Assessment of Thermalhydraulic Phenomena for External Water Make-Up

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Abstract

Following the Fukushima Daiichi accident, Canadian NPP licensees implemented a number of changes, including additional provisions for water make-up to the reactor/boiler systems. The CNSC has placed a contract with CNL to model some of the make-up options, focusing on cooling via the boilers to prevent core damage. Such strategies have been credited with sustaining thermo-syphoning in the primary system and thus prolonging the available time for the operator to provide pumped make-up to the boilers or emergency coolant injection to the core, thereby maintaining decay heat removal. This paper presents results of CATHENA calculations of an extended loss of all electrical power in which the operator manually depressurizes the boilers by crash-cooling, thus allowing water to flow to the boilers by gravity from the deaerator tank. The rapid cooling of the boilers promotes thermo-syphoning flow in the primary heat transport system and results in a corresponding cool-down and depressurization of this system.

1. Introduction

In the event of a Station Blackout (SBO) in a CANDU nuclear power plant, adequate cooling must be established to remove the decay heat from the fuel before the remaining coolant inventory boils away. If systems normally available to direct water to cool the fuel become unavailable, water may need to be injected from external supplies into the reactor systems via the steam generators (SGs, or boilers), the primary heat transport system (PHTS) or the calandria.

Sources of make-up water can vary between plants but, in the absence of normal onsite power, typically would be water from reservoirs in the plant in the short term, and emergency mitigating equipment in the long term. Emergency mitigating equipment comprises portable power supplies and pumps capable of delivering water to where it is needed. In order to determine how effective the addition of external make-up water would be in mitigating the consequences of insufficient decay heat removal, the CNSC requested that Canadian Nuclear Laboratories (CNL) perform simulations to assess the thermalhydraulic behaviour of injected make-up water. This paper presents some of the preliminary results related to simulations of a prolonged SBO.

In this work, the effectiveness of supplying the secondary side of the SG with water from the deaerator tank was examined. From previous analysis [1], the most effective heat removal strategy during a SBO would be to establish adequate water to the SGs. If the SGs do not dry out, then the decay heat can be removed from the PHTS through thermo-syphoning. The heat added to the PHTS in the channels and the heat removed through the SGs produce a density difference in the PHTS, producing a natural circulation flow. The natural circulation of the PHTS transfers the heat generated in the core to the SGs and has been confirmed to be an effective decay heat removal mechanism for heavy water reactors [2].

The deaerator tank is part of the normal boiler feedwater system and has a typical inventory of 319,244 kg. If the secondary side is depressurized, then the inventory of the deaerator tank should flow into the SGs and delay dry-out. Three scenarios were examined:

1. Prolonged SBO, with no mitigating actions (i.e., no crash cooling and no high pressure Emergency Core Cooling (ECC)).
2. Prolonged SBO, with crash cooling initiated 15 minutes after the SBO. The high pressure ECC system is unavailable.
3. Prolonged SBO, with crash cooling initiated 15 minutes after the SBO. The high pressure ECC system is available.

A brief description of the thermalhydraulic model is given in Section 2. The simulation results are given in Section 3. A summary of the results is given in Section 4.

2. Model

A CATHENA [3] (Canadian Algorithm for THErmalhydraulic Network Analysis) system model of a generic CANDU 6® was used for the analysis. CATHENA was developed to model the thermalhydraulic response of CANDU® reactors during postulated upset conditions; however, the code has found a wider range of application for the modelling of thermalhydraulic facilities. The two-phase flow in piping networks is modeled with a transient, one-dimensional, two-fluid representation. The thermalhydraulic models include pipe, volume, reservoir, T-junction and tank components. The code includes the thermophysical properties for both light water (H_2O) and heavy water (D_2O). Noncondensable gas properties are available for H_2, He, N_2, Ar, CO_2 and air. CATHENA contains a heat transfer package (called GENHTP) that can model radial and circumferential conduction, Zr-steam reaction heat generation, thermal radiation and contact conduction between solid surfaces. An extensive control system modelling capability is also provided for complete loop simulations.

The flow network model is shown in Figure 1 to Figure 3. Models for the following components are included: reactor header, feeders, end fittings, fuel and fuel channels, boiler inlet piping, boiler primary side, primary heat transport pump suction piping, primary heat transport pump and pump discharge piping, outlet header balance lines, pressurizer and interconnect piping, D_2O feed and bleed and purification interconnect, liquid relief valves and piping, SG feed water system, SG secondary side, steam main piping and turbine governing valves, and ECC system.

The idealization of the feedwater system, SGs, steam system, and PHTS is shown in Figure 1. In a CANDU 6®, there are 380 channels. However, the CATHENA idealization does not model all 380 channels, but rather groups the channels into “average” channels. The model used for the Prolonged SBO analysis includes 9 average channels per core pass. The CATHENA model for average channel 1 in core pass 1 is shown in Figure 2, as it is typical of the model used for other channels and core passes.

