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PHYSICAL ASPECTS OF THE CANADIAN GENERATION IV SUPERCRITICAL WATER-COOLED PRESSURE-TUBE REACTOR PLANT DESIGN

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Abstract

The form of the containment building is a function of the requirements imposed by various systems. In order to provide sufficient driving force for naturally-circulated emergency cooling systems, as well as providing a gravity-driven core flooding pool function, the Canadian SCWR reactor design relies on elevation differences between the reactor and the safety systems. These elevation differences, the required cooling pool volumes and the optimum layout of safety-related piping are major factors influencing the plant design. As a defence-in-depth, the containment building and safety systems also provide successive barriers to the unplanned release of radioactive materials, while providing a path for heat flow to the ultimate heat sink, the atmosphere. Access to the reactor for refuelling is from the top of the reactor, with water used as shielding during the refuelling operations. The accessibility to the reactor and protection of the environment are additional factors influencing the plant design.

This paper describes the physical implementation of the major systems of the Canadian SCWR within the reactor building, and the position of major plant services relative to the reactor building.

1. Introduction

As a member of the Generation IV International Forum (GIF), Canada is developing a channel-type supercritical water (SCW) cooled reactor called the Canadian SCWR. As with other Generation IV reactors, the key design goals of the Canadian SCWR are the improved economics, improved fuel sustainability, enhanced safety and enhanced proliferation resistance. To meet these goals, a reactor core design concept has been proposed [1]. While the details of the core design have been evolving, safety concepts are being developed to support the "enhanced" safety goal of the Canadian SCWR.

The Canadian SCWR is a pressure-tube reactor that uses SCW as the coolant, a low-pressure and temperature heavy water moderator with a direct-steam cycle. Figure 1 illustrates the current Canadian SCWR core design. The proposed design differs from traditional pressure-tube heavy water reactor (HWR) designs in three major features: (1) it uses an inlet plenum instead of inlet feeders, (2) it adopts a vertically oriented reactor core, and (3) refuelling is done off-line. The water enters the inlet plenum through inlet nozzles (inlet pipes are not shown) and then enters the fuel channels that are connected to the tubesheet at the bottom of the inlet plenum. Inlet conditions are specified to be subcritical at a pressure of 25 MPa and a temperature of 350ºC. Coolant is directed to the lower end of the fuel assembly through a central channel, and acts as moderator on its passage downward. The flow direction reverses, and the coolant is forced vertically upwards through the fuel, where it gradually becomes supercritical with the energy released by nuclear fission. Supercritical water from the individual channels are collected in the outlet header at a targeted average value of 625ºC temperature, and is discharged from the reactor through one of four outlet pipes. This temperature is chosen specifically to match the planned ultra-SCW turbines in coal power plants. A direct-steam cycle is used with a cycle efficiency approaching 48%.

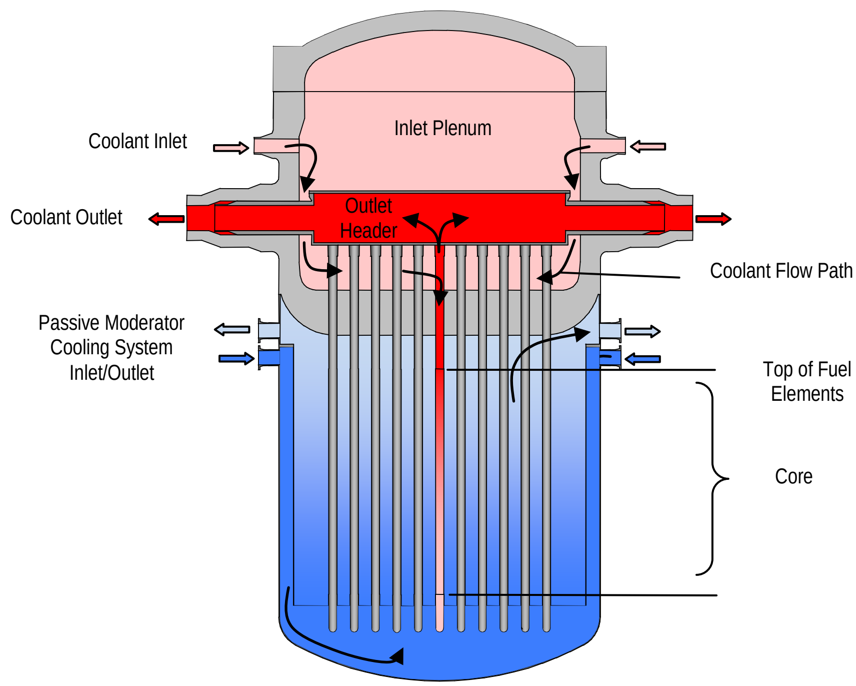


Figure 1 Schematic View of Canadian SCWR Reactor

2. Containment and Shield Building

The Canadian SCWR reactor building comprises an inner containment building and outer shield building, designed to provide defence-in-depth against the release of radioactive materials to the environment.

