Passive Safety Features In The ACR-1000

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Abstract

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®*** reactor design.

ACR utilizes passive, stored-energy, natural circulation, and gravity features for:

- Reactor shutdown,
- Cooling of the heat transport system when forced circulation is unavailable,
- Core refill and fuel cooling following a LOCA,
- Post-accident pressure and temperature suppression inside containment,
- Emergency feedwater supply to the steam generators, and
- Mitigation of postulated beyond design basis accidents.

This paper describes passive design elements and how they complement the active features, enhance reliability and improve the overall safety margins.

1. Introduction

CANDU power plants have traditionally included, over and above the normal power production systems, a separate set of dedicated protective safety systems to mitigate postulated events and combinations of postulated events that could potentially result in a radiological release.

The ACR-1000 follows a "defence in depth" approach, with different preventative, protective, and mitigating features to address a full range of accidents of varying probability:

- Systems and components used in normal power production operation are designed to high standards of quality and reliability to prevent, to the greatest extent achievable, failures leading to abnormal modes of operation,
- Means are provided to detect and control deviations from normal operation to prevent those deviations from progressing into an accident,
- In the unlikely event of an accident, protection systems and safety features restore the plant to a controlled state and minimize consequences of the event, and

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- In the extremely unlikely event that one of the protective systems should fail, back-up systems and features are provided to halt the progression and mitigate the consequences of the resulting beyond design basis accidents.

The "traditional" CANDU safety systems are included in the ACR-1000 design. The design and performance of these systems has been further enhanced by incorporating feedback and lessons learned from operating CANDU power plants. Moreover, additional passive features have also been added to the ACR-1000 design to further improve the overall reliability of the key safety functions, and enhance the overall safety of the plant.

This paper discusses many of the key passive safety features provided in the ACR-1000, identifying those systems that operate collectively to cool the fuel, maintain containment integrity and/or, in the unlikely event of a severe accident, to halt progression of the event and mitigate the consequences.

The safety enhancements made in the ACR-1000 encompass improved safety margins, performance, and reliability of the overall plant design.

Further background on ACR-1000 safety features and systems' designs can be found in References [1] through [6].

2. Overall Plant Design of ACR-1000

The ACR retains the core features of previous CANDU designs, such as horizontal fuel channels surrounded by a heavy water moderator (Figure 1). One of the major innovations in ACR is the use of low enriched uranium fuel and light water as the coolant. Since the reactor coolant is light water, tritium production is limited to the heavy water moderator systems, thus significantly reducing the rate of tritium production for the plant.

The equilibrium core is designed to have a negative power coefficient. The coolant void reactivity is small and negative under nominal design conditions.

The overall layout of an ACR-1000 reactor and its primary components is shown in Figure 2. The ACR-1000 reactor is designed to produce a nominal gross output of 1165 MW_e. As with all CANDU reactors, the high-pressure and high-temperature Heat Transport System (HTS) and the low-pressure and low-temperature Moderator System (Figure 3) are separate systems. The fuel channels (i.e. pressure tubes and endfittings) form the reactor coolant pressure boundary.

The HTS consists of two loops; each loop consists of 260 fuel channels, which contain the nuclear fuel bundles. The primary coolant system consists of 520 reactor fuel channels, stainless steel feeders, four inlet headers, four outlet headers and the interconnecting piping. The system also includes four steam generators and four electrically driven heat transport pumps in a two-loop, figure-of-eight configuration. The heat transport pumps circulate the water in the two loops such that flow in adjacent channels is in the opposite directions. There are 260 pressure tubes in each primary loop.

In normal operation, heat is generated in the reactor fuel bundles and exchanged with the coolant passing through the fuel channels. The heated water is transported through the feeder pipes to the headers and into the U-tubes inside the steam generators (SGs). The heat is then transferred to the water on the secondary side of the SGs to produce steam, which is then transferred to the turbine located in the Turbine Building (Figure 1) to generate electricity. The cooled light water coolant leaving the steam generators is pumped by the four HTS pumps through two separate HTS loops connected to a common pressurizer, which maintains the HTS at a constant pressure.

The pressure tubes run through the Calandria (see Figure 3). The low pressure and temperature heavy water contained in the Calandria moderates nuclear fission. The pressure tubes are contained within another set of tubes called calandria tubes, separated from the pressure tubes by an annulus gap filled with carbon dioxide. This keeps the high-pressure, high temperature coolant on the primary side separated and thermally isolated from the low-pressure, low temperature moderator. The moderator system consists of a closed heavy water recirculating loop that serves to cool and circulate the heavy water moderator through the calandria (Figure 3).

