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ANALYSIS OF PASSIVE RESIDUAL HEAT REMOVAL SYSTEMS FOR THE CANADIAN SUPERCRITICAL WATER-COOLED REACTOR

X. Huang, M. Gaudet, M. Yetisir, D.F. Wang, and S. Wang
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

Abstract

Passive Residual Heat Removal (PRHR) systems are being developed for the Canadian Super Critical Water-cooled Reactor (SCWR). PRHR systems provide guaranteed decay heat removal via natural circulation under extreme accident scenarios for the Canadian SCWR, and can eliminate the costs associated with the installation, maintenance and operation of active systems that require multiple pumps with independent and redundant electric power supplies. However, considering the weak driving forces expected during natural circulation, careful design and analysis are needed to ensure that the systems perform their intended functions. This paper presents a description of the PRHR systems for the Canadian SCWR, and an analysis of their performance using the CATHENA system thermalhydraulics code to demonstrate the heat removal capability of the PRHR systems during postulated station blackout (SBO) events.

1. Introduction

The safety of a nuclear power plant depends on the availability of a continuous and reliable source of electrical energy during all modes of operation of the plant. A Station Blackout (SBO) corresponds to the total loss of all alternate current (AC) power as a result of complete failure of both offsite and onsite AC power sources. Results of a recent probabilistic safety assessment show that station blackout is one of the main and frequently the dominant contributor to core damage events [1][2]. The accident at the Fukushima Daiichi nuclear power plant demonstrates the vulnerability of some currently operating nuclear power plants during extended station blackout events. A main issue of a nuclear reactor safety system is the need for removing the decay heat, even for a reactor in shutdown during SBO.

Passive Residual Heat Removal (PRHR) systems are being developed for the Canadian Super Critical Water-cooled Reactor (SCWR), a Generation IV nuclear reactor concept. The Canadian SCWR has two PRHR systems: a primary system that uses light water as the cooling fluid, and a secondary system that uses the heavy water moderator as the cooling fluid. Both PRHR systems use the Reserve Water Pool as their heat sink, and the heat is ultimately transferred to the environment. PRHR systems provide guaranteed decay heat removal via natural circulation under extreme accident scenarios for the Canadian SCWR, and can eliminate the costs associated with the installation, maintenance and operation of active systems that require multiple pumps with independent and redundant electric power supplies. However, considering the weak driving forces expected during natural circulation, careful design and analysis are needed to ensure that the systems perform their intended functions.

This paper presents a description of the PRHR systems for the Canadian SCWR, and an analysis of PRHR system performance using the system thermalhydraulics code CATHENA. The goal of this analysis is to demonstrate the heat removal capability of the PRHR systems during a postulated total station blackout.

The paper briefly introduces the design concepts of the PRHR systems for the Canadian SCWR in Section 2, and describes the CATHENA idealization for the SCWR and its PRHR systems in Section 3. A description of the simulated SBO scenarios is given in Section 4. Finally, the simulation results, including the calculated peak fuel centreline temperature and channel pressure are discussed in Section 5.

2. PRHR Systems for Canadian SCWR

The Canadian SCWR has two PRHR systems: a primary system referred to as the Isolation Condenser System (ICS) that uses the reactor's light water coolant as the cooling fluid, and a secondary system referred to as the Passive Moderator Cooling System (PMCS) that uses the heavy water moderator as the cooling fluid. Both PRHR systems use the Reserve Water Pool (RWP) as their heat sink, and the heat is ultimately transferred to the environment (Figure 1).