For all simulations, the initial conditions were steady-state, with fuel power at 2047 MW[1]. The SBO is initiated by:

- Stopping the primary heat transport pumps.
- Stopping the main boiler feedwater pump[2].
- Isolating the primary heat transport circuit from all reservoirs, except for the reservoir attached to the liquid relief system. The pressurizer remains connected to both loops because the isolation valves have no power to close.
- Isolating the secondary system from all reservoirs, except for the reservoirs (representing the atmosphere) attached to the Main Steam Safety Valves (MSSVs) and Atmospheric Steam Discharge Valves (ASDVs).
- Reducing fuel power to decay levels.

Crash cooling was initiated by opening the valves representing the MSSVs at a specified time, after the initiation of the SBO. Make-up water to the SGs would be supplied by the deaerator tank. The deaerator tank was modeled as a reservoir, with a pressure of 229 kPa. However, the CATHENA model tracked the inventory of the deaerator tank, and the flow from the deaerator tank could be stopped once the inventory (319,244 kg) was exhausted.

The high pressure ECC system was activated by opening the high pressure injection valve between ECCKP2 and ECCKP3, and opening the D_2O isolation valves, located near the bottom of the ECC system in Figure 3. The valves were opened when the conditions for ECC injection were satisfied: low heat transport system pressure (less than 5.25 MPa).

3. Results

Results from three scenarios are presented here, as these results are typical:

- Prolonged SBO, with no crash cooling and no high pressure ECC (see Section 3.1).
- Prolonged SBO, with crash cooling initiated 15 minutes after the SBO. The high pressure ECC system is unavailable. The simulation results are presented in Section 3.2.
- Prolonged SBO, with crash cooling initiated 15 minutes after the SBO. The high pressure ECC system is available. The simulation results are presented in Section 3.3.

The breakdown of sustained thermo-syphoning was of interest and as a result, the simulations were terminated if any sheath temperature exceeded 800°C.

3.1 No Crash Cooling, High Pressure ECC Unavailable

After the initiation of the SBO and loss of the PHTS pumps at time=0, the water mass flow through the core is established through thermo-syphoning, as shown in Figure 4. However, because crash cooling is not initiated to depressurize the SGs, no external source of make-up water is supplied and the SG inventory of liquid water boils off. The PHTS begins to heat up

[1] This is the fission heat from the fuel channels, less the heat loses to the moderator, end shield, primary piping, and PHTS auxiliaries.
[2] The auxiliary feedwater pump is assumed unavailable.

when the liquid water inventory of the SG secondary side drops to about 7.5% of the initial inventory (1.6 hr), as can be seen in the rise in inlet and outlet header temperature in Figure 4. The liquid water inventory in the SG secondary side is completely exhausted at 1.9 hr, while the PHTS continues to heat up. As the temperature of the PHTS fluid increases, the pressure also increases until the liquid relief valves open at 2 hr. The end of sustained thermo-syphoning is marked by flow reversal in the core pass: the flow in some of the channels reverse and the total mass flow through the core is reduced. In the simulation, the inlet and outlet headers void and the sheath temperature exceeds 800°C at 2.5 hr after the initiation of the SBO.

3.2 Crash Cooling, High Pressure ECC Unavailable

For the simulation results presented in this section, crash cooling is initiated 15 minutes after the initiation of the SBO. In this simulation, ECC is not modelled. While this is not representative of the CANDU 6® reactor modelled, results are expected to be of general relevance for reactor designs with pumped high pressure ECC systems, which would not operate due to the SBO. If crash cooling is initiated, then the pressure of the secondary side will decrease to a level below the deaerator tank, allowing the inventory of the deaerator tank to flow into the SGs. For the case considered here, the flow from the deaerator tank begins approximately 9 minutes after the initiation of crash cooling. The crash cooling and water from the deaerator tank is effective in reducing the temperature of the PHTS, as shown in the header temperatures of Figure 5.

However, the crash cooling does not result in sustained thermo-syphoning in the PHTS. As shown in Figure 5, flow reversal occurs at approximately 0.7 hr after the SBO, much sooner than if no crash cooling is used (2 hr, Figure 4). The crash cooling and water make-up from the deaerator tank effectively cools the PHTS, as shown in the header temperatures of Figure 5. However, the reduction in PHTS temperature also reduces the pressure (also shown in Figure 5). The reduction in pressure corresponds to a reduction in saturation temperature of the PHTS and boiling begins to occur within the core, producing local void and disrupting the thermo-syphoning. Intermittent flow begins and the sheath temperatures oscillate, exceeding a value of 800°C at 0.9 hr, at which point the simulation terminated.

The instantaneous void distribution within the PHTS at 0.9 hr is shown in Figure 6. Note that the void shown in the core pass volumes is the average of the void in the channels and feeders. The simulations predict that the void will occur primarily in the headers and the core, while the liquid phase is mostly in the primary side boiler tubes. Although the void is generated in the core, it would be expected that the void would migrate to higher elevations, such as the boilers (the top of the boiler tubes is 13.371 m above the middle of the inlet headers). In the current model, there appears to be resistance to void being transported to the boilers and this resistance may be due to the method used to model the boiler tubes. The flow through the boiler tubes is represented by a single flow path; the individual tubes are not modelled. Hence, it is not possible in the model for liquid and vapour to move through different flow paths and the net effect may be an over-estimation of the resistance to vapour flow in the boiler tubes. A sensitivity study should be implemented to determine the effect of modelling multiple flow paths through the boiler tubes.

