COMPARISON OF FIREBIRD III MOD1-77 AND CATHENA CODE SIMULATIONS OF A 100 PERCENT REACTOR OUTLET HEADER BREAK

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ABSTRACT

The objective of this study was to compare the predictions of a homogeneous thermalhydraulic code (FIREBIRD-III MOD1) with an advanced two-fluid code (CATHENA) for a postulated CANDU LOCA scenario, a 100% ROH break with pumps running. A CATHENA model was generated to resemble, as closely as possible, the existing FIREBIRD-III MOD1 model for the CANDU-600 reactor. Simulations were performed with each of the codes to 200 seconds using H_2O as coolant in the primary heat transport system, as H_2O will dominate after emergency core coolant injection following the short blowdown phase. FIREBIRD and CATHENA simulation results are compared, with emphasis placed on how the two codes model thermalhydraulic non-equilibrium effects associated with cold water injection into steam.

There are differences in predicted refill of the broken (non-critical) core pass, due to the treatment of cold injection water mixing in the inlet header with hot fluid from the steam generator. For the critical core pass, the agreement in the refill predictions between the two codes is very good.

1.0 INTRODUCTION

Most postulated loss of coolant accident (LOCA) thermalhydraulic analysis performed to date, has utilized computer codes using a homogeneous assumption for fluid flow. FIREBIRD-III MOD1, used for such analysis, solves the one-dimensional, homogeneous, thermal equilibrium fluid flow conservation equations. This is expected to give good results when the phase velocities are nearly equal and both phases are well mixed, and when the local temperature differences between the liquid and vapour phases are small. FIREBIRD-III MOD1 includes features to address the problem of cold water mixing with steam, in particular correlations for slip and drift, and property smoothing for unequal temperatures effects.

The two fluid code CATHENA has been developed at the Whiteshell Nuclear Research Establishment by Atomic Energy of Canada. CATHENA uses a full two-fluid representation of fluid flow in a piping network, or circuit. This results in a model in which the liquid and vapour phases may have different pressures, velocities, and temperatures. Interphase mass, energy and momentum transfer (e.g., condensation, boiling, interphase shear) are specified using constitutive relations obtained from the literature. These have been validated using separate effects tests, components tests, and integral tests.

This study was commissioned by New Brunswick Power and Hydro Quebec to compare a homogeneous simulation (FIREBIRD) of a CANDU LOCA scenario to a two-fluid simulation (CATHENA). The scenario chosen for this study was a 100% break at a reactor outlet header, with pumps operating during the transient. This scenario has been identified as being one of the limiting critical break scenarios in terms of Emergency Core Cooling System effectiveness for the Gentilly-2 and Point Lepreau Stations. A FIREBIRD model already existed for this event, and a CATHENA model was generated to resemble, as closely as possible, the FIREBIRD model. The simulations were performed with H_2O as the coolant in the heat transport system. This is done because emergency core coolant injection occurs early in the transient, filling the system with H_2O.

2.0 ANALYSIS METHODS, MODELS AND ASSUMPTIONS

A large break in the primary circuit is characterized by a rapid blowdown for one of the two heat transport system loops, causing rapid core voiding and a subsequent reactor power rise. A prompt reactor trip is initiated by the neutronic parameters-high power, and high rate log power. In a few seconds, the broken loop starts to refill quickly with high pressure emergency core coolant. Loop isolation prevents significant inventory loss from the unbroken loop.

The network models represent the heat transport system and Emergency Core Cooling System network of a CANDU 600 station, shown schematically in Figure 1. The analysis included comparisons of predictions for both heat transport loops, and the secondary circuit. Comparisons for the broken loop only are presented in this paper.

A break, 0.26 m^2 in area corresponding to twice the header cross-sectional area, is modelled in reactor outlet header number 3, which is connected to the pressurizer.

For this break, there will be stagnation in the fuel channels between headers 4 and 1 (critical pass). The reactor power transient following the break was imposed as a boundary condition. Reactor trip is assumed to occur on the backup SDS1 parameter (high rate log power); with the 2 most effective shutoff rods assumed unavailable. The signal to isolate the two heat transport system loops is assumed to occur based on the system design with low header pressure as a parameter. In addition to low header pressure, injection and steam generator crash cooldown require a conditioning signal, which for a large break is provided by high reactor building pressure (about one second after the break).

The heat transport pumps are assumed to operate throughout the transient. Feedwater flow to the steam generator is controlled throughout the transient by Boiler Level Control logic. Unloading of the turbine in response to reactor trip and subsequent falling secondary side pressure is also modelled according to Boiler Pressure Control logic, and Electrohydraulic Governor control.

FIREBIRD-III MOD1 is a general network code developed primarily for predicting the thermalhydraulic behaviour of CANDU reactor power plants during postulated loss-of-coolant accidents and the subsequent emergency coolant injection period. Because of its generality, the code can also be used to solve a large variety of general flow network problems for both light and heavy water. In the code, a set of user routines is provided which allows the user to program various boundary conditions and control logic for a given problem. The code then couples these boundary conditions and control logic with its fluid flow conservation equations, fluid state equations, and heat conduction equation to form the governing equations for the system being analyzed.

The FIREBIRD-III MOD1 representation of the circuit (Figure 2) models both heat transport system loops, the loop to loop connections via the pressurizer, D_2O feed, and purification circuit as well as the reactor outlet header interconnect pipe.

The CATHENA model (Figure 3) was created with the objective of representing the FIREBIRD-III-MOD1-77 model as closely as possible. Thus differences in predictions between the two codes could be attributed to two-fluid versus homogeneous representation of fluid flow.

The CATHENA code is an advanced two-fluid thermalhydraulic code, developed by Atomic Energy of Canada, Whiteshell Nuclear Research Establishment. It is a general network code developed primarily for analysis of postulated upset and LOCA scenarios in the CANDU system. CATHENA can model fluid flow of light water and heavy water with and without a non-condensible component in the vapour phase. CATHENA uses a full two-fluid representation of fluid flow in a piping network, or circuit. Conservation equations are solved for mass, energy, and momentum in the liquid and vapour phase (the vapour phase may include a non-condensible component). This results in a 6-equation (7-equation with noncondensible) model in which the liquid and vapour phases may have different pressures, velocities, and temperatures.

3.0 RESULTS

3.1 Event sequence

The simulations were conducted for 200 seconds covering the periods of blowdown and refill of broken loop fuel channels with high pressure emergency core coolant.