The containment building is a cylindrical structure 25 m internal diameter × 32 m height, and houses the reactor, high activity components and systems as well as the containment pool. It is designed to withstand an elevated internal pressure and is the primary defence against accidental releases from postulated major accident scenarios such as core breach and calandria failure.

For the purpose of this paper, all elevations quoted are relative to the reactor core, with elevation ‘0’ being the top of the fuel, allowing for a simple correlation between the various components and the reactor core. The reactor is centrally located within the containment building, with the top of the core located 15.0 m above the base mat. The containment building incorporates four major levels located at elevations -15.0 m, -7.0 m, +1.35 m and +6.15 m. A cross section of the containment building is included as Figure 2.

The containment building is divided into three pressure zones, based on the conditions likely to be found under accident conditions. The first is the steam tunnel and containment pool zone, occupying the space above elevation +1.35, with the exception of the drywell area, located immediately above the reactor. The steam tunnel is located at the height of the inlet plenum, and houses the high pressure coolant piping. The containment pool floor is located at elevation +6.15 m, and includes the containment steam condenser gallery. This zone would see the highest temperatures and moisture levels in the event of a LOCA, and would be subjected to flooding under emergency coolant injection.

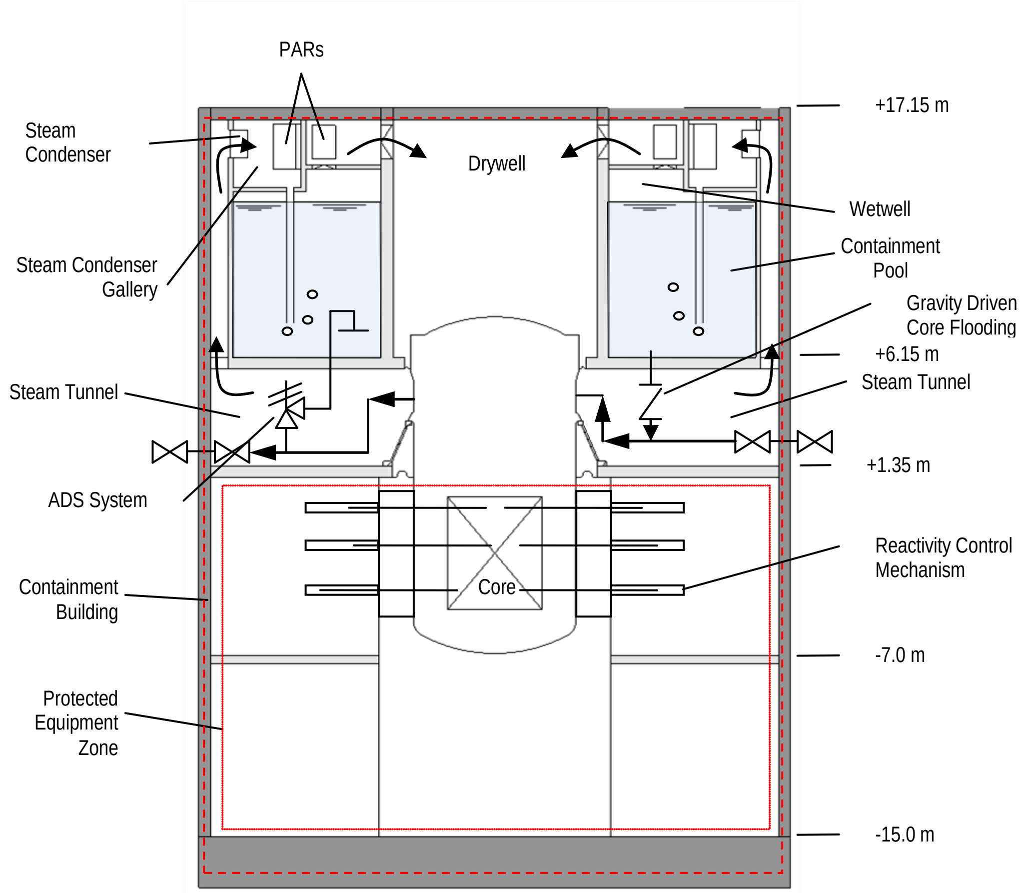


Figure 2 Canadian SCWR containment building (cross–section)

The second pressure zone is the drywell and fuel transfer pool, located above the reactor, and separated from the steam tunnel by rupture panels. During normal reactor operation, the drywell area is drained of water and, during an accident, serves as a lower pressure zone to drive steam flow from the steam tunnel through the containment pool.

The third pressure zone consists of the two levels below elevation +1.35 m, and would remain dry in the event of a LOCA or coolant leak. This is to ensure that critical equipment such as the reactivity control mechanism remains functional in case of an accident.

