ACR-1000 ECC DESIGN CONCEPT

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Abstract

The emergency core cooling (ECC) system in the Advanced CANDU Reactor™* is based on the existing CANDU-6 ECC design, with improvements to simplify operation and enhance safety. The high-pressure emergency coolant injection (ECI) system cools the reactor fuel following a loss of coolant accident (LOCA) and meets stringent targets for core cooling and refill time. Core make-up tanks (CMTs) limit the voiding in the intact loop of the reactor coolant system (RCS) following a LOCA event, or in both RCS loops during rapid cooldown events causing shrinkage of primary inventory. The four-division long-term cooling (LTC) system performs post-LOCA cooling and recovery, and cools the RCS following events with the pressure boundary intact, including normal reactor shutdown.

Keywords: Emergency Core Cooling (ECC), Emergency Coolant Injection, Loss of Coolant Accident (LOCA), Advanced CANDU Reactor (ACR)

1. INTRODUCTION

The Advanced CANDU Reactor™ (ACR™) is a Generation III+ pressure tube type reactor using light water coolant and heavy water moderator. The ACR-1000™ reactor design is an evolutionary extension of the proven CANDU 6 reactor design (References 1 and 2).

The main safety functions of reactor shutdown, containment protection, secondary side heat removal, and primary side heat removal are performed, respectively, by the two shutdown systems, the containment system (including containment isolation, atmospheric control, and pressure suppression subsystems), the emergency feedwater system, and the emergency core cooling (ECC) system.

This paper describes the ECC system design for ACR-1000 that consists of the high-pressure emergency coolant injection (ECI) system, the core make-up tanks and the long-term cooling (LTC) system. Key design targets for the ECC system were to meet stringent goals set for fuel sheath temperature, pressure tube strain, and core refill time following a postulated loss of coolant accident (LOCA). Thermalhydraulic analyses show that the ACR-1000 ECC system meets these important goals.

2. EMERGENCY COOLANT INJECTION SYSTEM CONCEPTUAL DESIGN

2.1 Configuration

The ECI system, depicted in Figure 1, supplies light water coolant to the two-loop RCS and refills the fuel channels in the short term after a postulated LOCA. During the high-pressure injection stage, water from pressurized accumulators is injected into the broken loop of the RCS.

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

The main steam safety valves (MSSVs) serve two purposes: the first is to act as a relief valve to provide overpressure protection for the steam generators (SGs); additionally, actuators are provided to open the MSSVs upon detection of a LOCA to provide a rapid cool-down of the secondary side of the steam generators (SGs) and depressurization of the reactor coolant system. This "crash cooldown" enhances the effectiveness of high-pressure injection by accelerating depressurization of the primary side, resulting in earlier injection.

Interconnections between the reactor outlet headers (ROH) of each RCS loop are opened upon detection of a LOCA to assist in establishing a cooling flow path, as shown in Figure 1. Addition of interconnect lines between ROHs is an improvement over existing CANDU-6 ECC system design.

There are four sets of ECI accumulators, each dedicated to one of the four reactor headers (inlet or outlet) on each RCS loop, and shared between RCS loops (see Figure 1). The accumulators contain light water coolant, pressurized by compressed nitrogen gas. The accumulator volumes and pressure are optimized via thermalhydraulic analysis to give the best possible performance (in terms of fuel temperatures and core refill time) achievable for the operating conditions and thermalhydraulic characteristics of the ACR-1000 RCS.

The ACR-1000 design includes four core make-up tanks (CMTs) that function to limit the extent and duration of voiding in the reactor cooling system (RCS) during events causing rapid shrinkage of inventory (this includes the intact loop of the two-loop RCS during a postulated LOCA). Keeping the RCS full gives increased assurance of thermosyphoning capability and heat removal via feedwater supplied to the steam generators (SGs), and allows back-up heat removal by the long-term cooling (LTC) system operating in shutdown cooling mode (as described in Section 3.2.2) without the risk of cavitation at the LTC pumps due to the potential for entrainment of void. This improves heat sink reliability by ensuring availability of two independent means of heat removal for an intact RCS.