The core power transient associated with the 100 percent ROH break was input to each code. Thus trip times are implicitly the same. The loop isolation and injection signals (5.5 MPa(a) in two of three instrumented headers of the broken loop) occur at 6.3 seconds in FIREBIRD and 5.0 seconds in CATHENA. This difference in the initial depressurization rates can be attributed to slightly higher initial stored energy in the broken loop for the FIREBIRD steady state. Injection to the broken loop begins at 15 seconds in FIREBIRD and 13 seconds in CATHENA. This is consistent with the differences in loop isolation signal timing. The simulations were terminated before injection to the unbroken loop and the onset of medium pressure injection. The intact loop remains well cooled with sufficient inventory and running pumps.

3.2 Break Discharge

The predicted break discharge flows and enthalpies are compared in Figures 4 and 5 respectively. Flows are very similar for the first 30 seconds. From about 30 to 50 seconds, the FIREBIRD prediction increases to about twice the CATHENA prediction, due to slightly higher pressure, and an earlier decrease in void as injection water enters the header.

The CATHENA discharge rate continues to decrease until about 45 seconds when the header starts to refill. Emergency core coolant that had been injected into inlet header 2 for the past 30 seconds had been accumulating in the channels and inlet feeders. With the partial head recovery of the downstream pump at 40 seconds comes an increase in pressure at inlet header 2, forcing flow through the channel and up into the broken outlet header. A spike in discharge flow rate and pressure between 50 and

60 seconds occurs as the header becomes liquid filled. The header quickly voids again and the mass discharge rate and pressure decrease. A second smaller spike in flow occurs as some remaining liquid held up in the outlet feeders reaches the outlet header. A more stable discharge rate then develops, with a drop at about 90 seconds, when the pump head degrades.

3.3 Pump Head in the Broken Loop

Both FIREBIRD and CATHENA predictions show pump 2 downstream of the break acting like a check valve preventing reverse flow to the break. Although the timing of events is slightly different, both codes indicate similar transient pump head (Figure 6). Immediately following the break, a sharp rise in pump head from 1.5 MPa (normal operating conditions) to about 3.0 MPa is a result of the rapid depressurization upstream of the pump. As fluid begins to flash, the pump head degrades over the next 30 seconds (FIREBIRD) to 40 seconds (CATHENA). Partial pump head recovery thereafter results from injection at inlet header 4. Because pump head is determined from upstream and downstream conditions at low flows, the refilling of inlet header 4 causes a partial head recovery. The 10 second difference in partial head recovery is due to small but sensitive differences in nodalization at the pump discharge.

Pump 1 (Figure 7), upstream of the broken pass, exhibits behaviour quite different from pump 2 in that the flow is pulled through the pump in the forward direction. The early pump head loss (2 seconds) results from the sudden pressure drop at the discharge of the pump due to a sudden increase in flow toward the break. A pressure recovery occurs as flashing downstream near the break reduces the break discharge rate and slows the flow through pump 1. Final head degradation occurs at 10 seconds as flashing at the pump occurs. Up to this point, both codes predict identical results. After this point in time, both codes agree that fluid continues to be pulled through the pump. The amount of fluid and the quality of that fluid is different between the two predictions resulting in different calculated heads. These differences would be expected because of differences between the homogeneous and two-fluid calculations.

3.4 Broken Loop Pressure

For header 3, the broken header, the two code predictions are nearly identical (Figure 8), with small differences associated with the head produced by the downstream pump (pump 2). The difference in predicted head of pump 2 shows a greater effect on pressure transients in the other 3 broken loop headers (Figure 9 compares pressures in inlet header 2).

There is good agreement between both codes for about 20 seconds, at which point the head of pump 2 increases in the FIREBIRD prediction, thus slowing the depressurization. In the CATHENA prediction, header pressure continues to fall until the head of pump 2 partially recovers around 40 seconds.

The increase in header pressures also causes a decrease in injection flows. In inlet header 2, a lower cold injection flow with an increased flow of hotter fluid from boiler 1 enhances the circuit pressure rise at 45 seconds in the CATHENA prediction.

After 50 seconds, the two code predictions are nearly identical except for a brief period of increased pressure in the CATHENA prediction from 70 to 90 seconds; again due to an increased steam flow through boiler 1. When pump 2 head degrades again, flow from boiler 1 decreases, such that the continued injection of cold ECCS water to inlet header 2 causes rapid condensation and the pressure falls again. Both codes subsequently predict a near steady pressure until the end of the simulation.

3.6 Refill of the Broken Core Pass

This core pass refills in the forward direction with injection to inlet header 2 mixing with warmer fluid from steam generator 1, then passing through the channels to the break.

The differences between homogeneous and two-fluid modelling are illustrated most strikingly in the comparison of coolant void fraction in inlet header 2 (Figure 10). FIREBIRD predicts rapid header refill by 20 seconds, after the initial voiding caused by loop depressurization. This occurs immediately after injection to this header begins. At 20 seconds, FIREBIRD predicts an injection flow of 210 kg/s, and a flow from the pump of 600 kg/s with a void fraction of 0.6; refill occurs very rapidly under these conditions in a homogeneous code calculation.

Up to 20 seconds, the CATHENA prediction is very similar to the FIREBIRD prediction. A 10 second delay in reducing header void, (30 vs. 20 seconds) is due to the time required for interphase condensation to occur in the CATHENA prediction. In the CANDU 600 design, the injection flow mixes with flow in one of the two pump discharge pipes. Hot fluid from the boiler enters the other turret via the second pump discharge pipe. The cool mixture, possibly totally liquid, from one turret mixes in the inlet header with the hot fluid from the other turret. Under these conditions CATHENA predicts void to persist in the header throughout the transient. For most of the transient, this fluid condenses further downstream, in the feeders. Evidence of this is seen in Figure 12, which shows liquid only at the centre of the core.

There is however, a period of time (40 to 90 seconds) when CATHENA predicts header 2 and the core to become highly voided. This corresponds to the increase in the predicted head of pump 2, which raises pressure in headers 1, 4 and 2, thus decreasing ECCS flow to all three headers. With reduced injection flow, and increased vapour flow from the boiler, the condensation rate is not sufficient to prevent re-voiding of the header. Hence, void becomes very large in the two-fluid code treatment. Under similar conditions of pump head, FIREBIRD's homogeneous model does not lead to regeneration of void. Eventually, when the CATHENA predicted pump 2 head drops at 90 seconds, the earlier conditions for mixing redevelop, and most of the steam in header 2 condenses. A small void is predicted to persist until the end of the transient as steam flow into the header persists. This void is condensed in the inlet feeders as evidenced by the lack of void in the channel after 90 seconds.