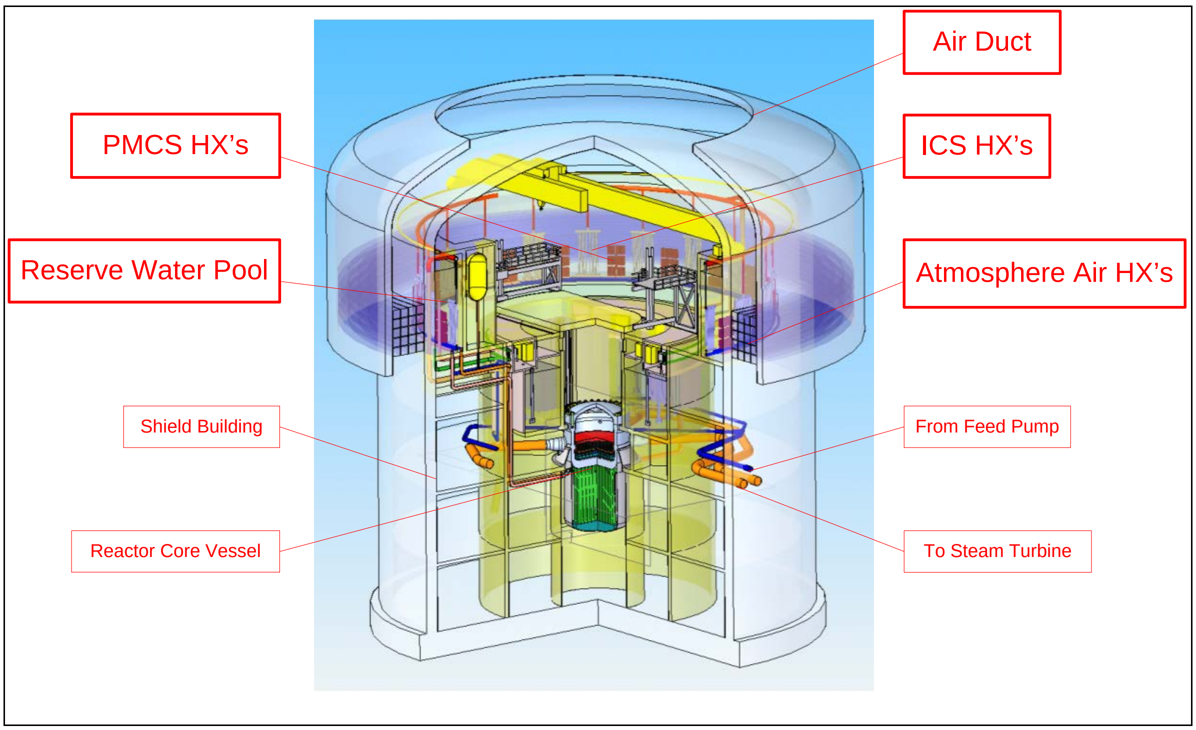

Figure 1: Schematic of PRHR Systems in Canadian SCWR

The ICS is located above the reactor core. The primary function of the isolation condensers (IC) is to remove sensible and core decay heat from the reactor passively, preventing reactor overpressure and to serve as a long term cooling system under station blackout conditions. The ICS heat exchangers connect with the reactor coolant piping, and remove heat from the reactor by depositing it into the reserve water pool. The ICS heat exchangers are divided into two independent banks, with each bank consisting of a piping loop running from the reactors outlet, to heat exchangers located in the reserve water pool, and returning to the reactors inlet. The system is pressurized and on hot standby under normal reactor operation (Figure 2).

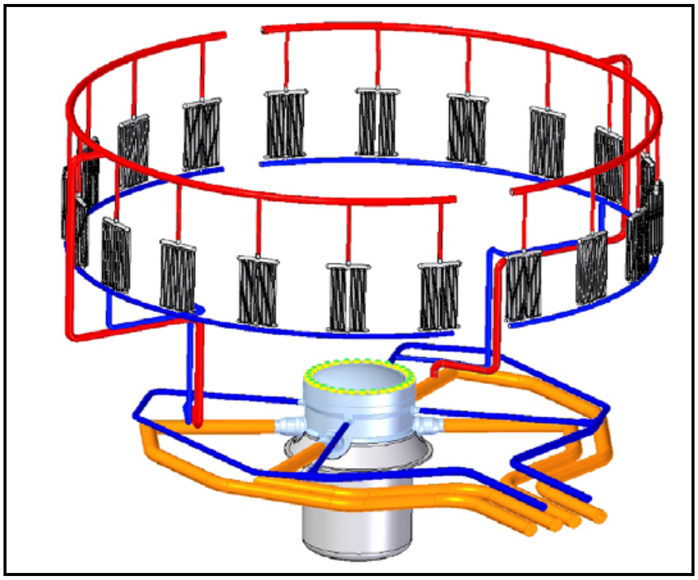

Figure 2: CAD View of Isolation Condenser System Heat Exchanges

The PMCS is also located above the reactor core with the heat exchangers submerged into the RWP. The PMCS serves as an additional barrier to core damage. In an accident scenario, decay heat generated within the fuel channels flows through the channels' insulator and is deposited into the moderator. The Passive Moderator Cooling System uses a flashing-driven natural circulation loop to remove heat from the moderator, and deposit this into the reserve water pool. The PMCS heat exchangers are divided into two independent banks, with each bank consisting of a piping loop running from the reactor calandria to heat exchangers located in the reserve water pool, and returning to the reactor calandria (Figure 3).

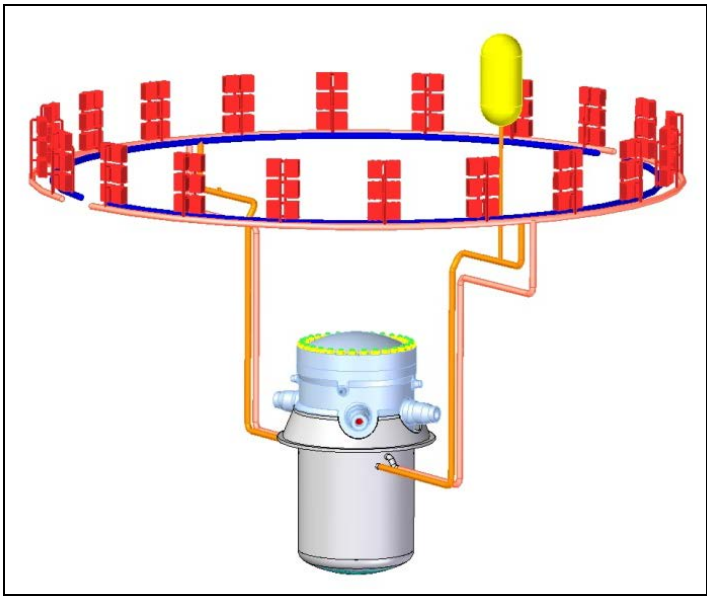

Figure 3: CAD View of Passive Moderator Cooling System Heat Exchanges

A more detailed description of the PRHR systems for the Canadian SCWR is available in [3].