3. Systems Important to Safety in ACR-1000

The following sections describe the key safety features provided in the ACR-1000, with emphasis on those features that operate passively to shut down the reactor, cool the fuel, maintain containment integrity and/or, in the unlikely event of a severe accident, to halt progression of the event and mitigate the consequences thereof.

3.1 Shutdown Systems

Shutdown systems SDS1 and SDS2 are fully redundant, physically separate and functionally diverse. Both shutdown systems execute their function via the low-pressure moderator contained in the calandria, not via the high-pressure HTS. Executing shutoff via the low-pressure moderator, instead of via a pressurized reactor vessel as in pressurized water reactors, eliminates the possibility of failures associated with high-pressure forces, such as ejection of the shutoff rods. The shutdown systems execute their functions using different passive methods, as described below:

- SDS1 consists of neutron-absorbing mechanical shutoff rods. A trip signal de-energizes the clutches that hold the shutoff rods out of the calandria and the rods then drop into the calandria by gravity, assisted by springs.
- SDS2 injects a concentrated solution of neutron-absorbing gadolinium nitrate solution directly into the low-pressure moderator. On a trip, fast-acting valves open, and high-pressure helium pressurizes tanks filled with neutron-absorbing gadolinium nitrate solution, forcing the liquid poison into the core via injection nozzles that disperse the poison for maximized shutdown effectiveness.

The use of stored energy in both of the shutdown systems; in SDS1 (utilizing gravity and springs), and in SDS2 (using pressurized helium gas) provides two means of shutdown that are completely passive.

3.2 Emergency Coolant Injection System

The Emergency Coolant Injection (ECI) system (Figure 4) provides make-up to the HTS to ensure fuel cooling for accidents causing a loss or shrinkage of HTS inventory that cannot be made-up by normal process systems.

- Accumulator tanks are filled with make-up water and pressurized by compressed nitrogen gas. When the HTS depressurizes to below the pressure of the accumulators, check valves at the HTS/ECI pressure boundary open, and expansion of the compressed nitrogen forces cooling water flow from the accumulators into the HTS, refilling the reactor core, and cooling the fuel following a postulated LOCA, prior to establishment of long-term recovery and cooling.
- Core make-up tanks (CMTs) are located above the top of the steam generator U-tube bundles, and are maintained close to the pressure and temperature of the reactor inlet headers. Following events causing rapid shrinkage of the HTS inventory, injection from the CMTs (by "flashing" of the CMT inventory when the HTS depressurizes) limits the extent and duration of voiding in the HTS. This increases assurance of thermosyphoning capability, or allows the long-term cooling system to take suction from the HTS for forced circulation and cooling without the risk of void entrainment and cavitation of the pumps.

Utilization of stored energy in both the accumulators (in the form of pressurized nitrogen gas), and in the core make-up tanks (in the form of stored enthalpy) makes the system completely passive, and totally independent of external power supplies or motive force.

3.3 Thermosyphoning in Heat Transport System

The HTS layout has the heat transport pumps and steam generators above the core (see Figure 2) to promote natural circulation of the primary coolant for accidents when forced circulation is not available. Natural circulation of the coolant allows the plant to recover from any reactor trip without relying on the heat transport pumps.

Thermosyphoning is supported by provision of feedwater to the steam generators for heat removal. Feedwater can be supplied at full pressure by either the main feedwater system or the four-quadrant emergency feedwater (EFW) system. If these active sources are not available, passive water supply can then be provided by gravity from the Reserve Water System (RWS) after auto-depressurization of the SGs.

Following events that cause rapid shrinkage of the HTS inventory (e.g. rapid cooldown due to a main steam line break) effectiveness of natural circulation is assured by the CMTs, which serve to keep the HTS full and free of void.

The configuration of the HTS promotes natural circulation for fuel cooling. With a passive source of feedwater available as a back-up (e.g. from the RWS), fuel cooling can be sustained for a prolonged period of time passively, without any forced circulation or active support services.

3.4 Reserve Water System

The Reserve Water System (RWS, Figure 5) is comprised of a seismically qualified reserve water tank (RWT), containing a large volume of water used by several systems to mitigate various postulated accidents.

- Injection to the HTS by gravity provides back up to pumped recovery following a LOCA to mitigate postulated accidents for which pumped recovery and cooling is impaired or unavailable.
- Water from the RWS flows by gravity to the containment cooling sprays for post-accident containment pressure and temperature suppression following an accident.
- After depressurization of the SGs (by opening the main steam safety valves), emergency feedwater water may be directed from the RWS to the SGs, following accidents for which active sources of feedwater (the main and emergency feedwater systems) are unavailable.
- Following a postulated severe accident, manual connections to the calandria and/or the reactor vault can be opened. Heat transfer to the moderator and shield cooling water inventory maintains fuel cooling, thereby halting progression of the accident.