3.3 Crash Cooling, High Pressure ECC Available

If high pressure ECC injection is available then crash cooling can result in sustained thermo-syphoning. As shown in Figure 7, the availability of high pressure ECC does not allow the inlet header pressure to drop below approximately 1.8 MPa. The ECC valve opens approximately 4 minutes after crash cooling is initiated, when the PHTS system pressure drops below 5.25 MPa, and remains open for the duration of the simulation. The volume of high pressure ECC used within the 4 hr shown in the figure is 67.4 m^3, of a total available volume of 170 m^3. With the pressure above 1.8 MPa, the PHTS remains as single phase liquid. Sustained thermo-syphoning is established, as shown by the positive mass flow through core pass 1 in Figure 7.

After the injection of high pressure ECC, the pressure of the PHTS is unsteady. The increase in pressure is due to thermal expansion of the water injected from the high pressure ECC system. The high pressure ECC water is injected from a reservoir at 30°C and will heat up to the temperature of the PHTS. A check valve prevents back-flow into the high pressure ECC tank; thus, the pressure of the PHTS will increase as the lower temperature ECC water expands. Over a longer time period, the pressure of the PHTS will decrease as the temperature of the system continues to decrease. But, because of the availability of the high pressure ECC, the inlet header pressure does not drop below approximately 1.8 MPa[3].

If make-up water is not added to the deaerator tank from an external source, the secondary side of the SGs will dry-out after the deaerator tank inventory is exhausted. For the simulation presented here, the inventory of the deaerator tank empties into the SGs within 0.5 hours[4] after crash cooling, and the SGs completely dry-out 11.1 hr after the initiation of the SBO. After the SG becomes dry, the PHTS heats up and follow the progression as described in Section 3.1.

4. Summary

A CATHENA model of a generic CANDU 6® reactor was developed to explore the effect of adding make-up water to the secondary sides of the SGs in response to a prolonged SBO. Preliminary results were obtained for three scenarios:

1. No mitigating action taken,
2. Crash cooling, without high pressure ECC, initiated 15 minutes after the SBO, and
3. Crash cooling, with high pressure ECC available, initiated 15 minutes after the SBO.

If no mitigating action is taken, flow reversal and the breakdown of thermo-syphoning in the PHTS occurs 2 hr after the initiation of the SBO. The high SG pressure prevented make-up water from entering the SGs.

Initiating crash cooling allows deaerator inventory to enter the SGs. This cools the PHTS, but if high pressure ECC is unavailable, flow reversal and the breakdown of thermo-syphoning occurs 0.7 hr after the initiation of the SBO. The breakdown of thermo-syphoning is caused by the pressure of the PHTS falling, induced by the PHTS temperature drop. The lower pressure, and saturation temperature, results in local void formation and thermo-syphoning breakdown.

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[3] The sharp drop in pressure near 4 hours that is shown in **Figure 7** is due to a liquid relief valve opening.
[4] The inventory of the deaerator tank over-fills the SG, partially flooding the steam drum.

If crash cooling is initiated with high pressure ECC available, single phase thermo-syphoning in the PHTS can be maintained as long as sufficient make-up water is supplied to the secondary side of the SGs. The ECC prevents the pressure of the PHTS from falling after crash cooling. With the deaerator tank inventory, the SGs will dry-out 11.1 hr after the initiation of the SBO.

It should be noted that these results are preliminary, and future work is needed to determine the sensitivity to key parameters. Some of these parameters are:

- The number of flow paths modelled for the primary side boiler tubes. The simulations show liquid water holdup in the primary side of the SGs, which may be caused by modelling a single flow path through the boiler tubes.
- The initial level of the pressurizer. For the simulations presented here, the pressurizer level was initially 8.6 m, prior to the initiation of the SBO. A higher initial pressurizer level would result in a higher PHTS level after crash cooling and a possibly a higher PHTS pressure.
- The rate of crash cooling. For the simulations presented here, crash cooling was initiated by opening 7/16 of the MSSVs. Opening fewer MSSVs during crash cooling could result in slower cooling of the PHTS and a higher PHTS pressure.
- Flow resistance between the deaerator tank and the SGs. For the simulations presented here, the flow resistance between the deaerator tank and the SGs is known to be under-estimated.
- Channel grouping methodology. There are several methods of grouping the channels into average channels (such as power or elevation), and may affect code predictions.

5. Acknowledgements

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6. Acronyms and Abbreviations

ASDV Atmospheric Steam Discharge Valve
CNSC Canadian Nuclear Safety Commission
CNL Canadian Nuclear Laboratories
ECC Emergency Core Cooling
MSSV Main Steam Safety Valve
PHTS Primary Heat Transport System
SBO Station BlackOut
SG Steam Generator