Figure 12 compares flow at the centre of the broken pass. Both code predictions indicate that fuel cooling is adequate in this pass. For about 30 seconds, the flows compare well. These are highly voided two phase flows, but large enough to prevent stratification. The increases in flow at 20 seconds for FIREBIRD and at 35 seconds for CATHENA reflect the increased inlet header 2 pressure caused by the head recovery in pump 2. The CATHENA flow continues to increase as single phase liquid is pulled through the channel towards the break. The mass flow rate decreases quickly as the channel is filled with steam, suddenly dropping when break flow increases. CATHENA predicts a second stagnation is predicted at 85 seconds lasting for 10 seconds. In the long term, both codes predict a liquid flow of about 500 kg/s for the core pass, or 5 kg/s per channel.

3.7 Refill of the Critical Core Pass

In both simulations, this core pass is predicted to refill slowly in the forward direction (Figure 13) from injection to inlet header 4, after a period of early flow stagnation. The head produced by pump 2 has a pronounced effect on refilling of this pass, since the pump head directly controls pressure in both headers, thus controlling injection flow.

Void in inlet header 4 is predicted to condense at about 20 seconds in both code simulations, as seen in Figure 14. In this case, the cold water injected at header 4 condenses only the steam already present in the header, feeders and channels. There is no flow from pump 2; it actually acts as a check valve to prevent reverse flow. Once the steam in inlet header 4 has condensed, there is no further source of steam, so the header remains liquid for the remainder of the transient. Under these refill conditions, the homogeneous and two-fluid model results are identical. These conditions are quite different from those in the broken pass, where cold injection flow mixed with a significant hot two-phase flow from the boiler.

The code predictions of void in the core of the critical pass (Figure 15) are also similar. Prior to refill, FIREBIRD predicts a period of pure steam flow, while CATHENA indicates the presence of both liquid and steam with a void fraction varying from 0.5 to 0.9. The flow is low enough to be stratified. Both models predict rapid core refill at about 80 seconds. Subsequently, except for two brief periods of re-voiding in the CATHENA prediction, the channel remains liquid filled in both simulations.

4.0 CONCLUSIONS

FIREBIRD assumes that the liquid and vapour phases are both at saturation. CATHENA allows the two phases to have different temperatures (boiling/condensation will minimize the difference). Injection of cold ECI liquid into steam filled regions will therefore be treated differently between the two codes. This effect was found to contribute either directly or indirectly to most of the differences seen between the two code predictions.

Some differences in code predictions are attributed directly to these effects, for example the difference in void fraction in headers. They also lead to different conditions in circuit components which have further effects on other results. For example, differences in predicted pump discharge density results in differences in calculated pump head, which leads to differences in header pressures, and injection flows.

In the broken core pass, where cold injection water mixes with hot fluid in the inlet header and condenses, the two codes showed differences in refill predictions. These differences are attributed directly to homogeneous non-equilibrium and two-fluid effects. In terms of safety analysis, this difference is not significant, as good fuel cooling was predicted by both codes.

Refilling of the critical pass is one of the important predictions required for such a simulation. FIREBIRD and CATHENA show excellent agreement in predicting this event. Both show the mid-point of the critical channel to refill at virtually the same time, 90 seconds. The good agreement is attributed to the nature of refill, with no hot flow from the upstream boiler mixing in the injection water.

