduced natural circulation case except for the non-symmetry between the cold legs and the degree of stratification. The total flow through the cold legs is approximately 1/5 that the of the reduced natural circulation case. Figure 20 shows that this allows the back flow from the downcomer to be more dominant. This leads to the non-symmetric flow between the cold legs, where one cold leg is dominated by the flow of hot water back toward the steam generator and the other is more thermally stratified and is experiencing a counter-current flow condition.

Cross sectional plots of the cold leg temperature and velocity are provided in Figures 21 and 22. The difference in stratification is clearly shown in these figures.

Figures 23 and 24 show the conditions within the steam generator lower plenum and cold leg penetrations. The strong upward flow of hot water in the left cold leg and the downward flow in the right cold leg are evidence of the non-symmetry of phenomena and illustrate the need for both cold legs in the model.

5. ONSET OF THERMAL STRATIFICATION

A convenient method for determining if thermal stratification will occur was generated by Theofanous (20). Because this method is based on analysis done only at the cold leg exit, it can be applied with equal validity in this study by substituting the PRHR for the HPI. The boundary for onset of stratification is expressed in the following equations,

$$Fr_{PRHR,CL} \approx \left\{1+\frac{Q_{NC}}{Q_{PRHR}}\right\}^{-7/5}$$

where the $Fr_{PRHR,CL}$ is defined as the following,

$$Fr_{PRHR,CL} = \frac{Q_{PRHR}}{A_{CL}}\left\{gD_{CL}\frac{\rho_{PRHR}-\rho_h}{\rho_{PRHR}}\right\}^{-1/2}$$

Where $Fr_{PRHR,CL}$ is the superficial Froude number in the cold legs, Q_{PRHR} is the PRHR injection flow rate, Q_{NC} is the natural circulation flow rate, A_{CL} and D_{CL} are the area and diameter of the cold leg respectively, ρ_{PRHR} is the density of the fluid injected through the PRHR and ρ_h is the density of the fluid outside the cold leg exit. Three cold leg conditions can be analyzed to create data points for examination in these equations. The first condition is natural circulation with PRHR injection. The second is the stagnant loop condition. The third, and most valuable, is the condition at the transition from well mixed to stratified. A summary of these values has been included in table 2 and the values have been added to the plot generated by Theofanous in figure 25.

Facility	System Condition	$Fr_{PRHR,CL}$	$1+\frac{Q_I}{Q_{PRHR}}$
APEX	Natural circulation	1.2 x 10^{-1}	11
	Stagnation	8.0 x 10^{-2}	1
ROSA	Natural circulation	1.8 x 10^{-1}	7
	Transition (single phase)	1.8 x 10^{-1}	3.5
	two phase stratified	9.0 x 10^{-2}	3.5
	Stagnation	9.0 x 10^{-2}	1
CFX	full natural circulation	1.2 x 10^{-1}	11
	Partial natural circulation	1.2 x 10^{-1}	5
	Stagnation	2.1 x 10^{-1}	1
AP600	Natural circulation	1.4 x 10^{-1}	7
	Stagnation	9.5 x 10^{-2}	1

Table 2 - Onset Criteria Data.

Figure 25 - The onset chart developed by Theofanous containing the onset line and data from the CREARE, APEX and ROSA facilities as well as points generated using CFX.

The values calculated for the natural circulation condition clearly lie on the well-mixed side of the figure. This is in agreement with the cold leg #4 thermocouple rake in the OSU APEX and ROSA facilities that show that thermal stratification does not occur when the natural circulation flows are high during the transient. The values calculated for the stagnant cold leg fall on the stratified side of the plot. This is also in agreement with the measured data that shows that two-phase stratification accompanies the stagnation of the cold leg. Most instructive though is the transition point calculated for the ROSA facility that falls very near the onset criteria line, further supporting its credibility as a threshold for stratification. The conditions within the AP600 where estimated and plotted on the chart also. The points show that the AP600 will cross the onset threshold during a LOCA in a manner similar to the experimental facilities, meaning that the AP600 will experience a two-phase stratification period during a

LOCA. The CFX data points were included as well. They show that CFX is reasonably good at predicting the flow conditions in the actual system.

The onset criterion is useful for determining if thermal stratification could possibly occur within a system without performing a detailed experimental or analytical analysis. It does not provide any insight to the degree of stratification though.

6. CONCLUSIONS

A description of thermal stratification in the subcooled blowdown phase of a LOCA and the factors that cause it on both the PRHR and CMT side of the OSU APEX facility was generated. This description showed that the stratification was predominately two-phase. A model was constructed to simulate the thermal hydraulic conditions within the steam generator lower plenum, cold legs and downcomer on the PRHR side of the facility using CFX 4.1, a computational fluid dynamics code. The model was able to predict thermal stratification and also suggested that the cold leg conditions may be non-symmetric. A criterion for predicting the onset of thermal stratification, based on the cold leg Froude number and the ratio of the natural circulation and the PRHR injection flow, was established. This criterion suggests that the AP600 will experience a period of two-phase stratification during a LOCA. The stratification, though, will not increase the risk of a PTS event occurring within the reactor.

7. BIBLIOGRAPHY

1. APEX Testing Facility, NRC-11 Quick Look Report, Corvallis OR, Oregon State University, 1995.
2. Chao, J., ET. Al., Analysis of Mixing With Direct Safety Injection Into the Downcomer Region of a Westinghouse Two-Loop PWR (NSAC-63), Nuclear Safety Analysis Center, EPRI, Palo Alto, California, May 1984.

3. Chen, M. J., ET. Al., Simulation of a Thermal Hydraulic Transient in a Pipe Using the COMMIX-1A Computer Code, Argonne National Laboratory, Argonne, Illinois, February 1980.
4. Chen, M. J., ET. Al., Turbulence Modeling in COMMIX Computer Code, Argonne National Laboratory, Argonne, Illinois, April 1984.
5. Chexal, B., ET. Al., EPRI Research and Application Efforts on Reactor Vessel Pressurized Thermal Shock, EPRI, Palo Alto, California, October 1983.
6. Daly, B. J., Three Dimensional Calculations of Transient Fluid Thermal Mixing in the Downcomer of the Calvert Cliffs-1 Plant Using SOLA-PTS, NUREG/CR-3704, Los Alamos, New Mexico, April 1984.
7. Domanus, H. M., ET. Al., COMMIX-1A: A Single-Phase Computer Program for Thermal Hydraulic Analysis of Single and Multicomponent Systems, Volume II: Assesment and Verification, Argonne National Laboratory, Argonne, Illinois, December 1983.
8. Domanus, H. M., ET. Al., Three-Dimensional Analysis of Thermal and Fluid Mixing in Cold Leg and Downcomer of PWR Geometries, Argonne National Laboratory, Argonne, Illinois, December 1983.
9. Levy, S., An Approximate Prediction of Heat Transfer during Pressurized Thermal Shock, S. Levy Incorporated, Campbell, California, June 1982.
10. Levy, S., Downcomer Annulus Thermal Shock for Beaver Valley Power Station, S. Levy Incorporated, Campbell, California, June 1983.
11. Levy, S., ET. Al., Simplified Predictions of Pressurized Thermal Shock, S. Levy Incorporated, Campbell, California, October 1983.
12. McGriff, R., ET. Al., Analysis in the Cold Leg and Downcomer of a Westinghouse Three-Loop Plant During a SBLOCA (NSAC-62), Nuclear Safety Analysis Center, EPRI, Palo Alto, California, May 1984.
13. Reyes Jr., Dr. Jose N., Low-Pressure Integral Systems Test Facility Scaling Report, Jan 1995, Westinghouse Electric Corporation, Pittsburgh Pennsylvania., 1994.
14. Rothe, P. H., ET. Al., Fluid and Thermal Mixing in a Model Cold Leg and Downcomer with Vent Valve Flow, EPRI, Palo Alto, California, 1982.
15. Rothe, P. H., ET. Al., Thermal Mixing in a Model Cold Leg and Downcomer at Low Flow Rates, EPRI, Palo Alto, California, March 1983.
16. Theofanous, T. G., ET. Al., Decay of Buoyancy Driven Stratified Layers with Applications to Pressurized Thermal Shock (PTS), Purdue University, West Lafayette, Indiana, May 1984.
17. Theofanous, T. G., ET. Al., REMIX: A Computer Program for Temperature Transients Due to High Pressure Injection After Interruption of Natural Circulation, Purdue University, West Lafayette, Indiana, May 1986.
18. Theofanous, T. G., ET. Al., Buoyancy Effects in Overcooling Transients Calculated for the NRC Pressurized Thermal Shock Study, Purdue University, West Lafayette, Indiana, May 1986.
19. Theofanous, T. G., ET. Al., A Unified Interpretation of One-Fifth to Full-Scale Thermal Mixing Experiments Related to Pressurized Thermal Shock, Center for Risk Studies and Safety, University of California at Santa Barbara, April 1991.