7. References

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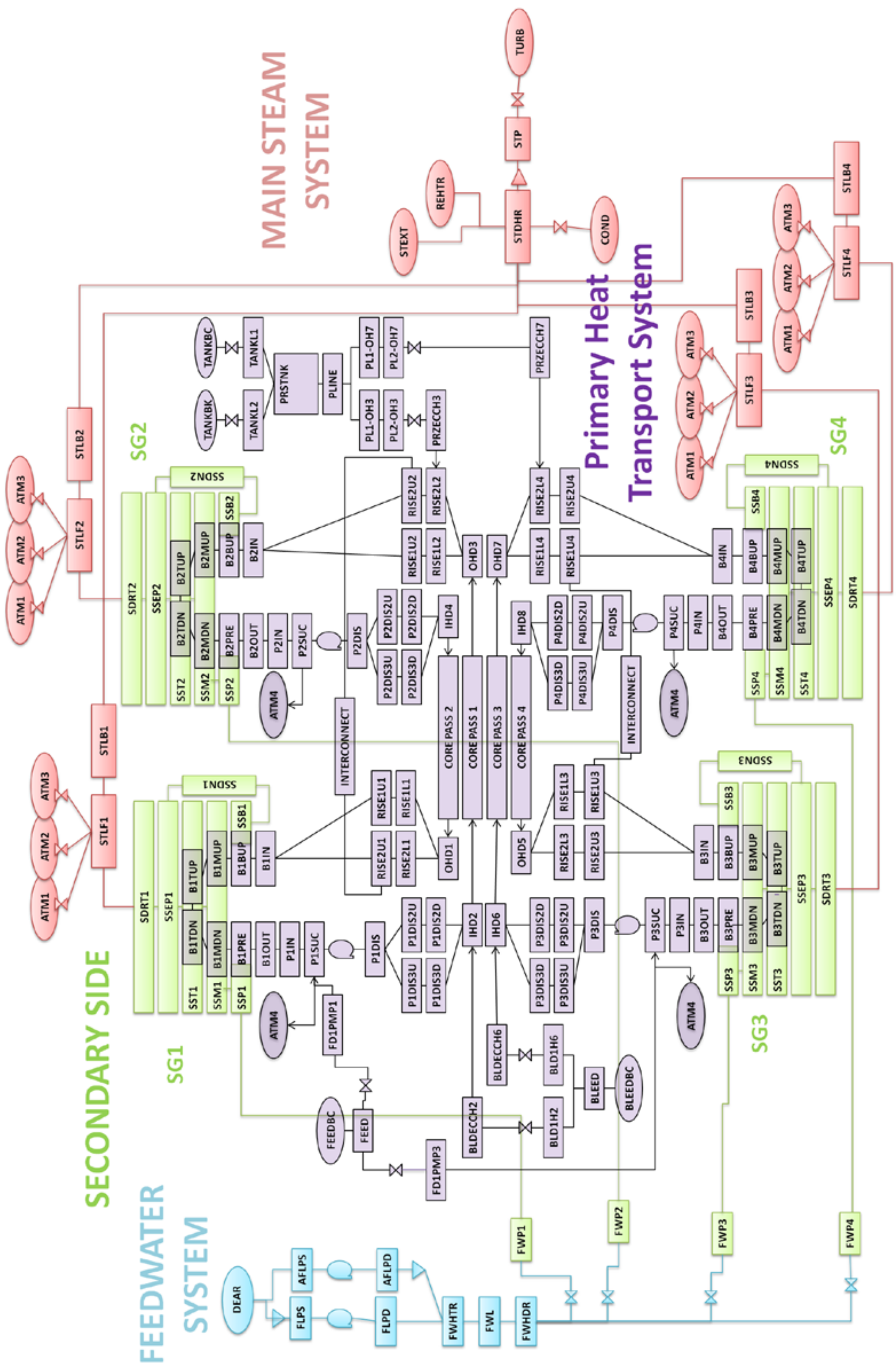

Figure 1 Flow diagram of CATHENA model (feedwater system, secondary side, main steam system, and primary heat transport system). Note that some details are omitted.

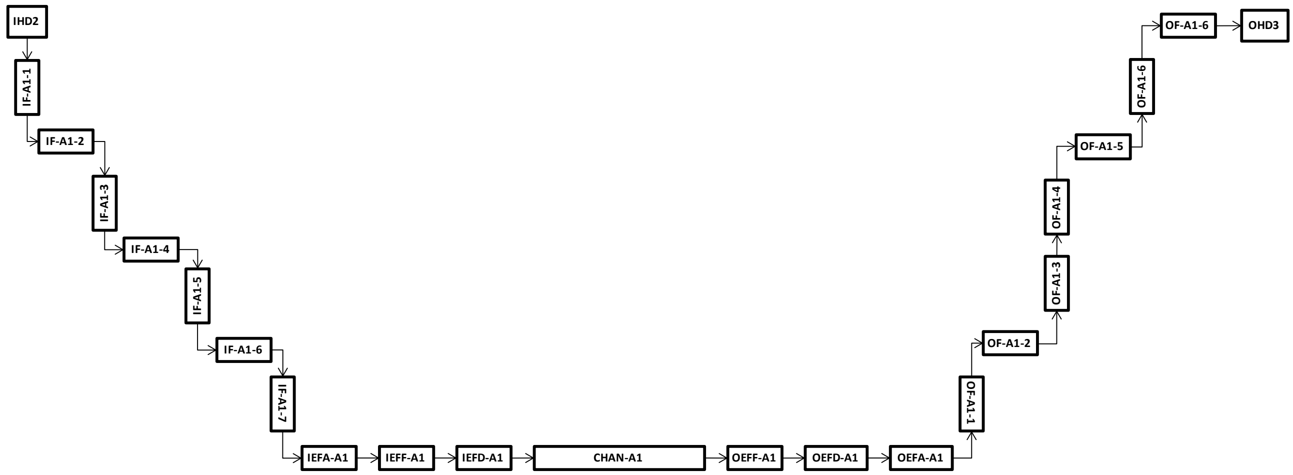

Figure 2 Flow diagram of CATHENA core model, core pass 1, channel group 1.