3. CATHENA Idealization

The CATHENA code was developed by Atomic Energy of Canada Limited (AECL) primarily for analysis of postulated LOCA events in CANDU reactors. It has also been used in safety analysis for research and other types of reactors. A preliminary CATHENA idealization for the reactor core of the Canadian SCWR has been developed and tested as described in [4]. The CATHENA idealization for this analysis was built up by adding required CATHENA models for the PRHR system analysis.

An overall schematic of the CATHENA model for the PRHR system analysis is illustrated in Figure 4. To more easily identify the different systems, the CATHENA idealization for the Canadian SCWR reactor core is coloured black. The pipe component models for the ICS are coloured red; those for the PMCS are coloured blue; and those for the Reserve Water Pool are coloured green. Note that due to design changes since the publication of [4], some modifications have been made to the original CATHENA idealization for the Canadian SCWR reactor core from [4], such as: new dimensions and geometry of the fuel bundles, additional pipes from the outlet headers to turbine, additional pipes from the feed water pumps to the inlet plenum, and addition of the auxiliary feed water pump line.

The CATHENA model for both banks of the ICS heat exchangers is illustrated in Figure 5. Each of the top hot-leg headers and bottom cold-leg headers is modelled using nine sequentially-connected pipe components. The twenty ICS heat exchangers are divided into two banks, which are linked between the hot-leg header and cold-leg header. Each ICS heat exchanger is modelled using three pipe components and two volume components. A wall heat transfer model is applied to the pipe component between the two volumes, which represents the 100 parallel pipes of the heat exchanger.

The CATHENA model for both banks of the PMCS heat exchangers is illustrated in Figure 6. Each of the hot- and cold-leg headers is modelled using nine sequentially-connected pipe components. The twenty PMCS heat exchangers are divided into two banks, which are linked between the hot-leg header and cold-leg header. Each PMCS plate-type heat exchanger is modelled using nine pipe components and six volume components. Three wall heat transfer models are applied respectively to three pipe components at three different elevations (top, middle, or bottom). The hydraulic behaviour of the plate-type heat exchanger is modelled using 37 parallel pipes of a similar flow area and resistance, while its heat transfer behaviour is modelled by applying the correction factor in the wall heat transfer models.

The connection or isolation of the PRHR systems (ICS and PMCS) is controlled by 14 valves, as shown in Figure 4. The opening and closing of these valves in a transient simulation is controlled by a time table in the CATHENA model.

The axial profile of fuel channel power implemented in the CATHENA idealization is shown in Figure 7. This power profile corresponds to the end of cycle fuel condition, which is the profile resulting in a slightly higher fuel sheath temperatures than the beginning of cycle power profiles. After the reactor trip, reactor power reduces significantly. Figure 8 shows the decay power corresponding to the end of cycle fuel condition, which is implemented in the CATHENA idealization to provide a conservative prediction of the SBO event. The normalized decay line was also applied to determine the decay gamma heating power of the moderator after the reactor trip.