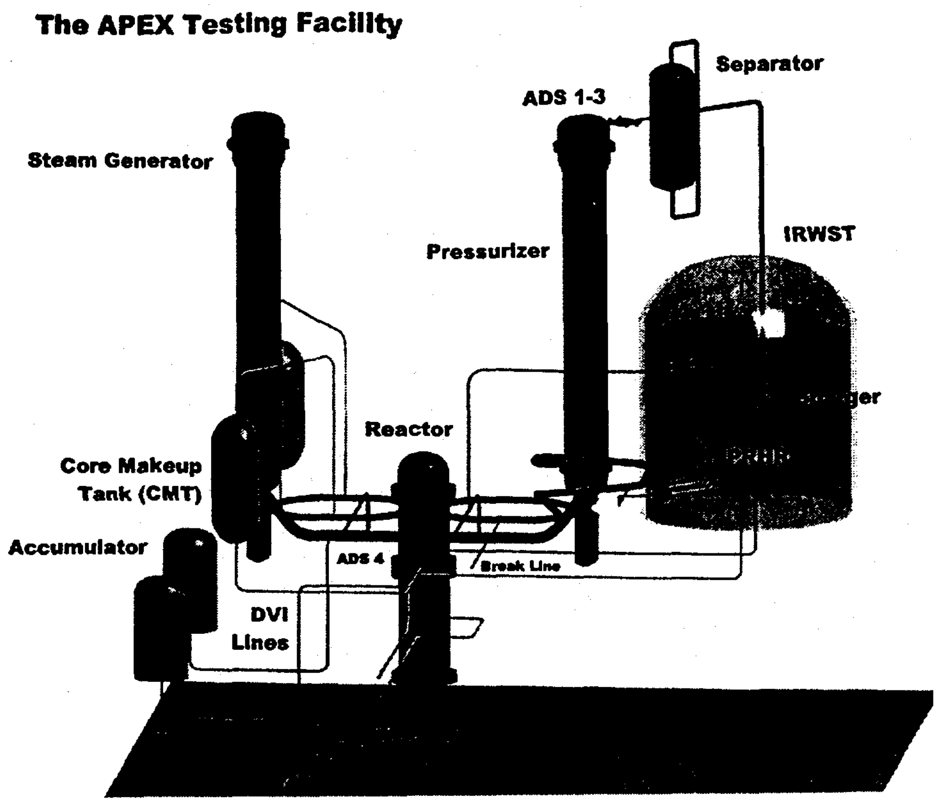

The APEX Testing Facility
Separator
ADS 1-3
Steam Generator
IRWST
Pressurizer
Reactor
Core Makeup
Tank (CMT)
Accumulator
ADS 4
Break Line
DVI
Lines

Fig 1

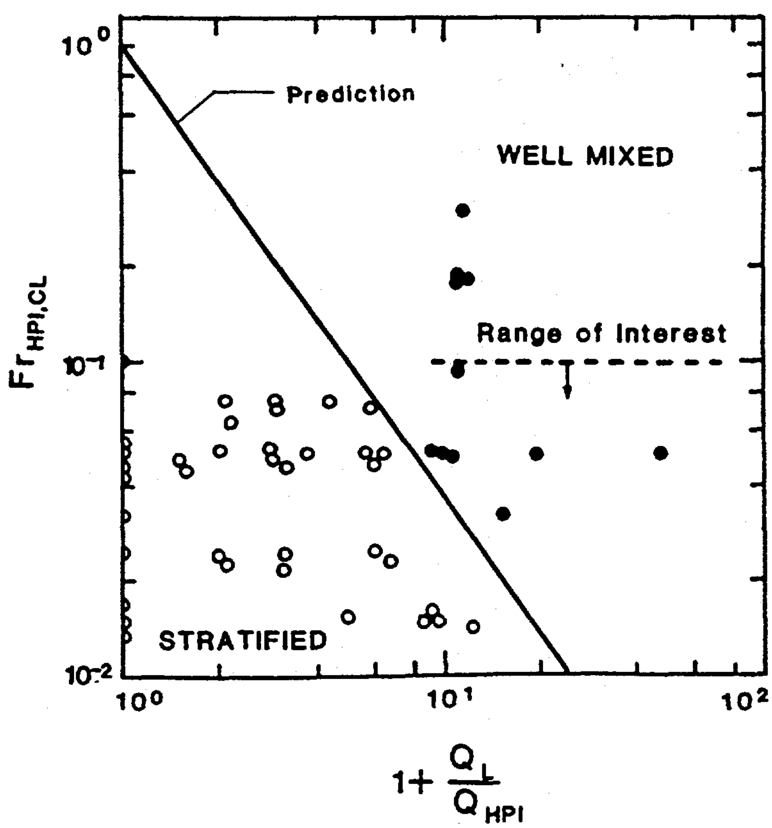

Prediction
WELL MIXED
Range of Interest
STRATIFIED
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
$Fr_{HPI,CL}$
$1+\frac{Q_L}{Q_{HPI}}$

Fig 2

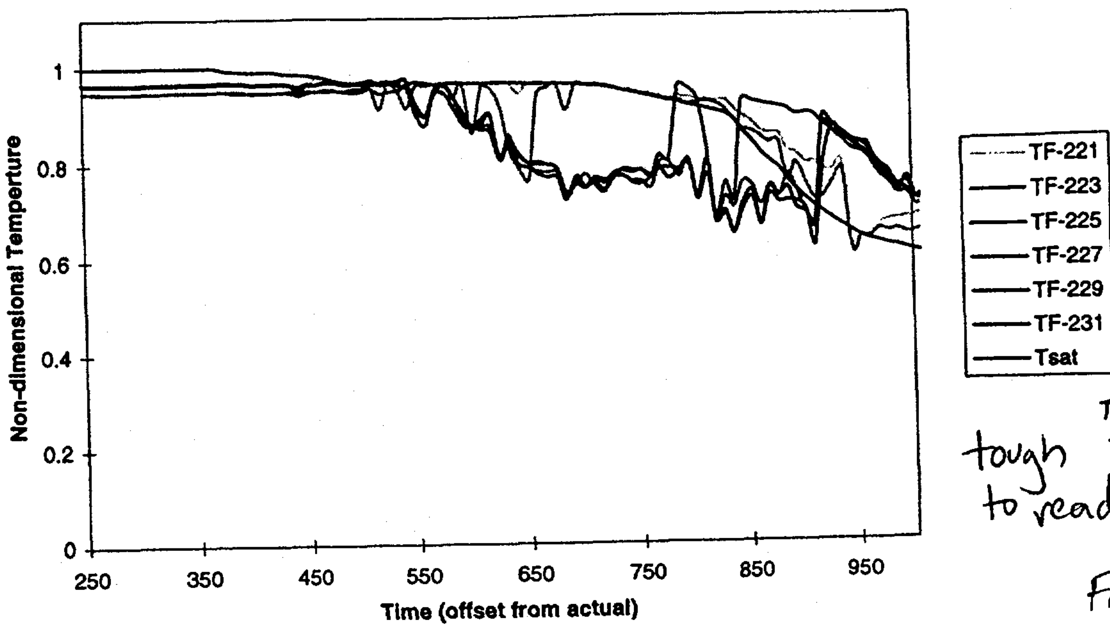

Non-dimensional Temperture
Time (offset from actual)
TF-221
TF-223
TF-225
TF-227
TF-229
TF-231
Tsat
tough to read!
TS

