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PASSIVE HEAT REMOVAL IN CANDU

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Abstract

CANDU has a tradition of incorporating passive systems and passive components whenever they are shown to offer performance that is equal to or better than that of active systems, and to be economic. Examples include the two independent shutdown systems that employ gravity and stored energy respectively, the dousing subsystem of the CANDU 6 containment system, and the ability of the moderator to cool the fuel in the event that all coolant is lost from the fuel channels.

CANDU 9 continues this tradition, incorporating a reserve water system (RWS) that increases the inventory of water in the reactor building and provides a passive source of makeup water and/or heat sinks to various key process systems.

The key component of the CANDU 9 reserve water system is a large (2500 cubic metres) water tank located at a high elevation in the reactor building. The reserve water system, while incorporating the recovery system functions, and the non-dousing functions of the dousing tank in CANDU 6, embraces other key systems to significantly extend the passive makeup/heat sink capability.

The capabilities of the reserve water system include makeup to the steam generators secondary side if all other sources of water are lost; makeup to the heat transport system in the event of a leak in excess of the D_2O makeup system capability; makeup to the moderator in the event of a moderator leak when the moderator heat sink is required; makeup to the emergency core cooling (ECC) system to assure NPSH to the ECC pumps during a loss of coolant accident (LOCA), and provision of a passive heat sink for the shield cooling system.

Other passive designs are now being developed by AECL. These will be incorporated in future CANDU plants when their performance has been fully proven.

This paper reviews the passive heat removal systems and features of current CANDU plants and the CANDU 9, and briefly reviews some of the passive heat removal concepts now being developed.

1. BACKGROUND

AECL has traditionally incorporated passive features and systems into CANDU plant designs whenever such systems were shown to economically and reliably meet all of the system requirements. An example, a passive feature relied upon during normal plant operation, is the ability of the reactor coolant to cool the fuel via natural circulation on the loss of power to the heat transport system (reactor coolant system) pumps and the inclusion of sufficient rotational inertia in the heat transport system pump motor assemblies to assure fuel cooling during reactor power and pump rundown. The heat transport system arrangement also caters to other design basis events, for example the `figure-of-eight' HTS arrangement, with reactor coolant pumps in series, caters to postulated pump seizure events.

The use of passive features and systems and concepts extends to the special safety systems in CANDU plants. For example, two passive, fully capable shutdown systems (one driven by gravity and the other by stored energy) are incorporated. Other examples include the gravity dousing system for post-LOCA reactor building pressure suppression in CANDU 6, and the vacuum building containment system employed in multi-unit Ontario Hydro stations.

The ability to assure fuel cooling under a range of design basis and beyond design basis events has received particular attention in CANDU plants. These systems which remove decay power from the fuel by passive mechanisms, or which provide makeup to cooling systems by passive mechanisms, are the focus of this paper. The provisions incorporated in operating CANDU plants are reviewed, followed by a brief review of the enhancements incorporated in CANDU 9, and a discussion of new features that are under development, and which may be incorporated in future plants.

2. THE MODERATOR HEAT SINK

2.1 Reactor and Heat Transport System Configuration

CANDU is a horizontal pressure-tube reactor, with the fuel bundles located inside several hundred 10.5-cm diameter, 0.48 cm thick pressure tubes (Figure 1). Twelve 0.5 m-long fuel bundles reside within each pressure tube. The 37-element fuel bundle is in close proximity to the pressure tube, separated from it by means of 1.1-mm high bearing pads on the outer fuel elements. The heavy water coolant flows over and through the fuel bundles and is contained by the pressure tubes within the core.

The pressure tube operates at approximately the coolant temperature (300°C), and is thermally insulated, during normal operation, from the heavy water moderator (70°C) by the carbon dioxide filled annulus formed between the concentric pressure tubes and calandria tubes. The calandria tube forms the outer boundary between the gas and the moderator (Figure 2). The assembly of fuel, pressure tube, gas annulus and calandria tube is collectively called the fuel channel. The total radial distance between the fuel and the moderator is 1.5 cm.

The moderator is contained within a low pressure tank, called the calandria. During normal operation, about 4.4% of the thermal output of the core is deposited in the moderator, a small amount by conduction from the channels, but mostly by direct deposition of fission gamma rays. This heat is removed via dedicated external circuit that includes heat exchangers and pumps; the pumps circulate the moderator D_2O through the heat exchangers and provides momentum to assist the mixing of the moderator within the calandria (see Figure 1). They are powered by normal Class IV electrical power, backed up by Class III emergency diesel power when required.