Each of the four CMTs has an upstream connection to one of the four heat transport pumps and a downstream connection to a RIH, as shown in Figure 3. The CMTs' elevation is such that the bottoms of the CMTs are above the tops of the SG U-tube bundles. Placement of the CMTs above the SG U-tube bundles puts them at the highest point in the reactor coolant system, and ensures that any voiding occurs preferentially in the CMTs, rather than in the SG U-tubes or in the RCS. During transients resulting in a loss or shrinkage of RCS inventory, the CMTs void first, and expansion of CMT inventory helps keep the RCS full to the tops of the SGs.

During normal operation, the CMTs will be maintained at approximately the pressure and temperature of the RIH by a small continuous recirculation flow. (The larger upstream valve depicted in Figure 3 is normally closed, and is used only during warm-up and cooldown of the RCS).

CMTs are more appropriate than gas-pressurized accumulators to maintain a relatively high pressure and restrict RCS voiding because "flashing" in the CMTs maintains a relatively high pressure (i.e. the saturation pressure corresponding to the normal operating temperature) even after making up for RCS inventory shrinkage. By contrast, compressed gas loses pressure significantly as it expands, making it difficult to maintain a high pressure without very large volume and/or high pressure of compressed gas. In short – a CMT can do the same job as a pressurized gas accumulator, but with a much smaller tank volume (and correspondingly less space occupied inside containment).

The CMTs contain adequate inventory to provide RCS make-up for shrinkage from 0% full power hot to 100°C, this supplements the inventory in the pressurizer, which is sized to make up for RCS shrinkage from 100% full power to 0% full power hot. Combined, the inventory of the CMTs and the pressurizer allows the RCS to be kept full following any postulated event with an intact RCS, without the need for inventory transfer from other sources.

2.2 Operation

During normal reactor operation the ECI system is poised at all times to detect and respond to a LOCA event. The motorized accumulator isolation valves on the injection lines to the RCS are normally open. The ROH interconnect valves are normally closed.

Following a postulated LOCA, the RCS depressurizes rapidly, at a rate dependent on the size of the break. The ECI system detects the event and generates an "ECI signal". The ECI signal opens the MSSVs, depressurizing the secondary side of the SGs and accelerating depressurization of the RCS. To assist in establishing a cooling flow path (to be utilized both during high-pressure injection and later by the LTC system during the recovery stage of ECC operation), large interconnects between the ROHs on each loop are opened by the ECI signal. The ECI signal also initiates the isolation of the two loops of the RCS, and starts the LTC system in preparation for recovery mode operation (this is described in Section 3 following).

When the pressure in the RCS drops below the pressure of the ECI accumulators, check valves at the RCS/ECI pressure boundary open, enabling coolant injection to the reactor coolant system. High-pressure injection from the accumulators continues, reducing the water level in the accumulators. When the water level in an accumulator is nearly depleted, the associated accumulator isolation valves automatically close to prevent injection of nitrogen into the RCS.

Closure of the accumulator isolation valves is backed up by floating ball seals located in each of the ECI accumulators. The balls are partially submerged in the water in the accumulators and travel down with the water level during injection. When the water level nears the bottom of the accumulator, pressure forces the ball against a seat at the bottom of the accumulator, creating a seal and terminating injection.

Based on the thermalhydraulic analysis results during a postulated LOCA event, coolant from the CMTs connected to the broken loop flows into the broken loop of the RCS at a rate dependent on the size of the break – this has little or no impact on the functioning of ECI to refill the broken loop. The CMTs connected to the intact loop inject to the RCS at high pressure. Injection begins when the RCS pressure drops to below the saturation pressure of the water contained in the CMTs (corresponding approximately to the RIH temperature). The high elevation of the CMTs (above the SG U-tube bundles) and expansion of the CMT inventory due to flashing forces coolant flow from the CMTs into the RCS and maintains a relatively high pressure in the intact RCS loop, limiting the extent and duration of void, giving assurance of thermosyphoning capability and/or allowing operation of the LTC system as described in Section 3.2.1.