RWS inventory is partitioned to ensure availability of sufficient inventory for each function when required, regardless of the relative initiation times of each function.

The RWS relies solely on gravity to perform all its above-indicated functions. After initial actuation of the system operation is completely passive, with no further need for component re-alignments or support services for any design basis accident.

3.5 Containment Cooling System

The Containment Cooling System (CCS, Figure 6) removes heat from the containment atmosphere during normal operation by forced air circulation and cooling using local air coolers. Following a design basis accident, a passive spray performs post-accident pressure suppression and containment cooling, without reliance on the LACs.

- Spray headers are located at a high elevation in the Reactor Building (RB). Spray nozzles diffuse cooling water fed from the RWT into fine droplets, which fall through the containment atmosphere, enhancing utilization of the RWT inventory to absorb heat and condense steam, thereby reducing pressure and temperature inside the RB.
- The spray is actuated automatically for any event resulting in pressures or temperatures that challenge the environmental conditions for equipment qualification or the integrity of the containment structure. Once the spray valves leading to the spray headers are opened the system relies only on gravity to deliver water flow from the RWT to the spray headers.

- The spray, utilizing the allocated inventory in the RWT inventory, maintains containment conditions within design limits for an extended duration, allowing time for action to be taken to enable active systems to sustain the containment heat sink.
- Following an accident, large airflow paths are opened between the major volumes of the reactor building (RB) and natural circulation flows mix the RB atmosphere, preventing formation of regions of locally high temperature and dispersing hydrogen following a postulated severe accident.
- Following a postulated severe accident, the spray, utilizing the allocated RWT inventory, will ensure containment pressure remains within design limits for at least 24 hours after the onset of core damage, after which time external action or intervention may be taken to establish a means of removing heat from containment indefinitely.
- The containment cooling spray may also be used following a postulated accident for which there is a significant radioactive release (e.g. severe accidents) to scrub radioactive products from the atmosphere in the RB.

3.6 Hydrogen Control System

Two features are provided in ACR-1000 for atmospheric hydrogen control, passive autocatalytic recombiners and active igniters (or "glow plugs") that limit the concentration of hydrogen in the RB atmosphere to below the threshold limit at which deflagration or detonation could occur:

- Seismically and environmentally qualified recombiners, strategically distributed throughout the RB, perform hydrogen control without external power or services, and operate at very low hydrogen concentrations to maintain the hydrogen concentration well below the flammability limit following postulated design basis events.
- In the event of severe accidents, should the hydrogen production rate released from the core (due to the interaction between zirconium and steam) exceed the capacity of the recombiners, localized accumulation of hydrogen in undesirable concentrations may occur. To complement the action of the passive recombiners, active igniters are also provided in strategic locations to ignite any accumulated hydrogen, hence considerably reducing the risk of uncontrolled deflagration or detonation.

3.7 Natural Circulation in Moderator System & Calandria

During normal operation the closed heavy water recirculating loop serves to cool and circulate the heavy water moderator through the calandria (Figure 3). For accidents when all normal means of fuel cooling and long-term decay heat removal are not available (e.g. a LOCA with a loss of active coolant recovery and cooling), the fuel and fuel channels will heat up until the pressure tubes contact the calandria tubes, resulting in direct conduction of heat to the moderator. If the forced circulation moderator cooling system is not available to remove heat, natural circulation inside the Calandria prevents further damage to the fuel channels and keeps the accident from progressing to a severe accident.

Adequate natural circulation flow to prevent channel failure will be maintained for as long as passive make-up water supply is available to keep the Calandria full (e.g. from the RWS).

Following a postulated accident leading to core damage, passive natural circulation in the moderator alone can prevent an accident from progressing to a severe accident. Supported by passive inventory make-up from the RWT, channel failure can be prevented for a greatly extended period of time without any active circulation or external support services.

3.9 Four-Quadrant Design Approach for Active Systems

The active safety systems and their supporting systems are designed following a four-quadrant separation philosophy. Each system consists of four redundant, functionally independent divisions. The divisions are physically separated by distance, by barriers, or both.

The four-quadrant design approach ensures that common cause events and functional interconnections will not impair the capability of these active systems to perform their safety functions. In addition, this approach provides significant operational flexibility for maintenance and testing.