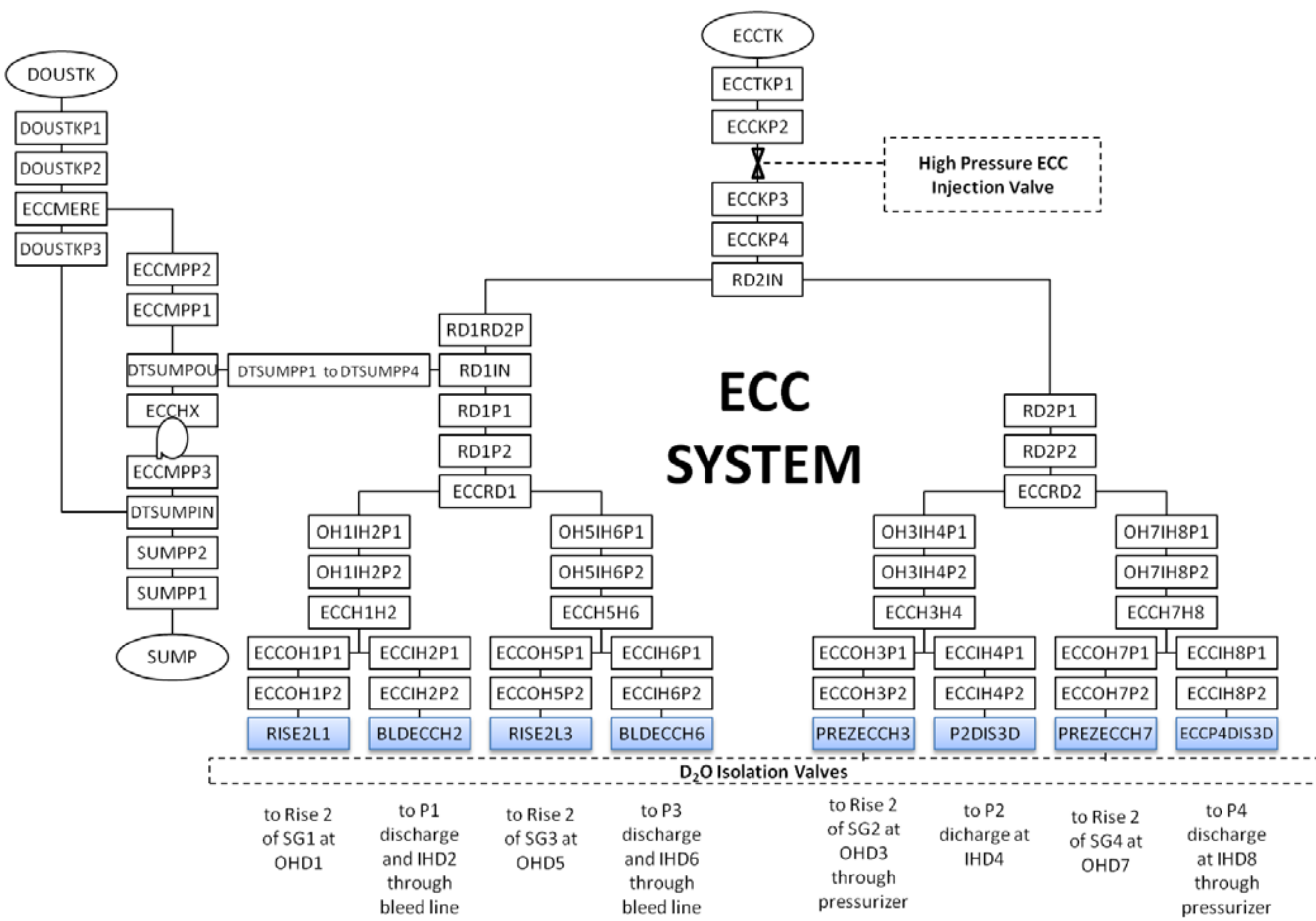

Figure 3 Flow diagram of CATHENA model (emergency core cooling system). Note that some details are omitted.