CMTs are playing a significant role during rapid cooldown events, which encompass a full range of secondary side events, ranging from spurious opening of the atmospheric steam discharge valves and/or condenser steam discharge valves, to spurious opening of the main steam safety valves, to a large break in one of the main steam lines. Any of these events causes a rapid cooldown and depressurization of the secondary side of the SGs, and causes an increase in heat transfer from the RCS resulting in rapid shrinkage of RCS inventory.

Injection from the CMTs begins when the RCS pressure drops to below the saturation pressure of the water contained in the CMTs (approximately equal to the RIH temperature). Injection from the CMTs maintains a relatively high pressure in the RCS, limiting the extent and duration of void, giving assurance of thermosyphoning capability and/or allowing operation of the LTC system as described in Section 3.2.1.

2.3 Performance

The ECCS shall meet all of the following requirements for all Design Basis Accidents involving a loss of coolant:

1) All fuel in the reactor and all fuel channels shall be kept in a configuration such that continued removal by the ECCS of the decay heat produced by the fuel can be maintained.
2) After adequate cooling of the fuel is re-established by the ECCS, the system shall be capable of continuing to supply sufficient cooling flow for as long as it is required to prevent further damage to the fuel.
3) For all Postulated Initiating Events except intermediate and large break LOCAs, fuel handling failures and single channel events, there shall be no fuel failures due to overheating.

In order to confirm that the above-mentioned high level requirements are met for conceptual ECCS design, thermalhydraulic analysis has been performed for a full range of break sizes and locations. Inlet header breaks, outlet header breaks, and pump suction breaks are all considered, ranging in size from small breaks (equal to the size of the largest feeder pipe) to very large breaks (up to and including a double-ended break in a reactor header). For all breaks evaluated, the ACR-1000 ECC system design is demonstrably capable of meeting the goals for maximum fuel temperature, pressure tube strain, and core refill time as stated in Section 1.

A large break in the heat transport pump suction line has been determined by thermalhydraulic analyses to be the “worst-case” break for ACR-1000 in terms of pressure tube strain and refill times. For this “worst-case” break, the maximum fuel sheath temperatures approach (but do not exceed) 1200°C, and core refill occurs within 200 seconds. This prompt refill and relatively low fuel sheath temperatures ensures sufficient margin on pressure tube strain.

The capability of the CMTs to limit the extent and duration of voiding in the intact loop has been demonstrated by thermalhydraulic analyses. A comparison of intact loop behaviour following a LOCA with and without CMTs shows a marked difference in the duration and extent of voiding in the RCS. For a case with no CMTs, there is significant prolonged voiding in the ROH, which diminishes confidence in thermosyphoning capability and prevents the use of LTC in its back-up heat sink configuration (taking suction from the ROH and returning flow to the RIH) for heat removal due to the possibility of pump cavitation. Thus, without CMTs, there *may* be heat removal capability via the SGs, but there is no back-up heat sink since LTC cannot be operated.

3. LONG-TERM COOLING SYSTEM

3.1 Configuration

The safety functions of the LTC system are to provide fuel cooling in the long term (recovery stage) after a LOCA and to remove decay heat in the long term of transients and accidents with the RCS pressure boundary intact. The LTC system for ACR-1000 is separated into four independent divisions, as depicted in Figure 2. Support services for LTC are similarly configured into four divisions, so that the independent divisions of LTC receive support from independent divisions of electrical and service water supplies. Each division is comprised of one pump and one heat exchanger (i.e. there is no redundancy within the divisions).

The ECI system, which is predominantly a passive system, is not a multi-division system, but instead contains redundant active components within each division and, where required, separate support services are provided to those redundant components (e.g. electrical power to motorized valves).

Each division of LTC is located inside of a separate confinement room in the reactor auxiliary building (RAB) at opposing compass points of the reactor building (RB) perimeter. Locating the LTC system in the RAB allows access to the LTC system for maintenance and repairs. This physical separation gives better protection against common mode external events, and improves overall reliability of the system.

Provision of four independent divisions of LTC gives flexibility for maintenance activities. With four divisions of electrical power and service water, major equipment of the LTC system, the service water system, and the electrical system can all be maintained (one division at a time) during reactor shutdown concurrent with RCS maintenance work. During shutdown there is always at least one available division of LTC on standby as a back-up heat sink (assuming one operational division per each of the two RCS loops and a third division out for maintenance). This facilitates the required outage duration for the plant.