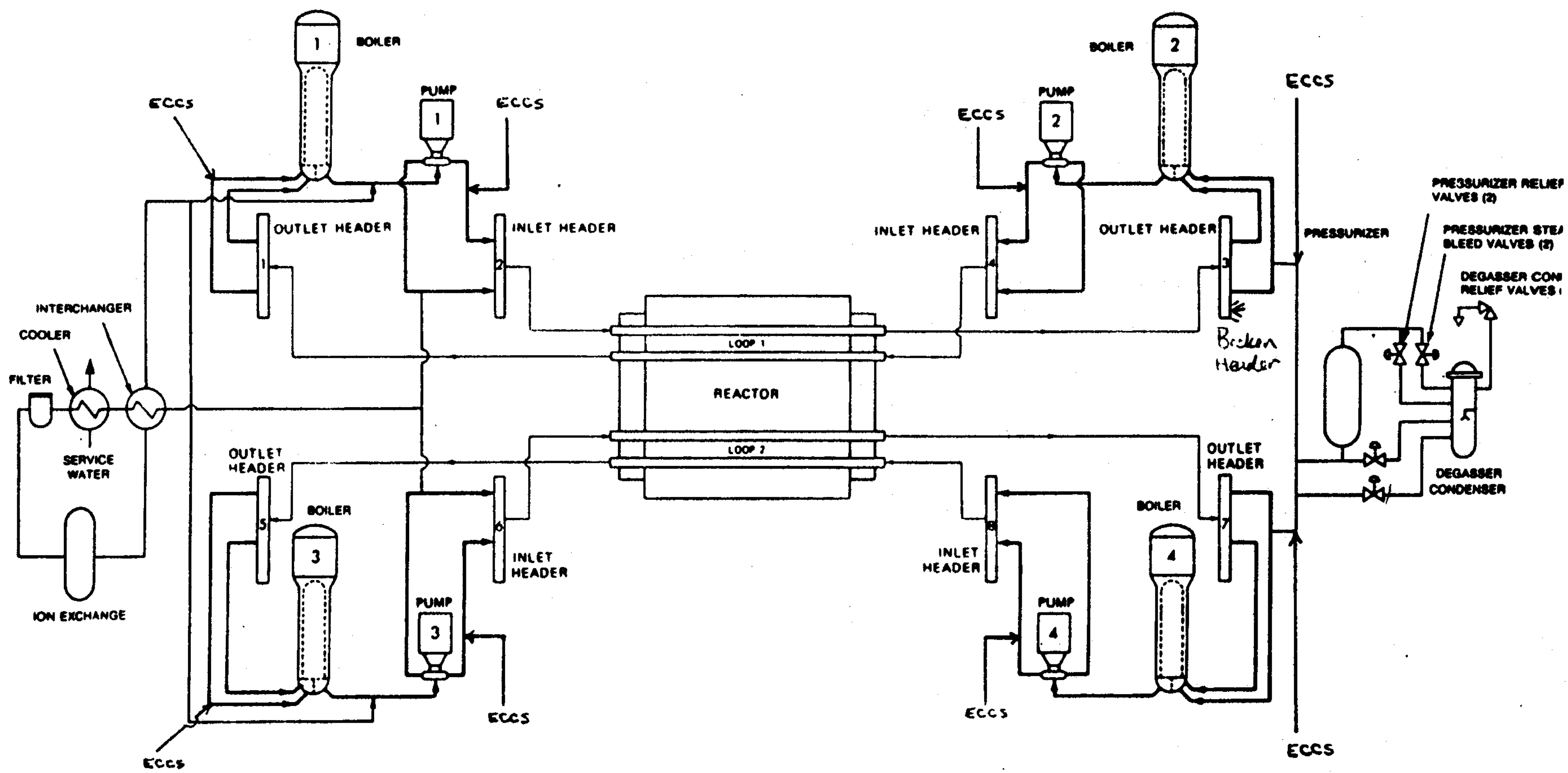

FIGURE I SIMPLIFIED HEAT TRANSPORT SYSTEM SCHEMATIC DIAGRAM

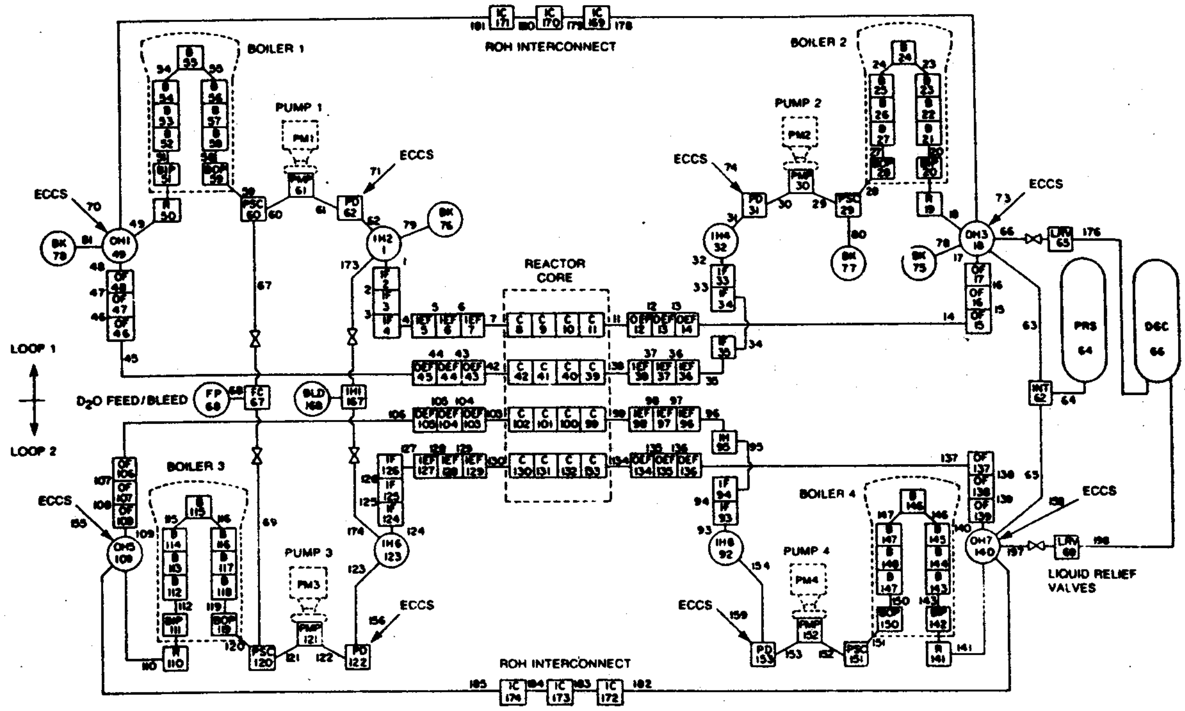

FIGURE 2 FIREBIRD III MOD1-77 TWO LOOP NETWORK NODALIZATION FOR POINT LEPREAU G.S.: HEAT TRANSPORT SYSTEM

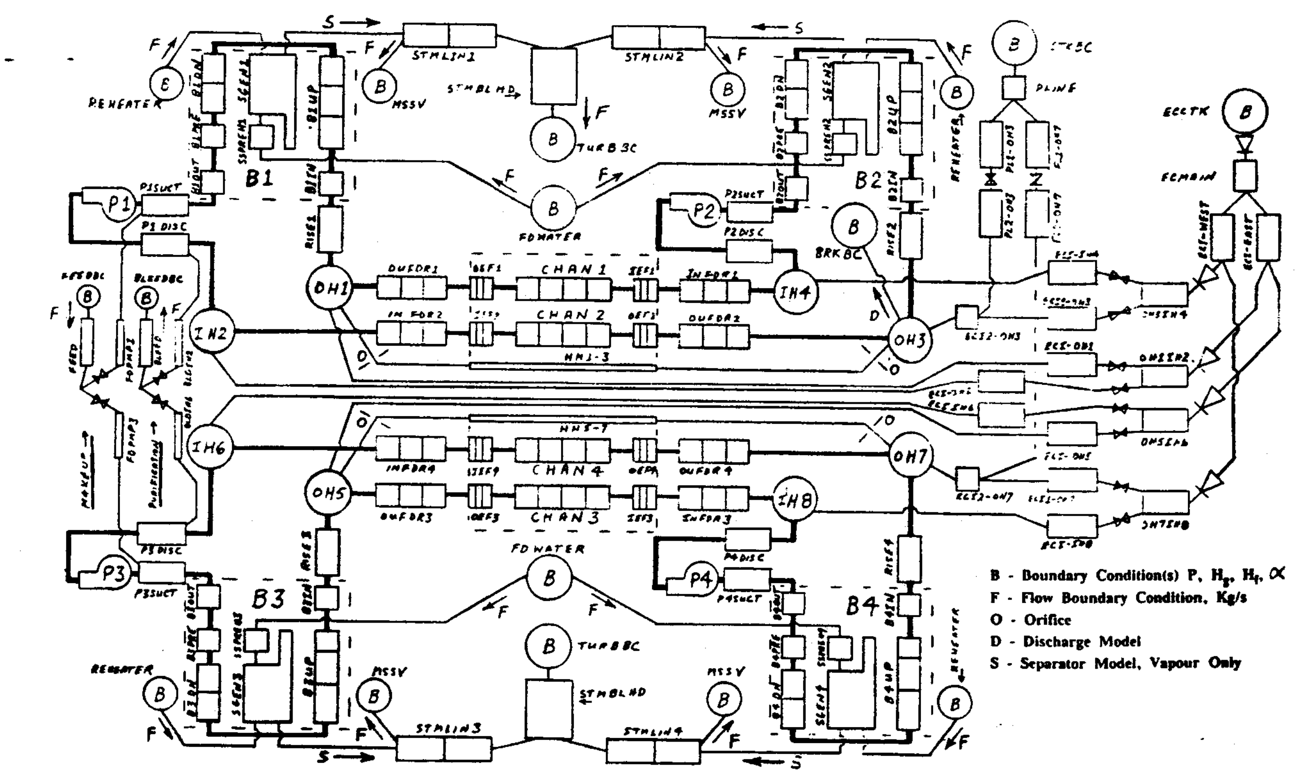

Figure 3 CATHENA Two Loop Network Nodalization for Point Lepreau G.S.