A flexible metallic seal, sealing the annular gap between the steam tunnel floor (elevation +1.35 m) and the reactor prevents coolant and steam from entering the lower containment building zones. Likewise, a seal between the steam tunnel ceiling (elevation +6.15 m) and the reactor prevents steam from escaping into the drywell during a postulated LOCA. This seal also maintains the liquid level in the drywell during refuelling operations.

The shield building is a cylindrical building, with a domed top 48.0 m external diameter × 54.3 m high, protects the containment building from external threats such as missiles and severe weather, and serves as a final barrier against the release of activity to the environment. It is designed for a nominal pressure difference to the atmosphere, and sealed to limit the passage of radioactive materials. The shield building houses all lower activity processes such as the containment pool filter system, drywell and steam tunnel cooling system, and fuel transfer pool cooling system. A cross-section of the shield building is included as Figure 3.

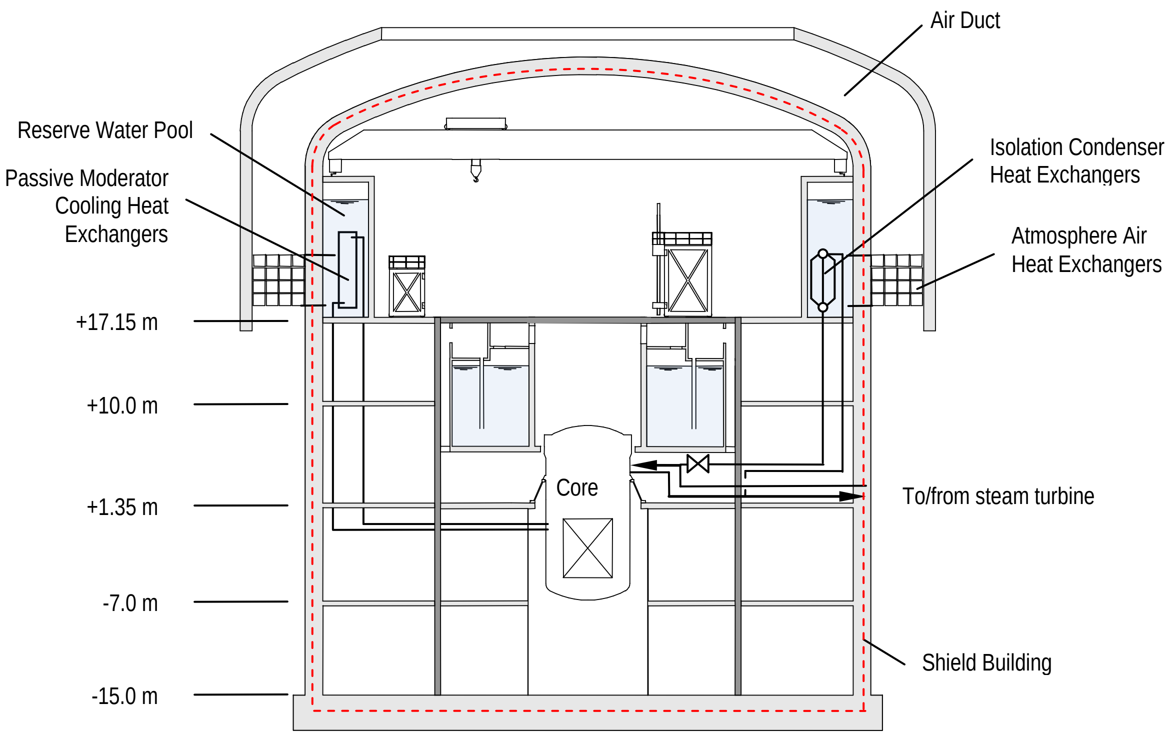
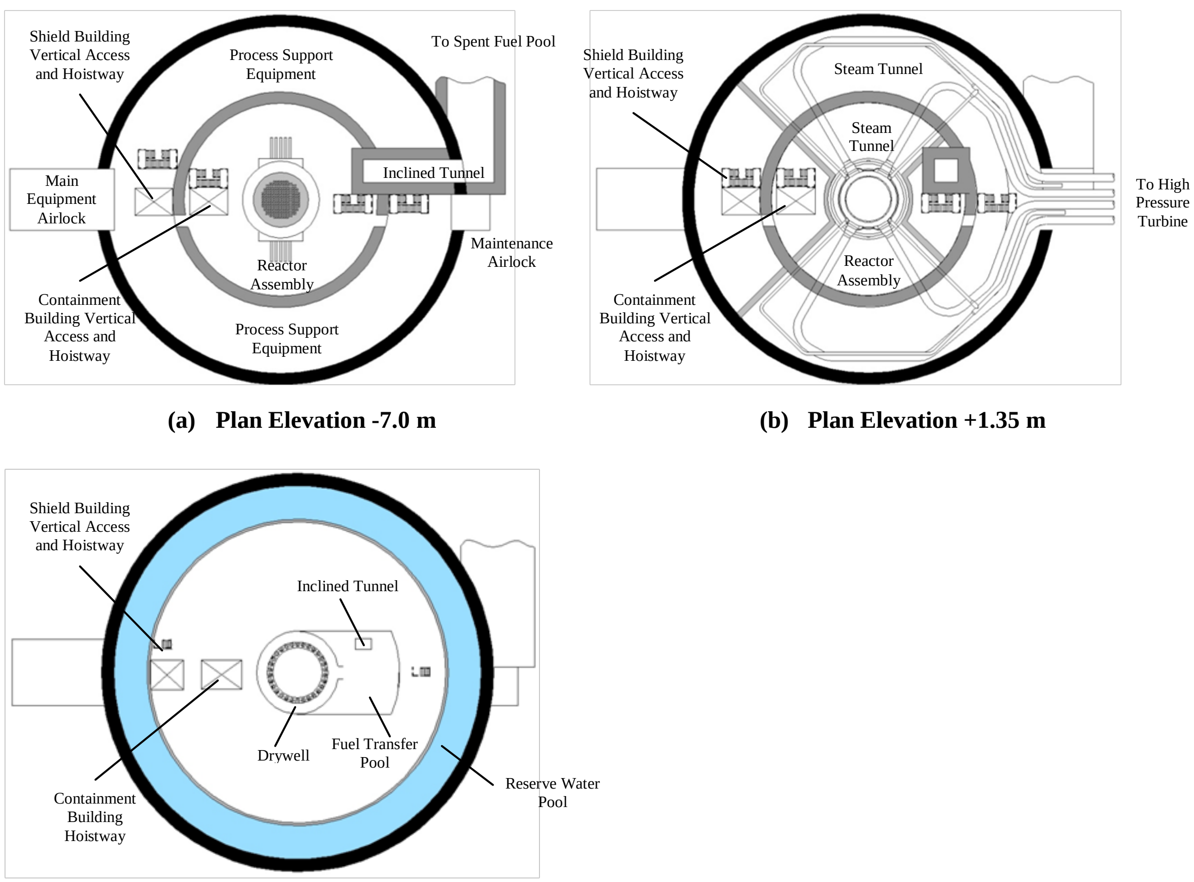


