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Scenario Description for ACR-700 Inlet Header Critical Break LOCA

ACR USA

108US-03532-225-002
Revision 0

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1. INTRODUCTION

This document provides a description of the Advanced CANDU Reactor™ (ACR™)[*] 25% reactor inlet header (RIH) critical break loss-of-coolant accident (LOCA). The description is based on a CATHENA calculation of this accident.

CATHENA [1] is a thermal hydraulics network analysis code developed for the analysis of postulated upset conditions in CANDU®[†] reactors. Reference 1 has been provided to the NRC/BNL-sponsored ACR Thermal-Hydraulics (T-H) PIRT panel on a CD-R disk carrying the following label: "Open Literature Provided to US NRC At meeting on Thermal Hydraulics, FEB 5-6, 2003, AECL".

The primary objective of the scenario description is to identify the processes and phenomena that occur (the WHAT requested by the T-H panel) and the underlying physics that result in the identified processes and phenomena (the WHY requested by the T-H panel).

[*] ACR™ (Advanced CANDU Reactor™) is a trademark of Atomic Energy of Canada Limited (AECL).

[†] CANDU® (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited (AECL).

2. PRELIMINARIES

The CATHENA circuit model consists of a one-loop reactor coolant system, steam and feedwater system, and Emergency Core Cooling (ECC) system. Figure 1 shows the CATHENA nodalization of the reactor coolant system (RCS). There are two inlet headers (RIH1 and RIH2), two outlet headers (ROH1 and ROH2), two steam generators, and four RCS pumps. There are two core passes. Each core pass is represented by an average channel that models 142 fuel channels. ECC is injected into RIH1 and RIH2. The break is specified to occur in RIH2. The downstream pass, i.e., the channel immediately downstream of the break, is labelled CHAN2-1 in Figure 1. The fuel cladding temperature excursions of primary interest arise in the downstream pass. The second channel, labelled CHAN1-1 in the CATHENA model, is called the upstream pass. This terminology is used in this scenario description.

The CATHENA model nodalization diagram of the ECC system is presented in Figure 2. The traces of the calculated results appearing in this document carry the identifying labels appearing in Figure 1 and Figure 2.

The scenario description is for the CATHENA calculation of the ACR 25% RIH critical break LOCA. That calculation employs some conservative assumptions, both as to initial conditions and modeling of a limited number of phenomena. For example, the variation of reactor power with time is an input rather than calculated. No credit is taken for negative reactivity insertion due to void generation. However, the calculated results do capture the key processes and phenomena expected to occur during the LOCA scenario.

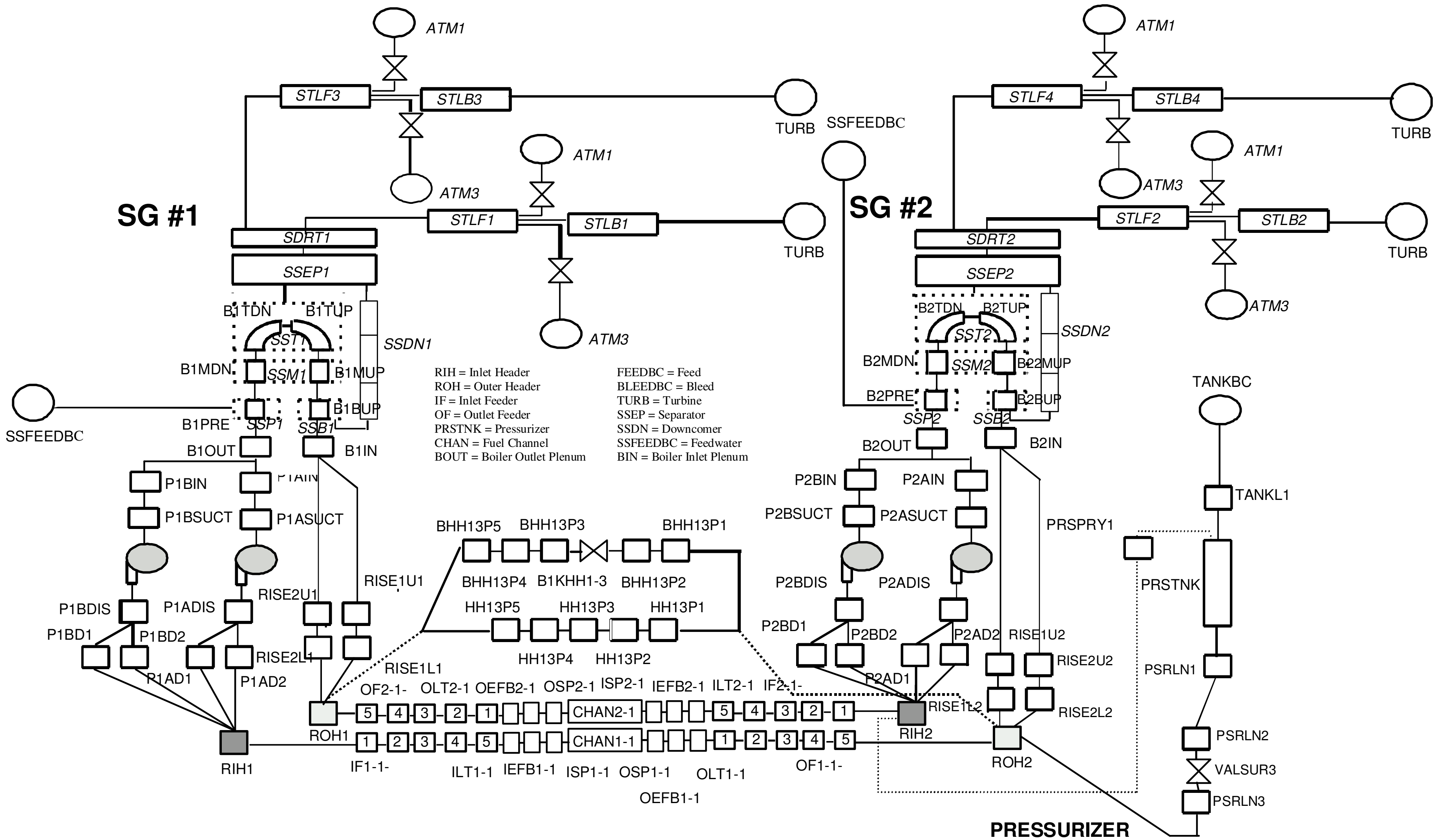

Figure 1 Nodalization Diagram of Primary Reactor Coolant System

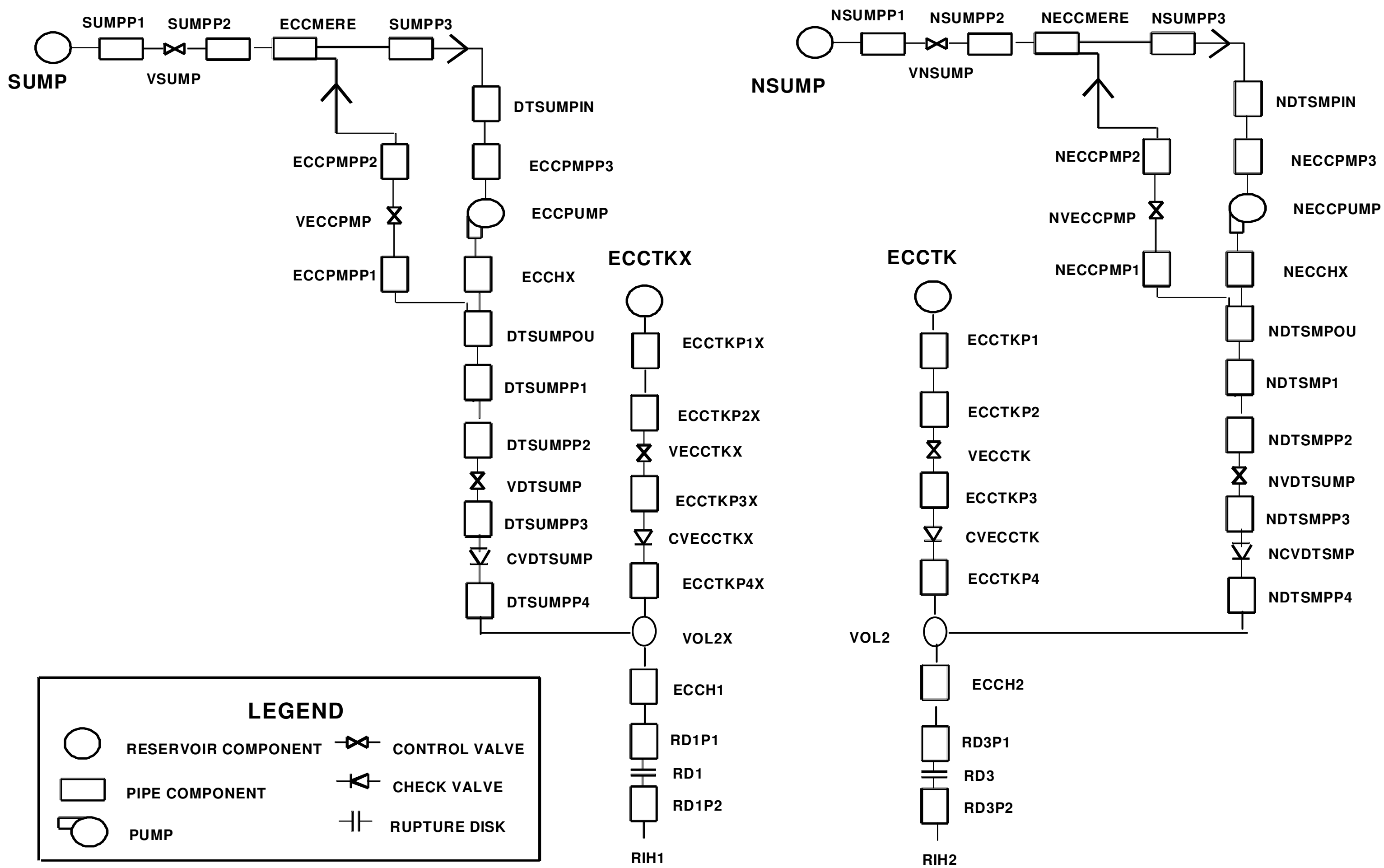

Figure 2 Nodalization Diagram of ECC System

3. GENERAL DESCRIPTION OF LARGE BREAK LOCA IN ACR-700

A general, brief, qualitative description of a large break Loss of Coolant Accident (LBLOCA) event sequence is as follows:

- A large break is postulated to occur in a large diameter pipe of the Reactor Coolant System (RCS), discharging coolant into containment.
- The RCS depressurization causes coolant voiding in the core and a decrease in core reactivity.
- The reactor shuts down on a process trip (e.g., low RCS pressure, low RCS flow) or on Reactor Building high pressure, depending on the break size and the initial reactor power.
- Containment isolation is automatically initiated on a high reactor building pressure signal. The high reactor building pressure signal also conditions the ECI signal and both of the two steam generator crash cooldown signals.
- The RCS loses inventory and depressurizes at a rate depending on the break size and location.
- Following reactor trip, the turbine trips and runs down. The condenser steam dump valves (CSDVs) open to by-pass steam to the condenser. The atmospheric steam discharge valves (ASDVs) open and close to maintain system pressure.
- The main feedwater system feeds the steam generators from the condenser hotwell until Class IV power is lost. Subsequently, water is supplied by auxiliary feedwater pumps which run on Class III power. The RCS flow decreases faster in the core pass downstream of the break. If the break is large enough, the flow will reverse in that pass. For some break sizes, the flow momentarily falls very low as the break upstream of the core pass balances the pumps. Some channels may become steam-filled and others may experience stratified two-phase flow, exposing some fuel elements to steam cooling. Fuel and cladding temperatures rise. A rise in fuel temperatures increases the internal fuel element gas pressures, whereas a rise in cladding temperatures reduces the cladding strength. Increased internal fuel element gas pressure along with the decreased coolant pressure increases fuel cladding stresses.
- The pressurizer discharges its inventory into the RCS. The decreasing pressurizer level causes the light water bleed valves to close, and feed valves to open up, adding light water makeup to the RCS.
- Following reactor trip, the average fuel temperature decreases as the heat generation rate decreases and the temperature profile in the fuel pin flattens out. The cladding temperature increases depending on the heat transfer from the cladding to the coolant, and subsequently decreases due to the reduced heat generation rate and blowdown cooling flow.
- When the RCS pressure falls below a specified setpoint, the ECI signal, which is conditioned by the high reactor building pressure signal, is generated. This signal results in the following events:
    - The high-pressure Emergency Coolant Injection (ECI) System is initiated by the ECI signal. The isolation valves in the lines from the high-pressure ECI water storage tank to the injection points into the RCS reactor inlet headers are opened. The one-way rupture discs burst open at a pressure differential of 0.52 MPa (0.52 MPa is the highest burst pressure observed in experimental results). The ECI piping downstream of the one-way

rupture discs is pressurized to the reactor coolant system pressure. Thus, the high-pressure ECI flow will begin when the pressure in the RCS is about 0.52 MPa less than the high-pressure ECI pressure from the ECI water storage tank. High-pressure ECI continues until the associated high-pressure ECI water storage tanks are nearly empty.