Fig 3

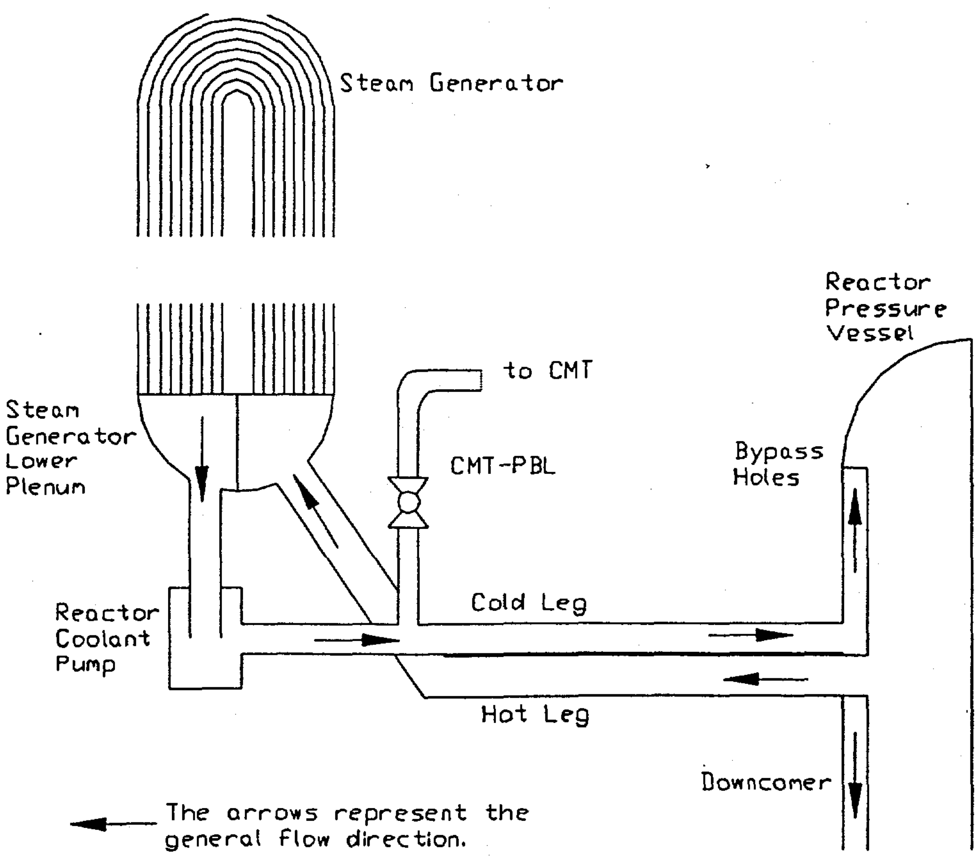

Steam Generator
Reactor Pressure Vessel
to CMT
Steam Generator Lower Plenum
CMT-PBL
Bypass Holes
Cold Leg
Reactor Coolant Pump
Hot Leg
Downcomer
Reactor Core
The arrows represent the general flow direction.

Fig 4

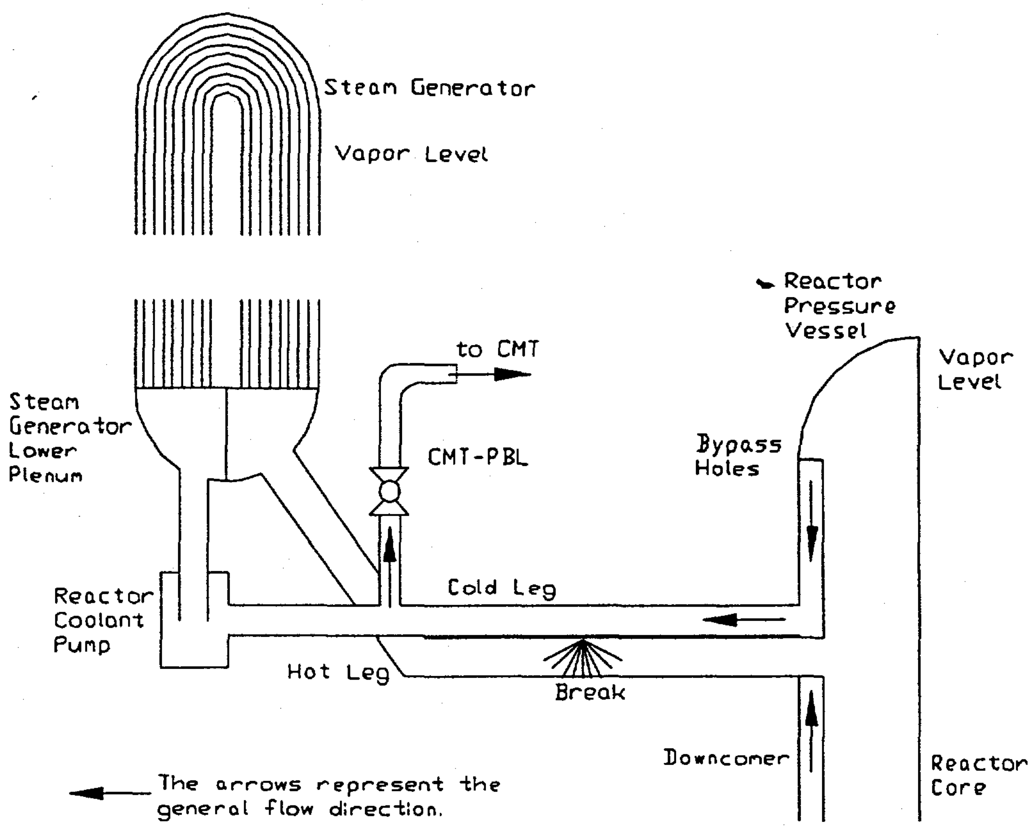

Steam Generator
Vapor Level
Reactor Pressure Vessel
to CMT
Vapor Level
Steam Generator Lower Plenum
CMT-PBL
Bypass Holes
Reactor Coolant Pump
Cold Leg
Hot Leg
Break
Downcomer
Reactor Core
The arrows represent the general flow direction.