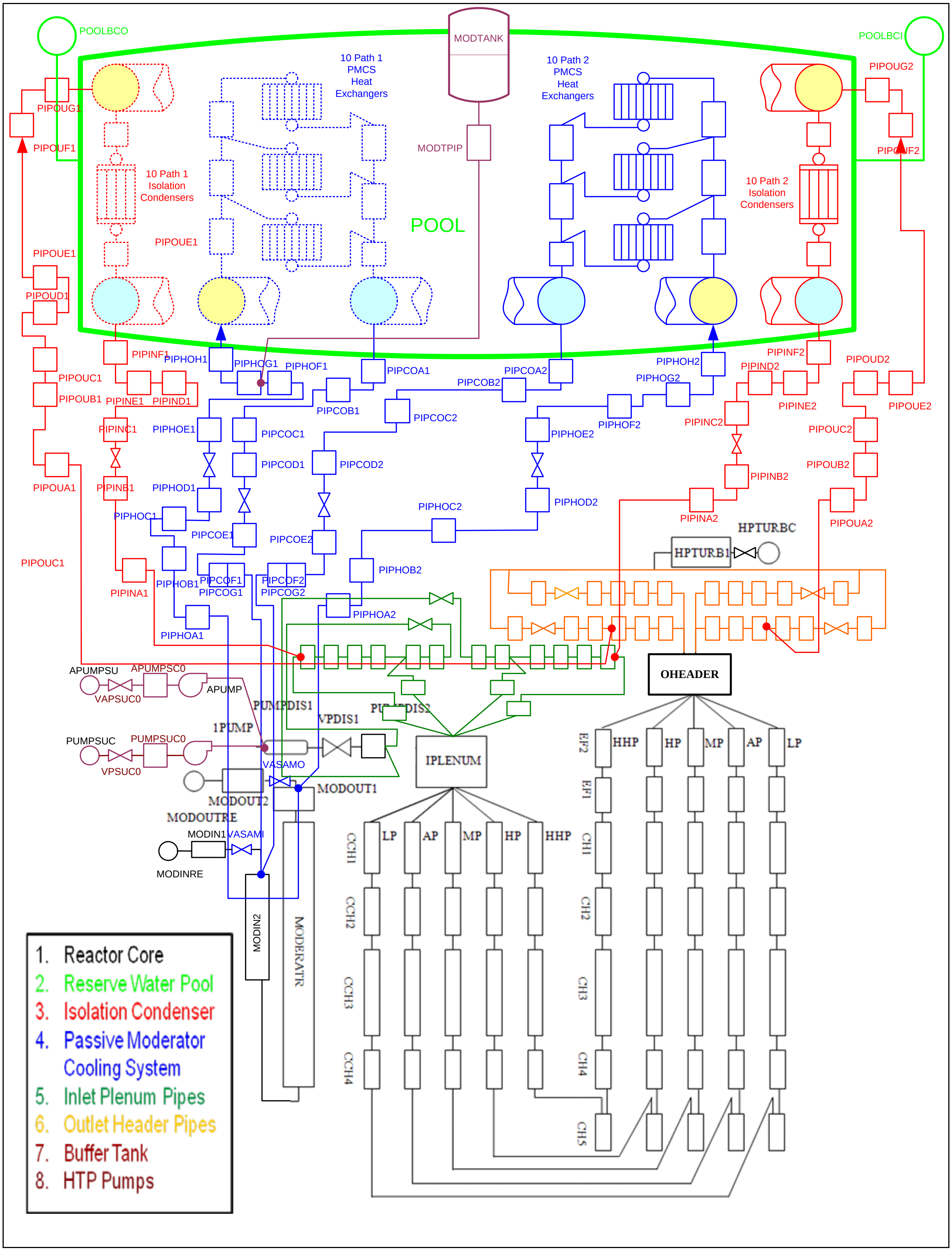

Figure 4: CATHENA Idealization for Canadian SCWR with PRHR Systems

The reactivity feedback effect of the coolant in the simulations was not considered in the idealization for this analysis. It can be added in the future once the reactivity data for the Canadian SCWR becomes available.

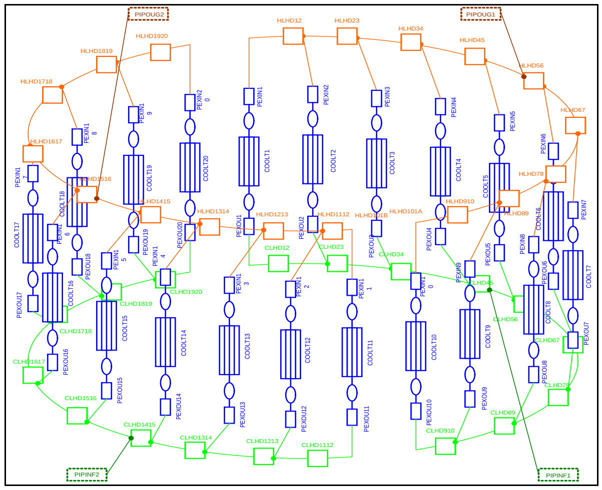

Figure 5: Thermal-hydraulics Model of ICS Heat Exchangers in CATHENA Idealization

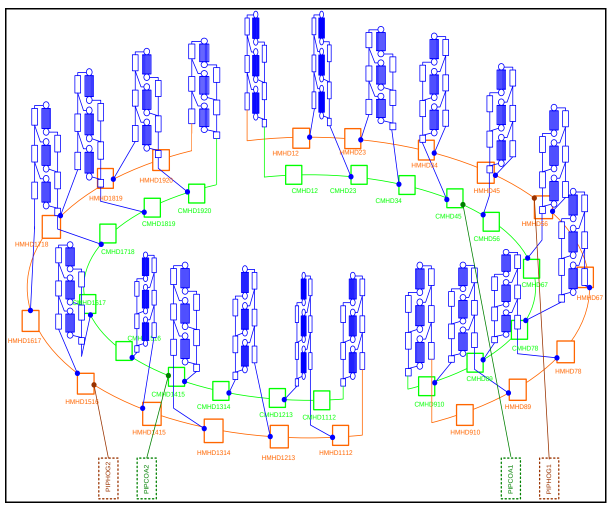

Figure 6: Thermal-hydraulics Model of PMCSS Heat Exchangers in CATHENA Idealization

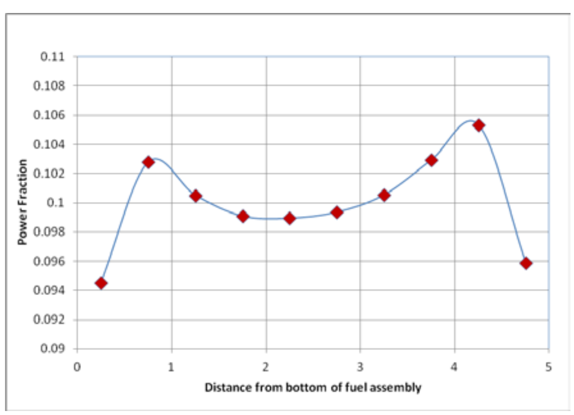

Figure 7: Power Axial Profile along the Fuel Channel

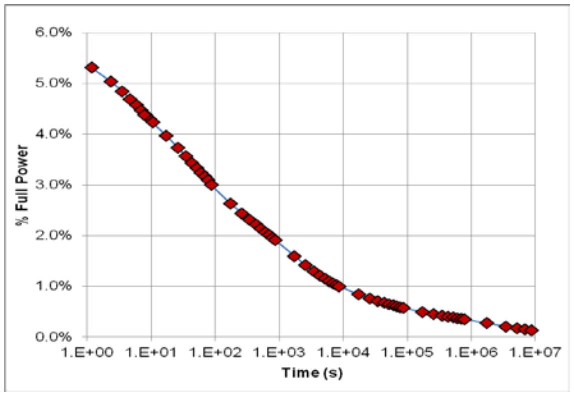

Figure 8: Power Decay Curve after Reactor Trip

4. SBO Scenarios Simulated and Analyzed

Figure 9 shows the two SBO scenarios (Case A and Case B) simulated in this analysis. Note that Phases 0, 1 and 2 of Case A and Case B are identical.