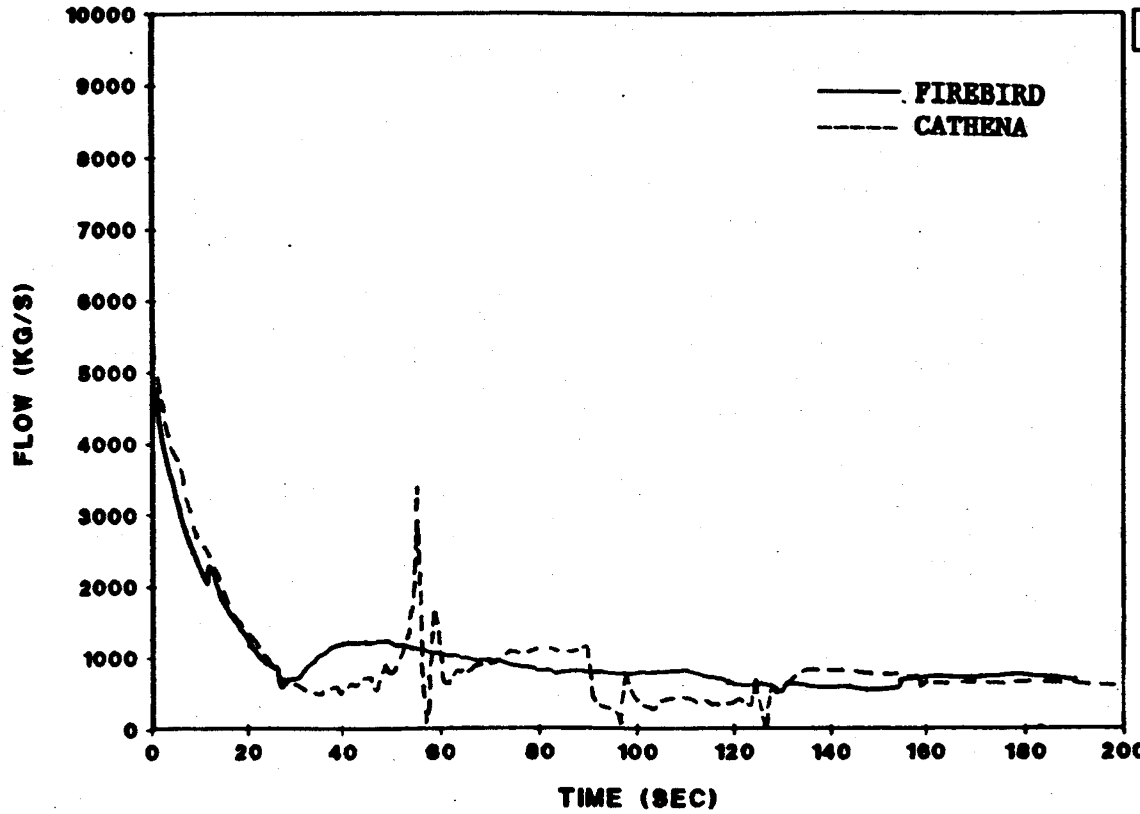

FIGURE 4 : 100% ROH(H2O) - BREAK DISCHARGE FLOW

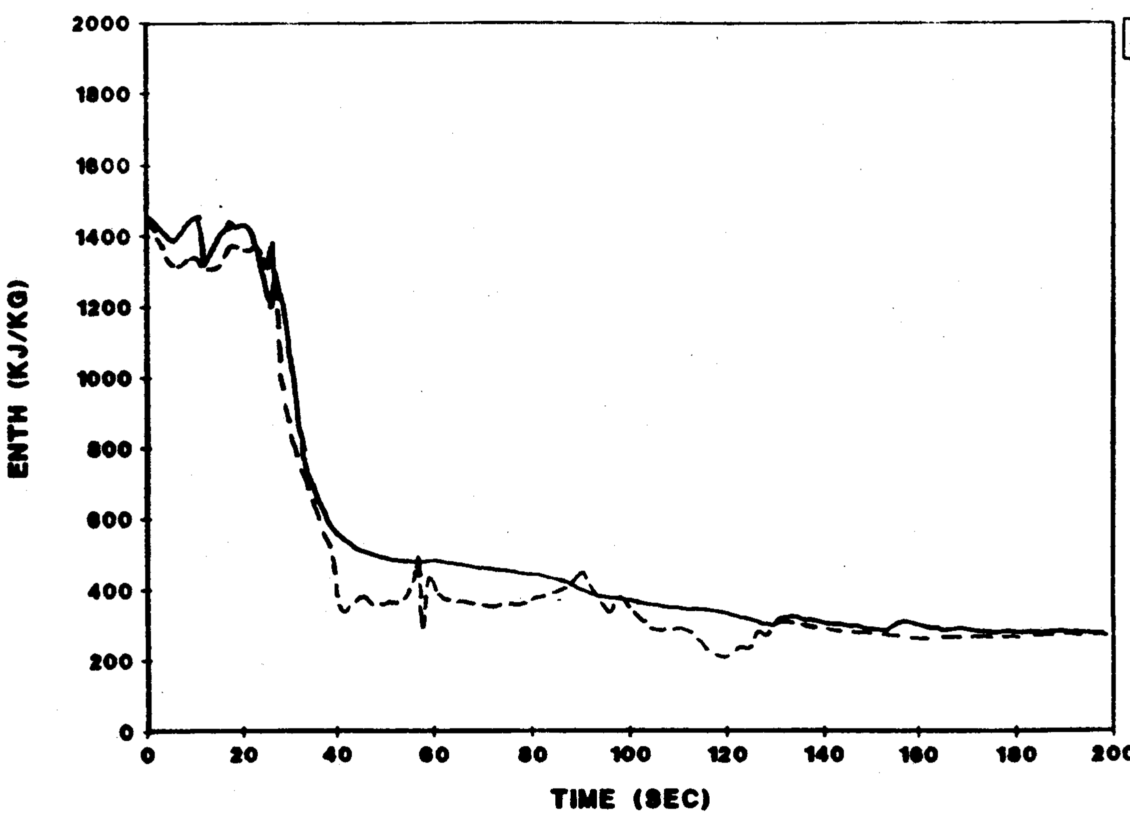

FIGURE 5 : 100% ROH(H2O) - BREAK NODE ENTHALPY

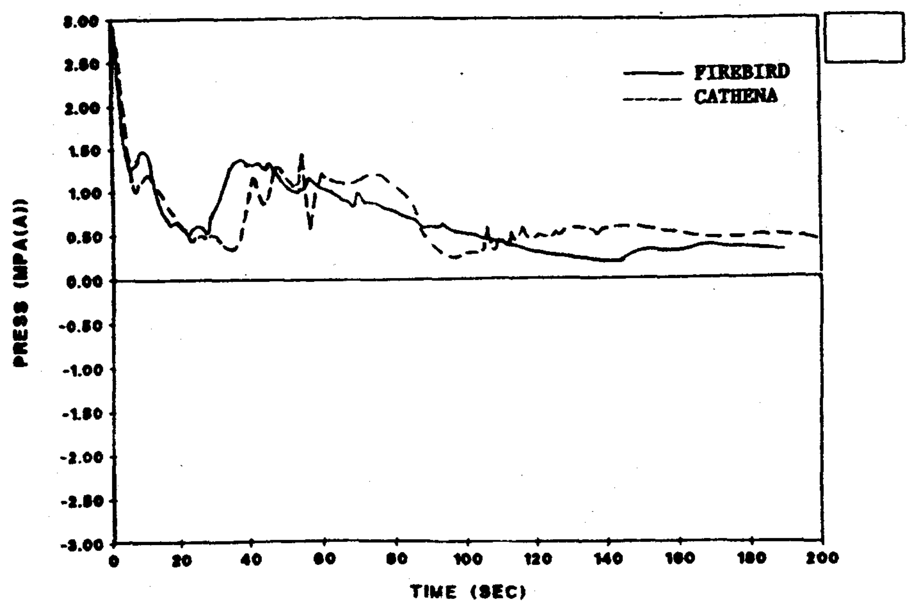

FIGURE 6 100% ROH(H2O) - PRESSURE DIFFERENCE ACROSS BROKEN LOOP PUMP2

