# A PASSIVE EMERGENCY HEAT SINK FOR WATER-COOLED REACTORS WITH PARTICULAR APPLICATION TO CANDU® REACTORS

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## *ABSTRACT*

*Water in an overhead pool can serve as a general-purpose passive emergency heat sink for water-cooled reactors. It can be used for containment cooling, for emergency depressurization of the heat transport-system, or to receive any other emergency heat, such as that from the CANDU® moderator.*

*The passive emergency water system provides in-containment depressurization of steam generators and no other provision is needed for supply of low-pressure emergency water to the steam generators.*

*For containment cooling, the pool supplies water to the tube side of elevated tube banks inside containment. The elevation with respect to the reactor heat source maximizes heat transport, by natural convection, of hot containment gases. This effective heat transport combines with the large heat-transfer coefficients of tube banks, to reduce containment overpressure during accidents. Cooled air from the tube banks is directed past the break in the heat-transport system, to facilitate removal of hydrogen using passive catalytic recombiners.*

## INTRODUCTION

New designs of water-cooled reactors as summarized by Ritzman [1] use pools of water for passive emergency heat storage and rejection. In the event of a loss-of-coolant accident (LOCA), the simplified boiling-water reactor (SBWR), by General Electric, uses a pressure-suppression pool within the containment to condense steam from the reactor pressure vessel (RPV), and a heat exchanger in another pool, outside containment, to condense steam from the containment atmosphere. Steam from the RPV is condensed to depressurize the RPV, enabling a flow by gravity of emergency coolant. Steam from the containment is condensed to limit the increase in pressure and maintain containment integrity.

Similarly, the AP600, by Westinghouse, uses a water pool inside the containment to condense steam from the RPV, facilitating gravity-feed of emergency coolant from that pool. Containment cooling is effected by heat transfer through a steel containment vessel to the outside air flowing upwards by natural convection. The air-side heat transfer is augmented by the evaporation of water, which flows from an elevated tank against the upflow of air and over the outside of the containment vessel.

In a LOCA, a passive concept by Spinks [2] uses a water jacket to cool the containment atmosphere and, as in CANDU reactors, the heat-transport system is depressurized by depressurizing the secondary side of the steam generators, rather than by discharging the primary fluid. Depressurization of the CANDU primary heat-transport system is needed to facilitate injection of emergency coolant. Depressurization is done by discharging steam from the steam generators to the external atmosphere, and then water is supplied by gravity from an elevated tank to the steam generators. In the event of a LOCA, with coincident loss of emergency coolant injection (ECI), depressurization of the heat-transport system, together with moderator cooling of the fuel-channels, ensures fuel channel integrity even under these conditions.

A drawback of the AP600 and the approach of Spinks [2] is the elevation of the heat sink, the containment wall, with respect to the heat source. Heat should be transferred from the containment atmosphere at the highest possible elevation to maximize natural circulation and heat transfer from containment gases. A further benefit of enhanced natural circulation would be the availability of a flow of air within the containment for passive hydrogen mitigation.

Another drawback is the poor heat-transfer coefficient that is usually encountered with flow tangential to a surface, as would apply both inside and outside the containment wall. The coefficient is typically an order of magnitude larger for flow across a tube bank (Compare Figures 13.3-1 and 13.3-3 of Bird et al. [3]). A similar drawback is the limited heat-transfer surface area that is available in these designs.

A drawback of the CANDU reactor approach is the release of steam outside containment in order to depressurize the reactor during an accident. Operator action is required to switch to an alternative heat sink in the event of steam-generator tube failure.

The intent of this report is to describe a passive emergency-water system (PEWS) that overcomes these pressurized water reactor (PWR) and CANDU reactor weaknesses. It uses the SBWR feature of an elevated pool vented outside containment but, for containment cooling, applies the water in a different manner maximizing heat transfer from containment gases and generating a flow of air for hydrogen mitigation. Maximum heat transfer leads to minimum containment over-pressure, which reduces cost and radioactivity releases.

## PEWS AS A HEAT SINK FOR CANDU

Figure 1 illustrates PEWS as applied to a CANDU reactor.