- Valves on the ECI large interconnect line between the reactor outlet headers open on the ECI signal to assist in establishing a cooling flow path.
- Steam generator crash cooldown is initiated 30 seconds after the ECI signal through the automatic opening of the main steam safety valves (MSSVs). This assists the ECI by further depressurizing the RCS.
- On the ECI signal, water is automatically introduced into the containment sumps from the Reserve Water System (RWS). The long-term cooling (LTC) pumps start automatically on a high reactor-building sump level signal. When the ECI water storage tanks are nearly empty, the storage tank isolation valves close and the LTC stage begins by pumping water from the reactor-building sump. The LTC delivers flow to the reactor inlet headers, thereby utilizing the cooling flow path already established by the high-pressure ECI system.

- Soon after ECI and SG crash cooldown begins, emergency coolant water begins to refill the core pass.
- The ECI refills both core passes and a quasi-steady-state flow pattern is established.
- Long-term cooling is maintained by the flow of LTC system coolant through the circuit, with decay heat removal by the LTC heat exchangers and through the break.

4. EVENT SEQUENCE FOR 25% RIH CRITICAL HEADER BREAK

The PIRT activity described in this document is specific to the ACR-700 reactor for the case of a 25% RIH LBLOCA with subsequent loss of Class IV power. At the time of the transient, the reactor is operating at full power with equilibrium poison levels. Design values are used for plant parameters.

The events occurring during the 25% RIH LBLOCA scenario are described in detailed point-form in Table 1. The description is based on a CATHENA simulation of this accident, which was performed for design-assist purposes. The CATHENA model reflects the status of the design at the time the simulation was performed.

The phases of a LBLOCA accident are defined according to the major time periods during the accident progression for which characteristic system behaviours are exhibited.

The identified phases of the ACR LBLOCA are,

1. Early blowdown cooling: The period during which the reactor is being shut down and the RCS blowdown continues prior to ECI initiation (i.e., opening of the ECI rupture disc). The dominant system behaviour during this period is a result of reactor coolant system depressurization, reactor shutdown, blowdown cooling, fuel and cladding heat-up, pressure tube heat-up, possible fuel failure and consequent fission-product release.
2. Late blowdown cooling / ECI / Refill: The period of ongoing reactor coolant system blowdown with ECI inventory entering into the reactor coolant system. The dominant system behaviour during this period again is due to reactor coolant system depressurization, blowdown cooling, ECI delivery, fuel heat-up, pressure-tube heat-up and fission product release. During the later stages, refill of channels in the core proceeds and a quasi-steady-state is attained. The dominant system behaviour during this period is determined by ECI delivery, reactor coolant system refill, fuel cooling and possible fission product release.
3. Long-term cooling: The period in which the long-term cooling (LTC) provides recovery flow to maintain core cooling.

The duration of each of these phases depends on the break size with longer phases associated with smaller breaks. The sequence of events for the ACR 25% RIH critical break LOCA is provided in Table 1.

Table 1
Event Sequence for 25% RIH Break with Consequent Loss of Class IV

Elapsed Time (s)	Event Description
Early Blowdown (0 – 53 seconds)	
0	• Break occurs • All other systems operating normally
0.1	• Maximum discharge flow occurs (7115 kg/s). Discharge from pump flow (forward direction) and inlet feeder (reverse direction) • Net coolant flow in downstream pass (i.e., RIH2 → ROH1) starts to decrease • Flashing of coolant into containment commences
0.4	• Low RCS flow trip signal (1st trip signal[1]) • Coolant discharge from pump flow (forward) and header / feeders / upstream pass fuel channels (reverse) • Reactor regulating system (RRS) attempts to maintain power
~0.5	• Containment pressure rises and exceeds containment high pressure trip setpoint of 3.45 kPa(g) - ECI signal conditioned - Closure of containment isolation valves initiated - Trip miscellaneous local air coolers (LACs), switch safety-related LACs to low speed - Reactor trip signal
2.0	• Low RCS pressure trip signal (2nd trip signal). • SDS1/SDS2 shutdown initiated. • Mechanical control absorbers (MCAs) drive in • Zone control absorbers frozen • Coolant inventory in upstream pass decreasing • Flow initiated in permanent header interconnect from ROH2 to ROH1 • Water flows from the pressurizer into ROH2; pressurizer pressure dropping; pressurizer level dropping - condenser spray valves close (normal control) - bleed valves close (normal control) - feed valves open (normal control)
3.0	• Reactor power at 36% of full reactor power • Fuel temperatures begin to decrease
3.6	• SDS1 fully inserted (-51 mk) • SDS2 poison spreading in moderator • Fuel heat generation due to decay heat and delayed neutron fission • Average fuel temperature decreasing; radial fuel temperature gradient flattening
5.0	• Reactor power at 11% of full reactor power • Heat transfer to SG decreasing rapidly; SG pressure dropping

[1] To meet Regulatory requirements, the first trip signal is generally not credited.

Elapsed Time (s)	Event Description
7.0	• ECI signal actuated on low RCS pressure - ECI valves start to open - ECI recirculation circuit isolation valves and the nitrogen charging system gas supply valves close - ECI large header interconnect valves start to open - signal to initiate SG crash cooldown (with delay) - signal to start Class III diesels (180 s until available). - Reserve Water System (RWS) dump valves start to open - RWS injection valves to RIHs start to open - LTC pumps start (2 x 330 L/s) - feed flow from the P&IC system is terminated. - temperature control valves on LTC heat exchangers open fully • Coolant flow in downstream pass starts to reverse; flow in some channels becomes 2-phase stratified or steam filled • Fuel cladding temperature depends upon local cooling - fuel in downstream pass experiences reduced coolant flow - cladding temperatures rise on fuel with reduced flow - fuel element internal gas pressures rise with increasing element temperature - cladding experiences increased strain • Water draining from pressurizer into RCS
9.1	• Turbine unloading begins • Loss of Class IV power (associated with load switching failures during turbine unloading) • RCS pumps trip and begin to rundown • Pressurizer heater turned off • Local air cooler fans stop, and restart when Class II power is available • RCW pumps, main feed water pumps and RCS feed pumps stop
10	• Break discharge flow dropping rapidly (~30% of peak flow); specific enthalpy increasing • Reactor header pressure ~7 MPa in all headers • Flow rate in downstream pass channels close to zero • Forward flow rate in upstream pass channels ~.50% of peak flow rate • SG still acting as heat sink for RCS • Flow starts through large header interconnect from ROH2 to ROH1 • Flashing at break filling containment with steam; containment pressure at ~200 kPa(a) and rising; steam condensing on "cold" surfaces and starting to flow down walls • Cladding temperatures rising rapidly to 1000°C in downstream pass • PT temperatures at 400°C in downstream pass and rising slowly
20	• Voiding in downstream pass • Cladding temperature remains at 1000°C • PT temperature rises to 450°C

Elapsed Time (s)	Event Description
27	• Reactor power at ~6% • ECI valves fully open • RWS dump valves fully open; LTC sump starts to fill with water (1000 m^3); sump level exceeds LTC pump head requirement before LTC injection valves open • Large header interconnect valves fully open
30	• Cladding temperature decreasing (~800°C) • PT temperature peaks at ~500°C
.37	• MSSVs open for crash cooldown • SG secondary side depressurizing • Flow through SG1 decreases to near zero because of voiding; flow through SG2 is ~500 kg/s
53	• Reverse flow continues in downstream pass • Cladding temperature <400°C • Fuel channel rewet; PT temperature <300°C
Late Blowdown / ECI / Refill (53 – 250 seconds)	
53	• ECI rupture disc on RIH2 opens (RIH1 pressure = 4.4 MPa) • Break discharge flow ~1000 kg/s • Cold (41°C upper limit) injection flow from the ECI water storage tank (at least 105 m^3 per ECI tank is available for injection) starts into RIH2 • Break discharge rises briefly with disc rupture as cold water mostly directed to containment through the break
55	• ECI rupture disc on RIH1 opens (RIH1 pressure = 4.4 MPa) • Cold injection flow from the ECI water storage tank starts into RIH1 - water flows through upstream pass; water cannot flow through SG (steam filled), so flow directed to large outlet header interconnect • SGs largely bypassed but act as heat source to limited steam flow
~100	• Flow through SG2 drops to low level (~100 kg/s) • Flow through upstream pass drops briefly to zero and then rises again (always forward) • Flow through downstream pass continues reversed
187	• All Class III powered loads have been sequenced • LTC pumps running on Class III power in recirculation mode • Local air cooler fans running on Class III power - Condensation flow in containment established • Service water available to air coolers and heat exchangers • Auxiliary feed water pumps start - cooling to SGs eliminates them as a heat source
Long-Term Cooling (250 – 2000 seconds; end of calculated accident)	
200	• Downstream pass rewet complete (upstream pass always cooled) • Reactor power at ~3.5% • Flow through SG2 drops to zero • Larger header interconnect flow ~200 kg/s from ROH2 to ROH1 - flow experiences transient pulses and oscillations

Elapsed Time (s)	Event Description
222	• ECI flow to RIH2 starts to terminate; ECI injection valves start to close • RIH2 pressure ~1.5 MPa • LTC isolation valves to RIH2 start to open (on high sump level) • Flow through downstream pass experiences large oscillations
236	• ECI flow to RIH1 starts to terminate; ECI injection valves start to close • RIH1 pressure ~1.5 MPa • LTC isolation valves to RIH1 start to open (on low ECI water storage tank level) • No water is flowing from the RWS to headers as header pressure is too high
250	• LTC flow to RIH2 begins
~500	• Pumped flow from RCS water storage tank stops on low tank level • P&IC feed pumps trip • Large header interconnect flow oscillates about a steady-state level of ~250 kg/s
~2000	• System in quasi-steady-state • No major oscillations in large header interconnect flow • Channel void is zero • Flow through SG is zero • Channel flow: upstream pass = 250 kg/s forward; downstream pass = 200 kg/s reverse

5. SCENARIO DESCRIPTION

The phase overview descriptions that follow emphasize the cladding temperature behavior and the phenomena and processes that cause the predicted behavior.

This is an appropriate focus for the phase overview discussion because the Figure of Merit for the critical break LOCA PIRT effort is the maximum cladding temperature during each phase.

While discussing the cladding temperature response, the system and component interactions leading to the cladding temperature response are discussed. Clearly, the processes and phenomena occurring in some components have a greater impact than those occurring in other components. Thus, the contributions of all components to the cladding temperature response are not covered in the same detail. The components above the headers, for example, receive less attention because they contribute little to the cladding temperature response during Phases 2 and 3. Exceptions, when they occur, are discussed.

5.1 Blowdown Period (Phase 1: 0 – 53 seconds)

Phase 1 is initiated by a break in the reactor inlet header (RIH2). Reactor coolant is discharged at a high rate through the break, flow immediately reverses in the downstream pass, and the void fraction in the channel rapidly increases. In this environment, the cladding temperatures rapidly increase, due both to the power generated in the fuel and the redistribution of stored heat to the cladding.

The cladding temperatures experience two peaks during Phase 1 (Figure 3). The first peak occurs at 7 seconds after break initiation. The rise in cladding temperature is terminated by a reduction in power following reactor trip (Figure 4), and a reduction in break flow (Figure 5) as voiding starts in RIH2 and the break begins to pass two-phase flow, which results in a brief period of positive flow from RIH2 into the downstream pass. The cladding temperature continues to decrease as forward flow supplied by the RCS pumps continues into the downstream pass. The valves in the large header interconnect line open (Figure 6) and flow passes through the large header interconnect line into ROH1. However, this flow does not immediately cool the downstream pass.