The following safety and safety support systems are designed in four divisions:

- Long-Term Cooling System
  Provides long-term decay heat removal following a reactor shutdown with HTS pressure boundary intact, or recovers and cools coolant from the RB sumps and restores it to the HTS following a LOCA.

- Emergency Feedwater System
  Provides pumped make-up feedwater to the steam generators from reserve feedwater tanks at full steam generator pressure when the main feedwater system is unavailable

- Essential Cooling Water (ECW) & Essential Service Water (ESW) Systems
  ECW circulates demineralized cooling water to safety systems for cooling and transfers it to the ESW system via heat exchangers. ESW disposes of the heat from the ECW to the ultimate heat sink.

- Safety Support Electrical Supply
  Electrical power to all four-division systems is supplied from four independent divisions of electrical power.

4. Conclusion

The ACR-1000 incorporates multiple and diverse passive systems and features for accident mitigation. Wherever practical, one or more of the mitigating features for any postulated accident event are passive in nature.

The inclusion of additional passive design features, in addition to the "traditional" passive and active safety systems used for accident mitigation improve the overall safety of the ACR-1000 design. By virtue of the simplicity and inherent reliability, and the capability of passive designs to operate without dependency on support services such as cooling water, electrical supply, or instrument air, the overall safety of the design is improved.

Enhanced reliability of safety functions through use of passive features reduces the release and core damage frequencies for the ACR-1000.

The passive features in the ACR-1000 design supplement and act as back-ups for active systems for shutting down the reactor, cooling the fuel, and containing releases from containment following low-probability postulated accidents:

- Redundant, physically separate and functionally diverse shutdown systems promptly shut down the reactor following a postulated accident.
- Passive HTS refill by ECI, CMTs, and RWS cools the fuel and ensure thermosyphoning capability following an accident leading to a loss or shrinkage of HTS inventory.
- Fuel cooling by thermosyphoning in the HTS, supported by feedwater supply from the main or emergency feedwater systems, or by gravity from the RWS when active sources of feedwater are not available.
- Containment cooling spray fed by gravity from the RWS suppresses containment pressure and temperature to within design limits following a postulated accident.
- Hydrogen control system using passive autocatalytic recombiners to aid in limiting the concentration of hydrogen in the RB atmosphere following an accident.
- Natural circulation in the moderator supported by inventory make-up from the RWS prevents progression of accidents into severe accidents.

For any postulated accident, there are at least two groups of systems available to mitigate the event, one of which is comprised solely of passive systems and features.

By enhancing the "traditional" passive and active systems for accident mitigation with new and improved passive features, the ACR-1000 design achieves improved overall reliability for the key safety functions, and a greatly enhanced safety case for postulated severe accidents.

5. References

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[4] K.F. Hau et al., "Review of the ACR-700 Heat Removal Capabilities", *Proceedings of the 25th Annual Conference of the Canadian Nuclear Society*, Toronto, Ontario, June 6-9 (2004)

[5] B. Lekakh 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)

[6] H. Shapiro et al., "Design Features of ACR in Severe Accident Mitigation", *Proceedings of OECD NEA Workshop on the Evaluation of Uncertainties in Relation to Severe Accidents and Level II Probabilistic Safety Analysis*, Cadarache, France, November 7-9 (2005)