Figure 3 Canadian SCWR shield building (cross–section)

The shield building incorporates five major levels located at elevations -15.0 m, -7.0 m, +1.35 m, +10.0 m and +17.15 m. Within the shield building, the volume above elevation+17.15 m is allocated to refuelling and maintenance activities, and is served by a polar crane. As well, the major emergency water supply, in the form of the Reserve Water Pool (RWP), is located above elevation 17.15 m, and occupies an annular space at the peripheral wall. In the lower levels, the annular volume surrounding the containment building contains process support equipment. The -7.0 m elevation floor is nominally at grade elevation.

The steam and feedwater piping within the shield building are enclosed in a piping tunnel which is sealed from the shield building. This tunnel extends into the high pressure steam turbine containment building, and can be considered an extension of the turbine building rather than part of the shield building. In a postulated stream line break in this area, the reactor is to be isolated by means of isolation valves at the containment building boundary, preventing excessive steam build-up within the turbine building.

A key practical feature is access and equipment removal routes for life cycle management. For this, vertical access is provided through two volumes located at opposite quadrants within the building. A grade level (elevation -7.0 m) main equipment airlock is communicates directly with one of these vertical volumes, with a personnel access airlock on the opposite side. Included as Figure 4 are a series of floor plans at various elevations within the reactor building.



(a) Plan Elevation -7.0 m

(b) Plan Elevation +1.35 m

(c) Plan Elevation 17.15 m

Figure 4 Reactor building floor plans at various elevations

Refuelling the Canadian SCWR is through a batch process, with a fuelling machine located at elevation +17.15 m. A fuel transfer pool equipped with an inclined transfer tunnel is located to one side of the drywell allowing fuel to be temporarily stored as the fuel shuffling occurs. During normal reactor operation, the drywell and fuel transfer pool are drained. The polar crane is used to remove the drywell hatch, reactor lid and outlet header lid.

3. Safety Systems

3.1 Containment Pool

The containment pool's primary function is to provide a volume of water into which steam flow from pressure relief valves and large scale LOCAs can be suppressed. As well, it provides a gravity driven water flow to the reactor inlet plenum to replace inventory lost during a LOCA and subsequent decay heat boil-off. This pool contains 2,000 m^3 light water, consists of an annular shaped tank, and is located in the containment building above elevation + 6.15 m. The liquid level during normal operating conditions is at elevation + 13.0 m giving a pool depth of 6.85 m. The pool is to be divided in two sections, to reflect the bilateral symmetry of the reactor and safety systems, each half functioning independently of the other.