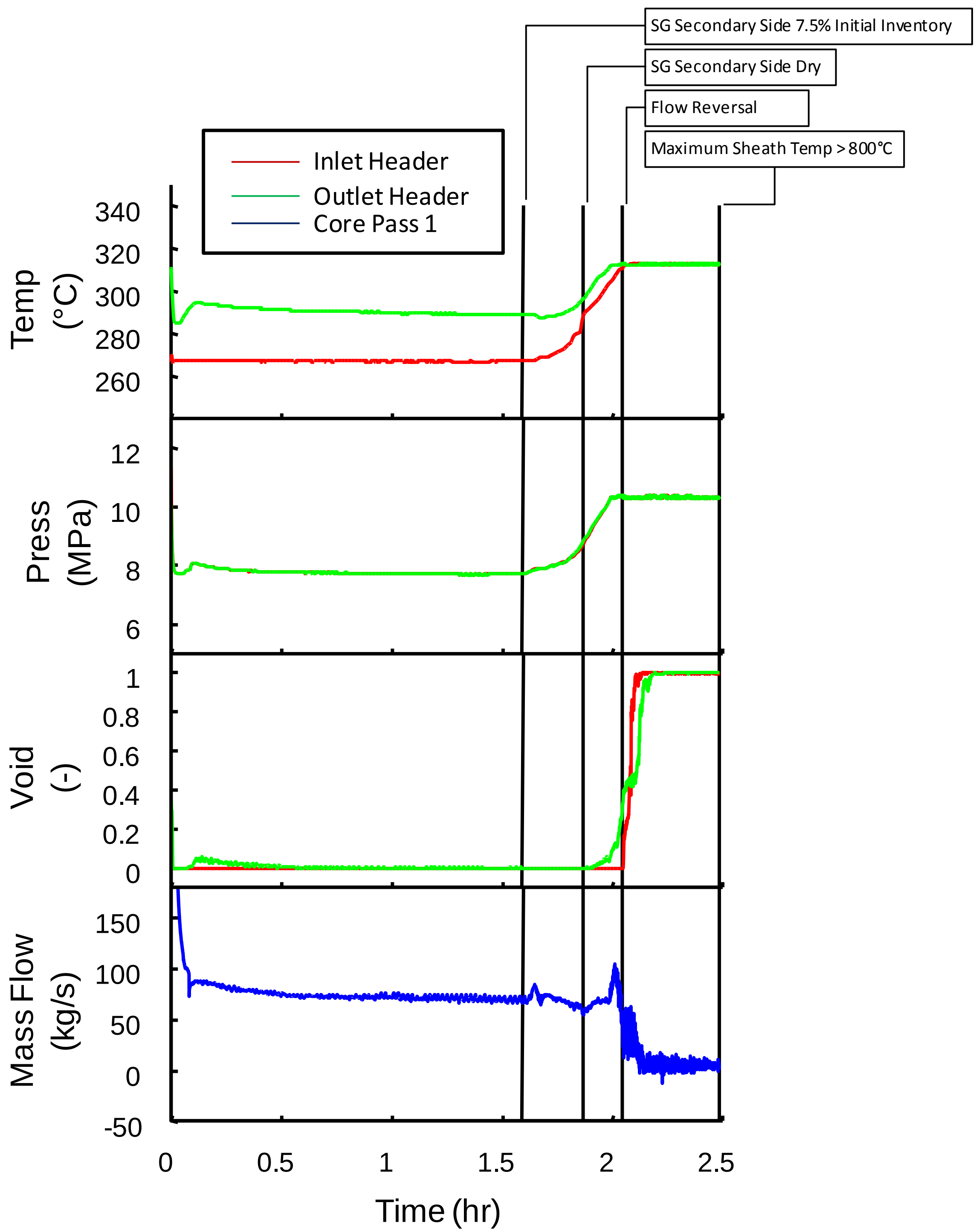

Figure 4 Temperature, pressure, void, and mass flow rate for core pass 1. No crash cooling and high pressure ECC is unavailable.