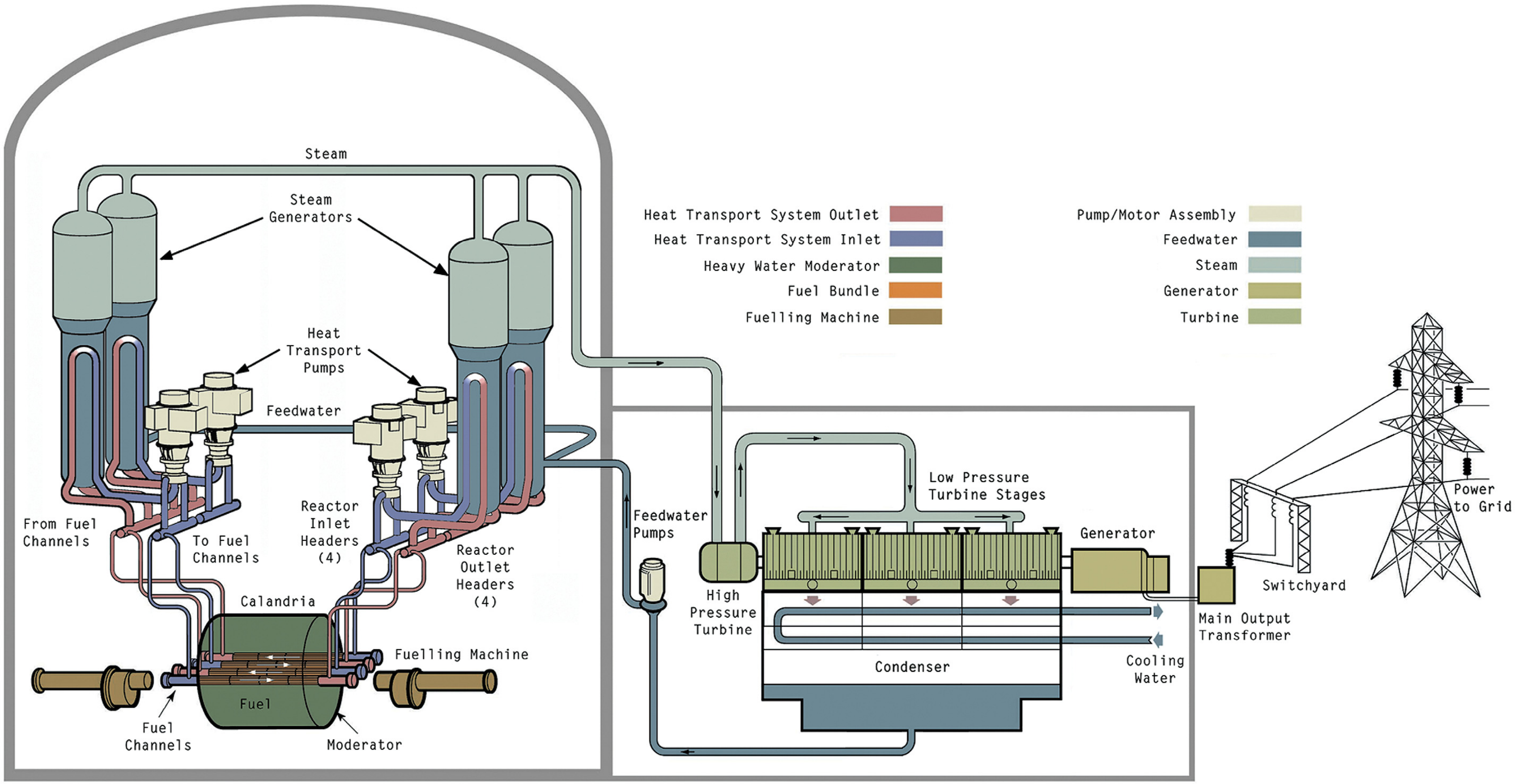

Figure 1 ACR-1000 Overall Plant Design

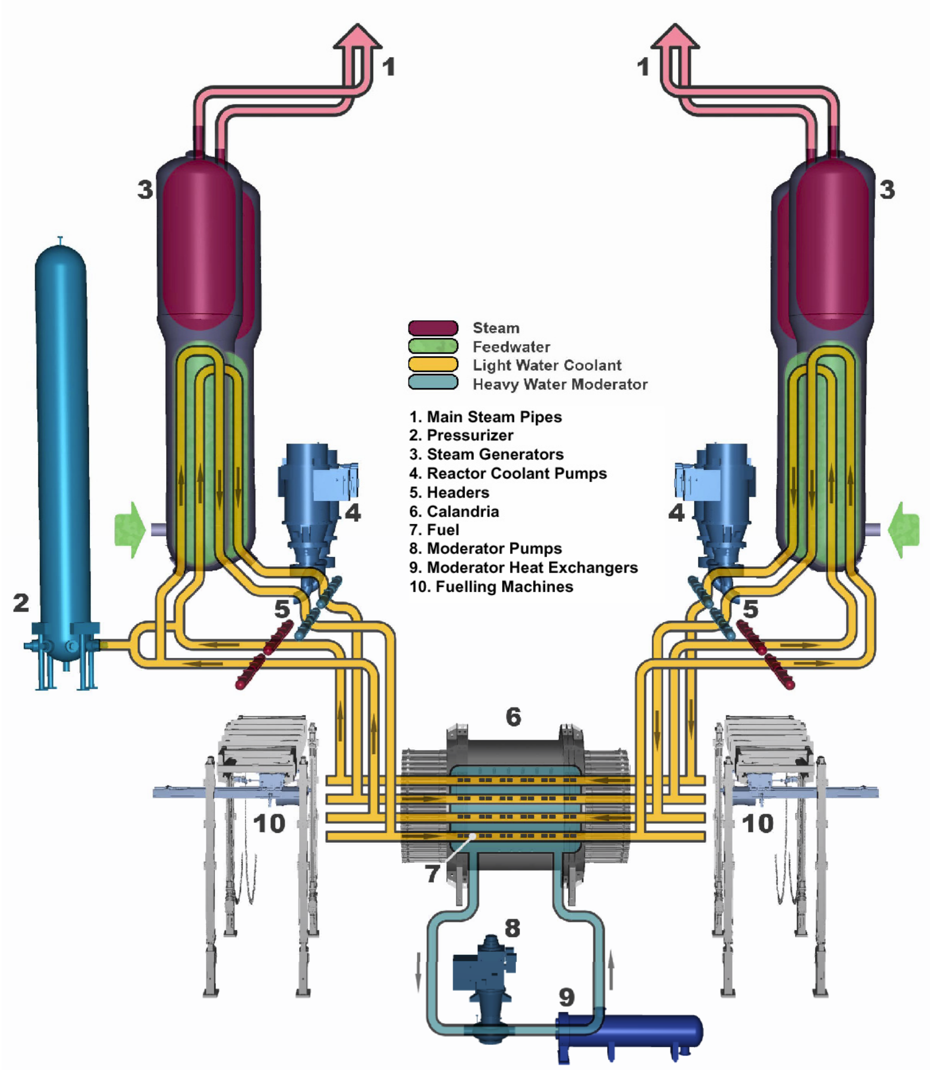