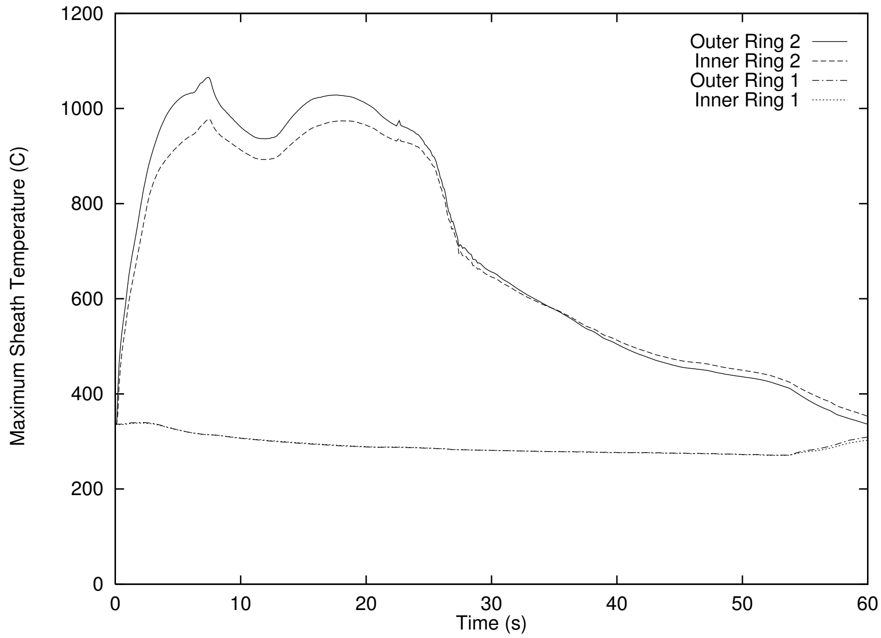

Figure 3 Phase 1 - Maximum Cladding Temperature

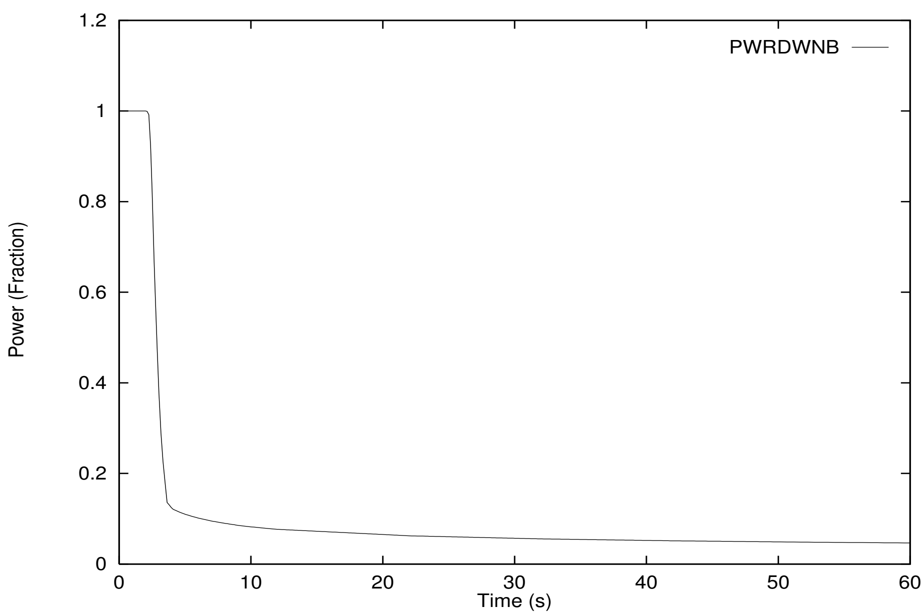

Figure 4 Phase 1 - Reactor Power

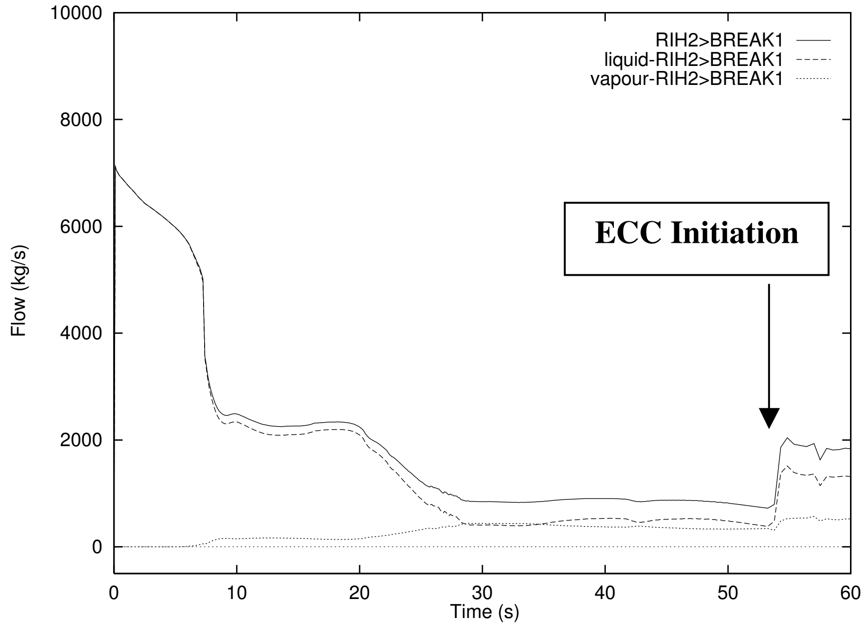

Figure 5 Phase 1 - Break Discharge Flow

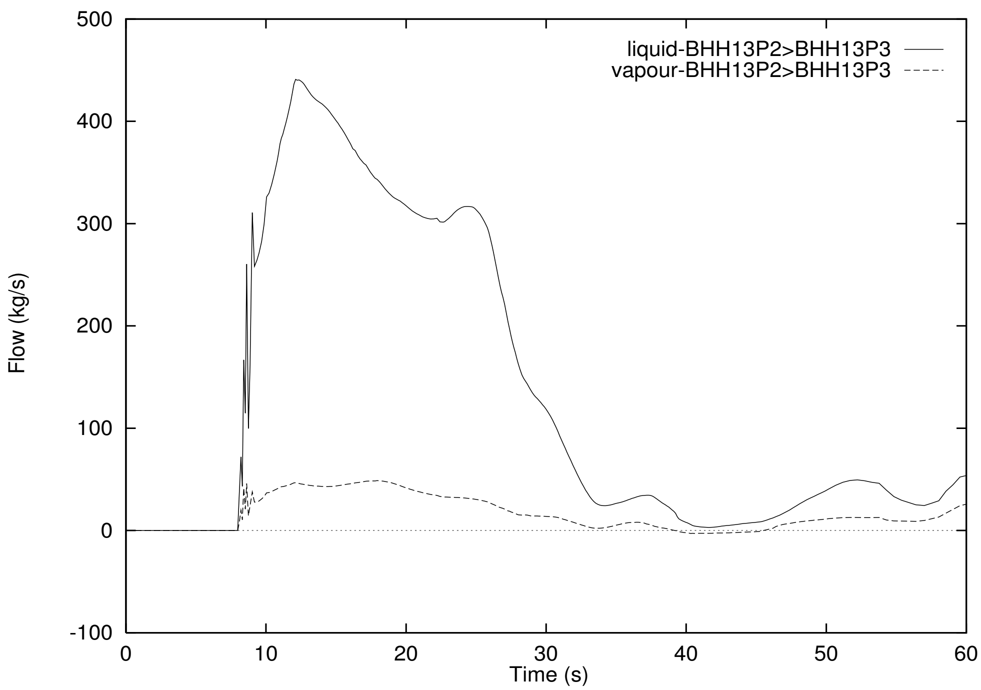

Figure 6 Phase 1 - Large Outlet Header Interconnect Flow

The cooling of the cladding deteriorates as the RCS pump flow decreases due to pump suction voiding, causing the flow in the downsteam pass to decrease and reverse. A second cladding temperature peak occurs at 18.5 seconds. This period of cladding heating is concluded as the decay power continues to decrease and the reverse flow in the downstream pass increases in magnitude. The reverse flow is maintained as the large header interconnect flow continues, albeit at a reduced level, and the inventory in the up leg of steam generator #1 drains into ROH1, whence it proceeds through the feeder pipe to the downstream pass channel. The cladding temperature continues to decrease until the end of Phase 1 at 53 seconds.

A detailed description of the processes and phenomena occurring during Phase 1 follows.

- The accident scenario is initiated by a break in RIH2. Taking a 100% double-ended guillotine break of the cylindrical cross section of the RIH as twice the cross-sectional area of the RIH, the area of a 25% break is 50% of the cross-sectional area of the RIH.
- For the first two seconds after break initiation and by assumption, the reactor continues at full power (Figure 4). The downstream pass channel, i.e., the channel immediately downstream of the break (Channel 2), rapidly voids (Figure 7) and the cladding temperatures increase at a near adiabatic rate (Figure 3).

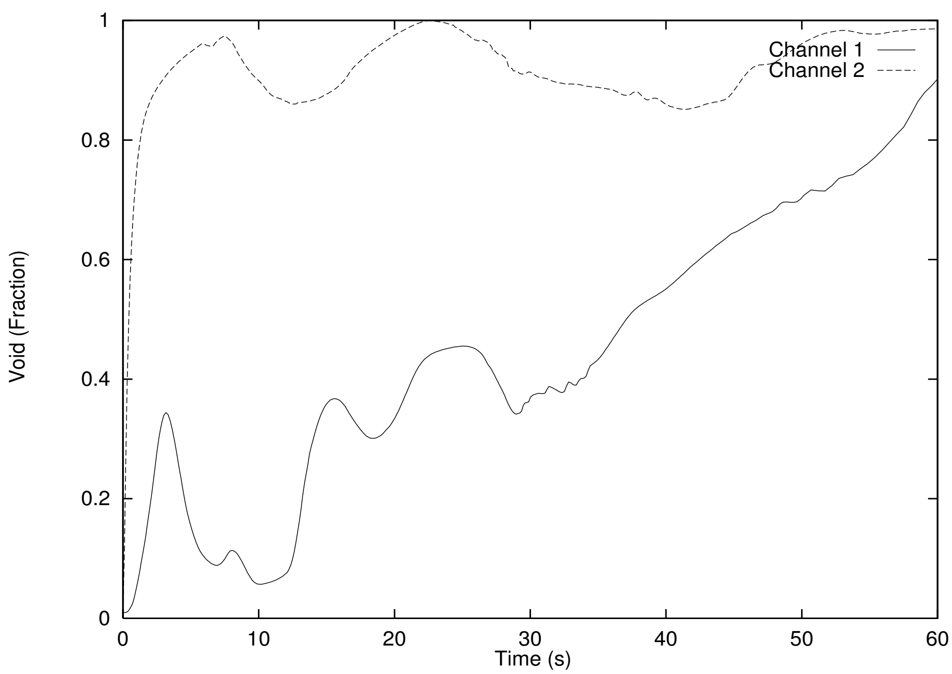

Figure 7 Phase 1 - Fuel Channel Integrated Voids

- The stored energy in the fuel bundles is redistributed from the fuel to the cladding, contributing to the early rise in cladding temperature. One consequence of the early voiding in the downstream pass channel is that little of the stored energy is rejected to the coolant compared to the stored energy release in the upstream pass channel (Figure 8). As the energy is not transferred to the coolant, it contributes to the cladding temperature rise as the temperature gradient through the fuel elements flattens.

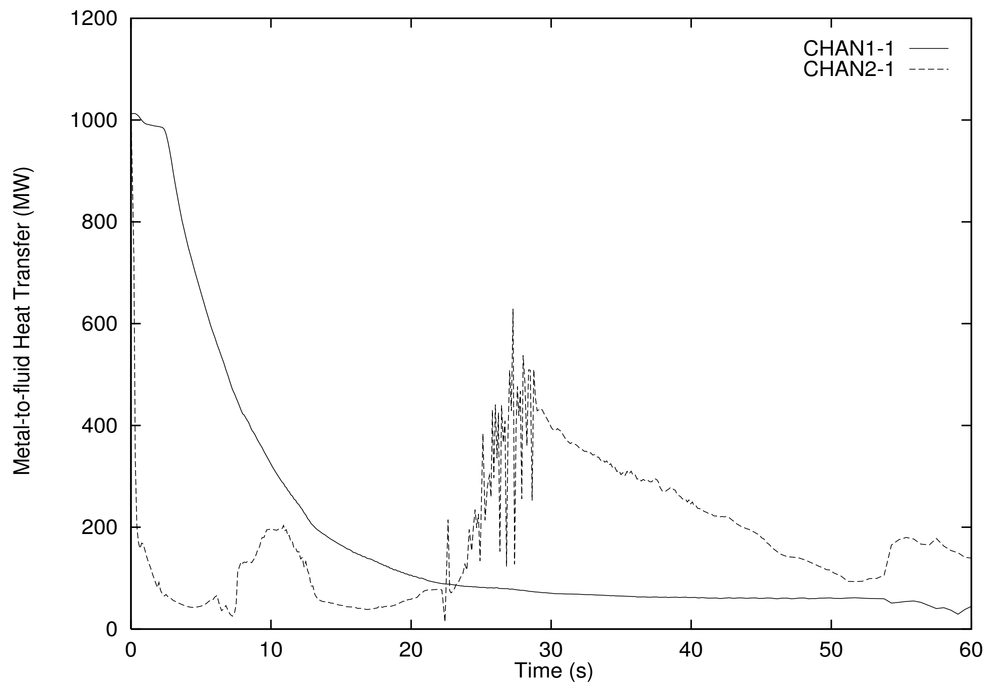

Figure 8 Phase 1 - Stored Energy Release in Fuel Channels

- At 2.0 seconds, Shutdown Systems 1 (SDS1) and 2 (SDS2) activate and reactor power rapidly decreases to approximately 11% of full power at 3.5 seconds (Figure 4). The rate of cladding temperature increase slows in response to the reduced power level. The rate of cladding temperature increase approaches zero at 5.5 seconds but a small calculated decrease in channel flow causes the cladding temperature to resume its increase to a temperature of 1066ºC at approximately 7 seconds (Figure 3).
- At 7 seconds, the cladding temperature (Figure 3) begins to rapidly decrease from its maximum, reaching a temperature of 937ºC at 11.5 seconds and then begins to increase. There are multiple processes that produce this result.
  - The reactor power has been reduced to decay heat levels.
  - RIH2, the inlet header in which the break occurs, remains liquid full until approximately 5 seconds, at which time the header begins to void (Figure 9 and 10).
  - With the onset of voiding in RIH2, the break flow begins to rapidly decrease from 5900 kg/s to approximately 2450 kg/s at 9 seconds (Figure 5).