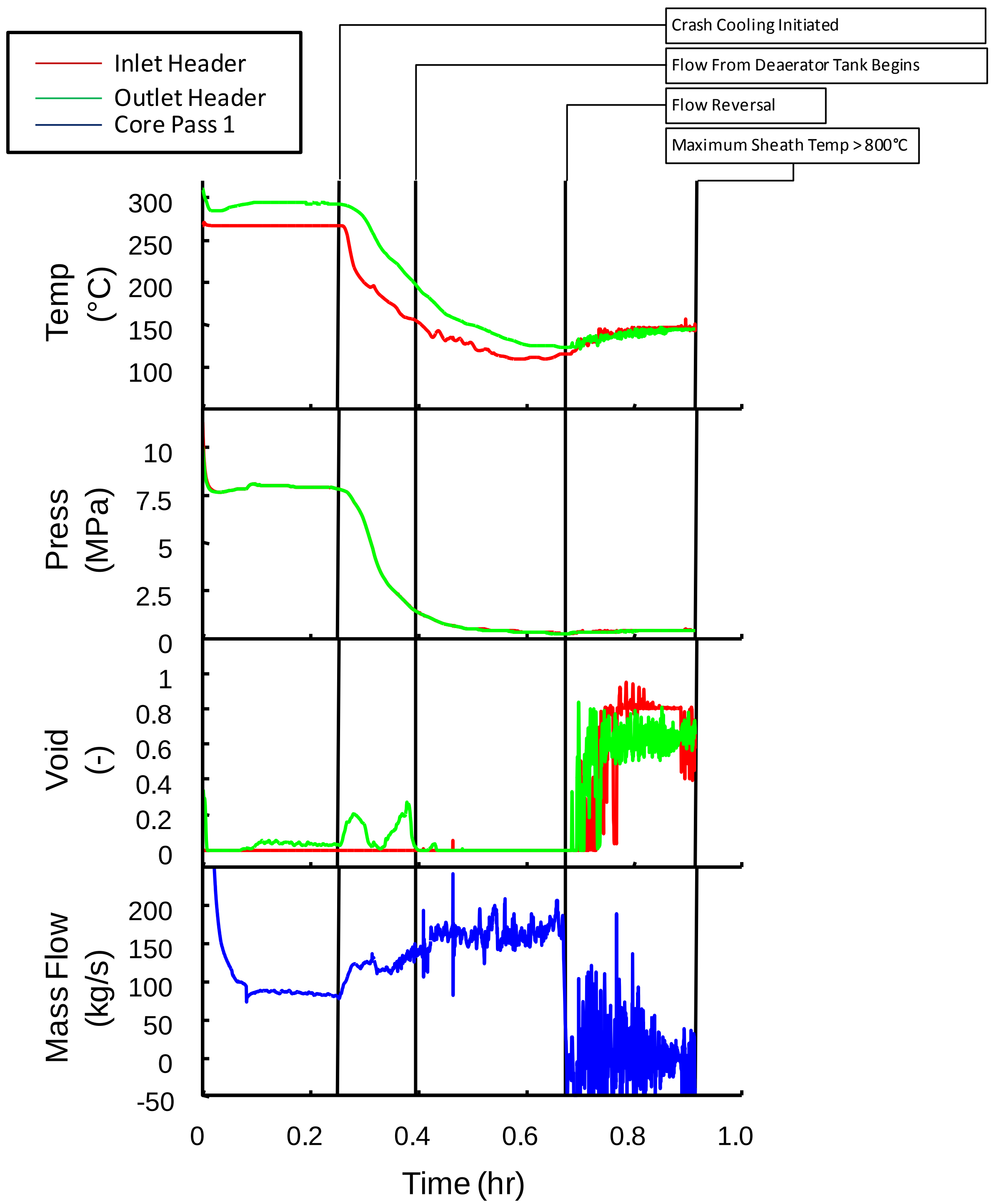

Figure 5 Temperature, pressure, void, and mass flow rate for core pass 1. Crash cooling initiated 15 minutes after SBO and high pressure ECC is unavailable.