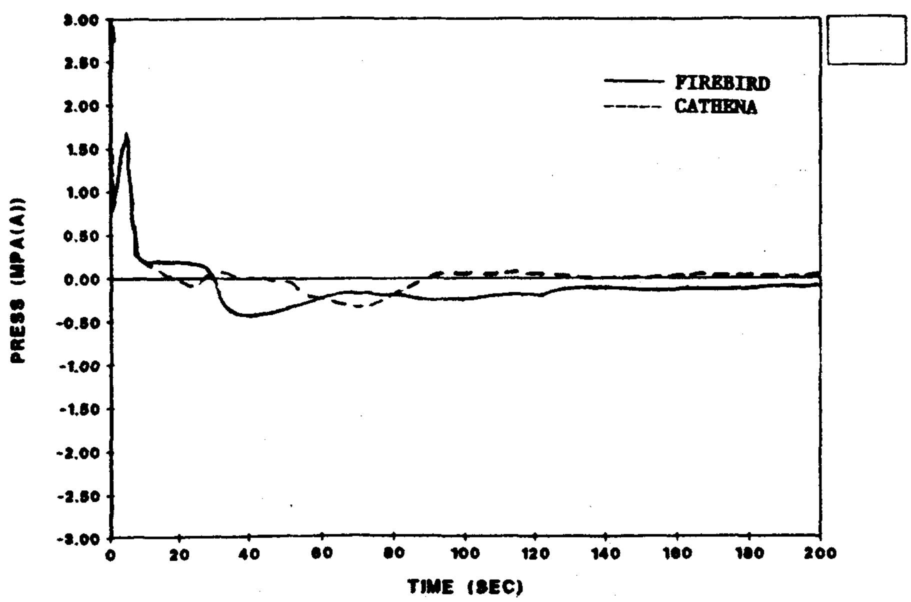

FIGURE 7 100% ROH(H2O) - PRESSURE DIFFERENCE ACROSS BROKEN LOOP PUMP1

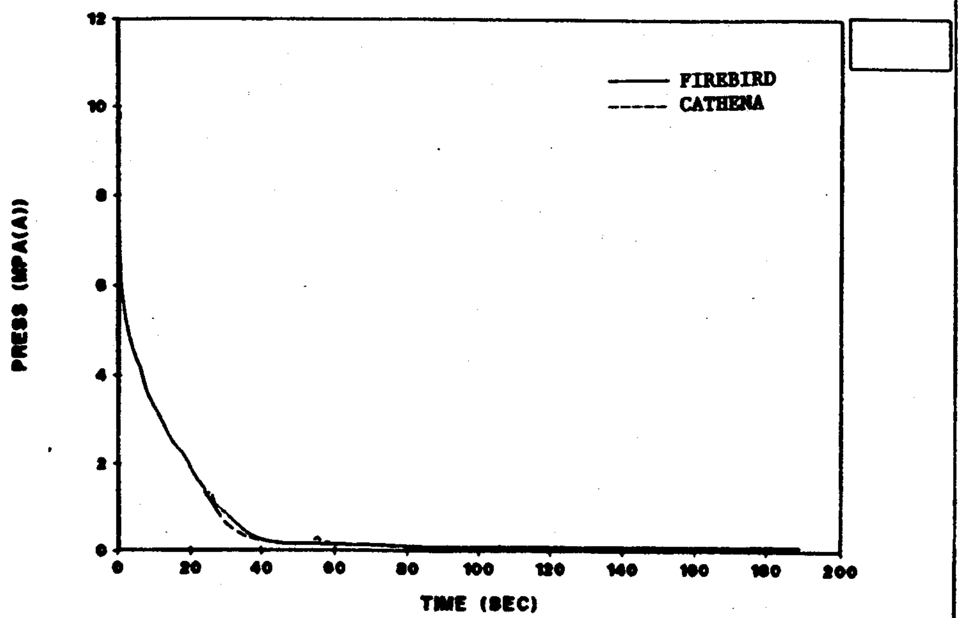

FIGURE 8 100% ROH(H2O) - PRESSURE IN ROH3 OF BROKEN LOOP

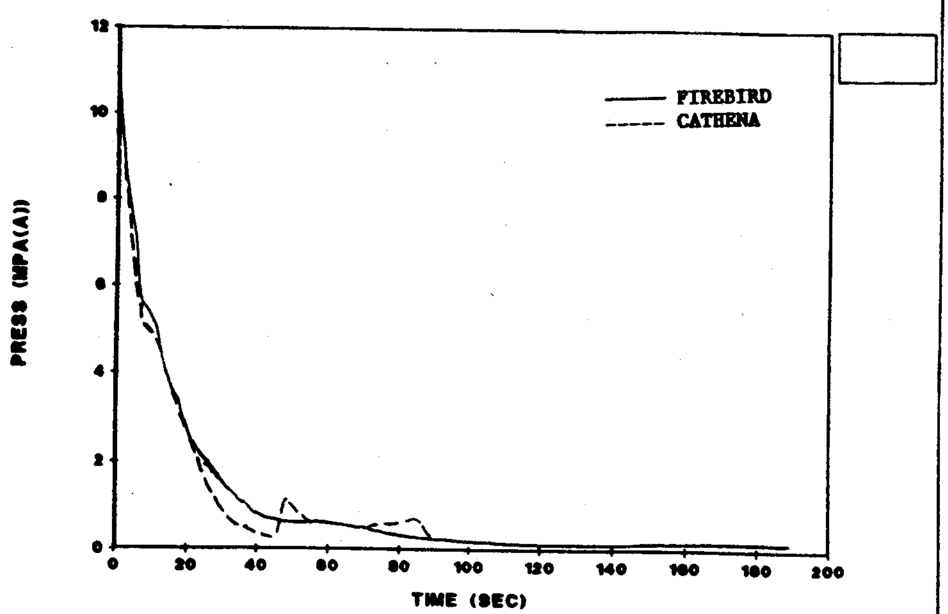

FIGURE 9 100% ROH(H2O) - PRESSURE IN RIH 4 OF BROKEN LOOP