Fig 5

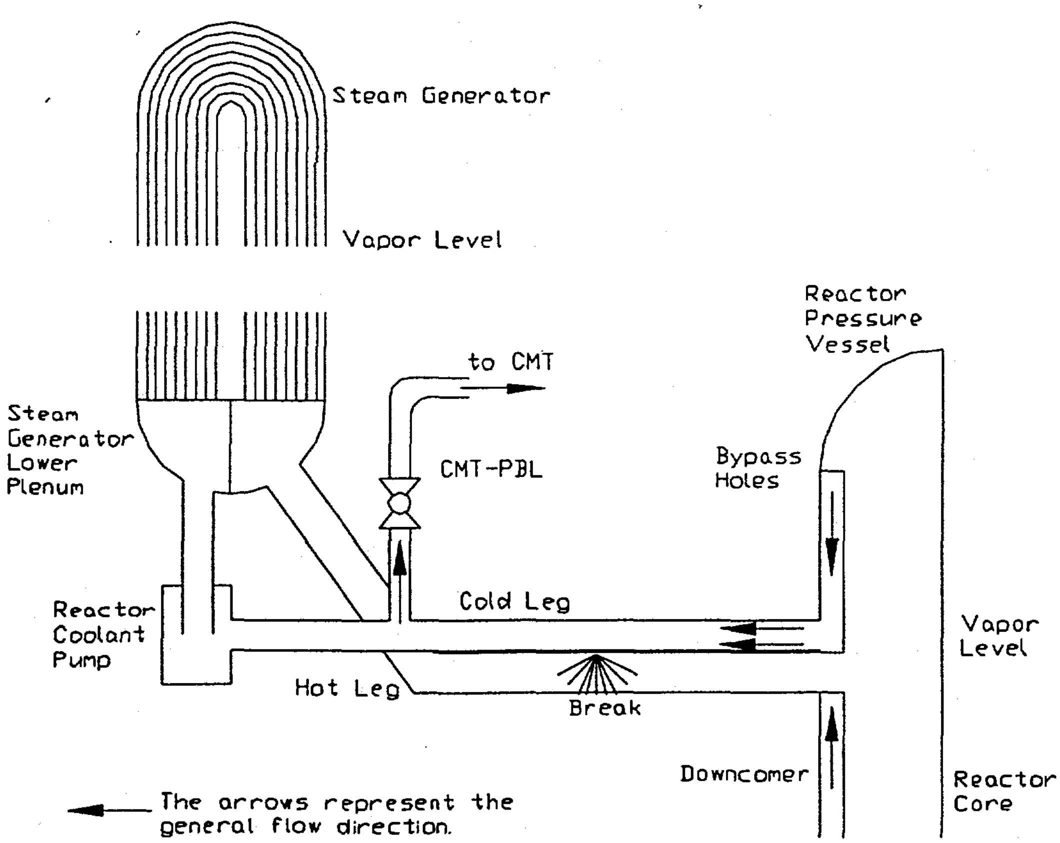
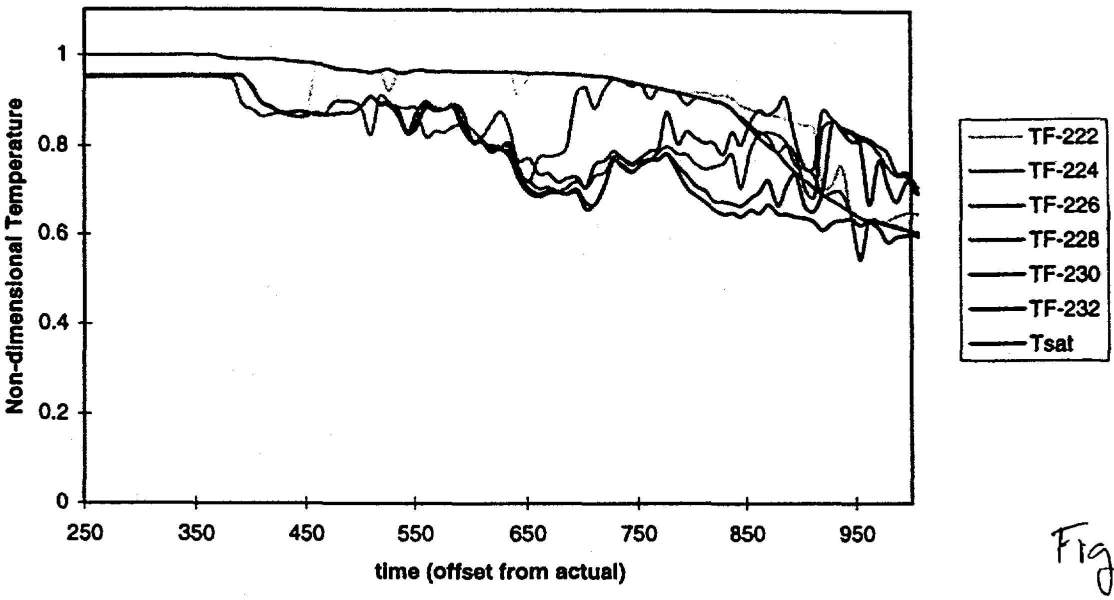
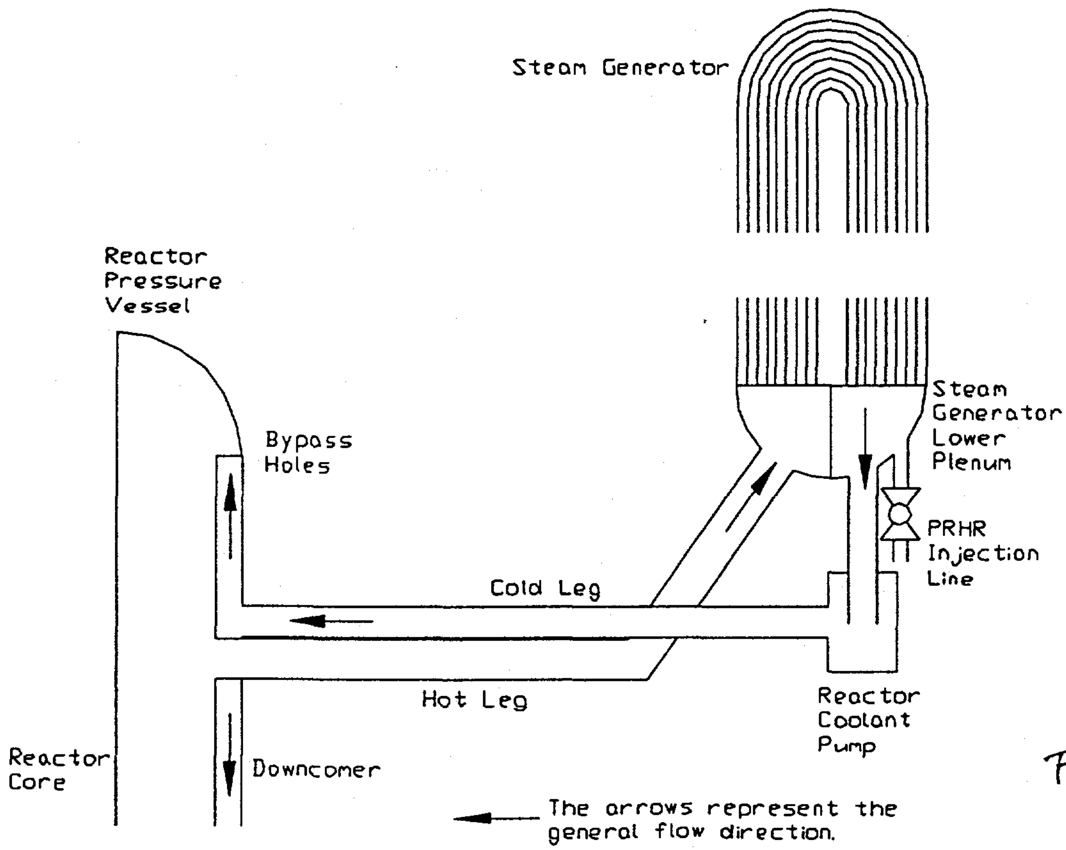

Steam Generator
Vapor Level
Reactor Pressure Vessel
to CMT
Steam Generator Lower Plenum
CMT-PBL
Bypass Holes
Cold Leg
Reactor Coolant Pump
Vapor Level
Hot Leg
Break
Downcomer
Reactor Core
The arrows represent the general flow direction.

Fig 6



1
0.8
0.6
0.4
0.2
0
250
350
450
550
650
750
850
950
Non-dimensional Temperature
time (offset from actual)
TF-222
TF-224
TF-226
TF-228
TF-230
TF-232
Tsat

Fig 7



Steam Generator
Reactor
Pressure
Vessel
Bypass
Holes
Steam
Generator
Lower
Plenum
PRHR
Injection
Line
Cold Leg
Hot Leg
Reactor
Coolant
Pump
Reactor
Core
Downcomer
The arrows represent the
general flow direction.

Fig 8

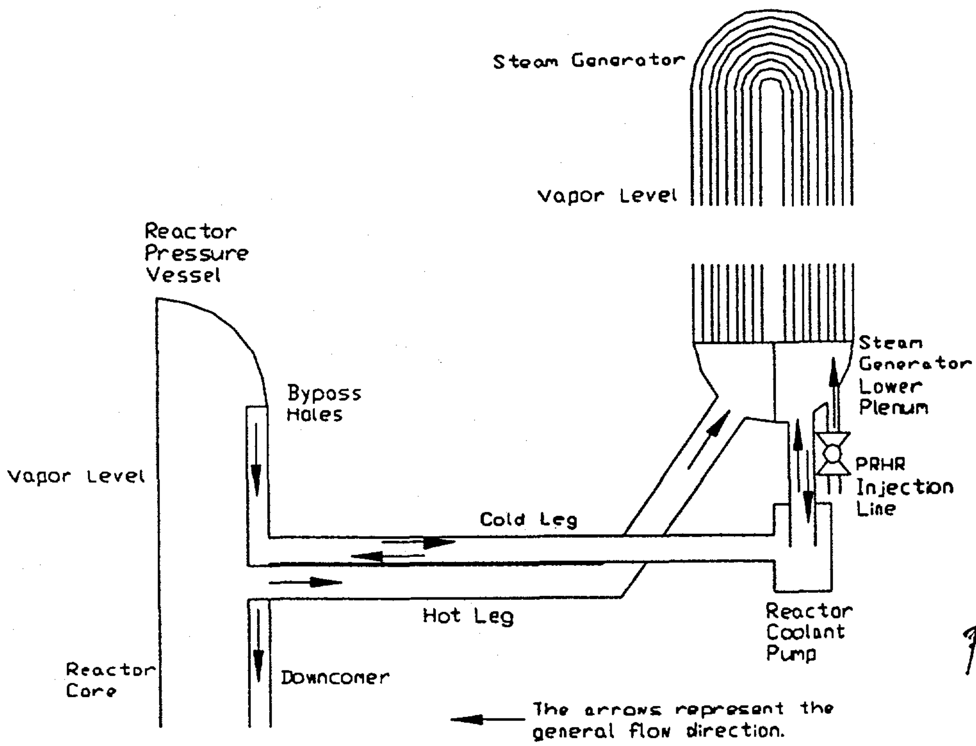

Steam Generator
Vapor Level
Reactor
Pressure
Vessel
Bypass
Holes
Steam
Generator
Lower
Plenum
PRHR
Injection
Line
Vapor Level
Cold Leg
Hot Leg
Reactor
Coolant
Pump
Reactor
Core
Downcomer
The arrows represent the
general flow direction.