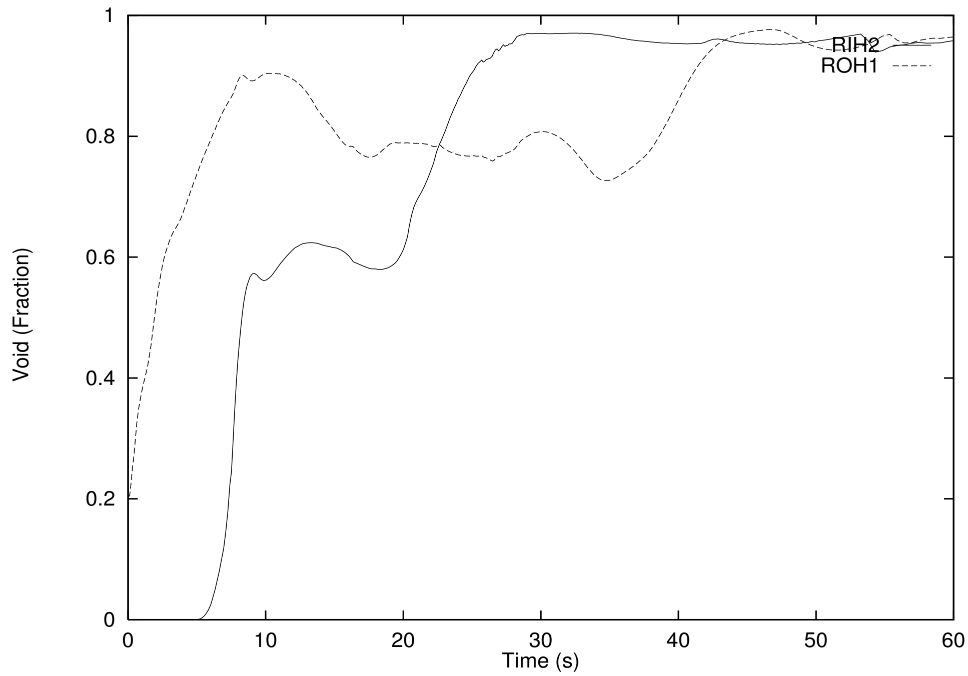

Figure 9 Phase 1 - Header Voids (RIH2 and ROH1)

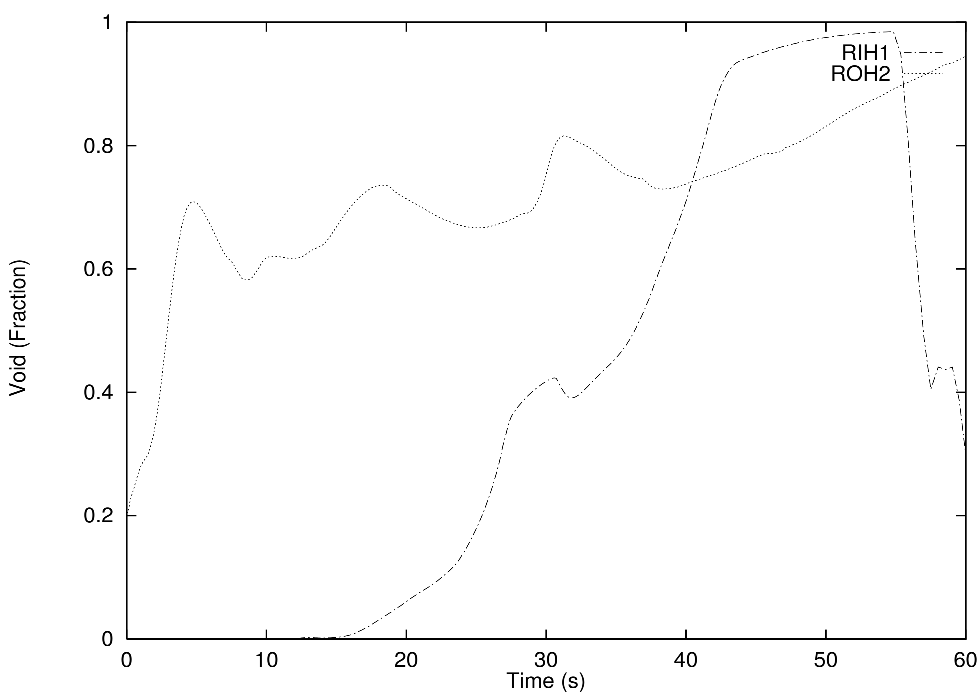

Figure 10 Phase 1 - Header Voids (RIH1 and ROH2)

- While the break flow is rapidly decreasing, the reactor coolant pump is still delivering two-phase fluid to RIH2 (Figure 11), although at a rapidly decreasing rate. The flow delivered to RIH2 is 2000 kg/s at 7 seconds and approximately 1350 kg/s at 10 seconds. The reduced flow is a result of voiding at the pump suction (Figure 12).

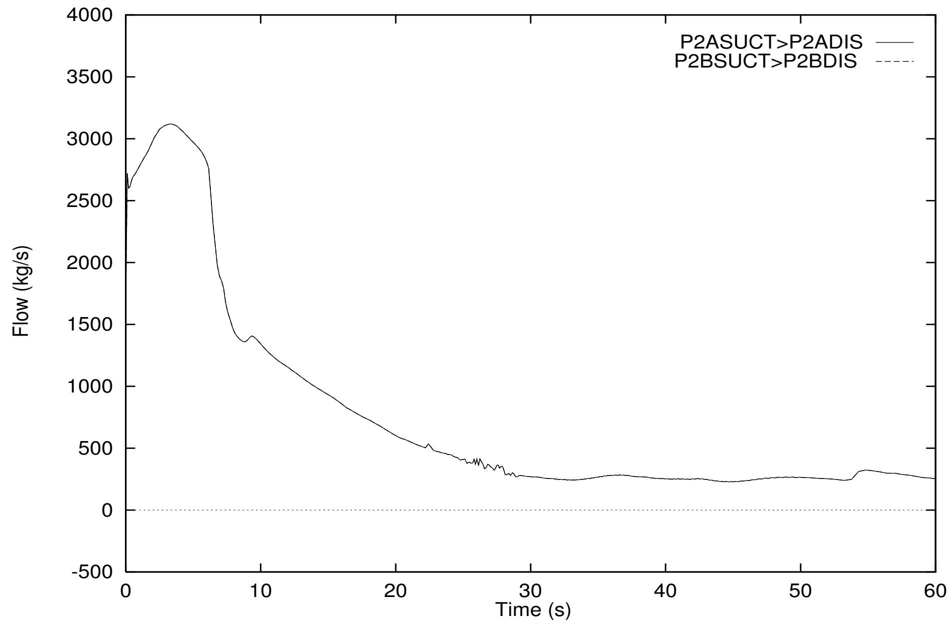

Figure 11 Phase 1 - Pump 2 Flow

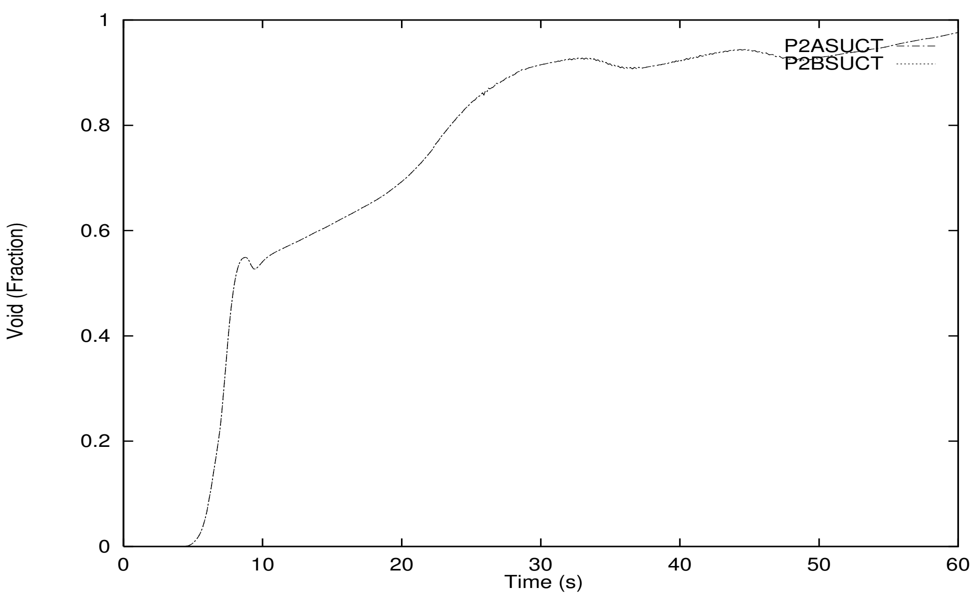

Figure 12 Phase 1 - Pump Suction Void

- At 7 seconds, the combination of reduced break flow and continued delivery of two-phase fluid from the pump to RIH2, produces a small coolant flow from RIH2 through the feeders (Figure 13) to the downstream pass channel. This flow terminates the cladding temperature increase and the cladding temperatures begin to decrease (Figure 3).

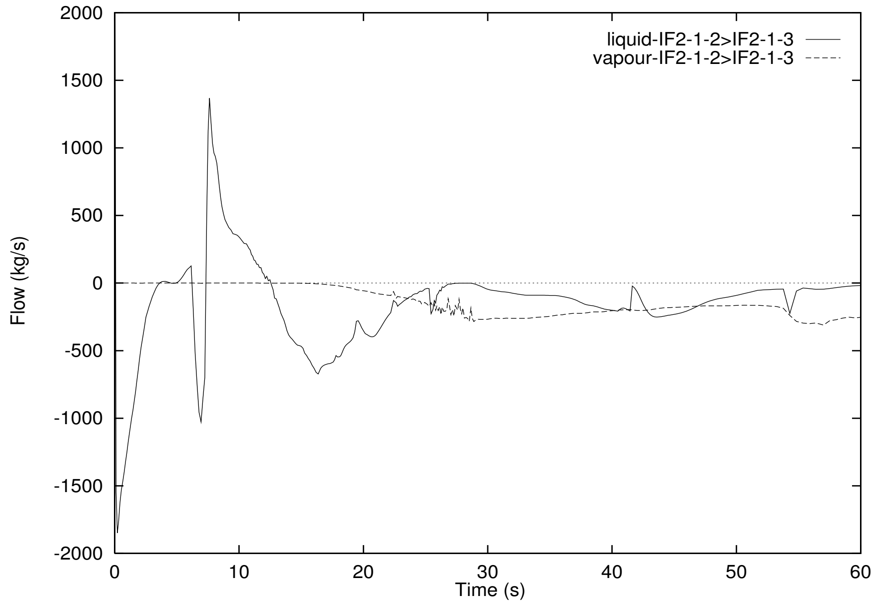

Figure 13 Phase 1 - Feeder 2 Flows

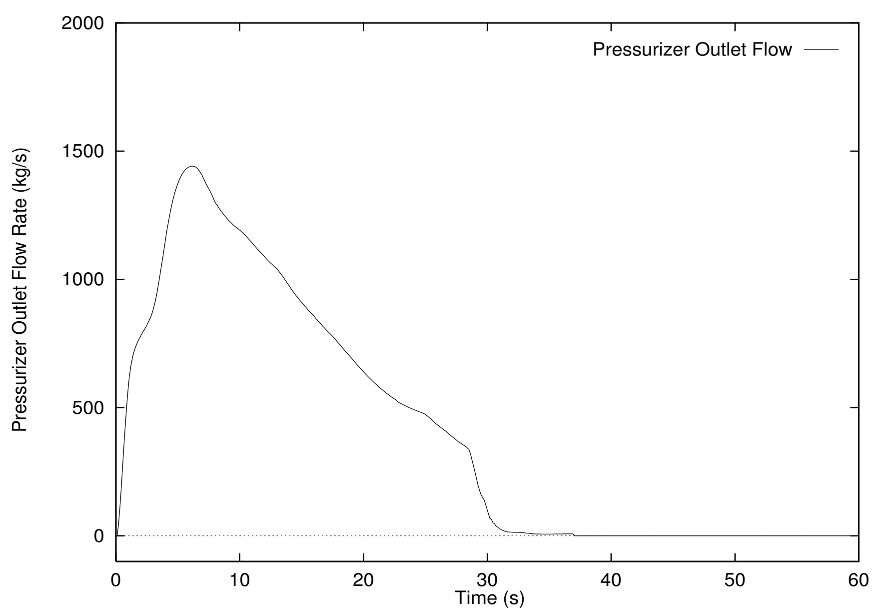

Figure 14 Phase 1 - Pressurizer Outlet Flow Rate

- The large header interconnect valve begins to open at approximately 7 seconds and coolant flows from ROH2, through the large interconnect line (Figure 6) into ROH1.
- A portion of the large interconnect line flow is contributed by the pressurizer, which discharges into ROH2 (Figure 14).