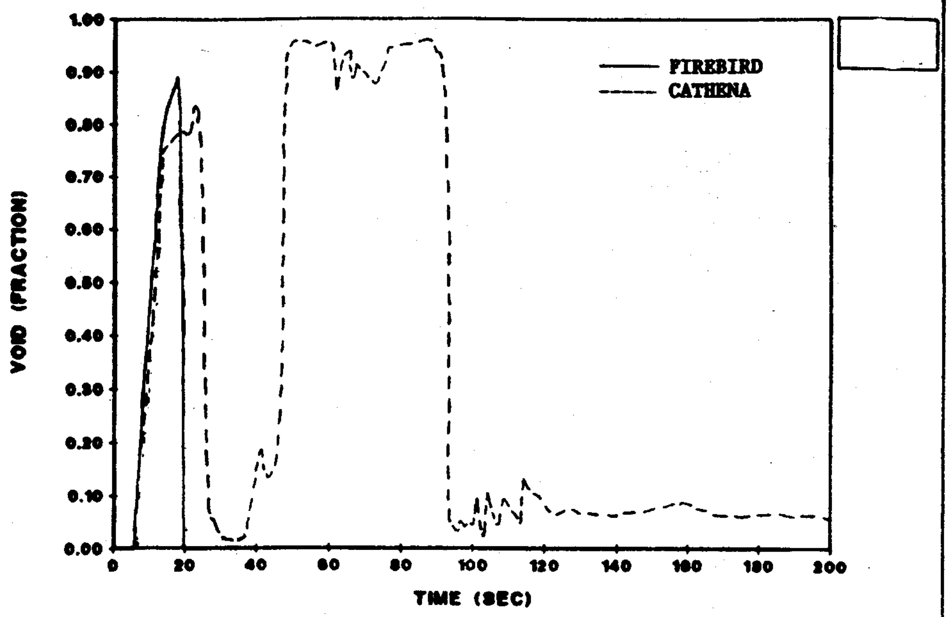

FIGURE 10 100% ROH(H2O) - VOID IN RIH 2 OF BROKEN LOOP

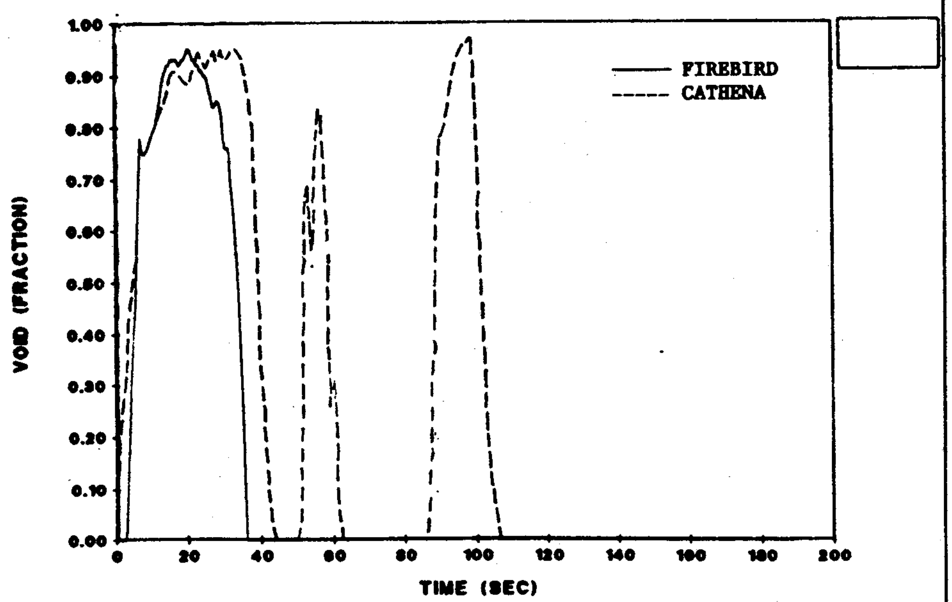

FIGURE 11 100% ROH(H2O) - VOID IN CORE PASS 1 OF BROKEN LOOP

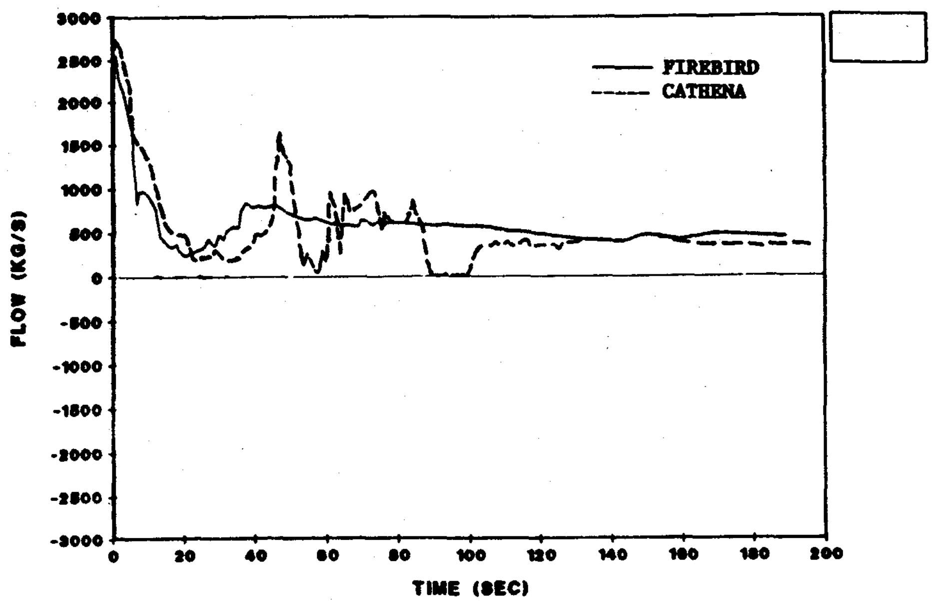

FIGURE 12 : 100% ROH(H2O) - GROSS CORE FLOW IN BROKEN PASS

