BWRX-300 Isolation Condenser System

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I. Introduction

GE Hitachi's new Small Modular Reactor (SMR), the BWRX-300, represents an exciting future for the nuclear landscape in Canada. Currently being developed in the Darlington Nuclear Site, the BWRX-300 will be the first of multiple SMRs to power Ontario. One of the key features of the BWRX-300 is its Isolation Condenser System (ICS), which it uses to passively remove decay heat from the reactor core after shutdown. This report models the BWRX-300's ICS to measure the time it takes to fully cool the core after shutdown.

Since the BWRX-300 has not been physically constructed as of 2024, there currently exists limited literature on it, aside from technical reports from the IAEA, GE Hitachi, and Ontario Power Generation. These technical reports focus on describing how the different systems in the BWRX-300 work but do not include much information on reactor operations and processes, such as how long the BWRX takes to shut down. This report uses the information in the technical reports on the BWRX-300 to model the ICS in Simulink and then simulates a reactor shutdown to estimate the time the shutdown takes and how parameters such as coolant temperature and pressure change.

This report starts with a brief summary of the BWRX-300 and its main subsystems in Section II. Section III explains how a reactor shutdown takes place and how decay heat is measured. Section IV explains how the ICS works and is modelled in Simulink. The simulation is then ran and parameters such as coolant temperature are graphed. Finally, Section V concludes the paper by discussing results and future research opportunities.

II. The BWRX-300

The BWRX-300 is a water-cooled SMR developed by GE Hitachi. It is the tenth generation of the Boiling Water Reactor (BWR) and has an output of 300 MWe [1]. Being an SMR, the BWRX-300 is designed to provide clean and flexible energy in a cost-effective and scaleable manner, while having a small footprint of 26,300 m^2 [2]. Ontario Power Generation is currently preparing to construct the first of four BWRX-300s at the Darlington Nuclear Generating Station in Clarington, Ontario. A view of the BWRX-300 reactor building can be seen in Figure 1.

The BWRX-300 has several design characteristics that make it different from other BWR and SMR designs. It takes a fully passive approach to safety systems. It uses natural circulation instead of pumps for coolant circulation, decreasing costs and improving reliability, especially in a loss of power situation. Additionally, the BWRX uses a dry containment, which uses air and cooling mechanisms to manage containment pressure and temperature, instead of a wet containment, which uses

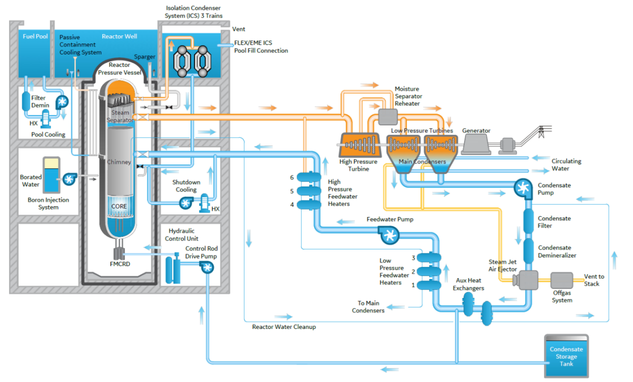

Fig. 1. Reactor Building Systems [1]

a suppression pool that condenses steam. Using a dry containment allows the BWRX to both reduce its footprint and help in containment if a Loss of Coolant Accident (LOCA) occurs. The BWRX also uses Reactor Isolation Valves that are attached to all of the core's process nozzles. The isolation valves can automatically close to quickly isolate the reactor vessel and reduce the effects of an LOCA [2].

The BWRX core is housed inside the RPV (Reactor Pressure Vessel), a 26m tall cylindrical pressure vessel with a diameter of 4m. In addition to the core, the RPV also contains core support structures, a chimney, steam separators, and the steam dryer assembly [1]. The RPV's height comes in part from the chimney on top of the core, as seen in Figure 2. The chimney allows an increased internal flow path length compared to typical BWRs, which allows coolant to flow through the core via natural circulation. The RPV is housed in the Primary Containment System (PCS), a 38m tall vertical cylinder with a 17.5m diameter made of a steel-plate composite, to provide radiation shielding and further reduce any effects of an LOCA.