Fig 9

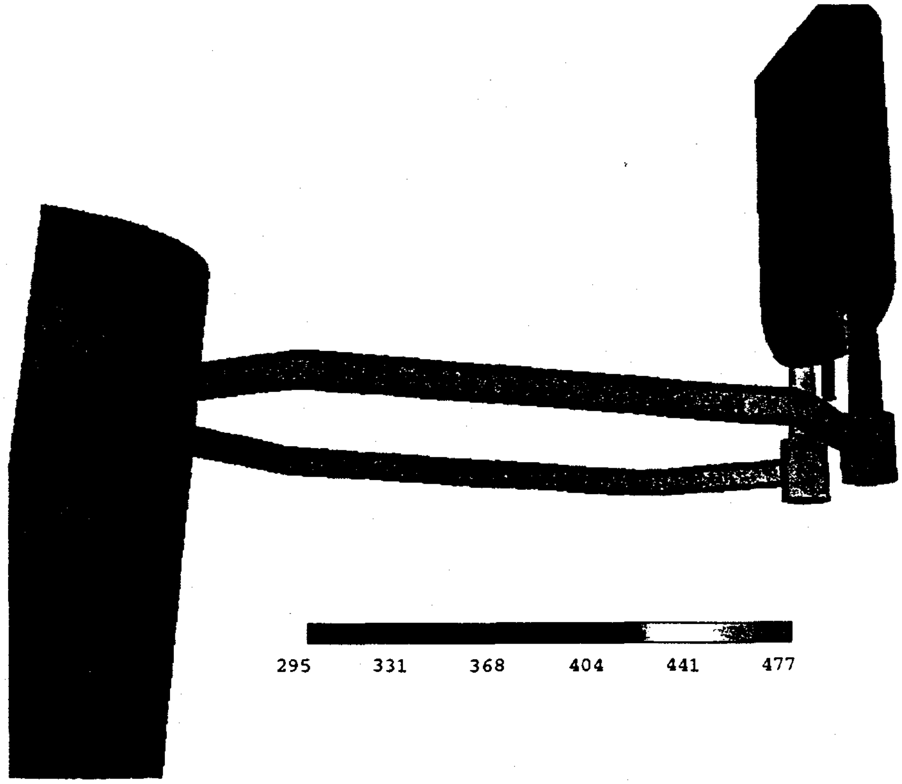

295
331
368
404
441
477

Fig 10

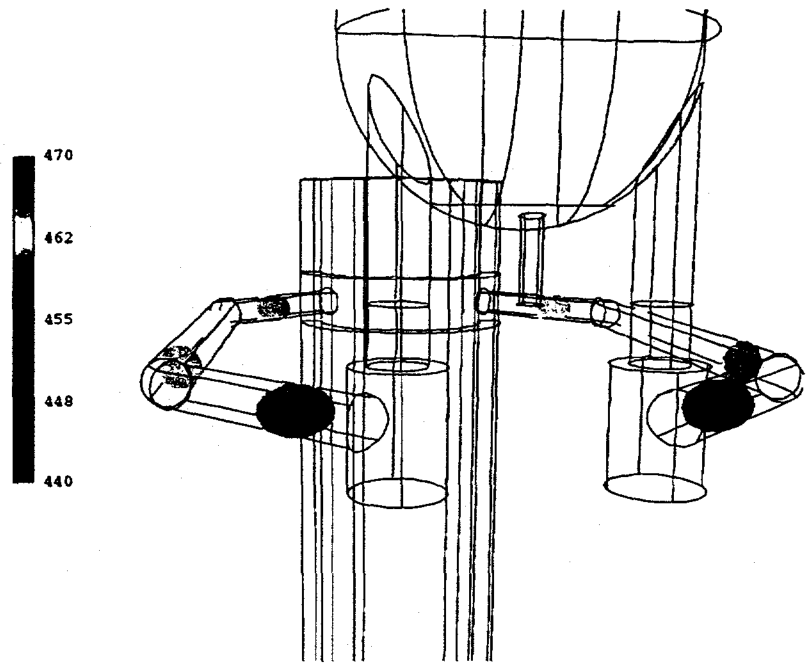


Fig 11

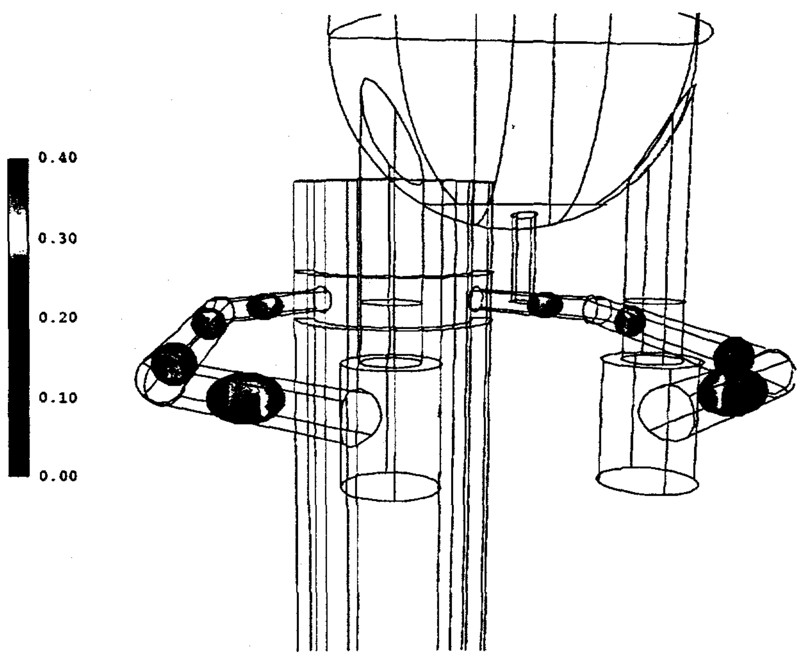


Fig 12

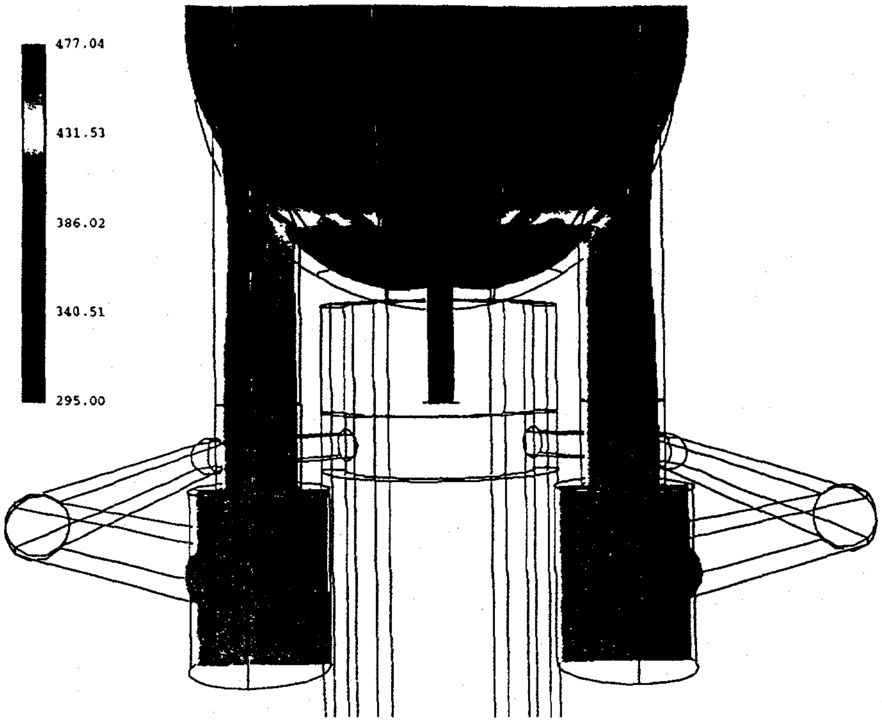


Fig 13

104