Inside the RB, grade level tanks (GLTs) are provided. These tanks are a dedicated source of cool water to be delivered to the RB sumps for recovery by LTC following a LOCA. The GLTs are connected with the sumps via the suction lines of the LTC pumps. This cross-connection ensures adequate net-positive suction head for the LTC pumps, such that LTC can begin operation even before the inventory of the GLTs has been delivered completely to the sumps, with the LTC pumps simultaneously taking suction from both the GLTs and the RB sumps with flowrates depending on the relative water levels.

The four-division configuration ensures that there are two heat sinks available for each RCS loop during normal reactor shutdown (or following events with the RCS pressure boundary intact) – one operating division and another independent division (which may be either operational, or kept on standby). The four-division LTC system design allows the system to perform both post-LOCA recovery for the broken loop and back-up cooling for the intact loop (if needed), with no potential for any event or occurrence that debilitates or degrades performance of one function to impact on performance of the other function.

3.2 Operation

3.2.1 Recovery Mode

On receipt of an ECI signal (generated by the ECI system as discussed in Section 2 preceding) the LTC pumps on all four divisions are started automatically. Water is automatically introduced into the containment sumps from the GLTs following a LOCA.

Though all four divisions of LTC are started upon receipt of the ECI signal, only two divisions (one on each side of the broken loop of the RCS) are required to mitigate the LOCA event. The other two divisions may be available either as back-up for recovery, or to operate as a back-up heat sink for the intact loop in the back-up heat sink configuration (as explained in the description of the CMTs in Section 2.1). In the long-term, only a single LTC division is required to operate in recovery mode to provide the required decay heat removal. No single failure can prevent the LTC system from meeting performance requirements for post-LOCA operation.

The LTC pumps operate in a recirculation mode until the RCS is sufficiently depressurized that the LTC pump head exceeds the RCS pressure, at which time the LTC pumps begin to recover coolant from the

RB sumps and return it to the RCS via heat exchangers for cooling. Depending on the RCS depressurization rate, LTC injection to the RCS can begin either before or after the GLTs have completely discharged their inventory to the RB sumps (as discussed in Section 3.1).

LTC begins operation independently of high-pressure injection. ECI system parameters (water volume, gas volume and pressure) and LTC system parameters (pump curve) are selected to ensure overlap between the high-pressure injection and LTC recovery phases so that injection flow to the RCS is not interrupted.

3.2.2 Shutdown Cooling Mode

Following any abnormal event with the RCS intact (or during normal shutdown), the LTC system provides a long-term heat sink after initial cool-down of the RCS by the SGs and the feedwater systems. Water is drawn from the ROHs, cooled via the LTC heat exchangers, and then returned to the RCS via the RIHs.

Following a normal shutdown, initially all four LTC divisions will be in operation. One LTC division per RCS loop is sufficient to cool the system, however two LTC divisions per loop are operated to improve the heat sink reliability. In the long term one LTC division has sufficient capacity to perform the required heat removal, however two LTC divisions will remain in operation, again for increased reliability.

The LTC system is also capable of running in “RCS pump mode” with the RCS pumps providing circulation via the LTC heat exchangers for heat removal. This capability increases the flexibility of the LTC heat sink and improves the reliability of the shutdown cooling mode heat sink.

4. SUMMARY

High-pressure injection from the ECI system to all headers, coupled with provision of a large ROH interconnect, ensures prompt establishment of a sustainable cooling flow path, ensuring that the requirements sated in Section 2.3 are met.

CMTs restrict the extent and duration of voiding in an intact RCS (including the intact loop of the RCS during a postulated LOCA). Keeping the RCS full ensures dual heat sink capability by increasing assurance of thermosyphoning capability and allowing operation of LTC in shutdown cooling mode without risk of pump cavitation and damage due to void entrainment from the ROHs.

The LTC system four-division design concept gives excellent separation between redundant divisions and their respective support services. This improved separation increases flexibility for maintenance during outages contributes to meeting the strict outage duration requirement for the plant. Additionally, the capability to operate in “heat transport pump mode” with the heat transport pumps providing forced circulation through the LTC heat exchangers adds flexibility for operations and improves reliability of the shutdown cooling heat sink.