The vented water pool in the containment dome is a general-purpose emergency heat sink. For a large CANDU reactor, a volume of some 2000 $m^3$ provides, after boil off, a three-day heat sink. It serves as a heat sink for the steam generators, for the containment, and for the moderator acting as an emergency-core-cooling (ECC) system. It could also serve as a heat sink for the ECI system, but this might be better designed to be independent of the moderator system. For redundancy, the PEWS tank can be divided azimuthally.

### Steam Generator Heat Rejection

Given a LOCA or steam-line break, the steam generators would be isolated from the main steam line using valves located close to each steam generator: see the normally-open valves in Figure 1. Following isolation, valves to connect the steam generators to the emergency heat sink would be opened: see the normally-closed valves in Figure 1. The steam generators would be depressurized by condensation of steam in condensers located in the PEWS vented water pool. The condensate would return by gravity to the steam generators. This return flow eliminates the need for a supply of emergency water, commonly fed from an overhead tank.

In the event of a steam-line break, depending on the speed of reactor trip and speed of closure of the main-steam-line isolation valves, the discharge of steam into containment is reduced. The steam-line break need not be a limiting break from the viewpoint of containment overpressure.

The PEWS tank could be subdivided into a division per steam generator. Then, in the event of a loss of water in one part of the pool, the remaining parts would be available to provide a limited-duration heat sink.

Note that the abovementioned condensers have a function similar to that of the SBWR isolation condensers. For CANDU they may have to be larger depending on the required rate of depressurization which, in turn, depends on the ECI injection pressure.

## Containment Heat Rejection

In the SBWR, in a LOCA, containment heat is rejected firstly to a pressure-suppression pool and, in the long term, to a vented pool via condensers in the pool. The tube side of the condenser is open to the containment atmosphere. The pressure-suppression pool is needed because of a limitation in size of condensers in the vented pool. This limitation is overcome in PEWS by employing tube banks located at an upper elevation within containment. Water from the external pool is supplied to and returns from the tube side of the tube banks by natural circulation via vertical headers.

The tubes are inclined to the horizontal, so that there is a preferred flow direction for the water. Water is supplied from the pool via the header at one end, and heated water is returned to the pool via the header at the other end of the tube bank. In the longer term, a boiling steam/water mixture is returned to the pool.

The containment itself is divided into an inner zone and an outer annular zone, as shown in Figure 1. Such is normally the case in CANDU containments, the outer zone being accessible during normal operation and not connected to the inner zone. However, a connection is required in this design, at least during accidents, to permit a natural-circulation flow of gases up through the steam-generator enclosure and down through the accessible area. The flow is induced by the difference in density of the hot gases (air, steam and hydrogen) rising from a break in the reactor coolant pipes, and the gases cooled in passing across the elevated tube banks. The elevation difference between the heat source, near the reactor, and the heat sink, at the tube bank, is larger than in other designs, leading to an enhanced natural-circulation flow. The flow is further enhanced by using the internal wall as a baffle, which eliminates restrictive interaction between downflowing and upflowing streams.

A reduced containment pressure follows from a high rate of heat transfer from the containment gases to the banks of water-cooled tubes. A large heat-transfer coefficient follows not only from the enhanced flow velocities, but also from the high heat-transfer coefficient for flow across a tube bank, compared to the coefficient for flow tangential to a surface, such as a vertical containment wall. Large-break LOCA calculations are being done using the Gothic code and show that, in the longer term, the containment pressure is insensitive to the tube bank size for heat transfer surface areas considerably less than the surface area of the containment wall. The containment temperature and pressure are governed by the temperature of the heat sink which is somewhat higher than 100°C when boiling takes place inside the tubes.

## Hydrogen Mitigation

The enhanced natural-circulation flow within the containment permits improved hydrogen mitigation. Hydrogen mitigation can be accomplished by directing recirculating air to the source of the hydrogen and locating catalytic hydrogen recombiners in the mixed air, steam and hydrogen stream. If the recombiners are located at low elevation in an upward flow of this stream, the heat of recombination acts to augment the buoyancy-induced flow.