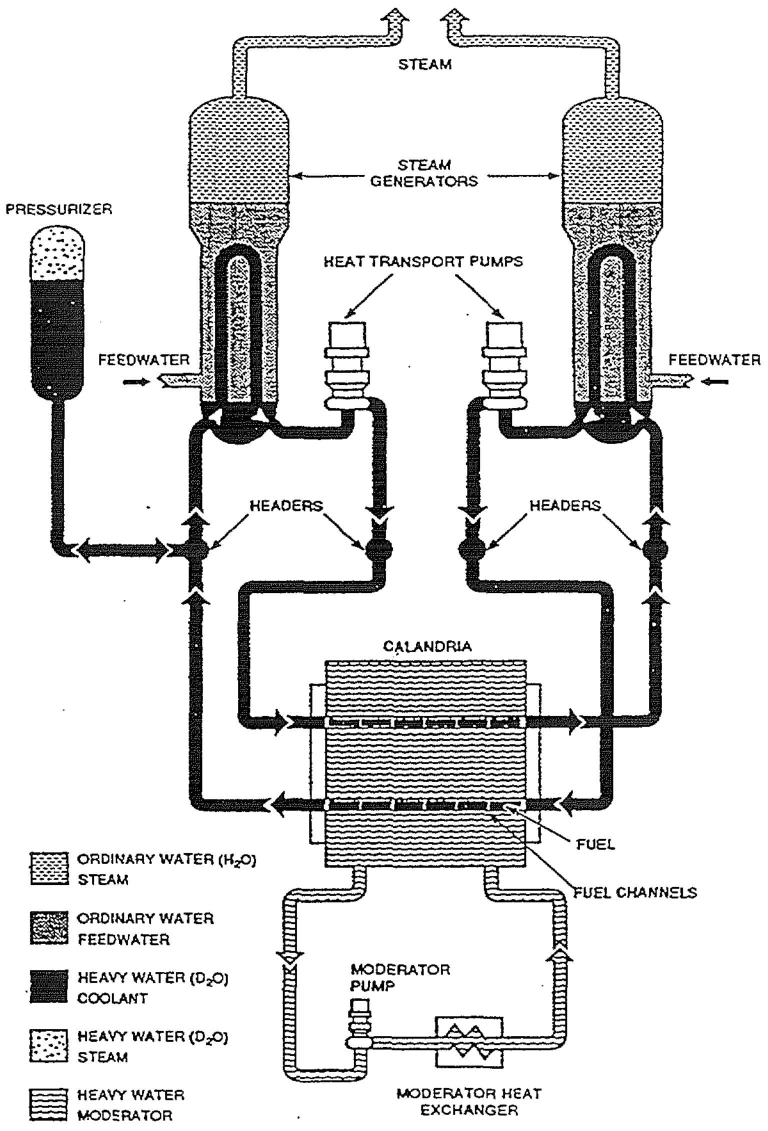


FIGURE 1: The CANDU Nuclear Steam Supply System

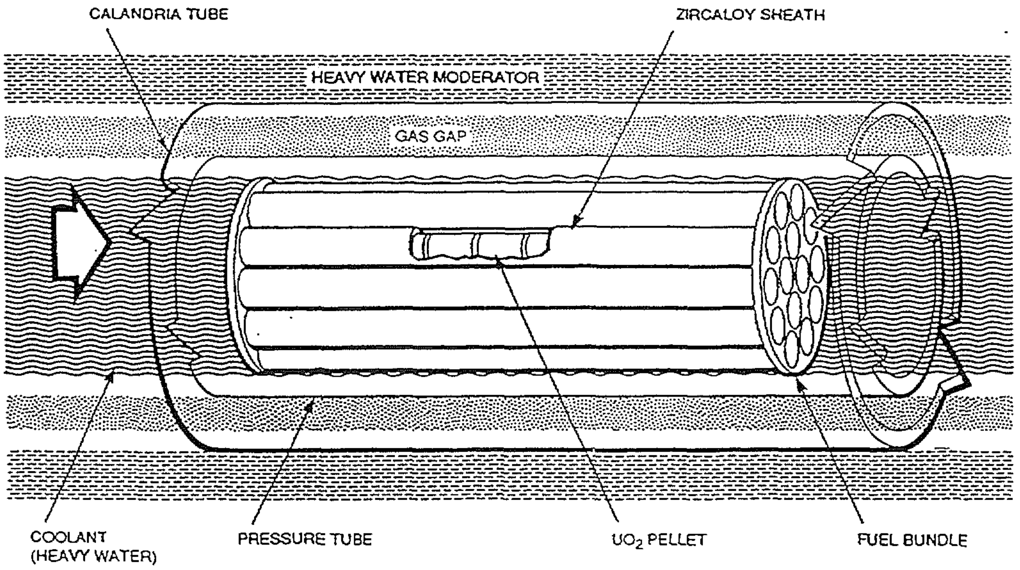


FIGURE 2: Separation of Coolant and Moderator

All large pipes in the CANDU Reactor Coolant System (RCS) are above the core. They consist of headers, or collectors, to which each channel is connected via a 6-cm to 8-cm diameter inlet and outlet feeder pipe; plus pump suction and discharge piping and steam generator inlet and outlet piping. A large break in one of these pipes would cause rapid voiding of the pressure tubes. As with other water-reactor designs, the emergency core cooling system (ECC) provides high-pressure injection of water to refill the core. In CANDU ECC water is supplied to all the reactor headers (see Figure 1).

2.2 The Moderator as an Emergency Heat Sink

The moderator system heat removal capability is enough to continuously remove all fuel decay heat 15 seconds after reactor shutdown. The moderator specific volume is typically 8 litres/kW(th) at 1% decay power, or enough to absorb (through heat-up and boil-off) over 5 hours of decay heat from the fuel, assuming no heat removal from the moderator D_2O.

A post-LOCA failure of ECC in light-water reactors, will, if uncorrected, lead to a meltdown of the core. In CANDU, a loss of coolant with a failure of ECC will be arrested by the transfer of heat from the fuel to the moderator short of UO_2 melting. The mechanism is as follows:

The fuel will heat up due to decay power, since no heat is being removed by the RCS. Since the pressure-tube is close by, it will also heat up, by conduction and radiation from the fuel, and convection by the steam remaining in the channel. At about 800^oC, the pressure tube will start to plastically deform under the loads from the weight of the fuel and any residual coolant pressure. If the coolant pressure is high (for example, for medium-sized breaks with failure of ECC), typically above 1 MPa, the pressure tube will strain radially outward until it contacts the cool calandria tube (Figure 3). If the pressure is below 1 MPa, the pressure tube will preferentially sag, until again it contacts the cool calandria tube. As long as the calandria tube remains cool, it is strong enough to arrest the deformation of the pressure tube. Heat can then be removed from the fuel, by conduction and radiation to the pressure tube and calandria tube, and then by convection to the bulk moderator. From there it is removed by the moderator cooling system. The pressure-tube thus acts as a passive fuse, deforming only when it overheats in an accident, and so creating a low-resistance heat transfer path to the moderator. This path can remove decay heat from the fuel without the UO_2 melting even with no coolant in the pressure-tube. This is due to the short physical distance from the fuel to the pressure-tube, the relatively thin walls of the pressure-tube and calandria tube, and the enhanced heat transfer through the two tubes when they touch.