Other notable systems of the BWRX-300 include the Containment Cooling System (CCS) which is responsible for maintaining the containment bulk average temperature using two redundant trains (pipe systems connected to a heat exchanger) of Air Handling Units that draw in and cool hot nitrogen gas from the top of the containment area. The Passive Containment Cooling System (PCCS) contains three independent trains that use natural circulation to remove heat from the containment to maintain temperature and pressure. The Isolation Condenser System and Isolation Condenser System Pool Cooling and Cleanup System (ICC) are key parts of the BWRX's cooling system and are explained further in Section IV. The Boron Injection System is responsible for injecting Boron-10 as a neutron absorber to reduce reactivity in the event of a reactor shutdown. The Control Rod Drive System is also used for reactor shutdowns and is explained in depth

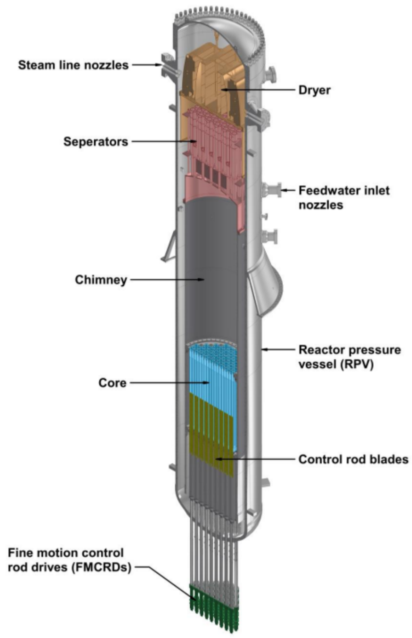

Fig. 2. BWRX-300 RPV [1]

in Section III. Finally, the Fuel Pool Cooling and Cleanup System (FPC) continuously cools and replenishes the coolant in the fuel pool to ensure fuel is safely submerged throughout the plant's life. The FPC also maintains the coolant quality through demineralization and particulate filtration [1].

III. Reactor Shutdown and Decay Heat

When a reactor needs to be refuelled or maintained, it must be shut down and brought down to a temperature cool enough to work on. In general, for a reactor to reach a cold stable shutdown, its coolant must be below 370 K and at atmospheric pressure, according to the United States Nuclear Regulatory Commission.

A reactor shutdown occurs through the insertion of control rods into the core to slow down and eventually stop the fission chain reaction. Control rods can be inserted immediately for an emergency reactor shutdown or SCRAM or gradually for a standard shutdown. For the BWRX-300, The Control Rod Drive System can quickly insert control rods into the core using hydraulic energy in the case of a SCRAM or by electrical motor insertion for normal control rod insertion. The BWRX-300 contains 57 control rods, which are inserted through the bottom of the core, with each rod being inserted between four adjacent fuel assemblies.

After the control rods have been inserted and the fission chain reaction has ended, decay heat will still be produced. Decay heat is the result of the energy that comes from gamma and beta decay of fission products slowing down in the fuel. The most accurate way of calculating decay heat involves simulating the nuclear transmutations and decay processes that take place in the nuclear core. However, it can be approximated using the Wigner-Way Equation, (1), and depends on the maximum thermal power of the reactor (P_0), in MW, and the time, in seconds, that the reactor was operating (t_0). P gives the thermal power generated from the radioactive decay in MW based on the amount of time (t), in seconds, after the reactor has shutdown.

$$P(t) = 0.0622 \times P_0[t^{-0.2} - (t_0 + t)^{-0.2}] \qquad (1)$$

The BWRX-300 has a max thermal power output of 820 MW and is refueled every 12-24 months. For a 12 month operational period, the thermal power generated from decay heat a day after a reactor shutdown can be seen in Figure 3.