- At approximately 11.5 seconds, the cladding temperatures begin to once again increase (Figure 3). There are several processes that contribute to this outcome.
  - The reduction in cladding temperature at about 7 seconds was the result of restored positive flow through the feeder to the downstream pass channel (Figure 12).
  - Beginning at approximately 11.5 seconds, the flow characteristics are altered.
    - The inlet feeder flow rapidly decreases and then reverses (Figure 13) under the influence of a reversal of the RIH2 to ROH1 pressure difference (Figure 15).
    - The interconnect flow, which reached a maximum for this phase at 11.5 seconds, begins to decrease (Figure 6).

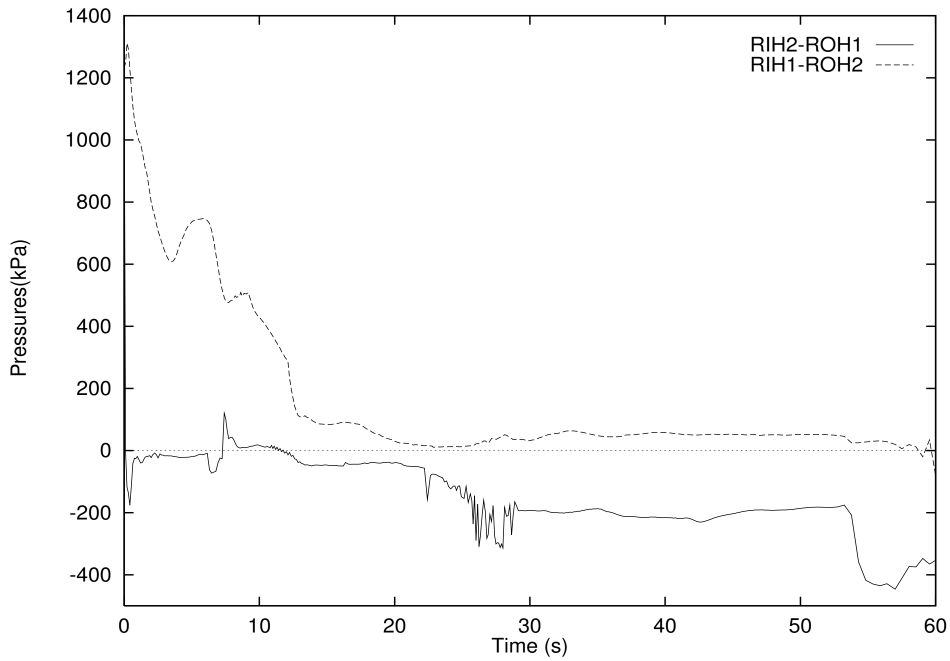

Figure 15 Phase 1 - Header Pressure Differences

  - The combination of reduced flow into the downstream pass channel combined with a nearly constant decay power results in a resumption of cladding heating (Figure 3) that continues until approximately 18.5 seconds. Also, RCS pump head and flow continue to decrease during this period due to pump suction voiding (and also pump trip at 9 s), while the break flow remains almost constant.

- The next major inflection point in cladding temperature begins at approximately 18.5 seconds when cooling is restored to the downstream pass channel and the cladding temperature begins to decrease. With the exception of a minor and short-lived temperature increase beginning at 22 seconds, the cladding temperature continues to decrease until it reaches 350 ºC at 53 seconds, the end of the first phase. There are several processes that contribute to cooling of the cladding during the remainder of Phase 1.

- The decay power decreases from 7 percent to 5 percent of full power between 10 and 50 seconds.
- A reverse flow is established passing through ROH1 (Figure 16), the outlet feeder (Figure 13), the downstream pass channel (Figure 17), the inlet feeder, and into RIH2. The reverse flow through the downstream pass channel is small at 18.5 seconds but increases with time. At 30 seconds, a reverse flow of 350 kg/s has been established. At this time the large interconnect line flow has decreased to 135 kg/s (Figure 6). The remainder of the flow passing through ROH1 is liquid draining downward from steam generator #1 (Figure 18).

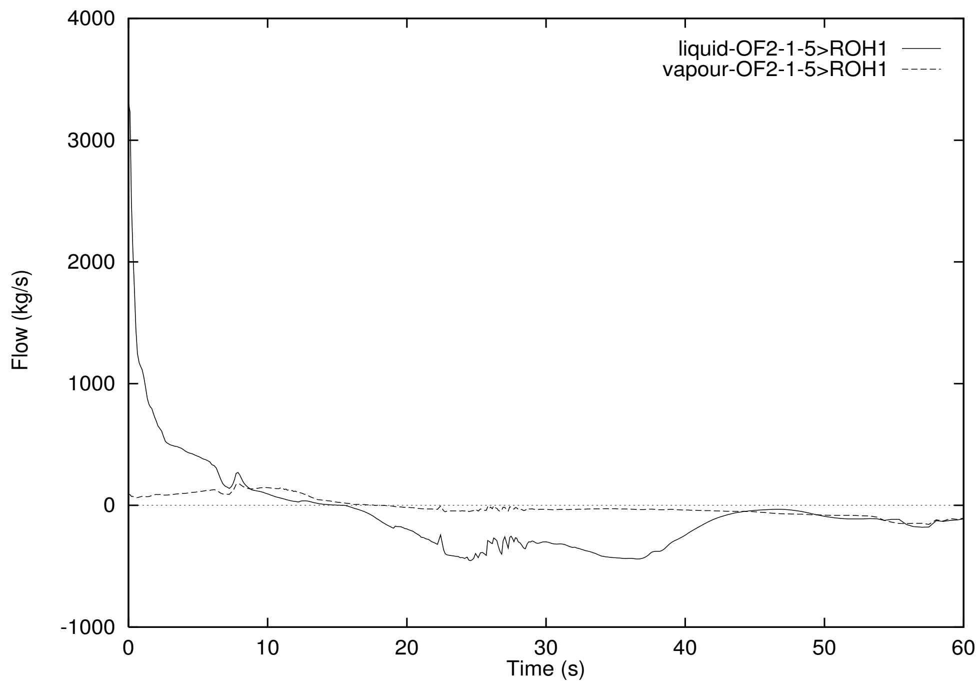

Figure 16 Phase 1 - Outlet Header Flows

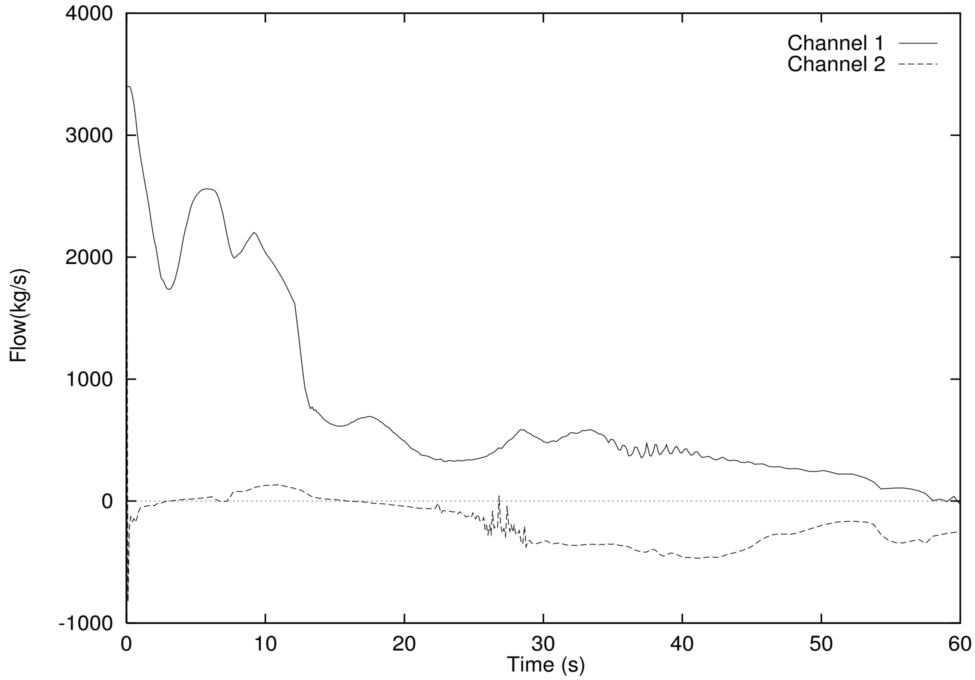

Figure 17 Phase 1 - Fuel Channel Flows

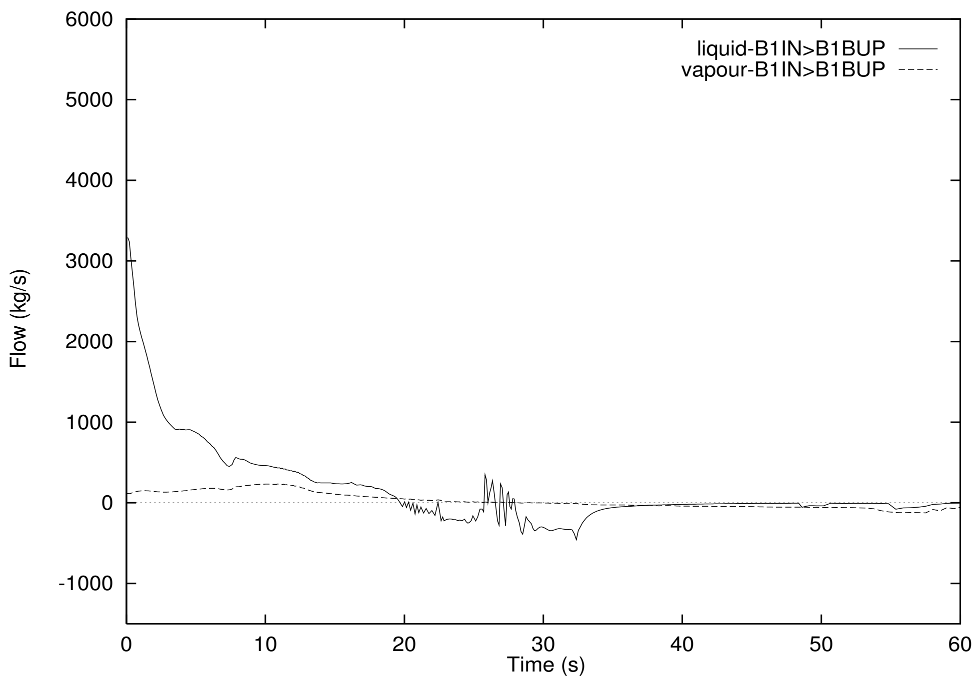

Figure 18 Phase 1 - SG Inlet Plenum Flows

- The rate of cladding temperature decrease slows at 42 seconds (Figure 3), which is caused by a reduction in the downstream pass channel flow rate (Figure 17). The reverse downstream pass channel flow derives from flows into ROH1. These come from two sources, the large interconnect line flow and the drainage flow from steam generator #1. The large interconnect line flow is small at this time (Figure 6). Also, the drainage flow from steam generator #1 is negligible (Figure 18). However, there is sufficient inventory remaining in ROH1 and the outlet feeder to continue the cooling trend by supplying flow through the outlet feeder (Figure 13) to the downstream pass channel, although the cooling continues at a reduced rate (Figure 3). The coolant moves under the negative pressure gradient (relative to steady-state operation) between RIH2 and ROH1 (Figure 15).

5.2 Late Blowdown / ECI / Refill (Phase 2: 53 – 250 seconds)

Phase-2 is initiated by actuation of the high-pressure ECI system. The plots in this section cover the time period between 60 and 250 seconds. The reader should refer to the plots in Section 5.1 for details of the initial Phase 2 behaviors between 53 and 60 seconds. Two nitrogen-pressurized ECI accumulators inject coolant into inlet headers RIH1 and RIH2. As the break occurs in RIH2, the ECI flow into RIH2 is discharged out of the break.

The behaviour of the maximum cladding temperature during Phase 2 (Figure 19) is most directly related to the sequential process of refilling the headers and components below the headers in the upstream pass and then the headers and components below the headers associated with the downstream pass.