Located above the liquid level within the pool is the containment steam condenser gallery, which houses containment steam condenser heat exchangers and PAR units. Physically, the condenser gallery is an annular shaped, enclosed area, with a series of openings located on the outer wall. This outer wall forms a separation between the steam tunnel and condenser gallery. Located within these openings are the containment steam condenser heat exchangers, placed to allow condensed steam to drain directly within the condenser gallery. The condenser gallery floor is equipped with a series of drains equipped with suppression nozzles, discharging into the containment pool below the liquid level.

This layout permits the containment steam condensers and containment pool to act in unison to condense steam accumulating in the steam tunnel due to a LOCA event. In a high steam flow regime found in a large-scale LOCA, the steam condensers will be overwhelmed, allowing steam to flow past these and be injected and suppressed within the containment pool via the drains. A low steam flow regime will result in the direct condensing of the steam by the heat exchangers, with the condensate draining into the containment pool.

The volume above the liquid level of the containment pool can be considered as a wetwell. In a high steam flow regime from the steam tunnel to containment pool, air and gases may be entrained, and deposited in the wetwell above the surface of the containment pool. In order to prevent the pressure in this area from rising excessively, a series of rupture panels are located above the containment pool water line, separating the drywell space from the wetwell. These allow gases and entrained air to escape to the larger drywell space should the wetwell volume be insufficient.

The secondary side of the containment steam heat exchangers are connected to the reserve water pool, with circulation established through gravity-driven flow. The heat exchanger centerline is located at elevation +15.58 m. The cold leg intake is located at the reserve water pool floor, at elevation +17.15. The heat exchanger hot leg discharge is located at elevation +23.0 m. With this, heat from a LOCA event will be deposited into the reserve water pool through the containment steam condensers.

3.2 Automatic Depressurisation System

The automatic depressurization system (ADS) consists of several valves through which the reactor can be rapidly depressurized, as described in [3]. As well, the ADS system provides overpressure protection to the reactor and outlet piping. The valve banks for these will be located in the containment building steam tunnel, with the discharge flow suppressed into the containment pool.

3.3 Gravity-Driven Core Flooding System

The gravity-driven core flooding system consists of a pipe connecting the containment pool to the reactor's cold leg coolant piping. A check valve permits the reactor to operate at its design pressure, yet allow water to flow into the reactor from the containment pool under accident conditions.

In order to assure long-term decay heat removal in the event of a piping breach within the containment building steam tunnel, the volume of the containment pool exceeds that of the steam tunnel. Due to the seal between the reactor and floor at elevation +1.35, coolant will accumulate within the steam tunnel, with steam condensed and returned to the containment pool. With the steam tunnel filled with water from the containment pool, a sufficient level will remain in the containment pool to cover both the suppression nozzles and the gravity driven core flooding system inlet pipe.

3.4 Isolation Condensers

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 isolation condenser heat exchangers connect with the reactor coolant piping, and remove heat from the reactor by depositing this into the reserve water pool. The function of this is further elaborated in reference [2].

The isolation condenser system is divided into two independent trains, with each train consisting of a piping loop running from the reactor outlet, to heat exchangers located in the reserve water pool, and returning to the reactor inlet. The system is pressurized and on hot standby under normal reactor operation. A connection valve is located on the system's low point near the reactor inlet, and is closed under normal reactor operation. The closed valve disrupts the flow through the system to minimize heat loss during normal reactor operation. See Figure 5 for details.

The isolation condenser relies on the difference of densities between the IC hot leg and cold leg fluid to initiate and maintain a gravity-driven circulation. Under station blackout conditions, the reactor can be depressurized and cooled by first closing the main steam and feed-water isolation valves, followed by opening the IC connection valve. The liquid column normally trapped by the connection valve is allowed to flow into the reactor inlet. As this drains into the reactor, the isolation condenser heat exchanger tubing will be exposed to steam from the reactor outlet, allowing heat transfer to the reserve water pool. Further steam produced by the reactor due to the decay heat will sustain the circulation.