The SBO occurs at the end of Phase 0 which trips the main Heat Transport (HT) pump and main moderator cooling pump immediately. At the same time, the reactor is tripped by the shut down system. Once the reactor trips, the auxiliary HT pump and auxiliary moderator cooling pump kick in, both having about 10% of their respective capacity during normal operation. The auxiliary HT pump and auxiliary moderator cooling pump run for 1 hour (3600 s) on auxiliary power (either diesel generator or turbine generator) in Phase 1. At the end of Phase 1, the auxiliary power is postulated to fail and the PMCS comes online immediately and stays online for the remainder of the simulation. The connection valves in the ICS are postulated to fail shut at the end of Phase 1 due to loss of battery power (or instrument air). The PMCS functions for 45 minutes (2700 s) in Phase 2. In phase 3 of SBO Case A, the reactor operator is able to manually open the ICS connection valves to enable the ICS operation.

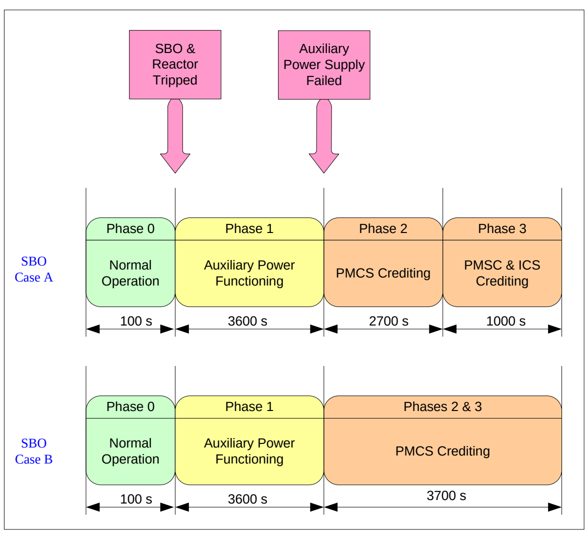

Figure 9: Time Frames and Major Events in SBO Simulation Cases A and B

The only difference between SBO simulation Cases A and B is in phase 3; the ICS is credited in Case A, but is not in Case B.

5. Simulation Results and Discussions

The simulations started from a steady-state run that covers a time period of 6000 seconds. The restart file obtained from the end of the steady-state run was then applied to form a new idealization for simulating Phases 0, 1, and 2 of SBO cases A and B. The obtained new idealization was revised by updating the required initial conditions in the ICS and PMCS loops and by setting constant open fractions for the individual orifices located at the channel inlet feeders [4]. The simulation for Phases 0, 1, and 2 of SBO cases A and B covers the time period of 6400 seconds as illustrated in Figure 9.

The simulation for Phase 3 of SBO case B was conducted using the restart file obtained from the simulation for Phases 0, 1, and 2 of SBO cases A and B. Phase 3 of case B covers a time period of 1000 seconds (6400 s ~ 7400 s as shown in Figure 9).

The current version of CATHENA is not reliable in simulating a depressurization transient across the critical point (~22 MPa). To avoid this, simulation for Phase 3 of SBO case A was divided into two stages, i.e., stage 1 and stage 2 corresponding to simulations for supercritical and subcritical conditions, respectively. Stage 1 of Phase 3 of SBO simulation case A was conducted using the restart file obtained from the simulation for Phases 0, 1, and 2 of SBO cases A and B and it covers a time period of 20 seconds (6400 s ~ 6420 s). The restart file obtained from the stage 1 simulation was then applied to form a new idealization for the stage 2 simulation. Stage 2 of Phase 3 of SBO simulation case A covers a time period of 980 seconds (6420 s ~ 7400 s as shown in Figure 9).

The simulations were performed using CATHENA MOD-3.5d/Rev 4, the latest version of CATHENA with a capability to simulate supercritical conditions.

5.1 Results for Phases 0, 1, and 2 of Cases A and B

The CATHENA simulation results of Phase 0, 1, and 2 for SBO cases A and B are shown in Figure 10 through Figure 12. It covers the simulation time period from 0 s to 6400 s.

The first 100-second run (Phase 0) is a continuation of the steady-state simulation; the results from the first 100-second run represent the normal full power operation conditions of the reactor. In Phase 0, reactor channel pressure is about 25 MPa, the maximum fuel centreline temperature is about 2656°C, and the channel flows are between 3.7 kg/s and 4.7 kg/s.

The channel pressure decreased slightly after 100 s (see Figure 10) due to an assumed change of pressure from 25 MPa to 24.3 MPa in the HT pump boundary condition, to represent the SBO effect on the feed water pump. The results between 100 s and 3700 s show that the auxiliary HT pump and moderator cooling pump work well. In Phase 1 of the simulation, the maximum fuel centreline temperatures are about 470°C, which is well below the fuel centreline temperature under normal operating conditions (2656°C) (see Figure 11). The simulation predicts lower and fluctuating channel flows after 1300 s (see Figure 12); this is likely caused by a significant density decrease of coolant in the channels. If the fluctuation becomes a concern in the future, it can be avoided by increasing the capacity of the auxiliary HT pump.