The calandria tube can be kept cold by preventing dryout on the outside surface at the time of pressure-tube contact. The surface heat flux at contact is determined by the pressure-tube temperature, the interface heat transfer coefficient and the moderator subcooling. The former cannot practically be controlled, but the latter two can. For existing CANDU reactors, a moderator temperature of about 70°C is sufficient to prevent calandria tube dryout.

The pressure-tube "fuse" is sensitive to moderator temperature, but NOT to active moderator heat removal - it is truly passive. However the moderator pumps and heat exchangers are used to bring the severe accident to a controlled steady-state.

Measures are taken to assure that the pressure tube does not fail before it reaches the calandria tube. Although such failure would not prevent the moderator from performing its emergency role, the sequence is less complex if the pressure tube remains intact. Pressure tube integrity depends on the pressure at which the pressure-tube strains - the higher the pressure, the more sensitive is the strain to non-uniformities in pressure tube temperature, and the higher the chance of failure before contact with the calandria tube. The pressure parameter varies slightly with the design of the RCS (HTS).

Another severe accident results from assuming *all* heat sinks for the RCS are lost. This is an unlikely sequence because the following systems are each capable of removing decay heat from an intact RCS:

- the main feedwater system
- the auxiliary feedwater system
- the shutdown cooling system (which can be brought in at full RCS temperature and pressure)
- the Group II emergency feedwater system (this is a separate means of adding water to the steam generators, taking its supplies from a separate seismically qualified source and using independent seismically-qualified power)
- a gravity supply of water to the steam generator from the high level dousing or reserve water tanks

If however they are all lost, the RCS will pressurize and the fluid will gradually be lost through the relief valves, and the fuel will overheat. Since this sequence occurs at or above operating pressure, typically 10 MPa, the overheated pressure tubes will start to

- Close isolation valves on the suction line from the dousing tank.
- Open cooling water valves to the ECC heat Exchangers.

2. 3 Performance

The CANDU 6 ECC system, through the provision of appropriate redundancy, meets all the requirements set for the system. The system, however, incurs relatively high capital and maintenance costs. Since the system does not operate during normal reactor operation, regular on-power testing must be performed to meet the unavailability target of 10^{-3}. A complete system operation cannot be tested on-power, therefore, a series of overlapping tests, generally on a monthly basis, are conducted to check sub-system operation, including valve operation. This increases operating cost. The incentive to reduce the above costs prompted the studies into ECC simplification.

3. THE CANDU 9 EMERGENCY CORE COOLING SYSTEM

The CANDU 9 ECC system utilizes the same high pressure, gas-driven water tank concept employed on the CANDU 6, Bruce and CANDU 3 power plants. However, the design is modified to significantly reduce the number of valves and achieve other system simplifications. A simplified flow diagram of the CANDU 9 ECC system is shown in Figure 2.

The principal improvements and simplifications made in the CANDU 9 ECC system include the following:

- Replacement of D_2O isolation valves with one-way rupture discs.
- Elimination of high pressure injection and test valves and incorporation of a floating ball seal in the water tanks.
- Location of additional ECC components inside the reactor building.
- Elimination of the ECC system medium pressure stage.

Each of these modifications is described in more detail below.

3.1 Replacement of D_2O Isolation Valves with One-Way Rupture Discs

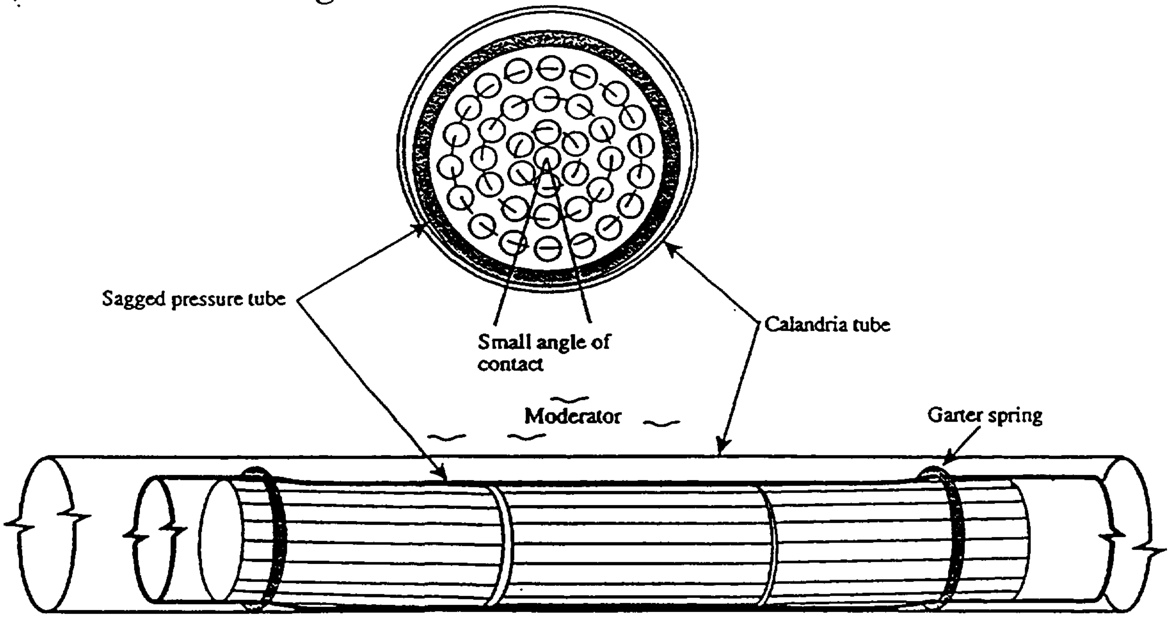
In the current CANDU 6 reactors, normally closed D_2O isolation valves are provided at the interface of the ECC system and the heat transport system. Low pressure rupture discs upstream of the D_2O isolation valves provide separation of light water and D_2O. The D_2O isolation valves isolate the high pressure heat fail before they contact their respective calandria tubes. The higher powered channels will fail first, and the pressure tubes will relieve the rest of the RCS fluid. This will reduce the RCS pressure and allow the moderator to act as an emergency heat sink as described above.