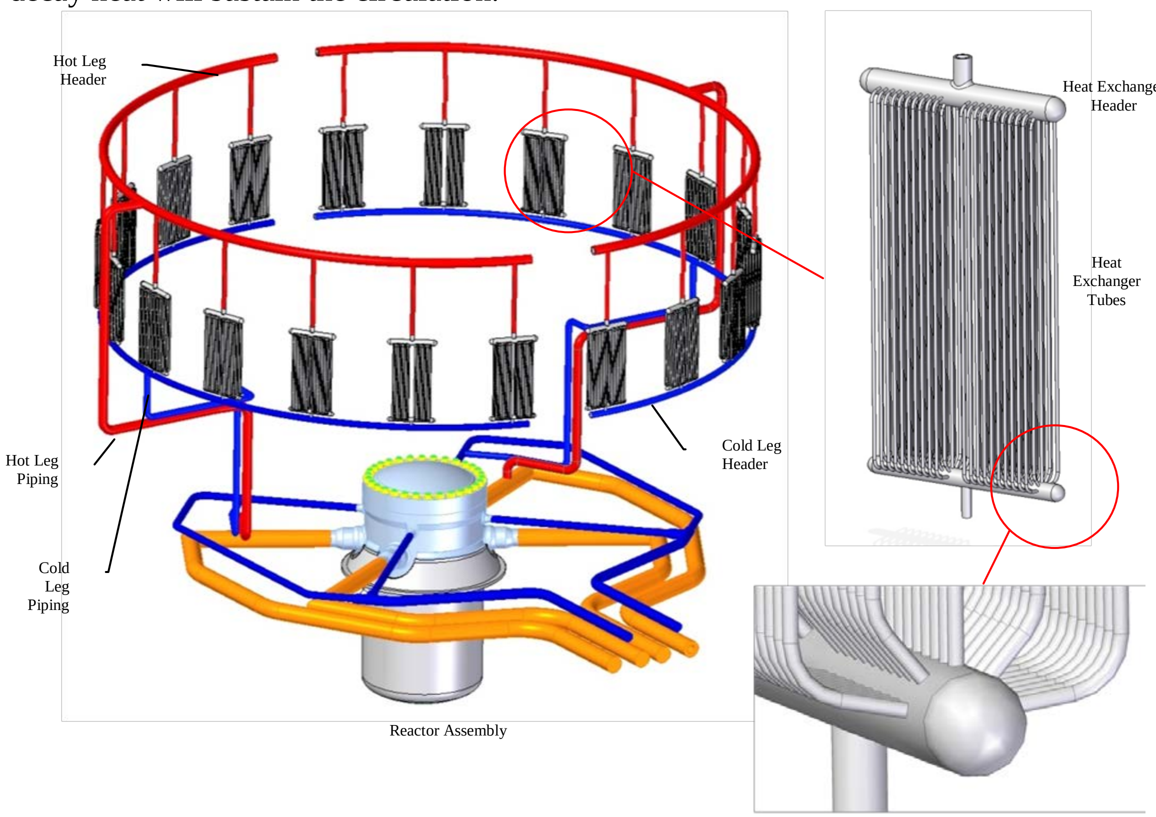


Figure 5 Isolation Condenser System

The isolation condenser hot leg piping consists of 500 mm OD × 290 mm ID piping, connecting the reactor's outlet to a header above the isolation condensers. This pipe is to be insulated, in order to maintain this at outlet condition temperatures. The lower end of the isolation condenser hot leg piping is connected to the top of the reactor outlet piping by means of a tee, creating an effective steam separator.

The centreline of the reactor outlet piping is at elevation 3.35 m (above the top of fuel), with the highest point of the system at elevation 28.15 m, giving an elevation difference of 24.8 m. Within the containment building, the isolation condenser piping is enclosed within the steam tunnel, and exits horizontally through the containment building wall at elevation 13.75 m. Within the shield building, a piping tunnel protects personnel against pipe breaks and the subsequent steam and contamination release.

A hot leg header distributes steam to the individual heat exchangers, and is placed above the reserve water pool liquid level. This allows the header to be maintained at outlet condition temperatures to reduce thermal shock following the initiation of reactor cool-down through the isolation condensers.

A total of twenty isolation condenser heat exchangers are placed in the reserve water pool, in two groups of ten. Each heat exchanger consists of 100 heat exchangers tubes, connected to headers. The tubes are fabricated from 33.4 mm OD × 20.7 mm ID tubes (1″ Schedule 160 pipe), and consist of five banks of twenty tubes, as shown in Figure 5. Average tube length is 5 m. This arrangement gives a 650 m^2 steam-side total heat exchange area and 1050 m^2 water-side total heat exchange area. The heat exchanger headers are fabricated from 320 mm OD × 190 mm ID sections, and are placed at elevation 23.0 m and 18.0 m. Refer to Figure 5 for details.

The internal volume of the individual heat exchanger is 0.6 m^3 and a combined volume of 12 m^3 for the twenty heat exchangers. This additional water inventory is available for the purpose of cooling the reactor in the event of an accident.

The isolation condenser cold leg piping size is 320 mm OD x 270 mm ID, and connects the isolation condensers to the reactor inlet piping. As noted earlier, a valve is located near the connection with the reactor inlet piping, which allows a column of condensate to accumulate within this piping during normal reactor operation. The condenser cold leg piping shares the same path from the reactor to the reserve water pool as the hot leg piping.