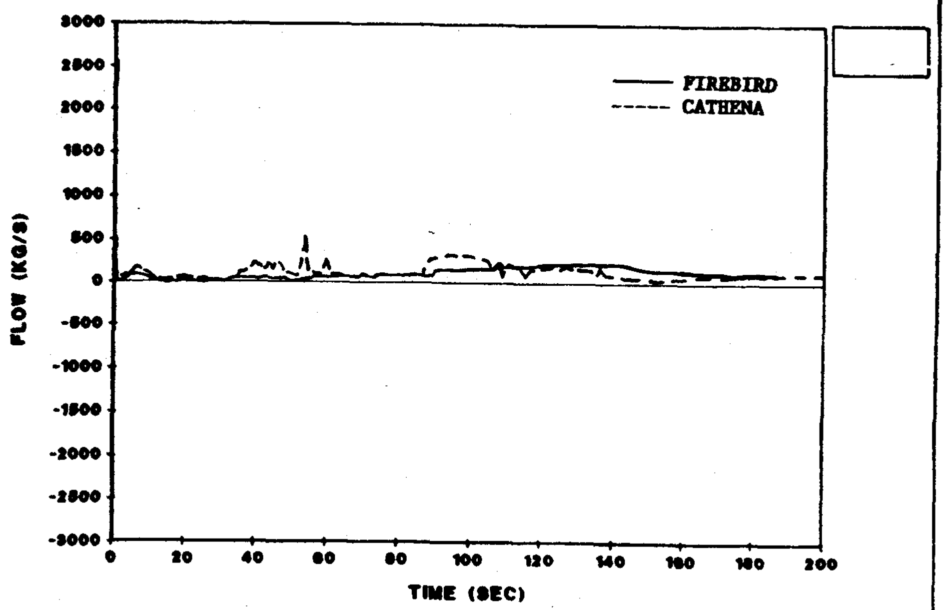

FIGURE 13 : 100% ROH(H2O) - GROSS CORE FLOW IN CRITICAL PASS

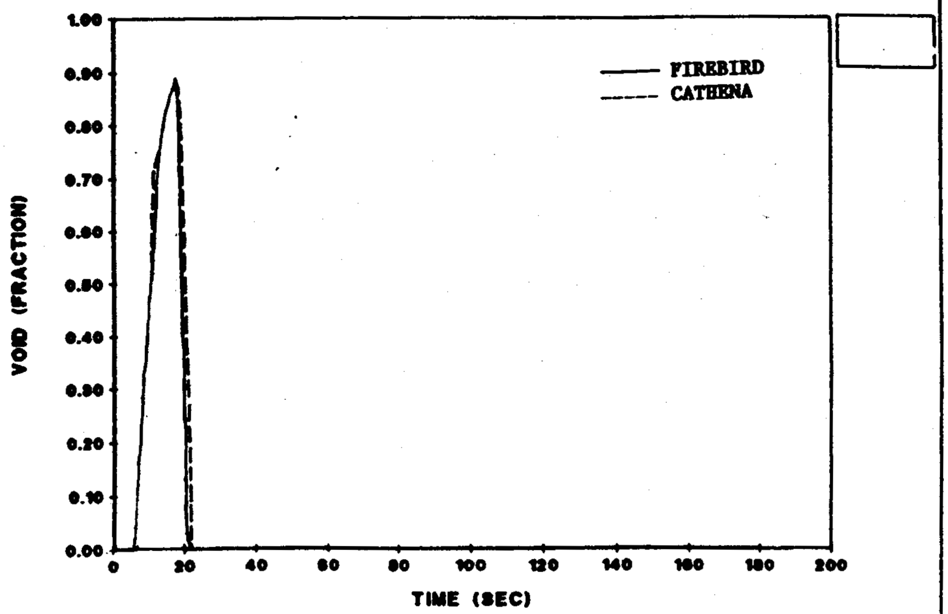

FIGURE 14 .100% ROH(H2O) - VOID IN RIH 4 OF BROKEN LOOP

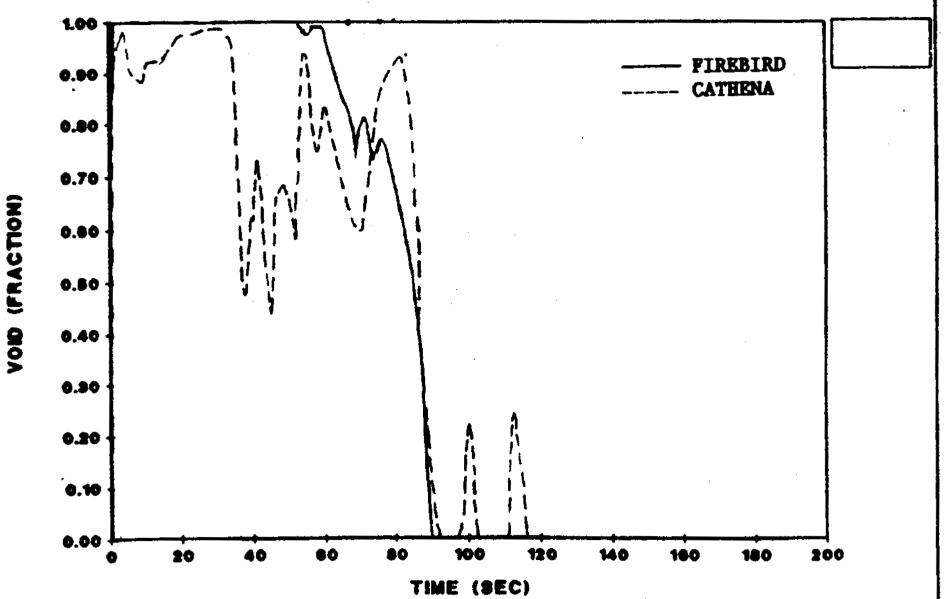

FIGURE 15 .100% ROH(H2O) - VOID IN CORE PASS 2 OF BROKEN LOOP