The pressure-tube/calandria-tube heat transfer has been fine-tuned. First, to reduce the sensitivity to initial moderator subcooling: When the two tubes contact in an accident, the stored heat in the pressure tube is transferred in a "pulse" through the calandria tube. To reduce the magnitude of this pulse, which sets the margin to CHF of the calandria tube, the inner surface of the latter has been roughened slightly (50 micron ridges). This "smears out" the heat transfer over a longer period of time and reduces the peak inter-tube heat flux. Second, to enhance the heat transfer after sag contact, and so to reduce the quasi-steady-state fuel temperatures, the inside of the calandria tube has been blackened.

3.2 SHIELD TANK AS HEAT SINK FOR THE CALANDRIA

The AECB requires that all combinations of a reactor system failure *and* the unavailability of a safety system be evaluated as design bases events - for example, the previous example of a large LOCA and failure of ECC injection. **Severe accidents** within this set, i.e., those for which the fuel heat is not removed by the RCS, result in damaged fuel, but do not lead to loss of pressure-tube geometry. Accidents which

a) Pressure Tube Sag



b) Pressure Tube Ballooning

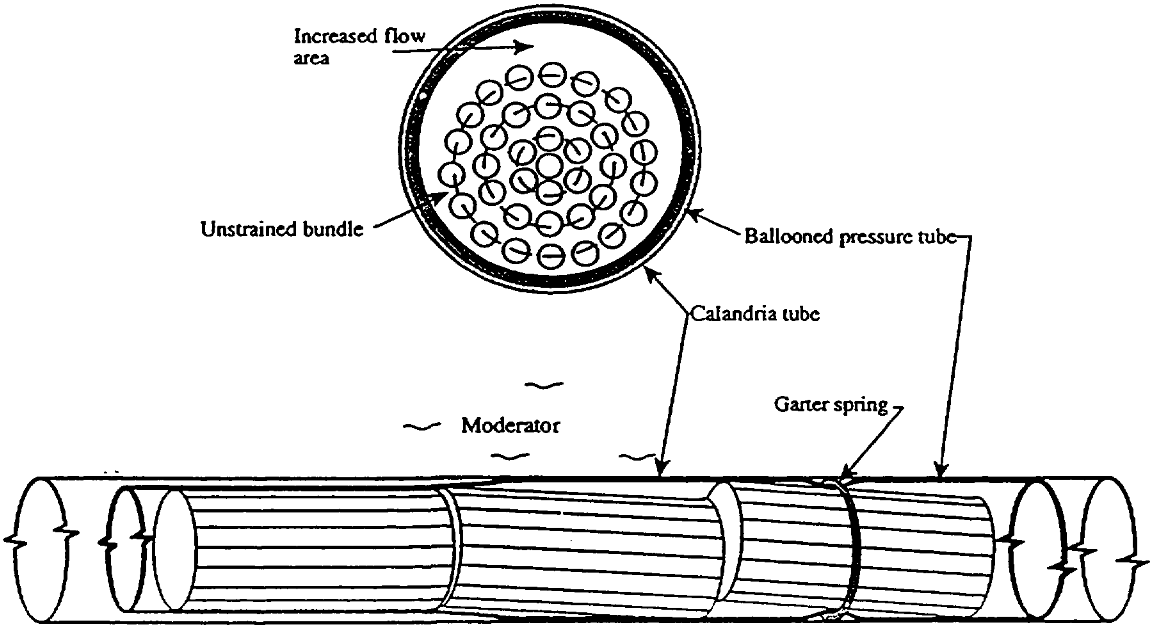


FIGURE 3: Pressure Tube Deformation Modes During a Postulated Loss-of-coolant Accident: a) Sagging, b) Ballooning

combine yet further failures are generally outside the design basis. They may result in loss of core geometry, in which case they are called **severe core damage** accidents. The two types of accidents are usually synonymous in other reactor types, but because the moderator can arrest severe accidents before the core geometry is lost, in CANDU they are distinct.

Severe core damage accidents in CANDU include sequences such as:

- loss of all feedwater and loss of cooling to all alternate heat sinks including the moderator

- loss of coolant, loss of ECC injection, and loss of moderator cooling.

The frequencies of such combinations are of the order of 10^{-7}/year, and are thus not within the scope of licensing analysis. They are, however, examined in the context of Probabilistic Risk Assessment. Because of the low frequency, the emphasis has been on scoping calculations rather than extensive experimental verification of detailed codes.

The calandria is contained within a shield tank, which provides biological shielding during normal operation and maintenance (Figure 4). It is a large steel or concrete tank filled with ordinary water. During normal operation, about 0.4% of the thermal output of the core is deposited in the shield tank and end shields, through conduction from the calandria structure and fission heating. This heat is removed via the end shield cooling system, consisting of pumps and heat exchangers.

The shield tank's role as an emergency heat sink for the fuel in a severe core damage accident is discussed below. In this role, its active heat removal capability is enough to continuously remove all fuel decay heat a few days after reactor shutdown. The shield tank specific volume is typically 16 litres/kW(th) at 1% decay power, or enough to absorb (through heat-up and boil-off) more then ten hours of decay heat from the fuel, assuming no heat removal from the shield tank water.