3.5 Reserve Water Pool

The primary function of the reserve water pool is to serve as a buffer between the various passive safety systems and the ultimate heat sink. The large mass of water available allows this to temporarily absorb heat which can be subsequently removed by the atmospheric air heat exchangers or by evaporation.

The pool is located in the upper section of the shield building, and occupies an annular space against the building's outer wall. The floor of the pool is at elevation 17.15 m, with liquid level at elevation 27.15 m, giving a pool depth of 10 m and a gross water volume of 5,000 m^3. This is divided into two sections, each section housing one train of the isolation condenser and passive moderator cooling systems.

The pool enclosure is equipped with a filtered vent to the atmosphere in order to permit the release of water vapour. As well, all heat exchange area of the isolation condenser and passive moderator heat exchangers are located below elevation 23.0 m. With this, approximately 2,100 m^3 pool water can be lost to evaporation from the pool, while still functioning as a heat sink for the isolation condensers and passive moderator cooling system. Pool levels can be remotely maintained by means of a fill line connected to an external emergency supply such as lake water or water truck.

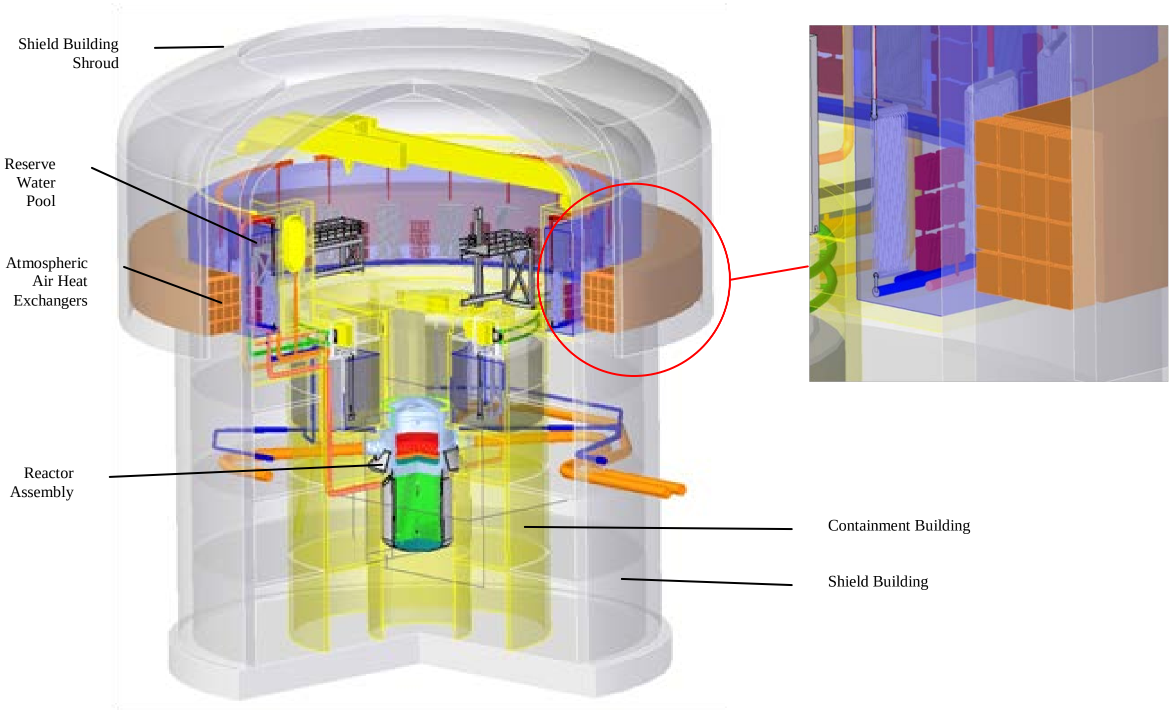


Figure 6 Cutaway View of Reactor Building

3.6 Atmospheric Air Heat Exchangers

The primary function of the atmospheric air heat exchangers is to reject heat from the reserve water pool to the atmosphere. Although not considered a safety system, the heat exchangers serve to extend the period of time in which the reserve water pool can function as a heat sink before intervention under a high core decay heat regime. At a lower core decay heat regime, the atmospheric air heat exchangers can reject the entire heat load, extending indefinitely the point of intervention.

The atmospheric air heat exchangers consist of a series of plate-type heat exchangers located on the periphery of the shield building with the plates arranged vertically and radial to the building exterior. Each element consists of a 1 m wide x 1.25 m high panel with a 5 mm water flow path thickness. The elements are placed in an array four wide and four high, thus allowing 23,200 elements to be arranged in 1,450 arrays, for a total available heat exchange area of 58,000 m^2. These are enclosed in a shroud having an inner diameter of 57 m, which forms a chimney to further increase gravity-driven air flow. Together with the 48 m outside diameter shield building, the area of the annular cross-section created by these two surfaces is 742 m^2.