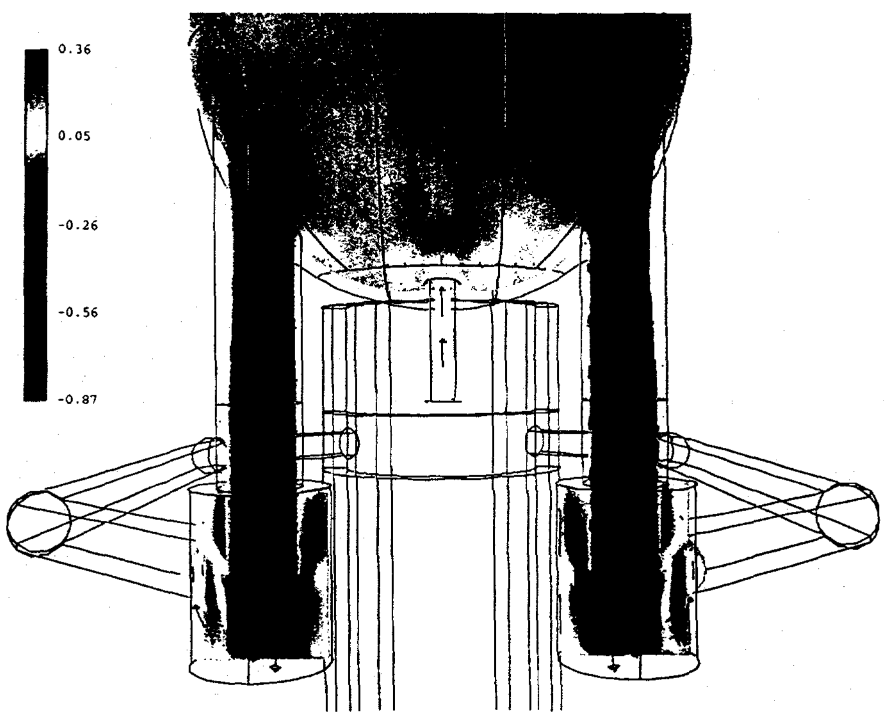


Fig 14

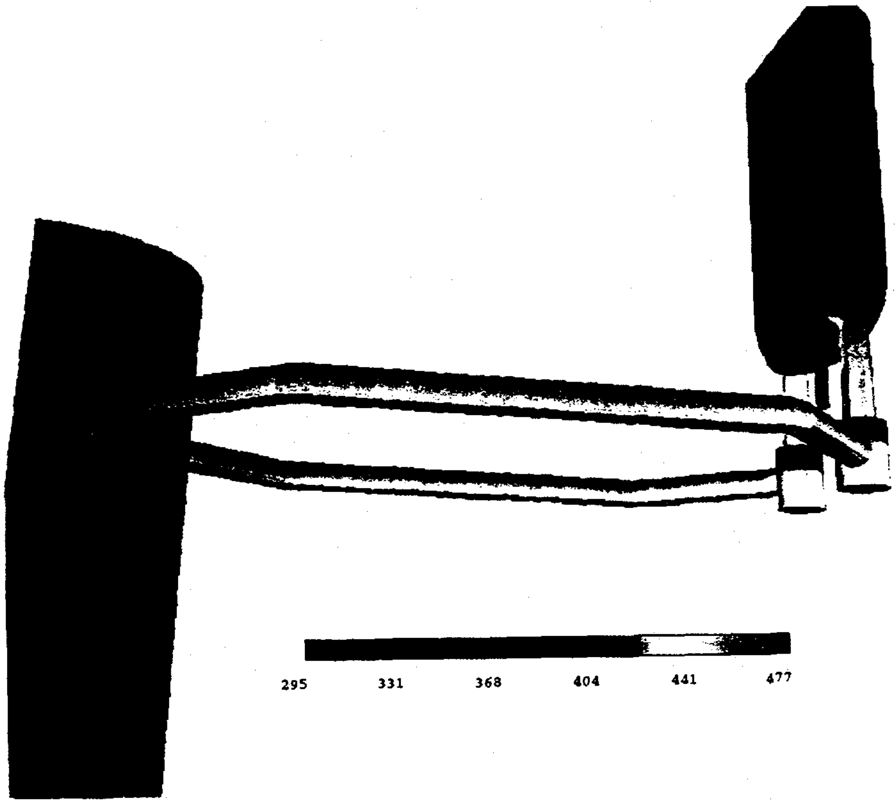


Fig 15

106

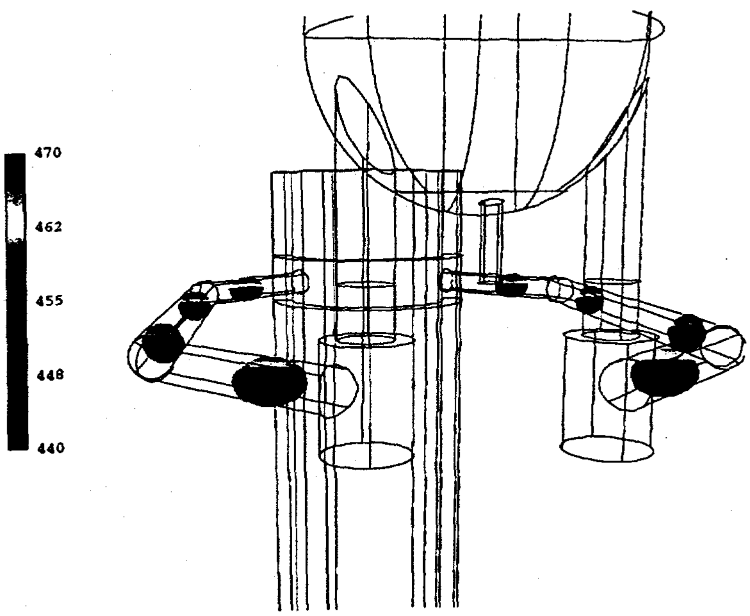


Fig 16

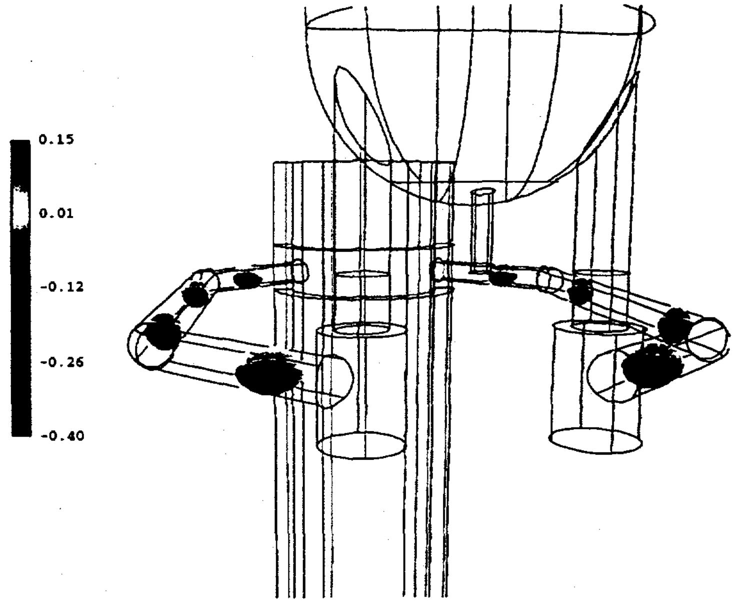


Fig 17

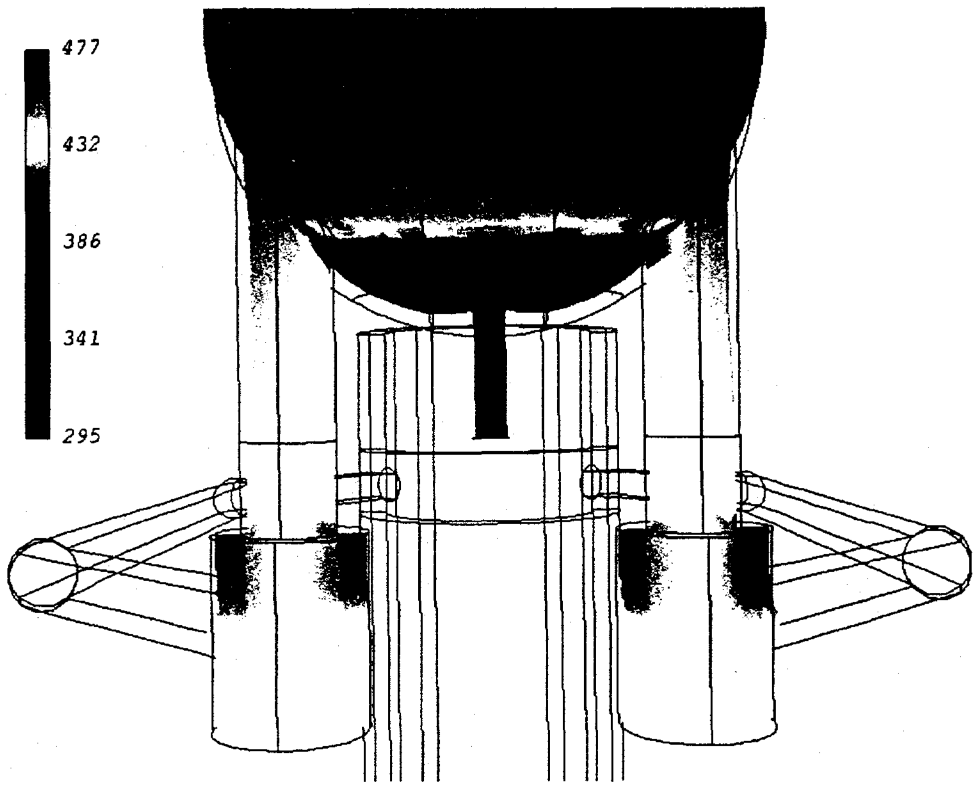


Fig 18