For such sequences, the moderator water will heat up and boil off. This will take some hours, during which time the pressure tubes will start to fail and the debris will collect in the bottom of the calandria. As long as there is water in the shield tank, the calandria shell will remain intact; the heat generated by the debris is less than the critical heat flux on the outer surface of the calandria. However, the shield tank heat removal rate is insufficient to keep up with the decay power until a few days have passed, so the shield tank water will boil off and the calandria shell will be penetrated. Nonetheless, the heat-up and boil-off of the moderator and shield tank buys valuable time, about 24 hours, so that accident management can be put into effect before the debris even reaches the concrete floor of the containment.

To ensure that steam is relieved from the shield tank without overpressurizing the vessel, engineered relief paths have been provided on the newer designs, sized to take the steam flow generated by decay heat removal.

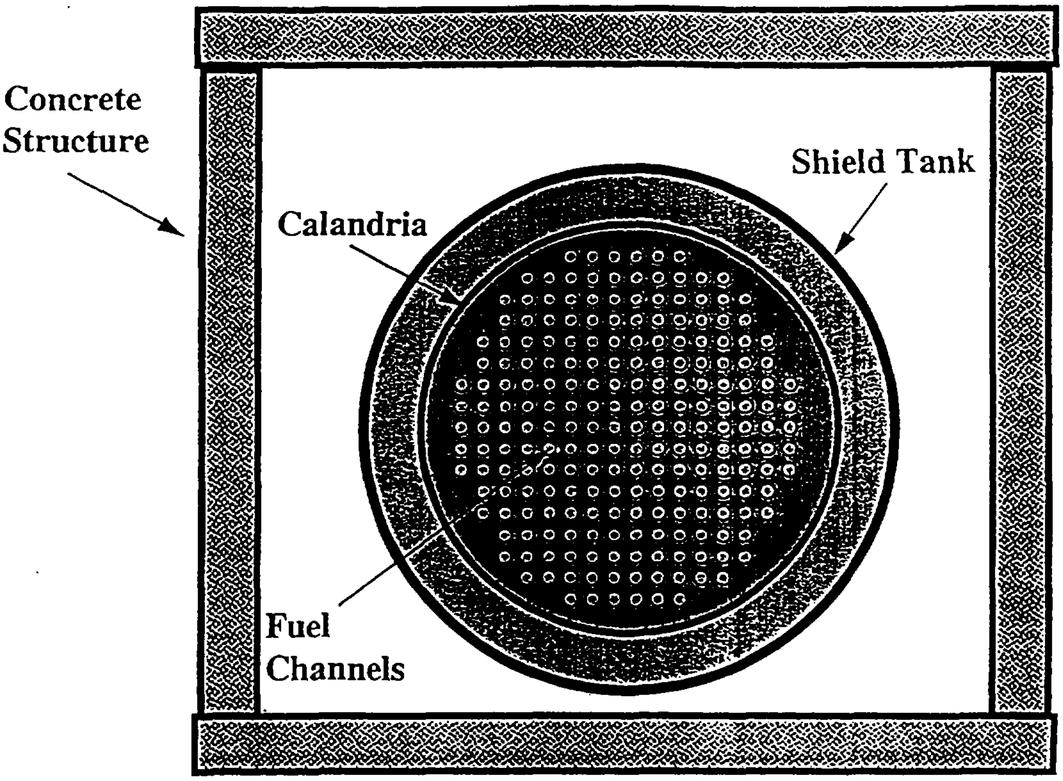


FIGURE 4: The Calandria - Shield Tank Arrangement

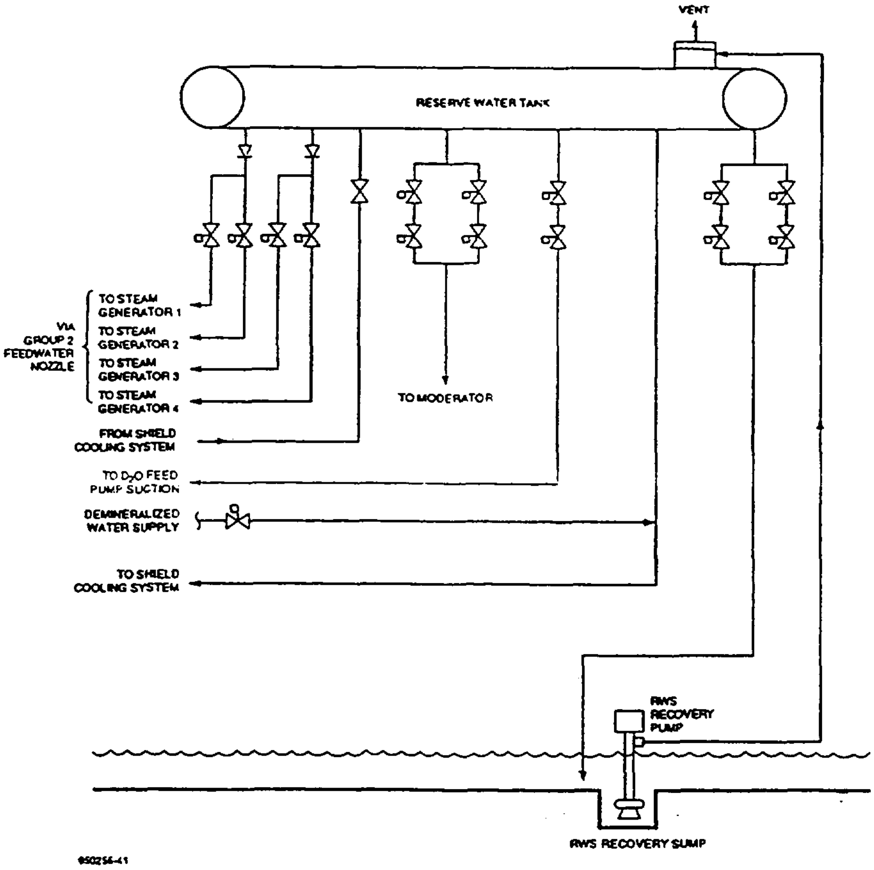


FIGURE 5: The CANDU 9 Reserve Water System

4. CANDU 9 ENHANCEMENTS TO IMPROVE PASSIVE HEAT SINKS

4.1 Moderator and Shield Tank Cooling Enhancements

Based on the previous descriptions, it is obvious how to extend the passive heat sinks provided by the moderator and the shield tank - simply add water. The advanced evolutionary CANDU 9 has done just that. An elevated reserve (Figure 5) water storage tank in containment provides emergency makeup water to the moderator and permits passive heat removal by thermosyphoning from the shield tank (Figure 6). The amount of water is sufficient for more than 40 hours of decay heat removal. During or after that time, a recovery pump collects water from the reactor building sumps and returns it to the reserve water tank. The heat is removed from containment through a combination of passive conduction through the reactor building walls and actively by containment air coolers

4.2 Provisions for HTS, Steam Generator and ECC System Makeup

The CANDU 9 also utilizes the reserve water tank to provide a gravity supply of makeup water to the steam generators, the ECC system, and to the heat transport system (Figure 5). The first two functions are conceptually similar to functions provided by the dousing tank of CANDU 6. Water can be fed from the reserve water tank to the secondary side of the steam generators to maintain the steam generator heat sink in the event that both Group 1 and Group 2 feedwater is lost.

Water is also fed from the reserve water tank to flood the reactor building floor on a loss of coolant accident (LOCA) signal to temper the D_2O from the break and provide net positive suction head to the ECC system pumps. In addition, CANDU 9 provides a connection from the reserve water tank to the D_2O feed pumps, which can be utilized to feed water to the heat transport system in the event of a very small LOCA.

The piping connection to the serve water tank assures that inventory is maintained in the reserve water tank to fulfill the various functions noted.

5. THE NEXT STEPS

A number of systems with passive features, generally extending the use of the CANDU 9 reserve water tank, are under development and evaluation. These are discussed in the following sub-sections.

5.1 Passive Moderator Cooling

A conceptual arrangement for passive moderator cooling upon the loss of the normal heat exchanger and/or pumps is shown in Figure 7. The moderator system circulates heavy water through the calandria to remove the nuclear heat generated in the moderator, and the heat transferred to the moderator from the fuel channels.

During normal operation the moderator pumps draw D_2O from the top of the calandria via the moderator heat exchanger. In the event that the moderator system pumps and/or heat exchangers are lost, the reactor is shut down, and flashing in the riser (see Figure 7) initiates natural convection circulation of the moderator. In this