In order to minimize the number of penetrations into the shield building, the heat exchangers are grouped and connected to common hot leg and cold leg headers. Valves are located on both the hot leg and cold leg headers and are closed under normal reactor operating conditions to prevent freezing in cold climates.

Under accident conditions, with the valves opened, water is drawn from the upper surface of the pool, allowed to cool in the heat exchanger, and returned to the bottom of the pool by means of a gravity-driven convection current. Similarly, cooler air is drawn through the heat exchangers from the bottom of the shroud, with the heated air escaping at the top of the shroud.

The hot leg header and penetration to the reserve water pool is located at elevation 23.0 m, with the cold leg header and penetration returning at elevation 17.5 m. This allows the continued rejection of heat through the atmospheric air coolers from the reserve water pool, provided the pool level remains above elevation 23.0 m.

3.7 Passive Moderator Cooling System (PMCS)

The passive moderator cooling system serves as an additional barrier to core damage. In an accident scenario, decay heat generated within the fuel channel flows through the channels' insulator and pressure tube, 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 passive moderator cooling system is divided into two independent trains, with each train consisting of a piping loop running from the reactor calandria to heat exchangers located in the reserve water pool, and returning to the calandria. The system is totally passive, and is allowed to function during normal reactor operation. A head tank, located above the heat exchangers, maintains a constant pressure within the system, with the liquid level nominally at elevation +25.5 m. See Figure 7 for details.

The PMCS hot leg piping consists of 324 mm OD × 315 mm ID (12″ Schedule 10) piping. The calandria outlet nozzle is located at elevation +0.80 m, and drops to elevation +0.25, level with the inlet nozzle, in order to clear structural details. Both the hot leg and cold leg distribution headers are located within the reserve water pool at elevation +17.5 m.

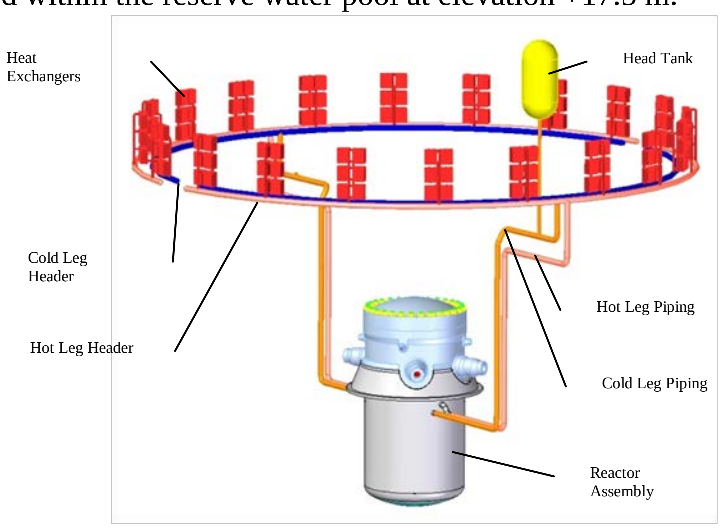


Figure 7 Passive Moderator Cooling System

4. Summary and Conclusions

The arrangement within a reactor building is a function of the requirements imposed by various systems. In the present reactor building concept, the location of the major components and safety systems relative to the core were identified. The locations of the safety systems provides sufficient elevation differences from the reactor to ensure adequate driving force for naturally-circulated emergency cooling systems. The heat flow path from the reactor to the ultimate heat sink was identified.

Maintenance access and refuelling schemes were also identified. The key design goal of defence-in-depth was met through a double containment system provided by the reactor building design. Additional space within the reactor building was identified for process support equipment.

Future work will consider the design and configuration of the reactor start-up system, the shut-down system, the shield building vent filters and will lay out the major process equipment supporting these systems within the reactor building.

5. References

[1] M. Yetisir, M. Gaudet, D. Rhodes, “Development and Integration of Canadian SCWR Concept with Counter-Flow Fuel Assembly,” Proceedings of The 6th International Symposium of Supercritical Water-Cooled Reactors, ISSCWR-6, Shenzhen, Guangdong, China, 2013 March.

[2] X. Huang, M. Gaudet, M. Yetisir, D.F. Wang, S. Wang, “Analysis of a Passive Residual Heat Removal System for the Canadian Supercritical Water-Cooled Reactor”, 2014 Canada-China Conference on Advanced Reactor Development (CCCARD-2014-019), Niagara Falls, Ontario, 2014 April.

[3] D. Novog, G. McGee, D. Rhodes, M. Yetisir, “Safety Concepts and Systems of the Canadian SCWR,” The 3rd China-Canada Joint Workshop on Supercritical Water-Cooled Reactors (CCSC-2012), Xi’an, Shaanxi, China, 2012 April.