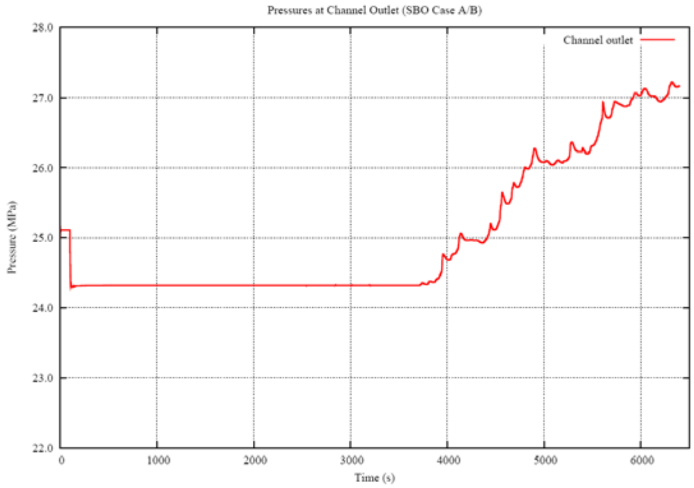

Figure 10: Channel Pressure in Phases 0, 1, and 2 of SBO Simulation Cases A/B

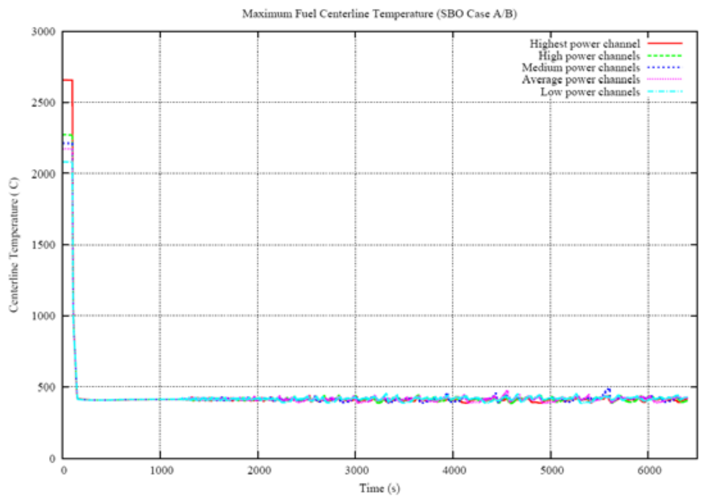

Figure 11: Maximum Fuel Centreline Temperatures in Phases 0, 1, and 2 of SBO Simulation Cases A/B

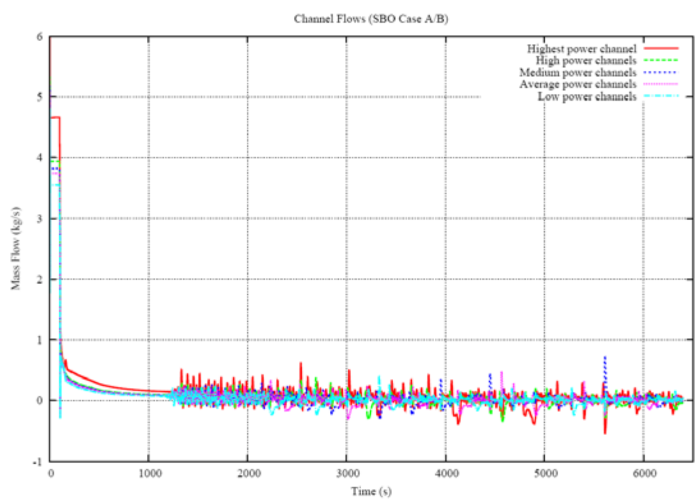

Figure 12: Channel Flows in Phases 0, 1, and 2 of SBO Simulation Cases A/B

Because of the failure of the auxiliary power at 3700 s, the auxiliary HT pump trips immediately(begins to run down), the moderator flow driven by the auxiliary moderator cooling pump reduces to zero immediately, and the PMCS kicks in (begin to close the PMCS isolation valve and open the PMCS connection valves) immediately. The simulation shows that the channel pressure increases slightly after 3700 s (see Figure 10). In Phase 2 (from 3700 s to 6400 s) of the simulation, the total increase of the pressure from the normal operation pressure (25.2 MPa) is about 2 MPa, which is still below the design limit of 27.5 MPa. This pressure ramp up is caused by the decay power and relies on the total heat exchange rate of the PMCS and the duration of Phase 2.

In Phase 2 of the simulation, the maximum fuel centreline temperatures are about 475°C, which is still well below the fuel centreline temperature under normal operating conditions (2656°C) (see Figure 11).

5.2 Results for Phase 3 of SBO Case A

The CATHENA simulation results of Phase 3 for SBO case A are shown in Figure 13 through Figure 15. They cover the simulation time period from 6400 s to 7400 s.

After crediting the ICS at 6400 s, the channel pressure decreases significantly (see Figure 13). It takes about 20 s for the channel pressure to drop below the critical pressure (22 MPa). At the end of Phase 3 the predicted channel pressure is about 0.49 MPa. The channel pressure is expected to continue to reduce slowly if the simulation extends beyond 7400 s. The maximum fuel centreline temperatures reduce significantly in Phase 3 from about 430°C to 165°C indicating that ICS efficiently cools the reactor core (see Figure 14). It can be expected that the maximum fuel centreline temperatures will reduce further if the simulation extends beyond 7400 s. The channel pressure and fuel centreline temperature decreases predicted are directly associated with the passive cooling effect of the ICS. Figure 15 shows that relying on thermo-siphoning effects of the ICS loops, positive flows are dominantly built up in the fuel channels. The flow fluctuations observed in Figure 15 indicates that the thermo-siphoning flows are strongly unstable.