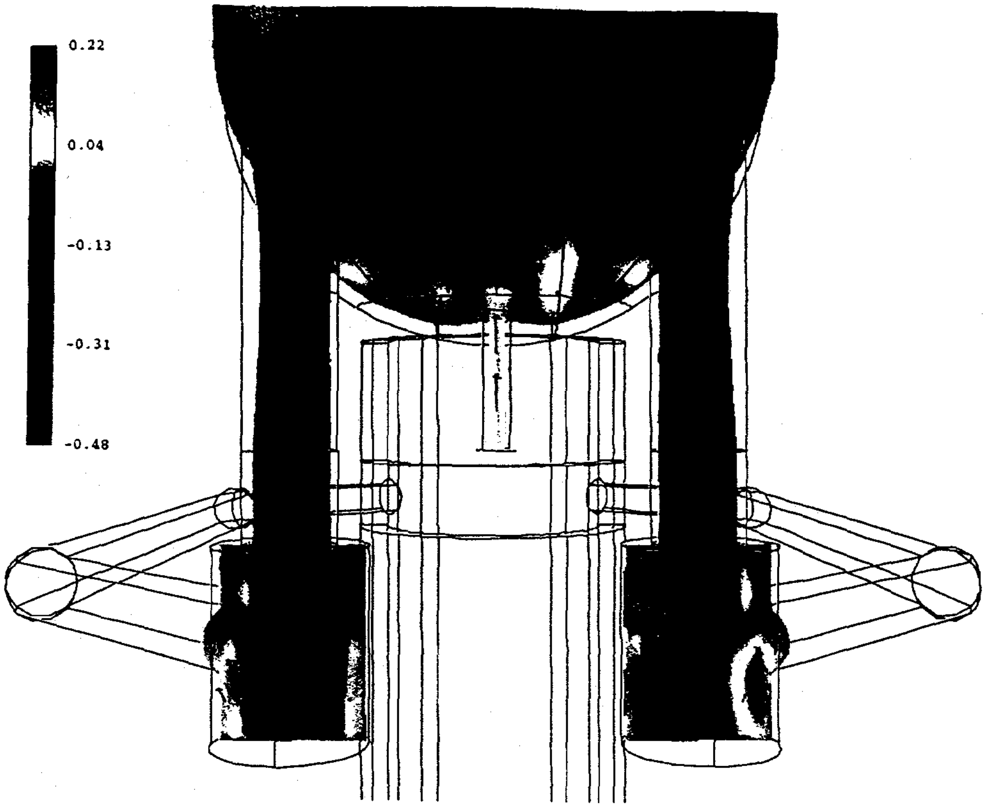


Fig 19

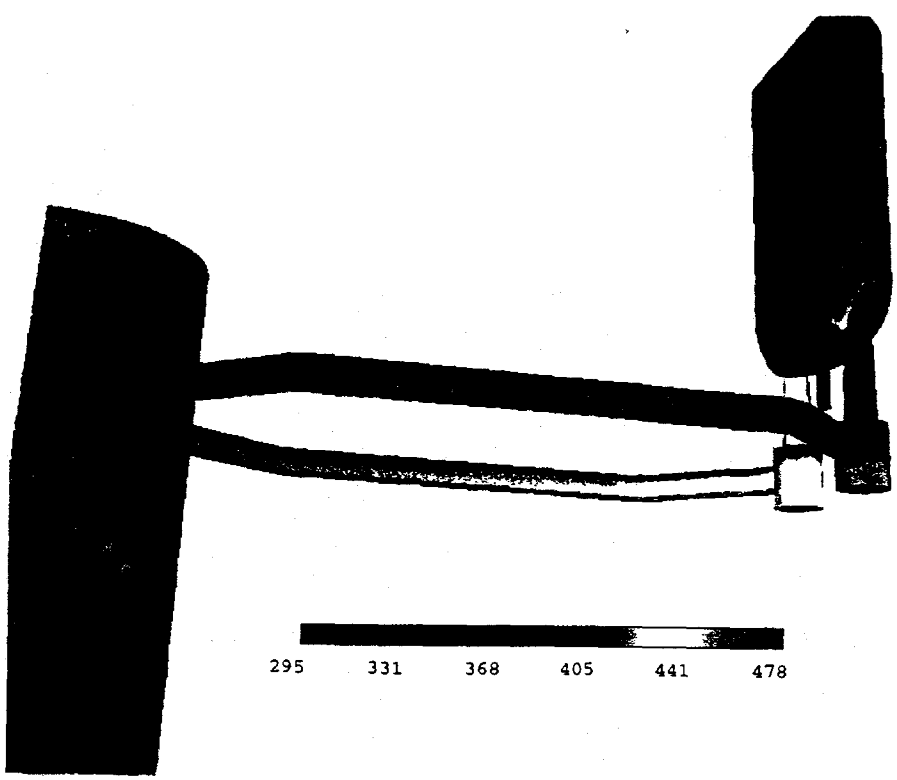


Fig 20

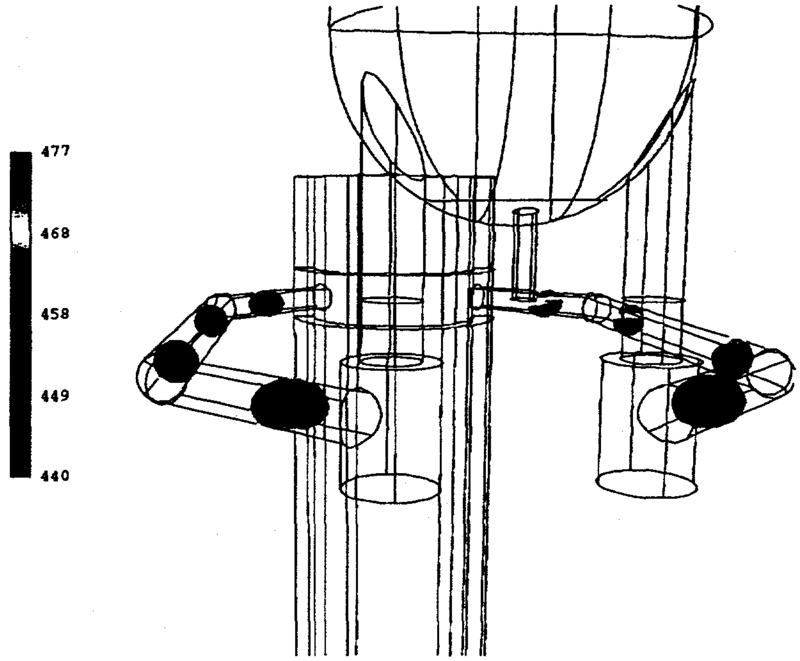


Fig 21

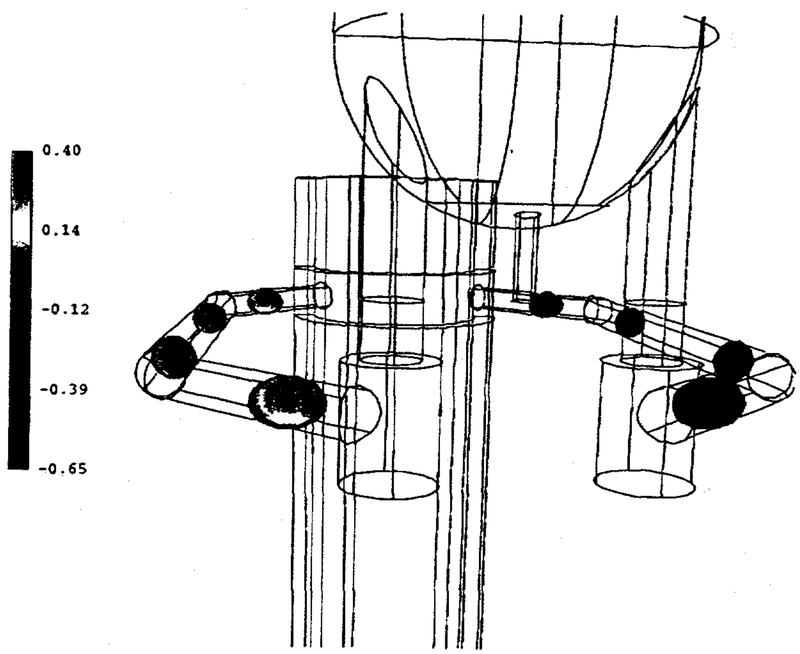


Fig 22

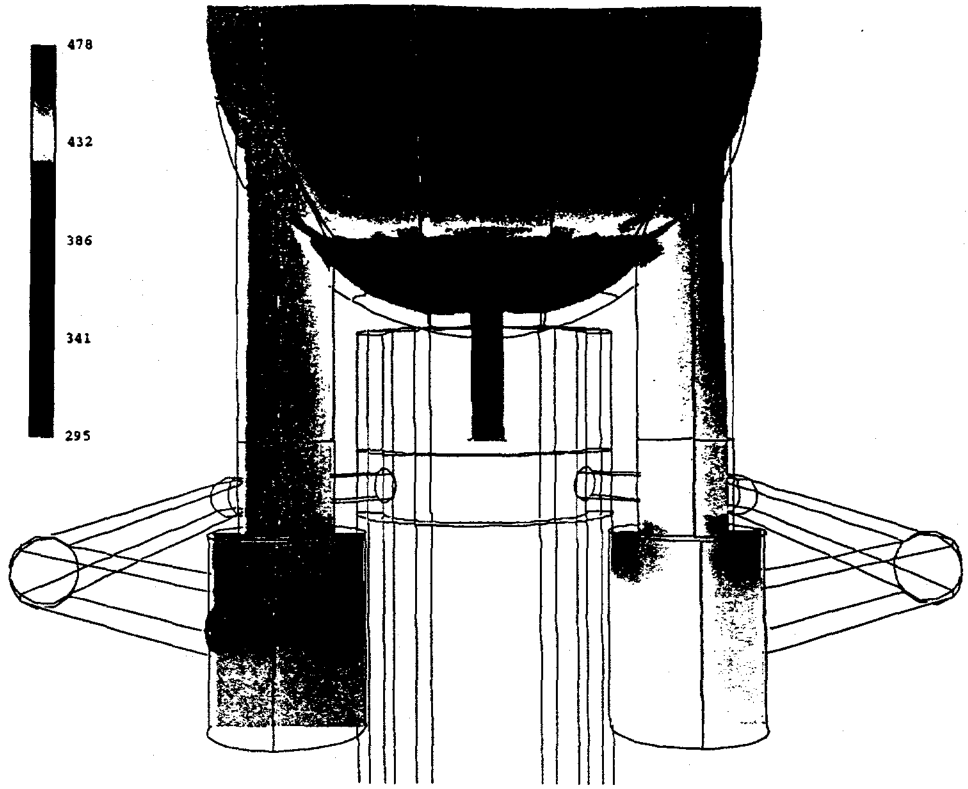


Fig 23