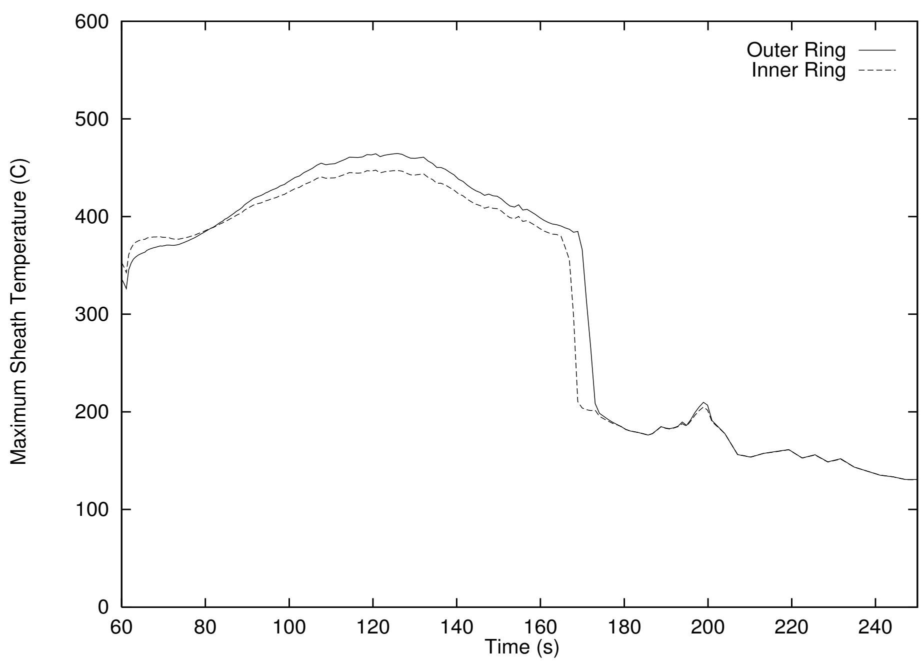

Figure 19 Phase 2 - Maximum Cladding Temperature

As ECI begins, the RCS is highly voided. The ECI flow into RIH2 condenses steam and much of the coolant remaining in the system is pulled through the downstream pass and flows out the break. The refilling begins with RIH1, moves through the upstream pass, fills ROH2 and re-establishes flow through the large header interconnect. Filling of components connected to the downstream pass then commences. As filling of ROH1 proceeds, two-phase flow passes into the downstream pass channel and terminates the temperature increase that began shortly after the start of Phase 2. Shortly before the end of Phase 2, the downstream pass channel is refilled.

A detailed description of the processes and phenomena occurring during Phase 2 follows.

- At the transition from Phase 1 to Phase 2 at 53 seconds, the maximum cladding temperature (Figure 3) is decreasing as residual inventory in ROH1 and the outlet feeder for the downstream pass moves through the downstream pass to the inlet feeder and RIH2. However, there is little flow into ROH1 from either the large header interconnect or draining from steam generator #1 at the end of Phase 1.
- Cooling of the cladding continues until approximately 61 seconds, after which the maximum cladding temperature begins to increase from its minimum value of 255ºC.

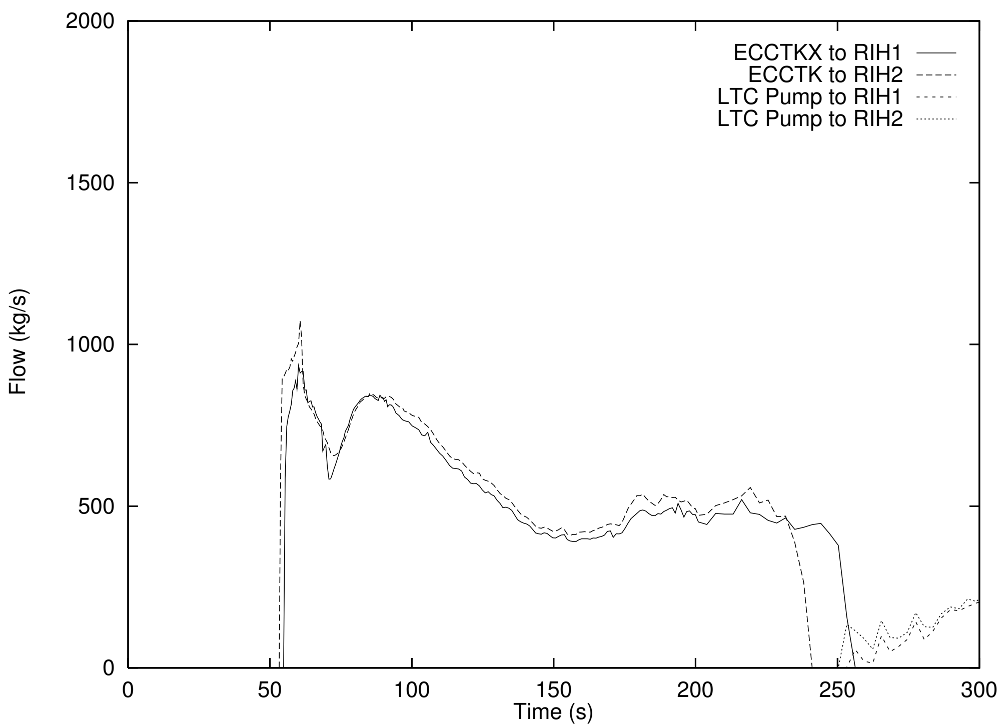

Figure 20 Phase 2 - ECI Flows

- ECI flow into RIH2 begins at about 53 seconds; ECI flow into RIH1 begins shortly thereafter (Figure 20), and slowly decreases until 256 seconds when the ECI tanks are nearly depleted. With the ECI flow into RIH2, the break flow rate increases immediately to 2000 kg/s (Figure 5 and Figure 21).

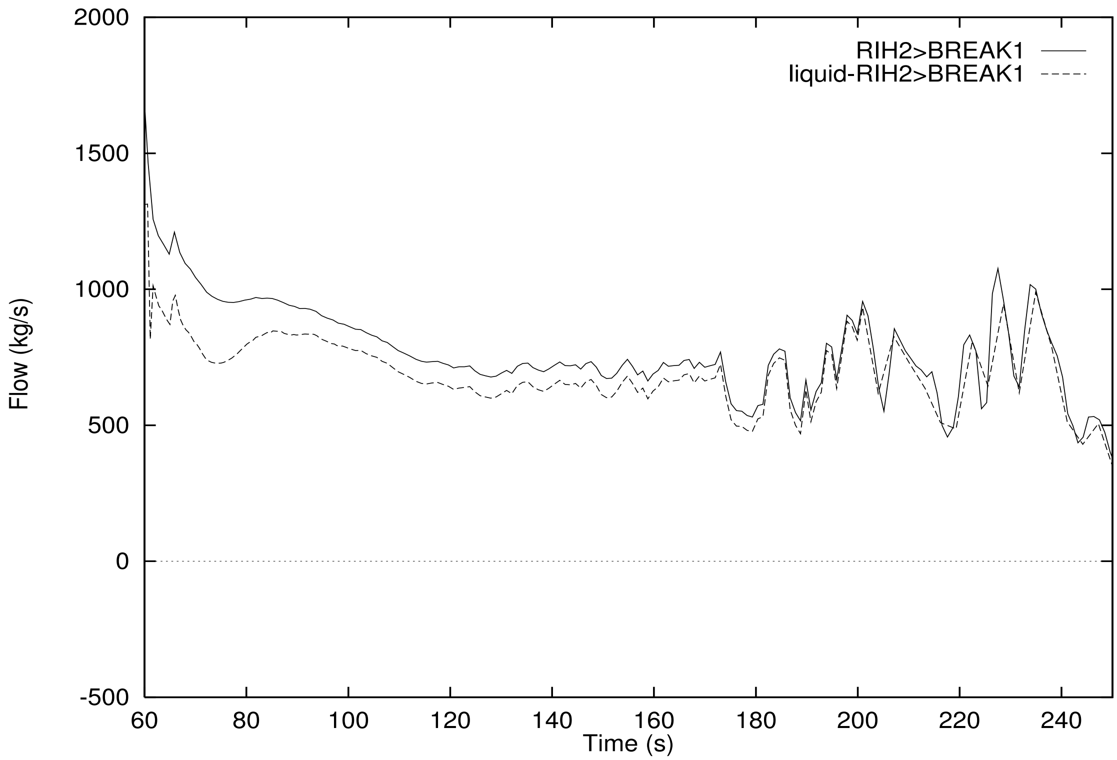

Figure 21 Phase 2 - Break Discharge Flow

- At the start of ECI flow into RIH1 and RIH2, the headers are almost fully voided (Figure 4 and Figure 10 and Figure 22 and Figure 23). The steam in RIH2 begins to condense, rapidly decreasing the RIH2 pressure and increasing the negative pressure difference from ROH1 to RIH2 (Figure 15 and Figure 24). With the increased pressure difference, a two-phase mixture is pulled through the downstream pass and into RIH2 to be condensed by the ECI flow (Figure 25). The flow pulled through the downstream pass under the influence of the reduced RIH2 pressure due to condensation and the flow pulled through the reactor coolant pumps and piping connected to RIH2 due to condensation, combined with ECI flow, constitutes the break flow after the ECI start.

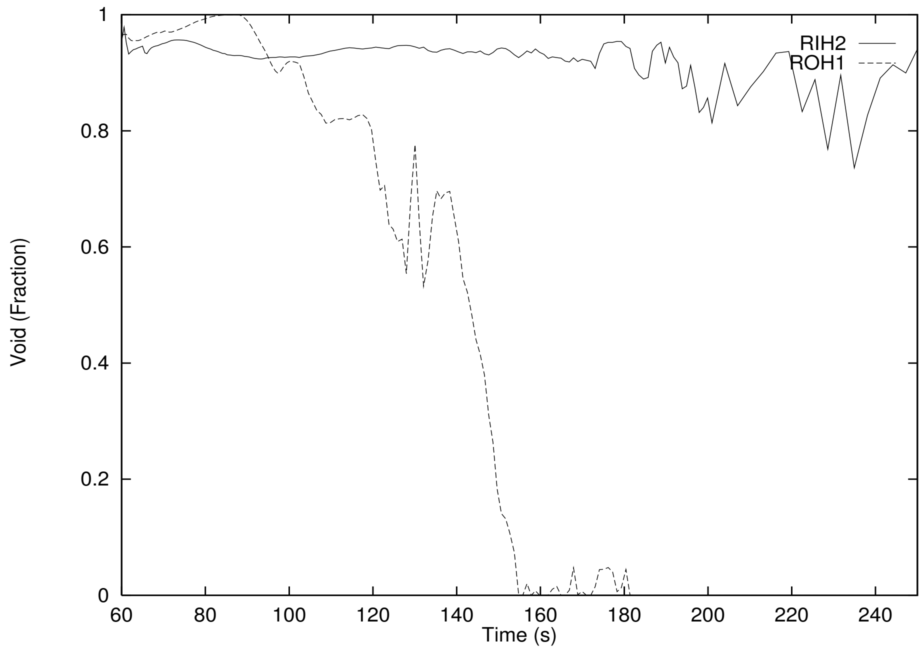

Figure 22 Phase 2 - Header Voids RIH2 and ROH1)

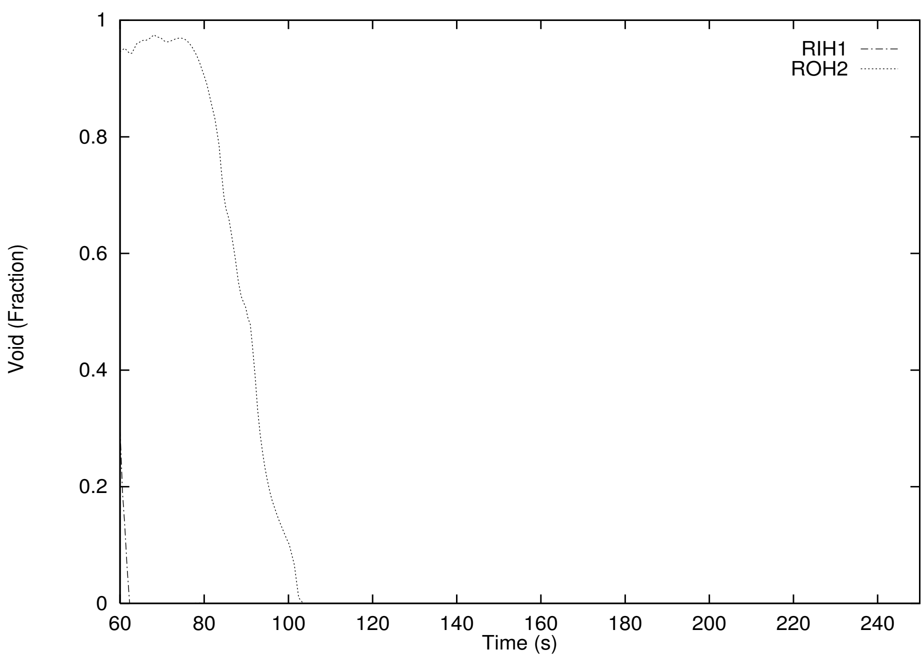

Figure 23 Phase 2 - Header Voids (RIH1 and ROH2)