Figure 2 Schematic of ACR-1000 Nuclear Systems

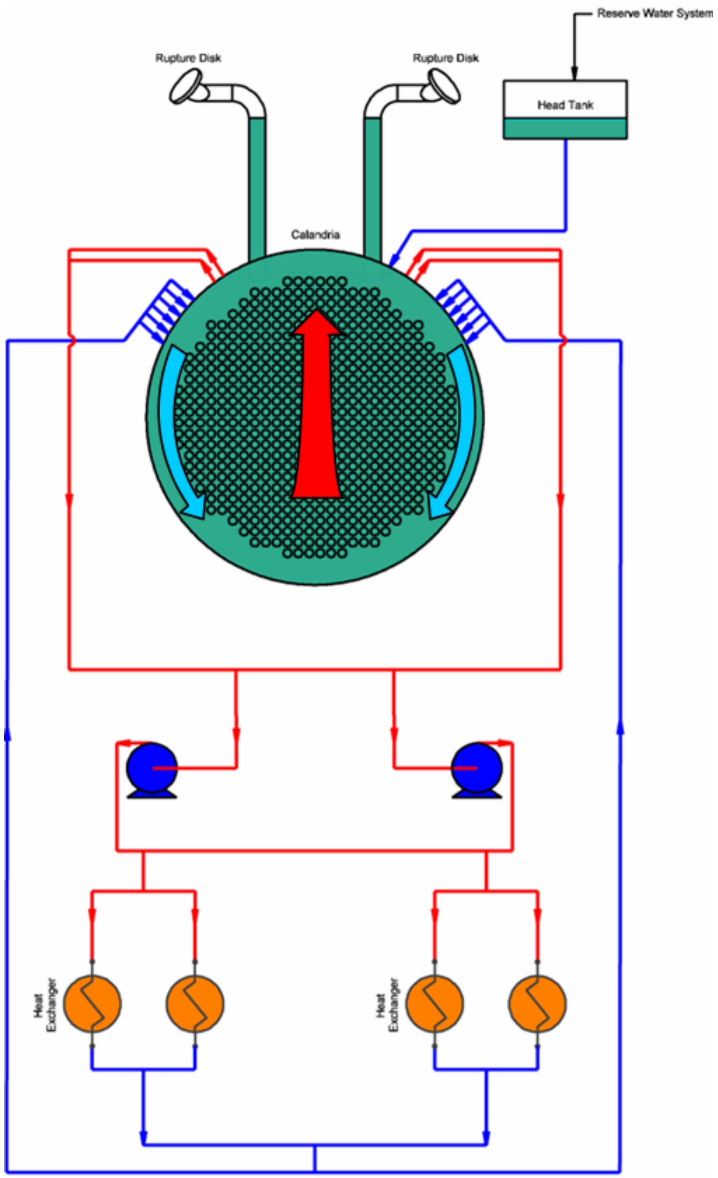

Figure 3 Moderator System & Calandria