The design of the ECC system as a whole enhances the safety of the ACR-1000, allowing safety goals and requirements to be met with high confidence. The flexibility of the four-division LTC system design also provides significant benefits in terms of operations and maintenance and overall lifetime capacity factor of the ACR-1000 plant.

5. ACRONYMS

ACR	Advanced CANDU Reactor
CANDU	CANadian Deuterium Uranium
CMT	Core Make-Up Tank
ECC(S)	Emergency Core Cooling (System)
ECI(S)	Emergency Coolant Injection (System)
LOCA	Loss of Coolant Accident
LTC(S)	Long Term Cooling (System)
RB	Reactor Building
RCS	Reactor Coolant System
RIH	Reactor Inlet Header
RWS	Reserve Water System
SG	Steam Generator

6. REFERENCES

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[2] B. Lekakh, M.R. Lin, et al., *Advanced CANDU Reactor Emergency Core Cooling System*, Proceedings of the 24th Annual Conference of the Canadian Nuclear Society, Toronto, Ontario, June 8-11 (2003)

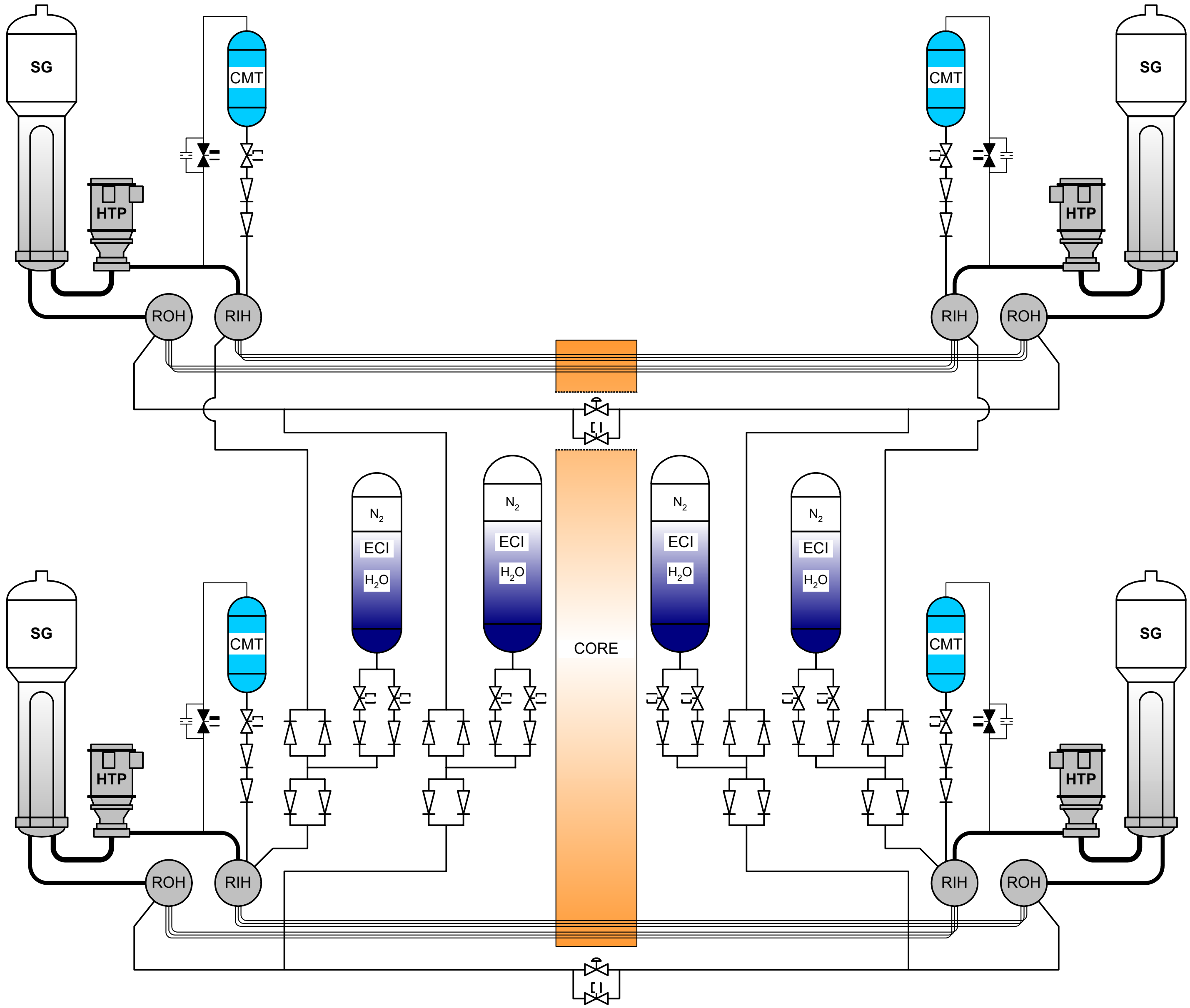

Figure 1 ACR-1000 Emergency Coolant Injection System

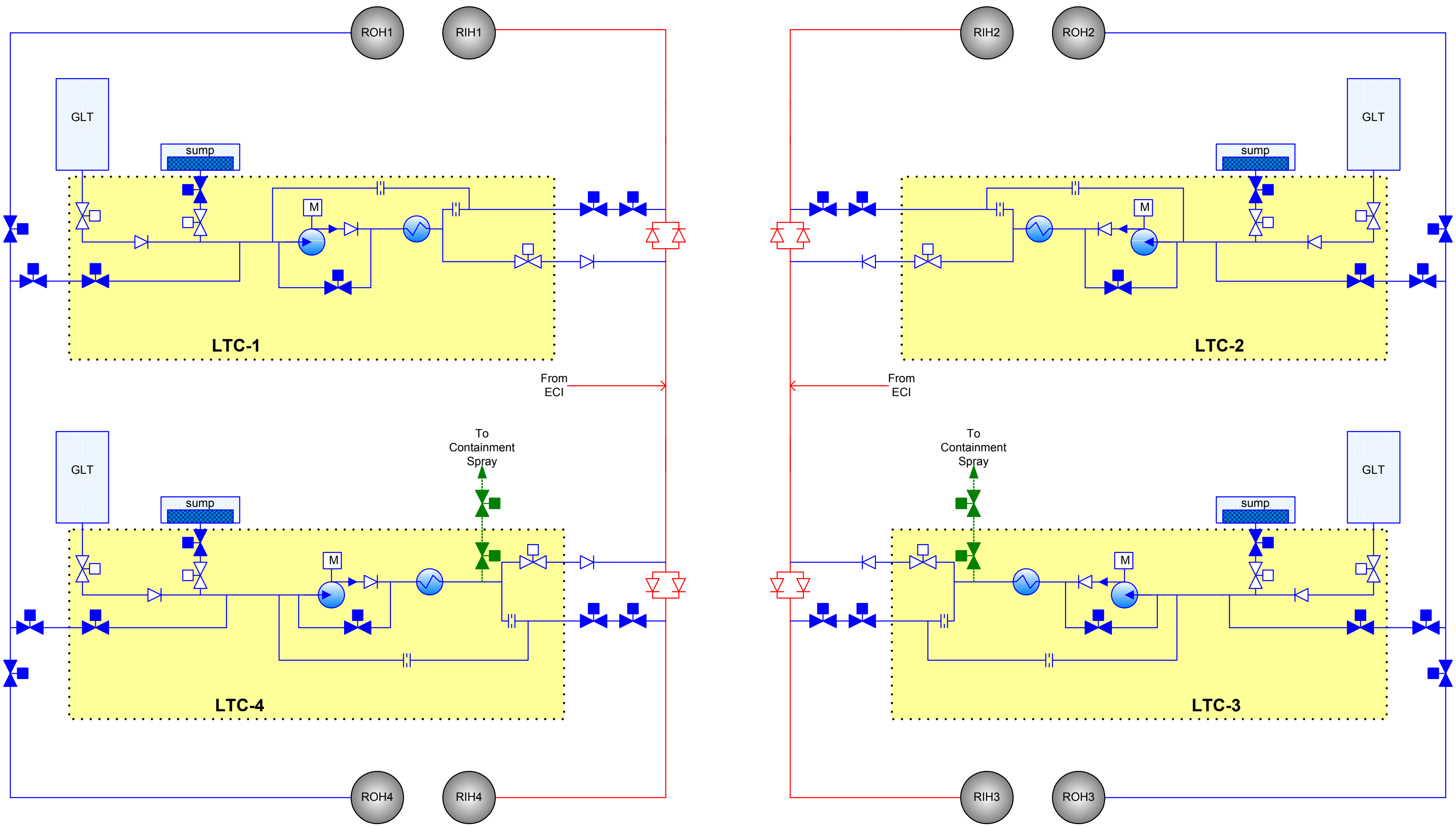

Figure 2 ACR-1000 Long-Term Cooling System

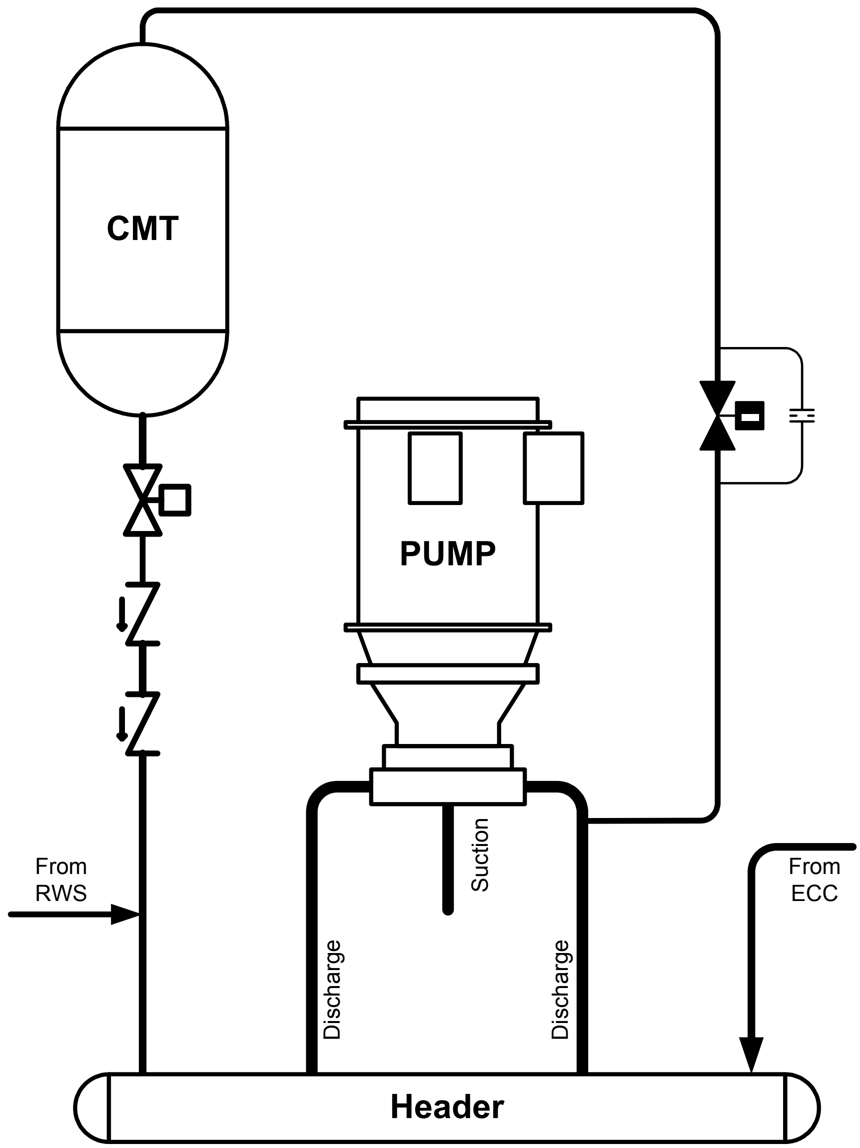

Figure 3 ACR-1000 Core Make-Up Tank Configuration