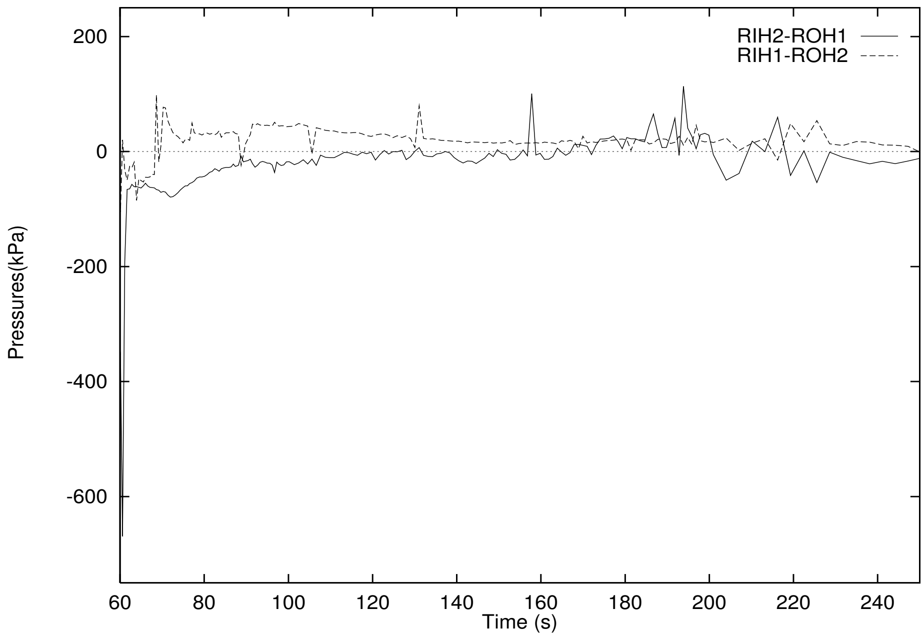

Figure 24 Phase 2 - Header Pressure Differences

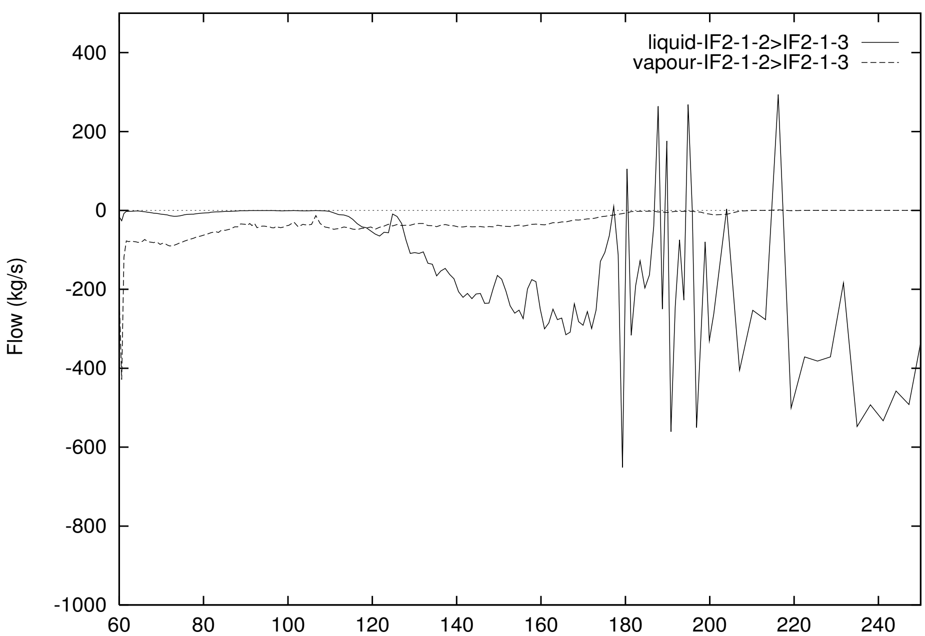

Figure 25 Phase 2 – Feeder 2 Flows

- Although ECI flow into RIH1 begins at 55 seconds, there is a time delay before a flow rate approaching the ECI flow into RIH1 reaches the downstream pass through the large header interconnect (Figure 26). During the interval between 55 and 88 seconds, the maximum large header interconnect flow is 60 kg/s. At 88 seconds, the large header interconnect flow rapidly increases and maintains an average flow rate of approximately 400 kg/s until the end of Phase 2 at 250 seconds.

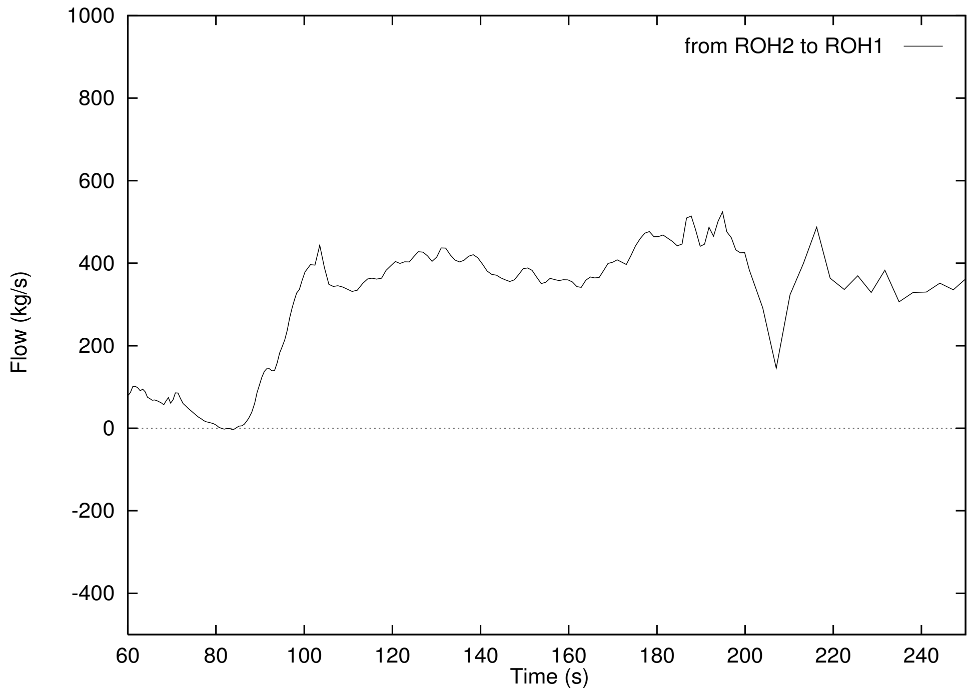

Figure 26 Phase 2 - Large Outlet Header Interconnect Flow

- The interval between 55 and 88 seconds is a period of refilling volumes. RIH1 is almost fully voided as the ECI flow begins and is the first component to refill at 62 seconds (Figure 10 and Figure 23). The inlet feeder for the upstream pass is the next to refill at 65 seconds. The outlet feeder for the upstream pass fills at 87 seconds (Figure 27) and a rapid increase in flow through the large header interconnect follows immediately (Figure 26).
- The filling of components in the downstream pass path by the flow through the large header interconnects then begins. ROH1 fills at 155 seconds (Figure 22). The outlet feeder for the downstream pass channel fills at approximately 130 seconds (Figure 28). The inlet feeder for the downstream pass channel first refills at 215 seconds and permanently refills at 225 seconds (Figure 28).

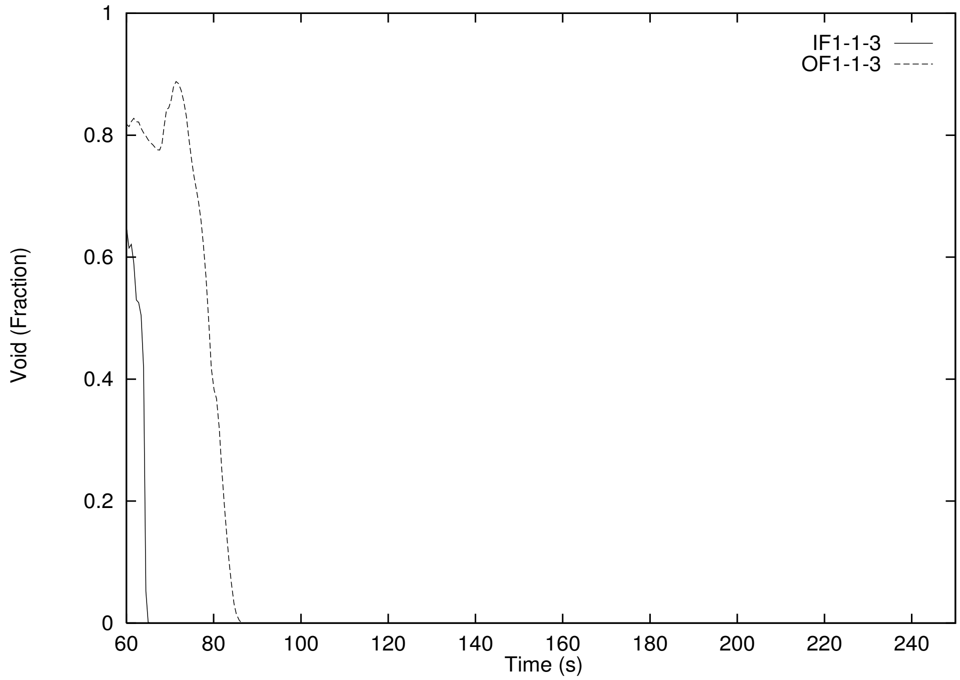

Figure 27 Phase 2 - Feeder Voids in Upstream Pass

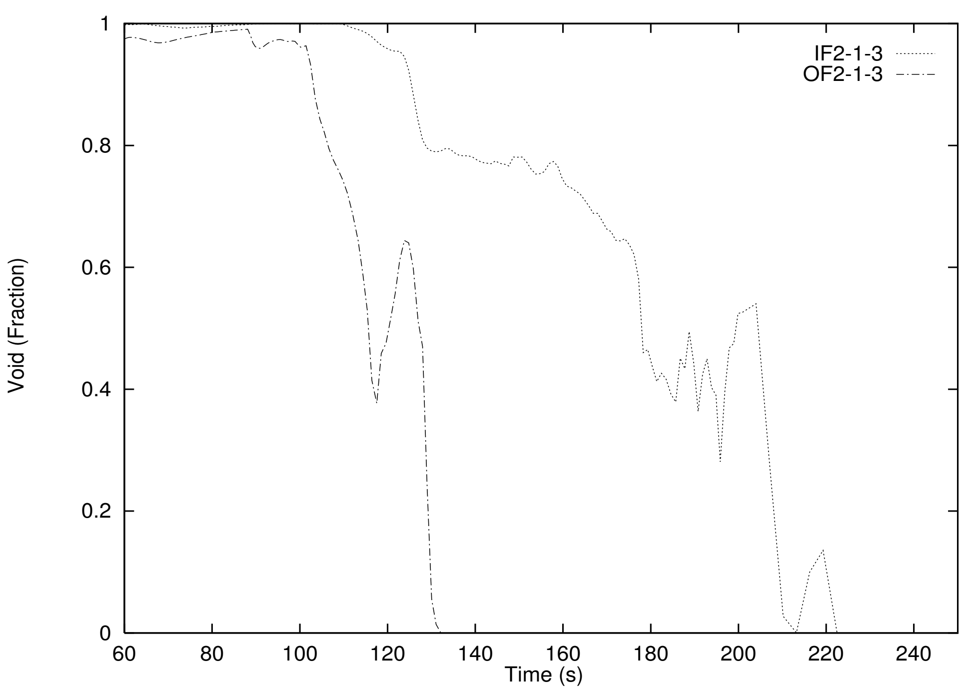

Figure 28 Phase 2 - Feeder Voids in Downstream Pass

- The downstream pass channel begins to refill at 105 seconds (Figure 29). The downstream pass channel first refills at 180 seconds. It remains liquid filled for 10 seconds, has a recurrence of voiding to 50% for 15 seconds and permanently refills at 205 seconds (Figure 29).