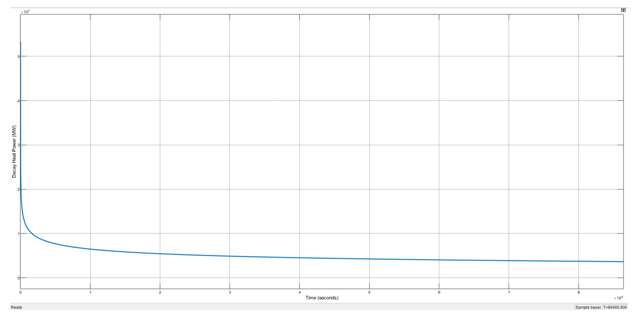

Fig. 3. BWRX-300 Power generated After Shutdown

IV. Modelling the ICS

A. How the ICS Works

The ICS is responsible for removing decay heat from the reactor fuel following a reactor shutdown. The ICS is made up of three independent trains. One of the ICS trains can be seen in Figure 4. Each loop uses natural circulation and consists of a steam feed line, which connects to a heat exchanger that is submerged in a dedicated pool of water, which then connects to a condensate return line. Each ICS loop has a capacity of 33 MWth [3].

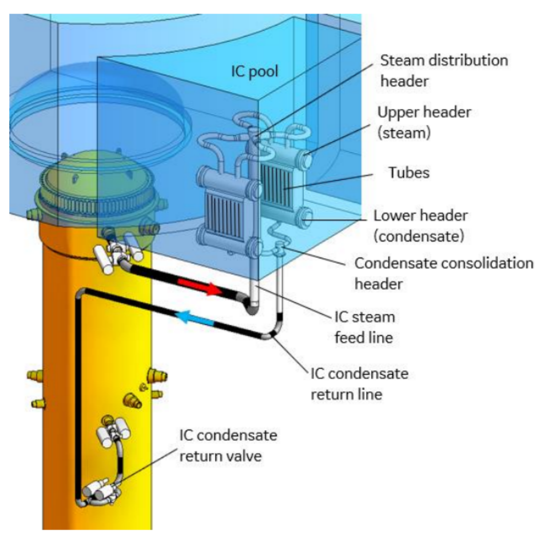

Fig. 4. Single Train of the Isolation Condenser System [2]

The ICS is started automatically following a reactor shutdown or a loss of power. The ICS is started by opening the condensate return valve, allowing condensate in the condensate return line to enter the reactor core, where it will heat up and boil as it travels through the core. It will then travel up to the heat exchanger, where the heat is transferred to the water in the pool [4]. The water in the pool then boils, and steam is vented into the atmosphere via the ICC. The ICC also cleans the pool water and monitors pool temperature and volume. Each pool has a capacity of 7 days of decay heat but can be replenished for continued heat rejection.

B. Modelling the ICS in Simulink

In order to model the ICS in Simulink, the decay heat function, the fuel assemblies, and the coolant loop all need to be modelled. The decay heat is modelled by implementing (1) using Simulink Blocks, as seen in Figure 5. A saturation block is used to prevent the power from exceeding 53.3 MW, as the decay heat generated immediately after a reactor has shutdown is expected to be 6.5% of the reactor's maximum thermal power, or from dropping below 0.

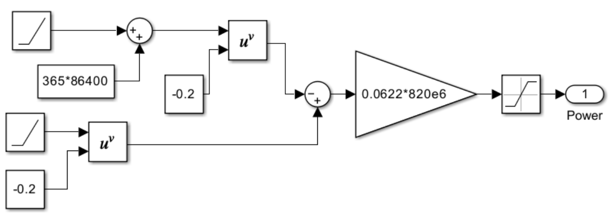

Fig. 5. Decay Function in Simulink

The fuel assemblies are modelled using the Simscape Thermal Library. There are 240 fuel assemblies, each with a mass of 324 kg, giving a fuel mass of 77,760 kg for the BWRX-300. A Heat Flow Source block is used to heat the fuel assemblies from the decay heat, as seen in Figure 6, and a Convection block is used to model the heat transfer from the fuel bundles to the coolant through the Zircaloy-walled coolant channels.