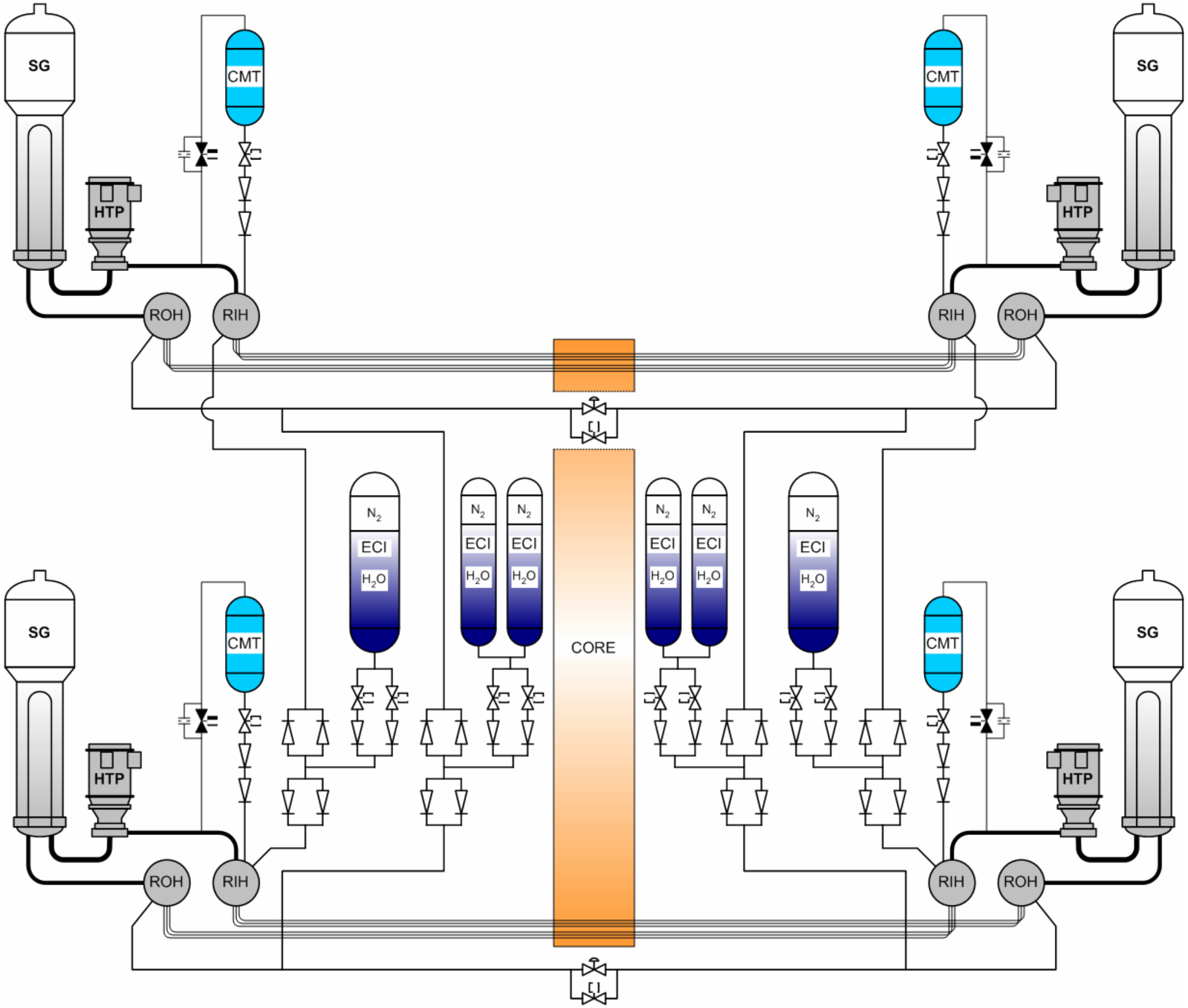

Figure 4 Emergency Coolant Injection System

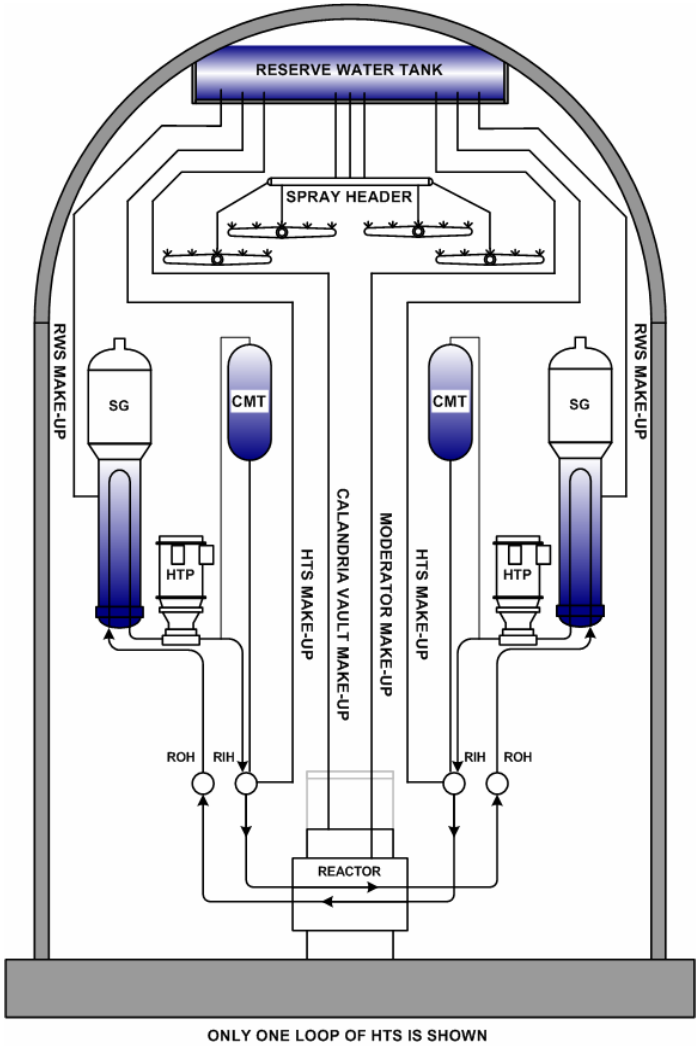