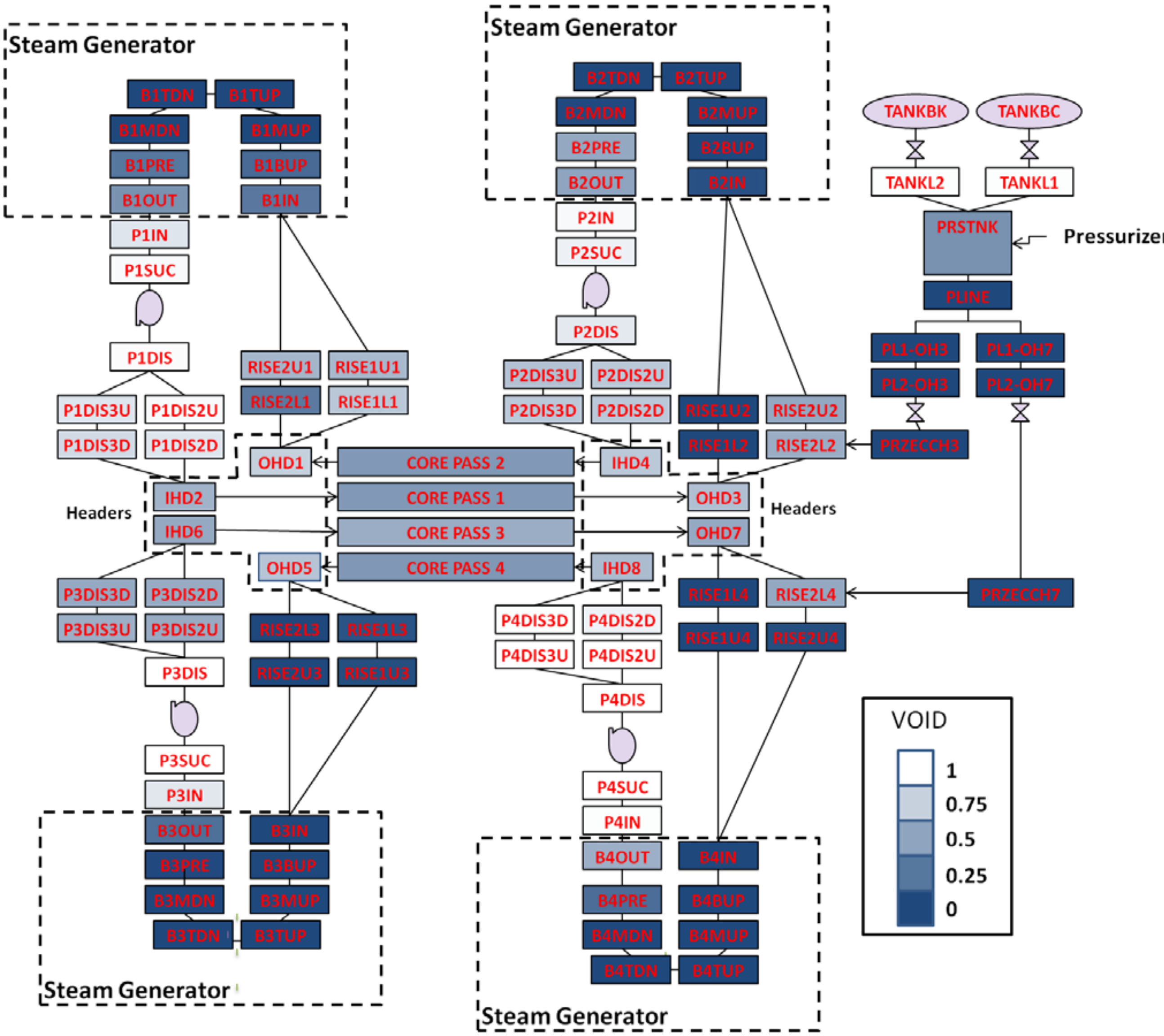

Figure 6 Void in the PHTS at 0.9 hr for scenario with crash cooling initiated 15 minutes after SBO and high pressure ECC unavailable.

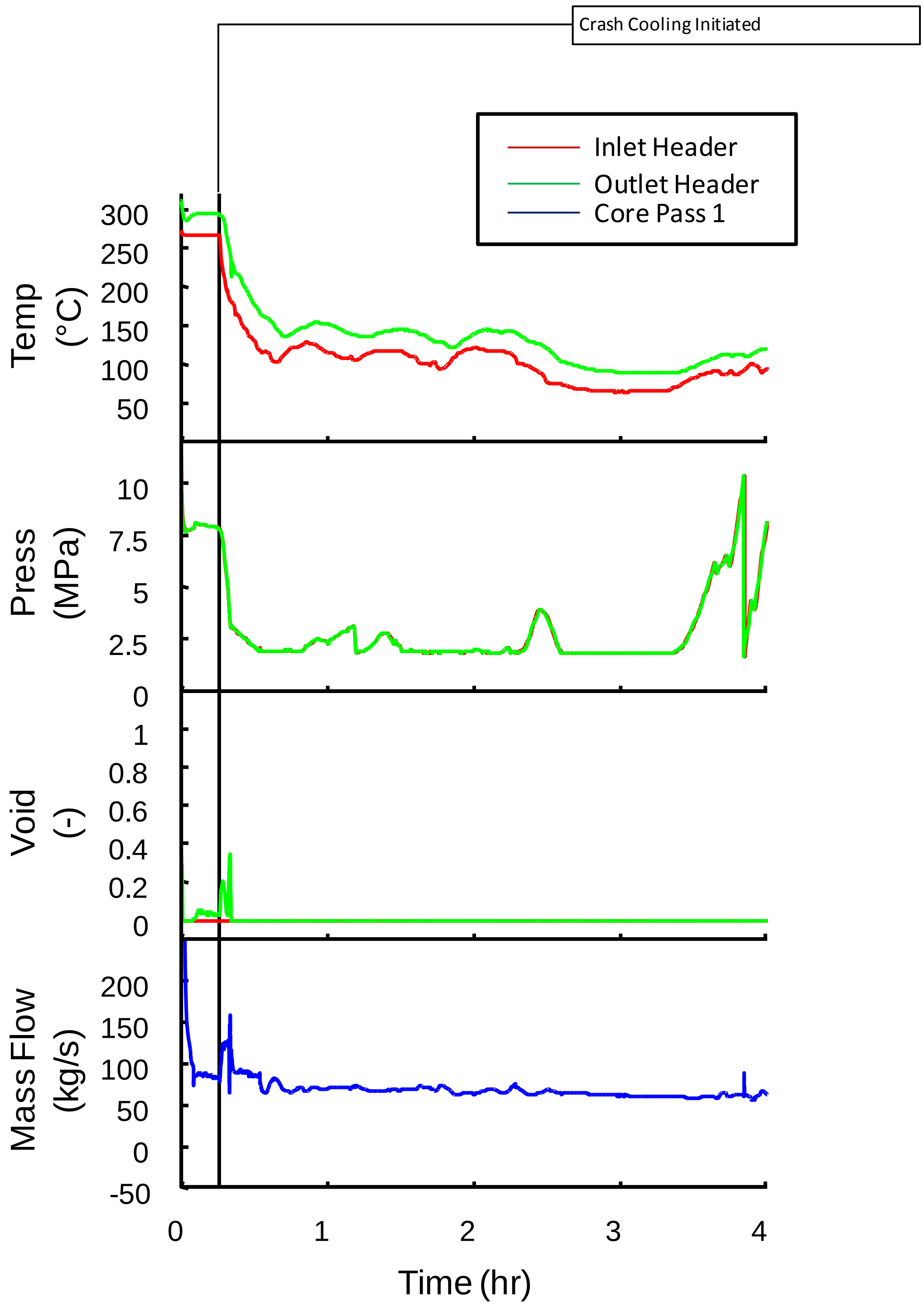

Figure 7 Temperature, pressure, void, and mass flow rate for core pass 1. Crash cooling initiated 15 minutes after SBO and high pressure ECC is available.