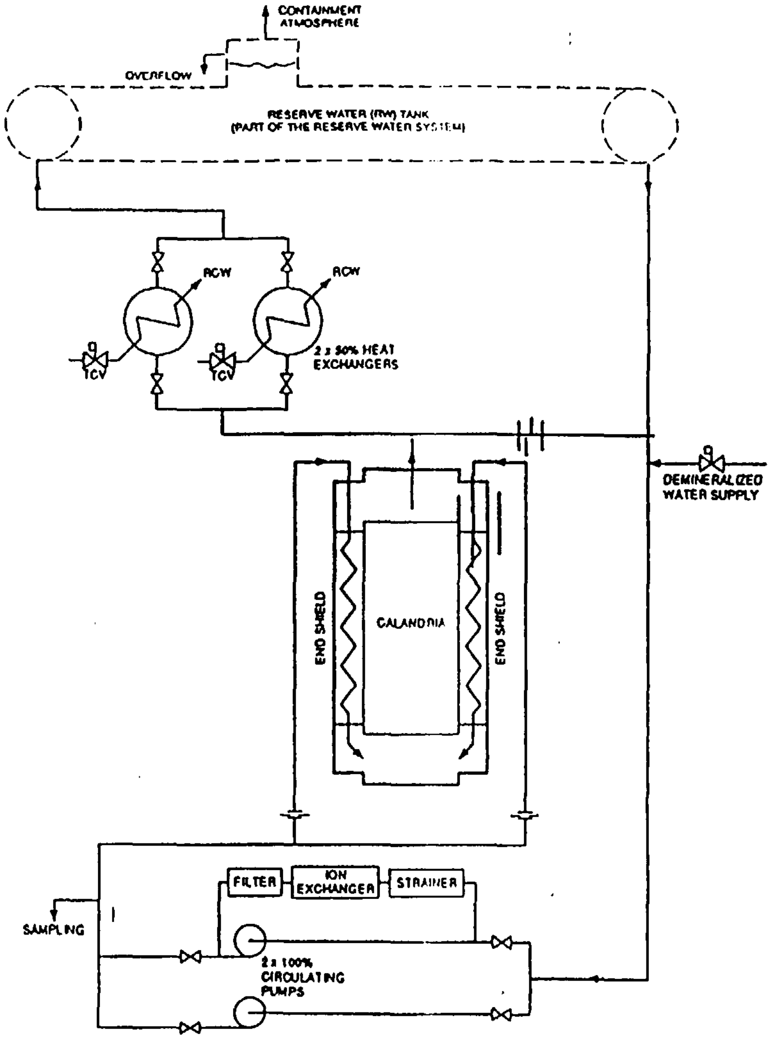


FIGURE 6: Passive Shield Cooling System

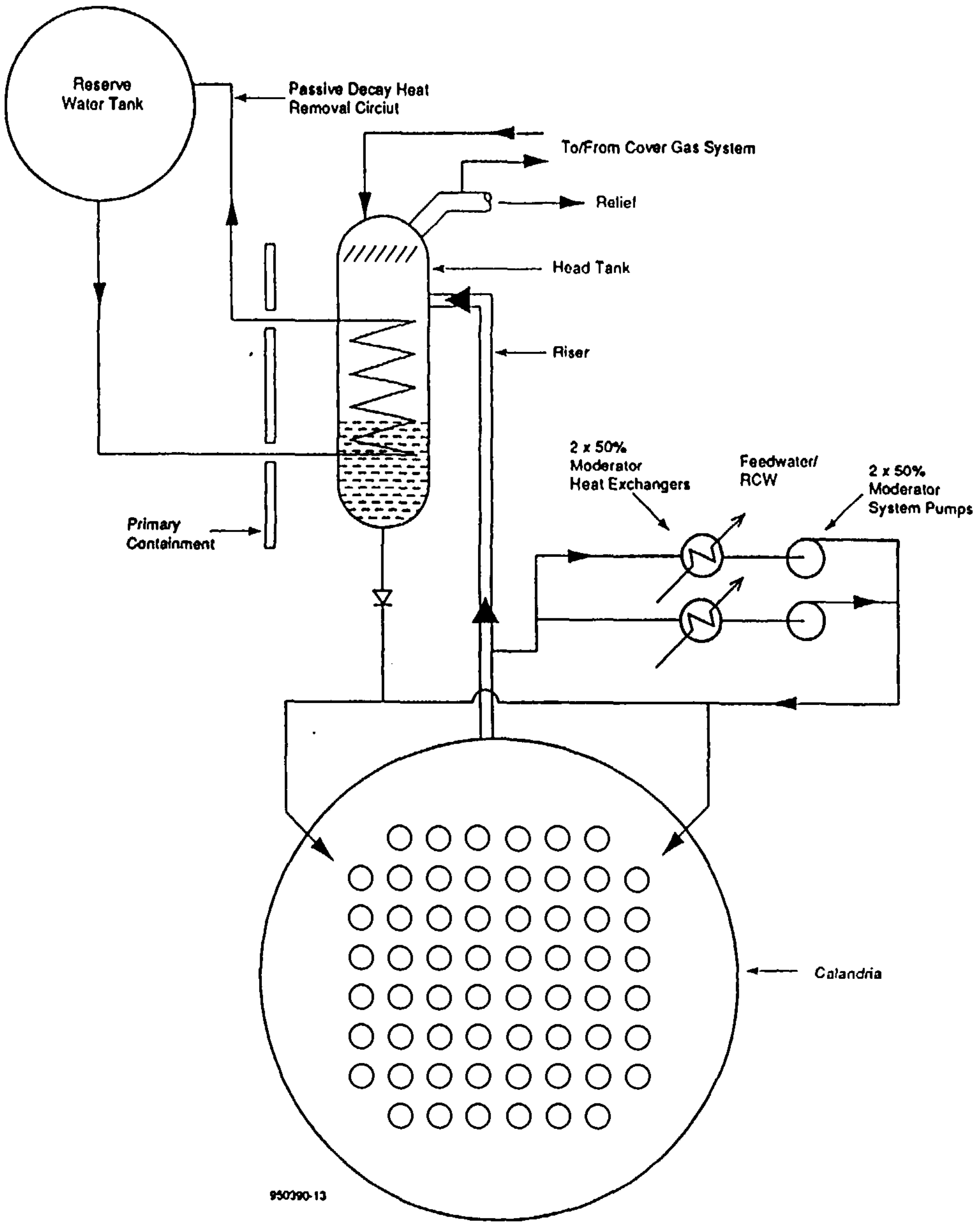


FIGURE 7: Passive Moderator Cooling System

mode, heat is rejected to the water in the reserve water tank via natural convection. The capacity of this mode of moderator cooling is sufficient to remove decay power under conditions of coincident loss of coolant and loss of emergency core cooling, without makeup or cooling being provided to the reserve tank for a period of 72 hours.

Testing is complete at AECL's Chalk River Laboratories on a full height / 1/60 diameter scale rig to evaluate the natural circulation mechanism. Work is now underway to assess the effect of D_2 and O_2 produced by radiolysis of the moderator on natural circulation during normal full power operation. The hope is to utilize natural circulation during both normal and upset conditions, thereby further reducing system cost.

Initiation of moderator cooling via the head tank cooling coil/reserve water tank is totally passive. No operator or control action is required.

5.2 Passive Steam Generator Heat Removal

The steam reject system being evaluated, shown in Figure 8 includes a reject condenser, connected to each steam generator.

When water level in the steam generator is within the specified operating range, the condensing coil in the reject condenser is filled with water, and circulation is prevented by the vapor (steam) lock. In the event that feedwater flow is lost, and the water level in the steam generator drops significantly below the top reject condenser coils, steam is condensed in the reject condenser coils, and the condensate is returned to the steam generator down
comer.

The secondary side of the reject condenser is cooled by natural convection, via flow from and to the reserve water tank. The water available to the reject condensers from the reserve water tank (water in the reject condenser compartment plus the water in the common portion of the reserve water tank) is sufficient to remove decay heat, via evaporation, for a period of 72 hours without makeup or cooling to the reserve water tank.

The operation of the reject condenser system is fully passive; no valve operation or operator action is needed to initiate operation.

5.3 Passive Containment Cooling

In the system under consideration, the containment is cooled via a water circuit, with coils located within a cooling duct inside the containment, and heat rejection to the reserve water tank (see Figure 9). During normal operation, circulating fans located in the cooling duct and pumps in the water circuit assure that temperatures in the containment do not exceed design values.

Following a postulated accident (loss of coolant accident or a steam line failure within the containment), all circulation fans and pumps may be lost. Under these conditions, natural convection in the water circuit and the heat rejection duct maintain the primary containment temperature below 125°C (except for an initial transient period).