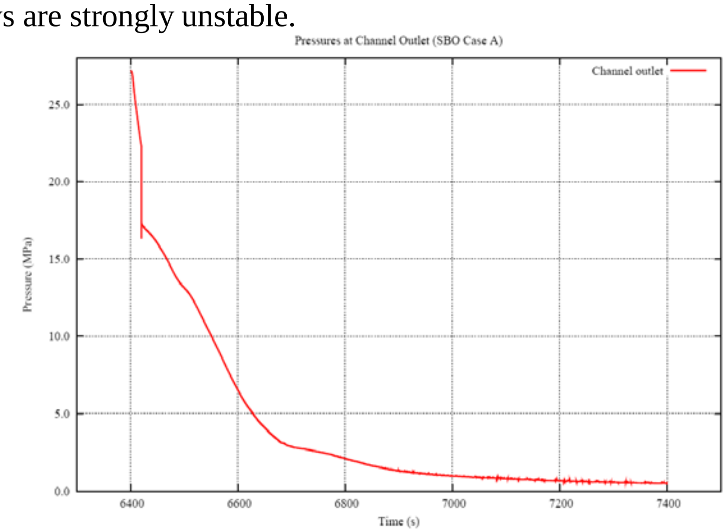

Figure 13: Channel Pressure in Phases 3 of SBO Simulation Case A

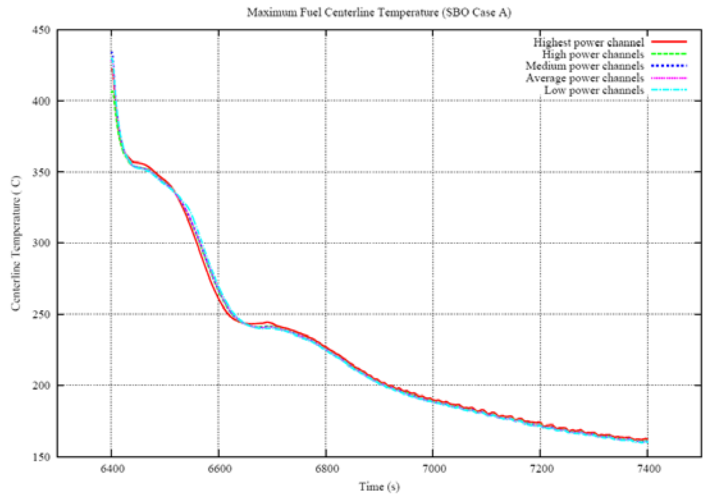

Figure 14: Fuel Centreline Temperatures in Phases 3 of SBO Simulation Case A

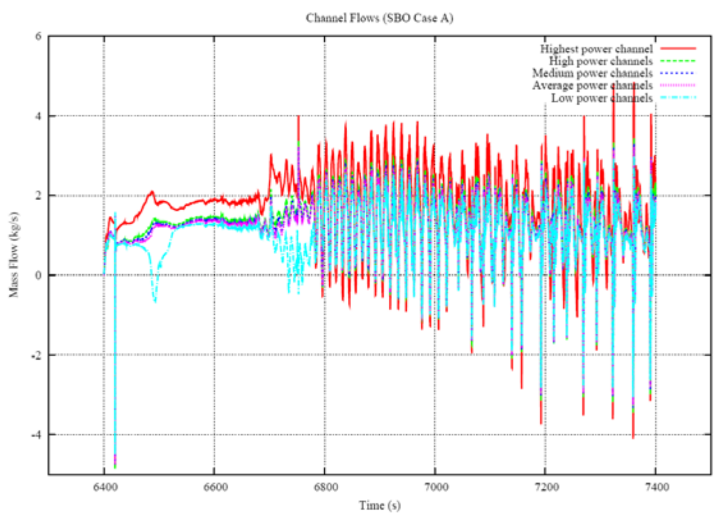

Figure 15: Channel Flows in Phases 3 of SBO Simulation Case A

5.3 Results for Phases 3 of SBO Case B

The CATHENA simulation results of Phase 3 for SBO case B are shown in Figure 16 through Figure 18. It covers the simulation time period from 6400 s to 7400 s. The CATHENA boundary conditions in Phase 3 of SBO simulation Cases B are identical to those in Phase 2 simulation as discussed in Section 5.1. This simulation actually extends the Phase 2 simulation for additional 1000 seconds.

As expected, the channel pressure increased slowly by about 0.4 MPa (from 27.2 MPa to 27.6 MPa) in 1000 seconds (see Figure 16). The pressure increase rate is smaller than in Phase 2 and is expected to reduce further after 7400 s, because the reactor decay power decreases continuously (Figure 8).

In Phase 3 of SBO simulation case B, the maximum fuel centreline temperatures fluctuate between about 390°C and 460°C, which is below the normal operating condition temperature (2656°C) (see Figure 17). Figure 18 shows that thermo-siphoning flows are well established in both banks of the PMCS heat exchangers.