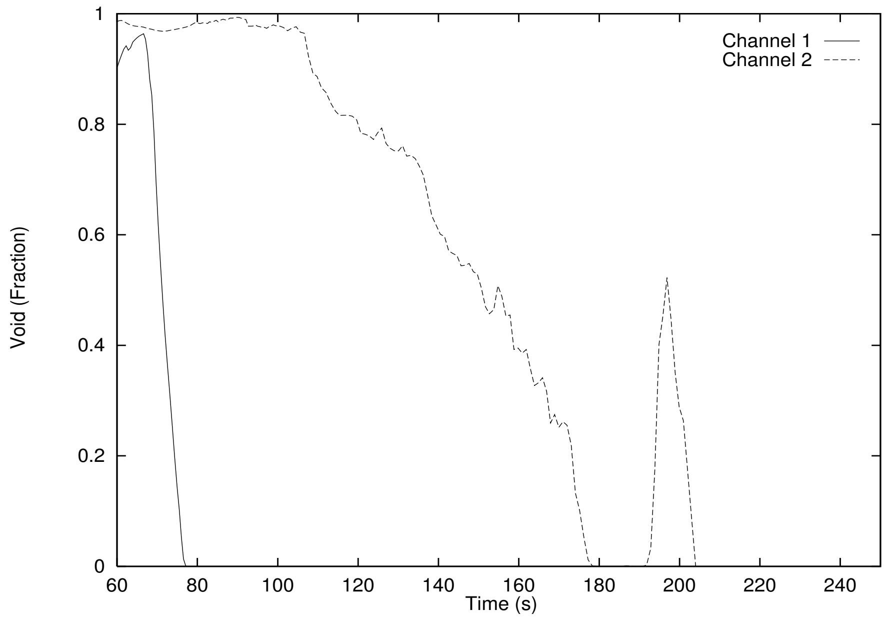

Figure 29 Phase 2 - Fuel Channel Integrated Voids

- The behavior of the maximum cladding temperature (Figure 19) during Phase 2 is the direct outcome of the refilling process just explained. Cooling of the cladding continues for a brief interval following the start of ECI as the condensation occurring in RIH2 induces flow through the downstream pass. However, small amount of coolant is being supplied to ROH1 through either the large header interconnect or by continued draining of the steam generator #1 inventory into RIH2. At 61 seconds, the maximum cladding temperature begins to increase.
- The cladding temperature increase continues until refilling of the components between RIH1 and ROH2 is accomplished and flow is re-established through the large header interconnect to ROH1. With the interconnect flow re-established, filling of the components between ROH1 and RIH2, including the downstream pass, proceeds.
- Although refilling of the downstream pass starts at 105 seconds, sufficient coolant to terminate the cladding temperature increase is not present in the downstream pass channel until approximately 130 seconds. The downstream pass channel integrated void at 130 seconds is approximately 75%.
- There is a brief overlap between the termination of ECI flow and the start of long term cooling (LTC) injection. ECI flow continues to 256 seconds; LTC injection begins at 250 seconds, which is defined as the start of Phase 3.

5.3 Long-Term Cooling (Phase 3: > 250 seconds)

Phase 3 is initiated by injection of coolant flow in the headers by the LTC system. The LTC system draws its coolant supply from the reactor building sump and delivers coolant to RIH1 and RIH2. There is a 75 second interval between the termination of ECI flow and achieving full LTC flow, causing the maximum channel cladding temperature to increase. After full LTC flow is established, the maximum channel cladding temperature decreases and the core quenches. Fuel Cladding temperature is shown in Figure 30.

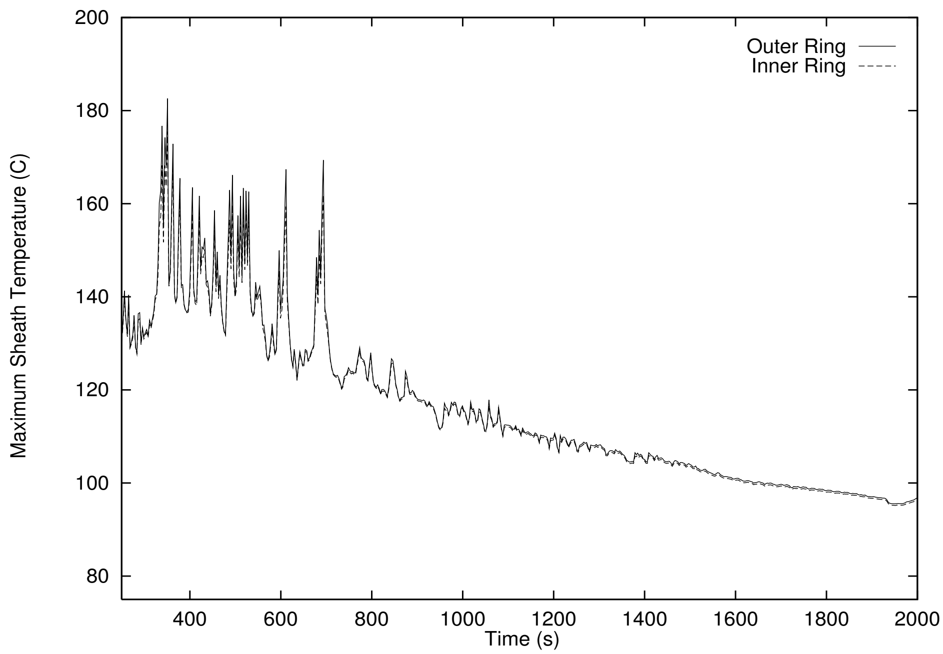

Figure 30 Phase 3 - Maximum Cladding Temperature

A detailed description of the processes and phenomena occurring during Phase 3 follows.

- There is an interval of approximately 75 seconds between the termination of ECI flow at 256 seconds and establishing full LTC flow at about 330 seconds.
- During this interval, the cladding temperature increases by 70ºC (Figure 30).
- At full flow, the LTC delivers approximately 250 kg/s coolant to each inlet header (Figure 31). The flow delivered to RIH1 first passes through the upstream pass channel, through the large header interconnect, and then through the downstream pass channel and into RIH2 (Figure 32) and thence out the break.

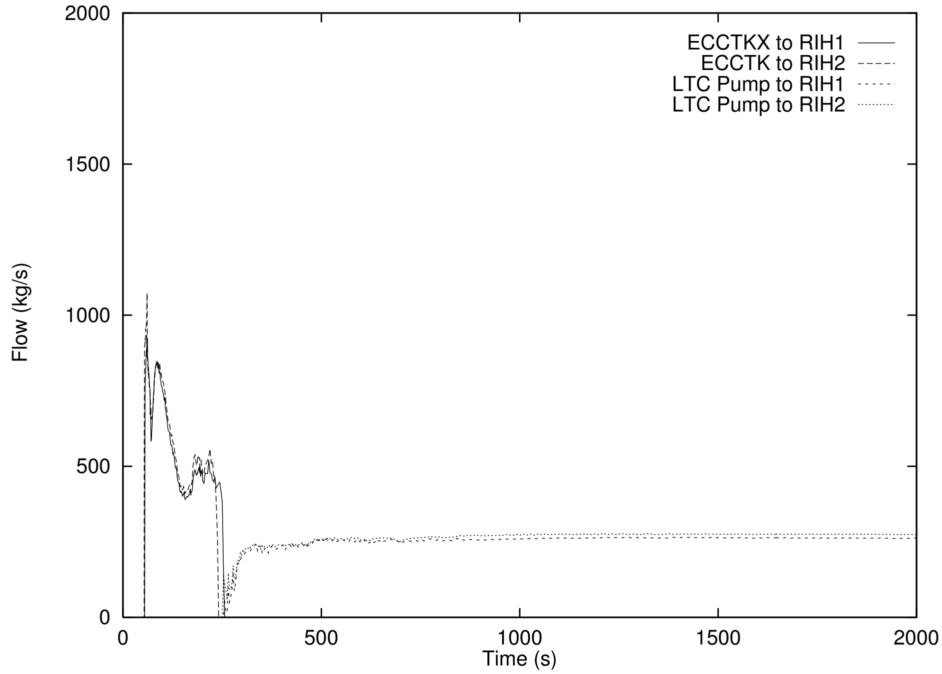

Figure 31 Phase 3 - ECC Flows

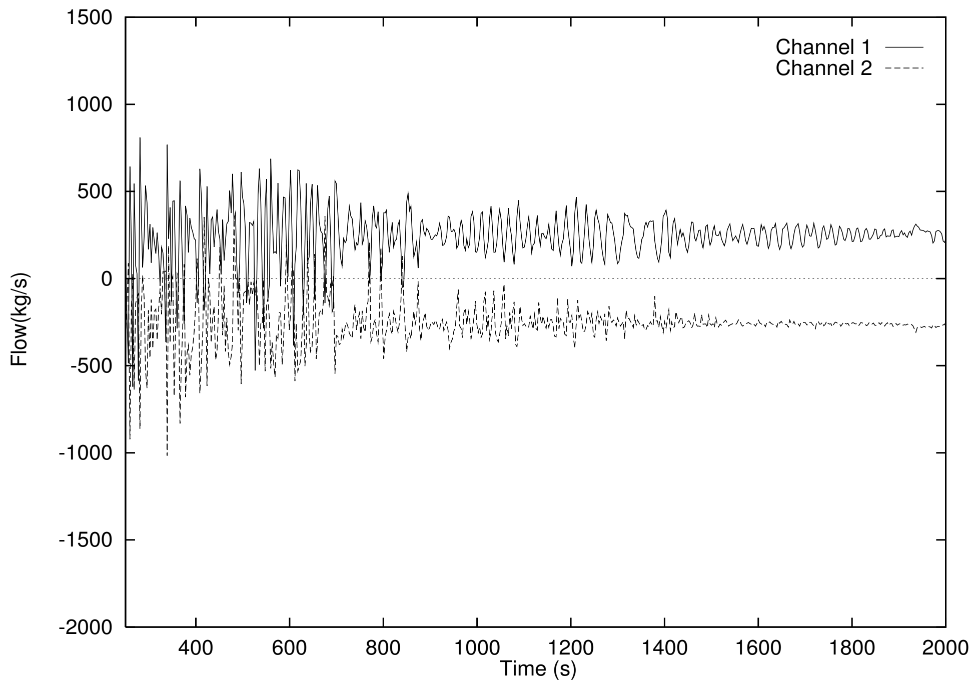

Figure 32 Phase 3 - Fuel Channel Flows

- The total break flow of 500 kg/s (Figure 33) is equal to the LTC flow of the same amount (Figure 31). The 250 kg/s delivered to RIH2 passes directly out the break while the 250 kg/s delivered to RIH1 passes through both the upstream and downstream pass channels before going out the break.

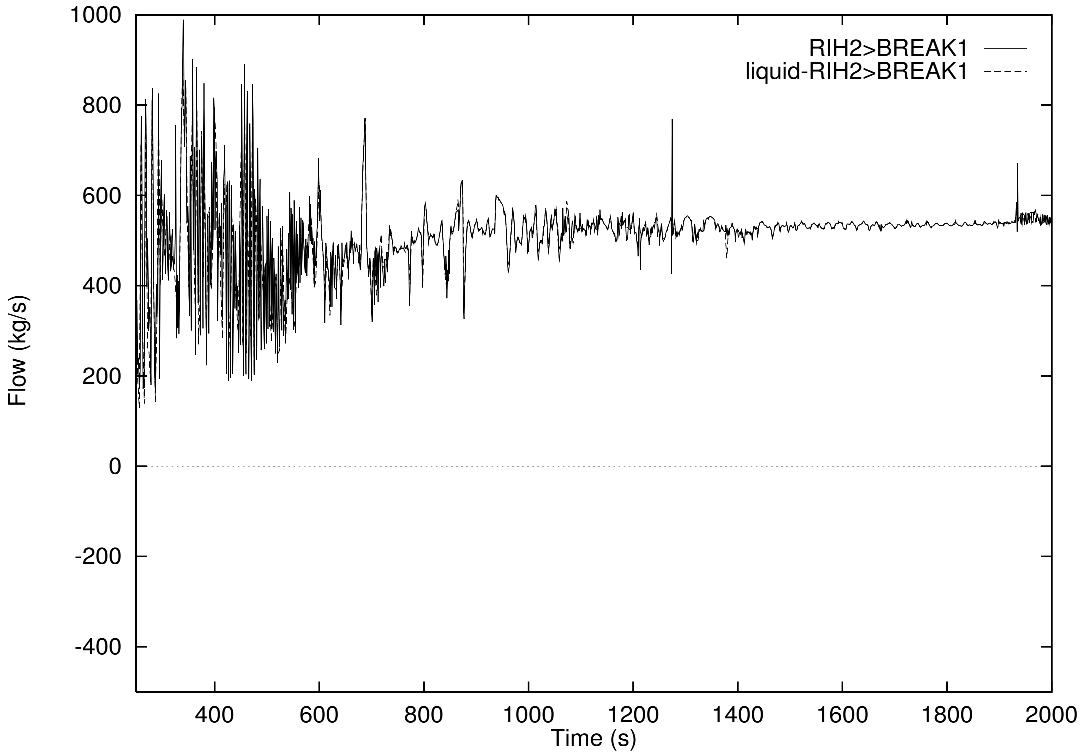

Figure 33 Phase 3 - Break Discharge Flow

- At 390 seconds, approximately 60 seconds after full LTC flow is established, the cladding temperature peaks and begins to decrease.
- Core cooling at full LTC flow continues until the end of the calculated transient. The LTC flow results in an initial core quench at 740 seconds.

6. REFERENCES

[1] B. N. Hanna, “CATHENA: A thermalhydraulic code for CANDU analysis,” Nuclear Engineering and Design 180, 113-131 (1998).