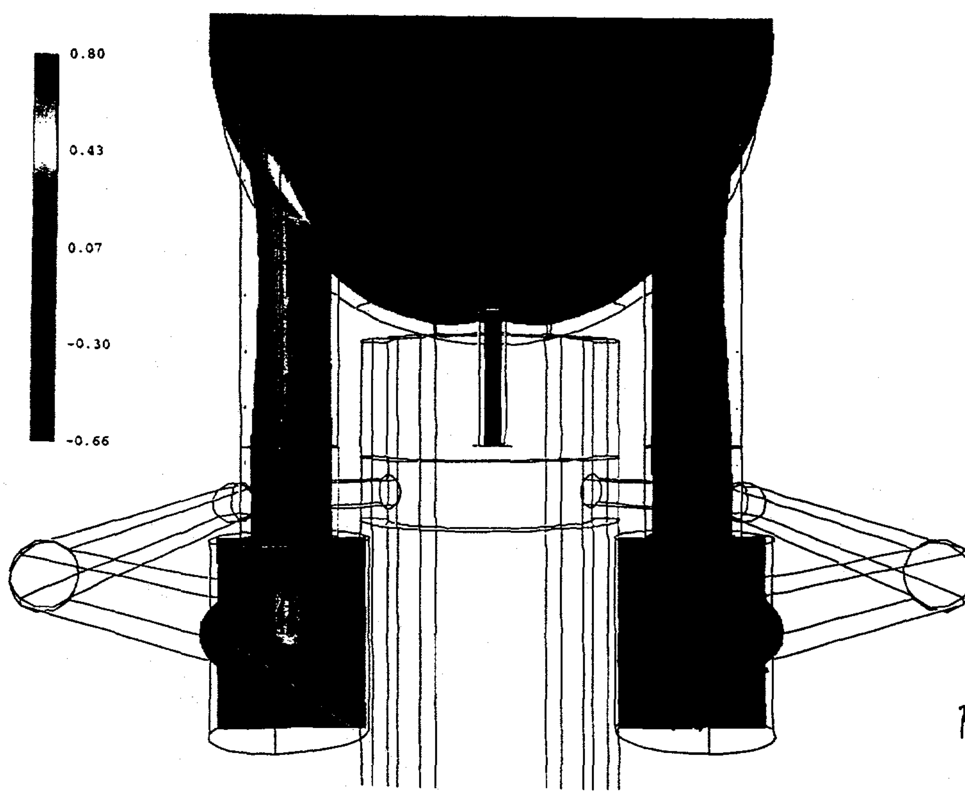
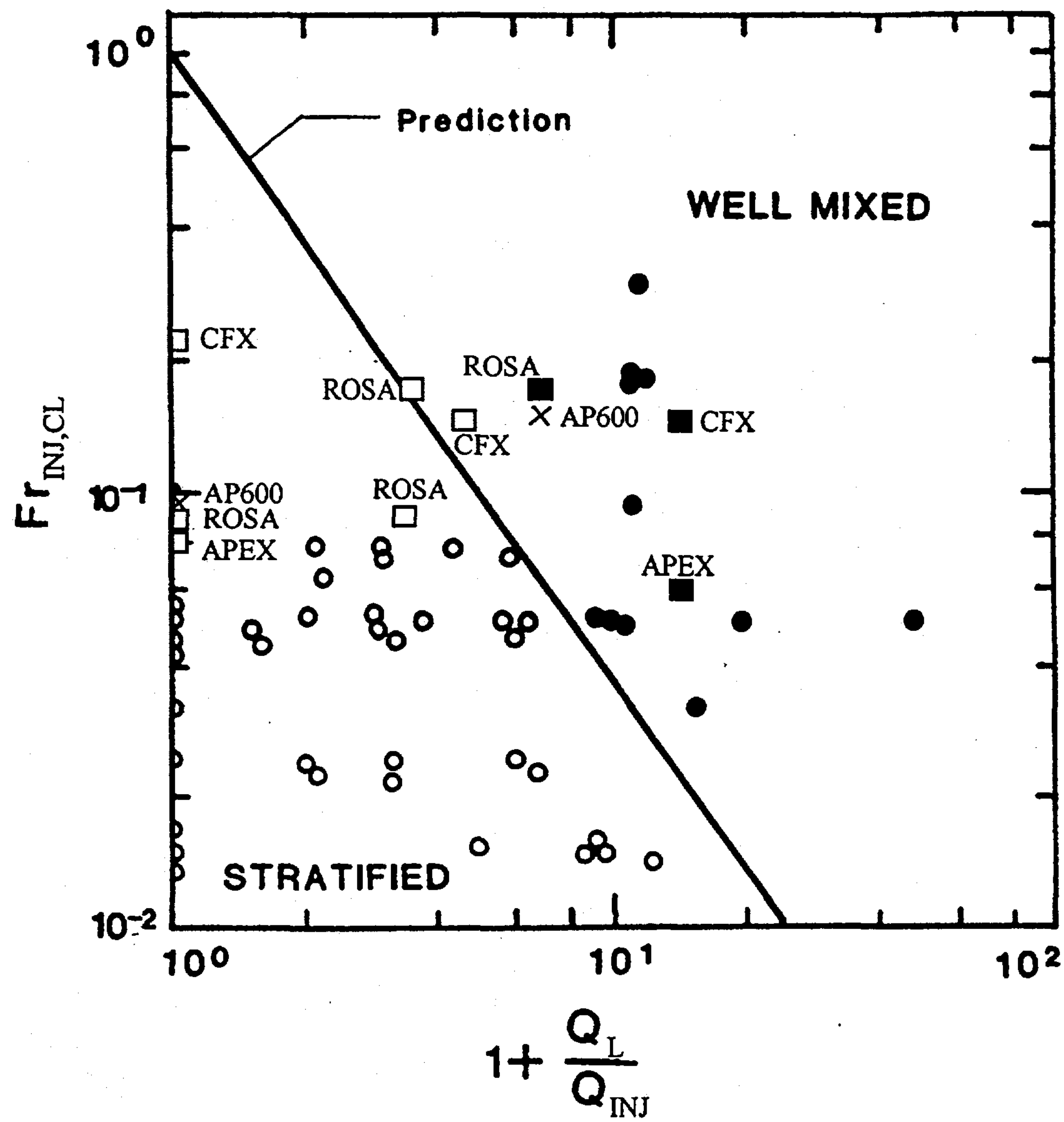


Fig 24


Prediction
WELL MIXED
STRATIFIED
CFX
ROSA
CFX
ROSA
X AP600
CFX
AP600
ROSA
APEX
ROSA
APEX
10^0
10^{-1}
10^{-2}
10^0
10^1
10^2
$Fr_{INJ,CL}$
$1+\frac{Q_L}{Q_{INJ}}$