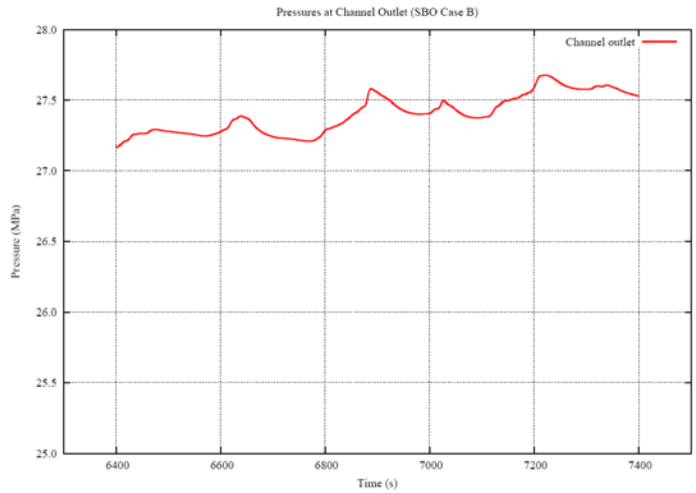

Figure 16: Channel Pressure in Phases 3 of SBO Simulation Case B

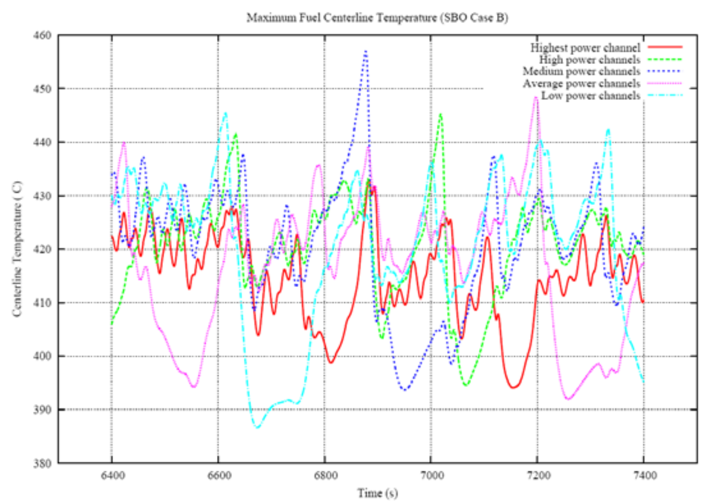

Figure 17: Maximum Fuel Centreline Temperatures in Phases 3 of SBO Simulation Case B

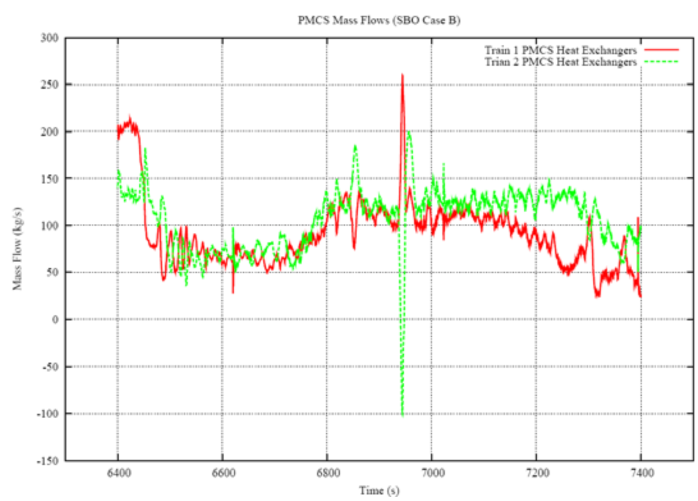

Figure 18: Mass Flows through Bank 1 and Bank 2 PMCS Heat Exchangers in Phases 3 of SBO Simulation Case B

6. Conclusions

CATHENA analysis was performed to support the design of the PRHR systems for the Canadian SCWR. The CATHENA idealization for the reactor core was revised by adding models for the ICS, PMCS, RWP, and auxiliary HTP and moderator cooling pump systems. Two SBO cases, one with and one without crediting the ICS, were simulated and analysed using the developed CATHENA idealization.

Major conclusions that can be drawn from this analysis are:

- After the SBO and the reactor trip, current capacities of the auxiliary HT pump and moderator cooling pump (10% of that for normal operation) are appropriate to cool the reactor for at least the 1 hour simulated by CATHENA.
- Once the backup power for the auxiliary HT pump and moderator cooling pump fails after 1 hour of the SBO, crediting only the PMCS can provide enough cooling to the fuel elements for at least 1 hour, although the pressure in the reactor core ramps up slowly at a rate of about 1.4 MPa per hour.
- Crediting both the PMCS and ISC 6300 seconds after the SBO can adequately remove the reactor decay heat and effectively cool the reactor fuel. Both the fuel temperature and reactor core pressure are significantly reduced.

Future work may consider:

- Performing a series of sensitivity study using the developed CATHENA model as a tool to optimize designs of the reactor core, the auxiliary pump system, and the PRHR systems.
- Improving the CATHENA idealization by modelling the reactivity feedback effect of the coolant in the simulations once the data becomes available.
- Improving CATHENA code's capability for seamlessly handling the simulations across the critical pressure (~22 MPa). With this improvement, the simulation for Phase 3 of SBO case A can be done in one stage.

7. Acknowledgement

The authors would like to thank Jeremy Pencer (Computational Reactor Physics Department, AECL) for providing the channel axial power profile and decay power data for the Canadian SCWR concept.

8. References

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