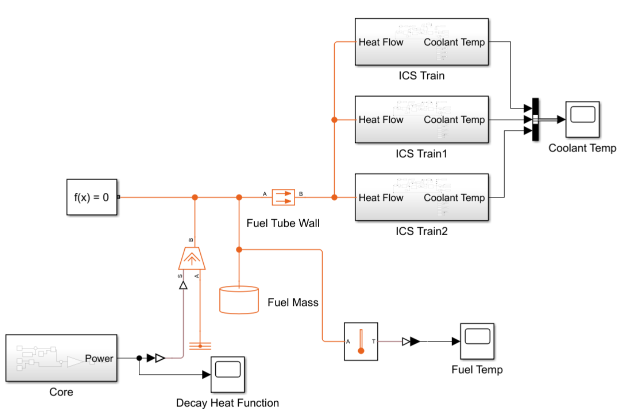

Fig. 6. Fuel Assemblies Model in Simulink

The ICS is modelled using the Simscape Two-Phase Fluid Library, as the coolant needs to both boil and condense. There are three, independent ICS trains in the BWRX-300, which are all identical. One of the trains can be seen in Figure 7. Each ICS train contains three pipes: the Coolant Channel that travels through the core, the Steam Feed Line that leads into the heat exchanger, and a Condensate Return Line that returns to the core. The coolant in the Coolant Channel contains water at 560 K, which is used as the initial temperature of the coolant channel as the reactor has just been shutdown in the simulation. It feeds into a vertical Steam Feed Line which leads into a Heat Exchanger. Each Heat Exchanger has a maximum heat capacity of 33 MW and contains 360 1800mm long tubes [5]. On the other side of each Heat Exchanger are two Resevoir Pool blocks from the Simscape Thermal Liquid library to represent the IC pools that are vented to the atmosphere. The Heat Exchanger feeds into the Condensate Return Line, an additional vertical pipe that returns to the bottom of the RPV and loops back into the Coolant Channel.

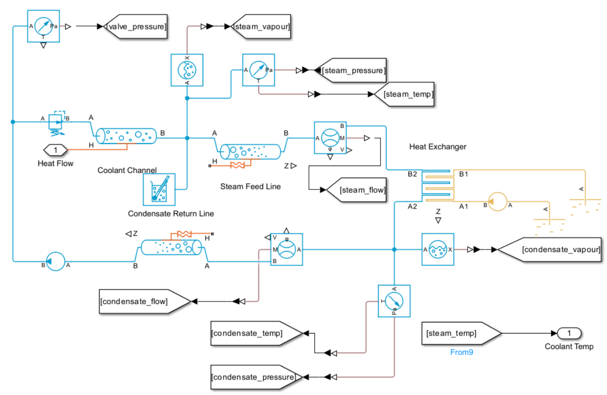

Fig. 7. Single ICS Train Model in Simulink

The temperature of the coolant after the reactor has been shut down for one day can be seen in Figure 8. The reactor successfully reaches a cold stable shutdown after one day, with the temperature reaching below 370 K.

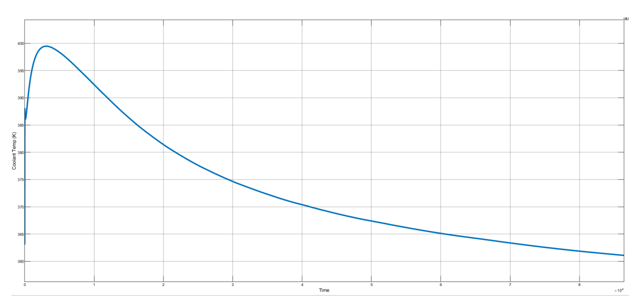

Fig. 8. Coolant Temperature one day after Shutdown

V. Conclusion

The ICS is a critical part of the BWRX-300's passive safety system. This report has found that the BWRX-300's ICS can successfully cool a reactor down after shutdown in under one day by using a Simulink simulation.

The BWRX-300 that is planned to be built in the Darlington Nuclear Site is hopefully one of many SMRs that will change how Canadians get their energy. If the project is a success, it will show that cost effective nuclear reactors can be built in a modular fashion, even in remote communities. Further research could be done into other safety systems of the BWRX-300, such as its Control-Rod Drive or Boron Injection System to test their effectiveness and reliability.

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