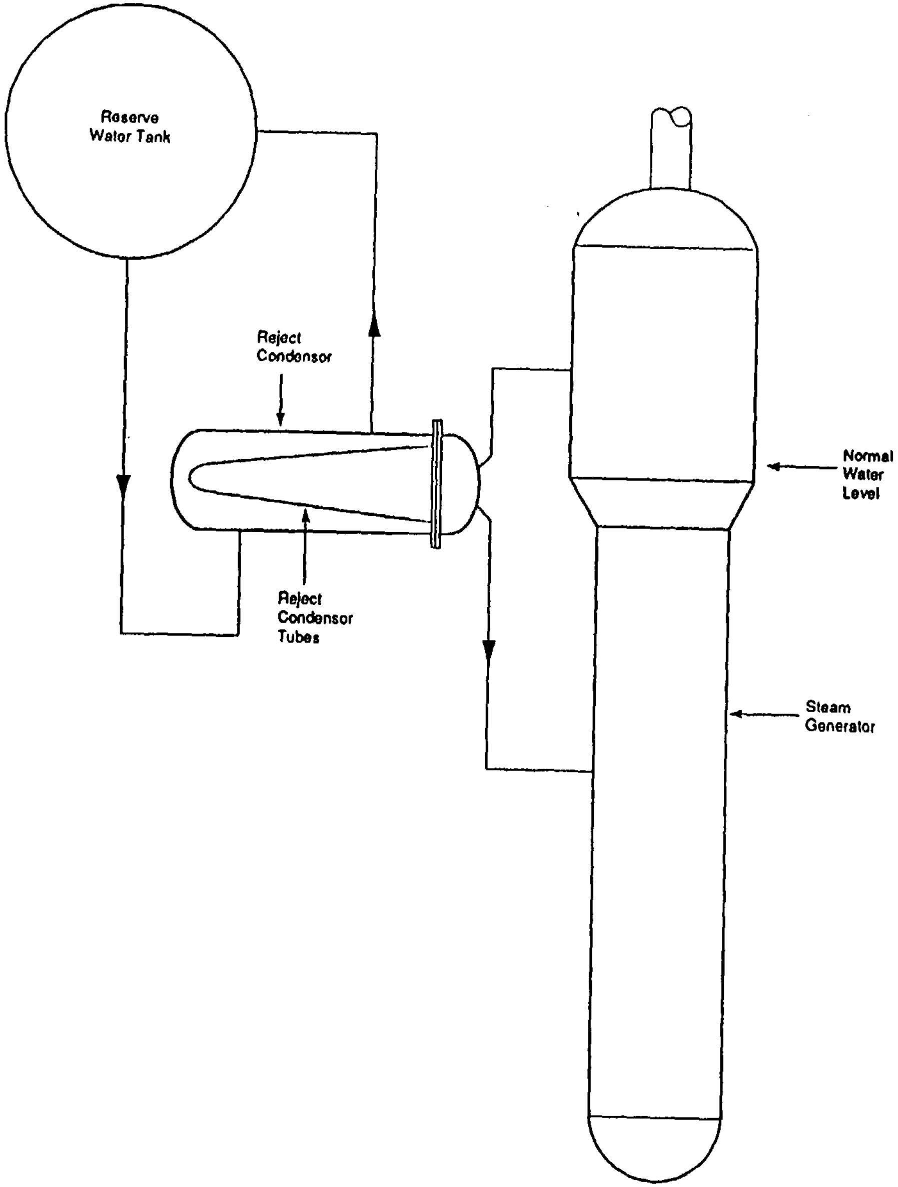


FIGURE 8: Reject Condenser Arrangement

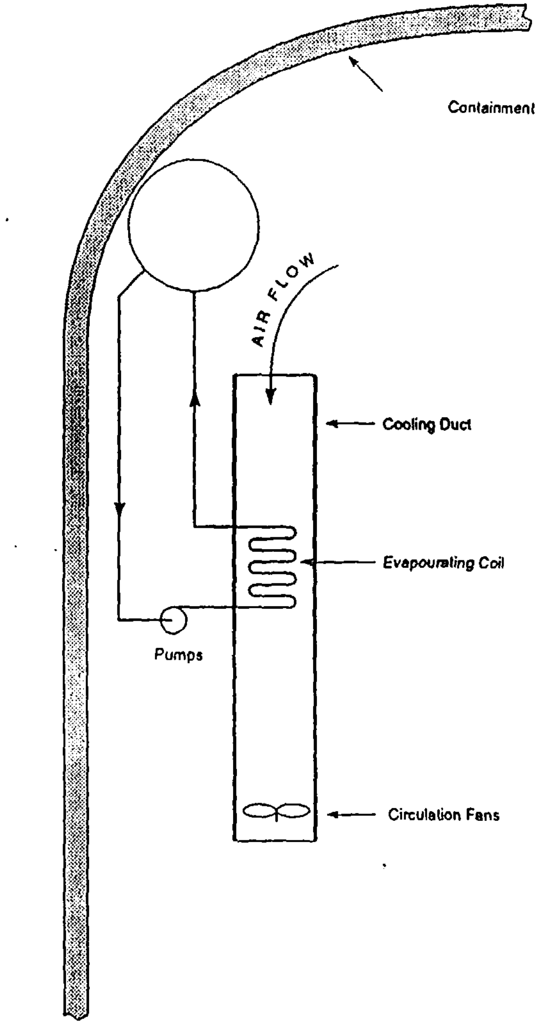


FIGURE 9: Passive Containment Cooling System

SUMMARY

Operating CANDU plants make extensive use of passive systems and features when their use has been shown to be economic and capable of meeting all requirements. The CANDU 9 increases the use of passive features, particularly in the area of decay heat removal capability under design basis and beyond design basis events. Additional passive features are under evaluation and development at AECL, and will be incorporated in future CANDU plants when their capability has been fully established.