Figure 5 Heat Transport System & Reserve Water System

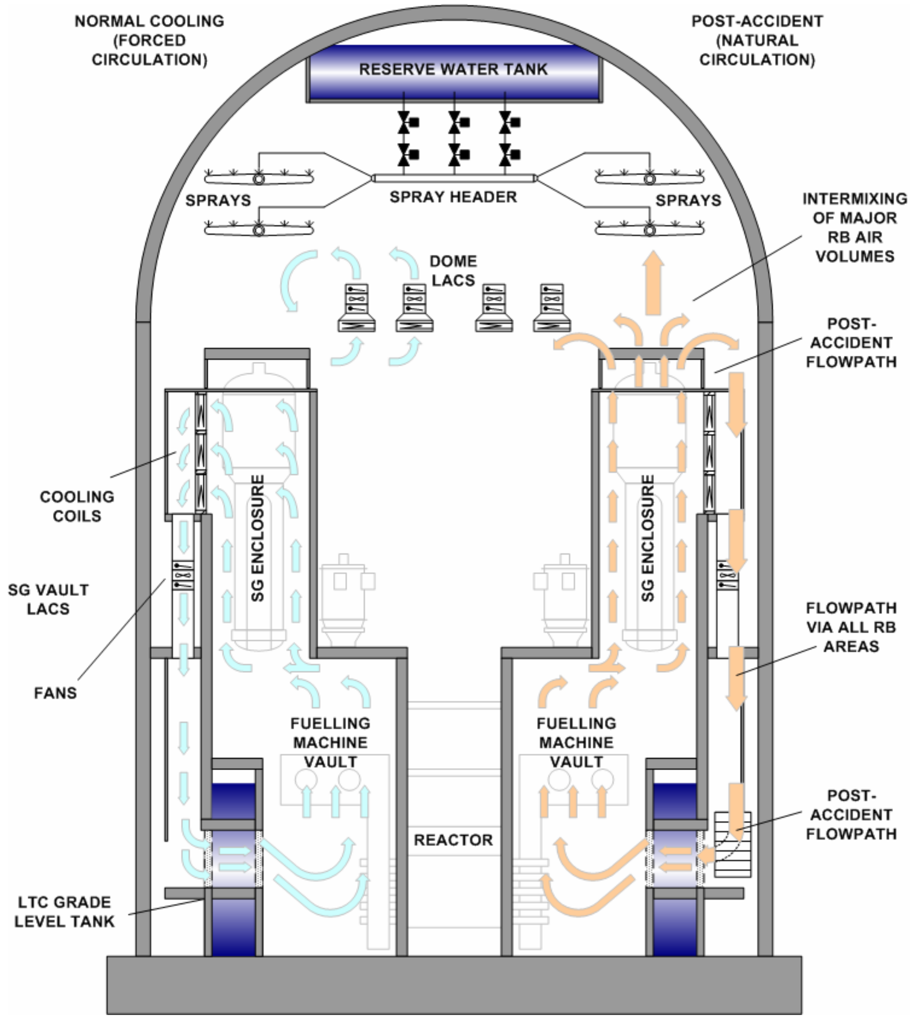

Figure 6 Containment Cooling System