Figure 1 shows hydrogen recombiners located in the steam-generator enclosure. The intent is to blank off any alternative flow path, so that the entire recirculating air flow is available for hydrogen mitigation. This greatly increases the effectiveness of recombiners, compared to the conventional strategy of dispersing recombiners throughout containment and relying on local convective flows for supply of air to each recombiner. The abovementioned LOCA calculations, being done using the Gothic code, show air and steam flow rates which would dilute hydrogen concentrations to less than deflagration levels even at inlet to the recombiners. Higher concentrations can be expected upstream of the recombiners and nearer the break but with the recombiners located so close to the break, the mass of hydrogen is small limiting the effects of a sudden deflagration.

Catalytic hydrogen recombiners located in a strong flow of air can have single-pass efficiencies above 80%. This leads to small hydrogen to air ratios in the upflowing stream at exit from the recombiners and precludes the need for any additional downstream recombiners.

### Moderator and Emergency Coolant Heat Rejection

PEWS can be a heat sink for the CANDU moderator, which, in surrounding the fuel channels, can act as an ECC system [4]. Moderator emergency heat rejection would be done passively, by transferring heat from a $D_2O$ natural-circulation loop to a $H_2O$ natural-circulation loop, the latter being part of PEWS, as shown in Fig. 1.

Full-height, but reduced-scale, testing of a natural-circulation loop, driven by flashing of water to steam as it rises to an elevated heat exchanger [5], has demonstrated the feasibility of this mode of moderator heat rejection.

The PEWS pool could similarly accept heat from the ECI system. However, this would detract from the potential independence of the two ECC systems. Two fully-independent ECC systems can lead to a CANDU core-melt frequency of less than $10^{-7}$ per unit year [6].

### Advantages for CANDU

To summarize, the advantages of PEWS as applied to CANDU reactors are as follows:

a) Steam-generator depressurization inside containment avoids the need for operator action in the event of failed steam-generator tubes.
b) The condensed water is returned to the steam generator, avoiding the need for another source of emergency water.
c) Passive containment heat rejection, which avoids any dependence on emergency power supplies, is effected in an optimal manner: the elevated heat sink maximizes the flow of emergency water and the flows of containment gases. Containment design pressure is reduced, reducing containment cost and radioactivity release.
d) The containment air-flow facilitates hydrogen mitigation.
e) Passive moderator heat rejection, which avoids any dependence on emergency power supplies, is effected in an optimal manner: the elevated heat sink maximizes the flows of light water and heavy water.

## APPLICATION AND ADVANTAGES FOR PWRs, SPECIFICALLY AP600

For a passive PWR, PEWS could provide both a pressure-suppression function and a containment cooling function.

PWRs are typically depressurized by a discharge of steam from the RPV, rather than from the steam generators, as in CANDU reactors. A discharge of steam from the steam generators would have the advantage of removing energy from the RPV without causing a further loss of coolant inventory. However, in either case, discharge of steam from the steam generator or from the RPV, the PEWS tank could be used to condense steam from the vessel and return the condensate.

PEWS, used for containment cooling, would eliminate the need for a thermally conducting containment vessel, and the need for external water and air cooling, as in the AP600. Also it would be more reliable, because it would always absorb a known quantity of heat, whereas the water in the external tank of the AP600 could be released when the full cooling capacity is not required. Depending on the scenario, full cooling could conceivably be required at some time after the release of water.

The PEWS containment advantages of improved heat transfer, and improved hydrogen mitigation apply when compared to the AP600. The heat-transfer coefficient for flow across a tube bank is typically an order of magnitude greater than that for flow tangential to a heat-transfer surface such as the AP600 containment walls.

Note also that the development requirements for PEWS are modest compared with the AP600. Several BWRs have used condensers in an external pool. Tube banks are commonly used for air-to-water heat exchange, and vertical pipes have often been applied in natural-circulation loops. The AP600 containment heat rejection by external flooding is novel, but requires design-specific tests, which, in reduced scale, are not easy to apply.

## CONCLUSIONS

A passive emergency water system (PEWS) has been described that uses an elevated and vented pool of water that can act as a general-purpose passive heat sink for water-cooled reactors. Containment cooling and hydrogen mitigation are improved compared with other designs of passive water-cooled reactors. The application to and advantages for CANDU reactors and PWRs have been described.

## REFERENCES

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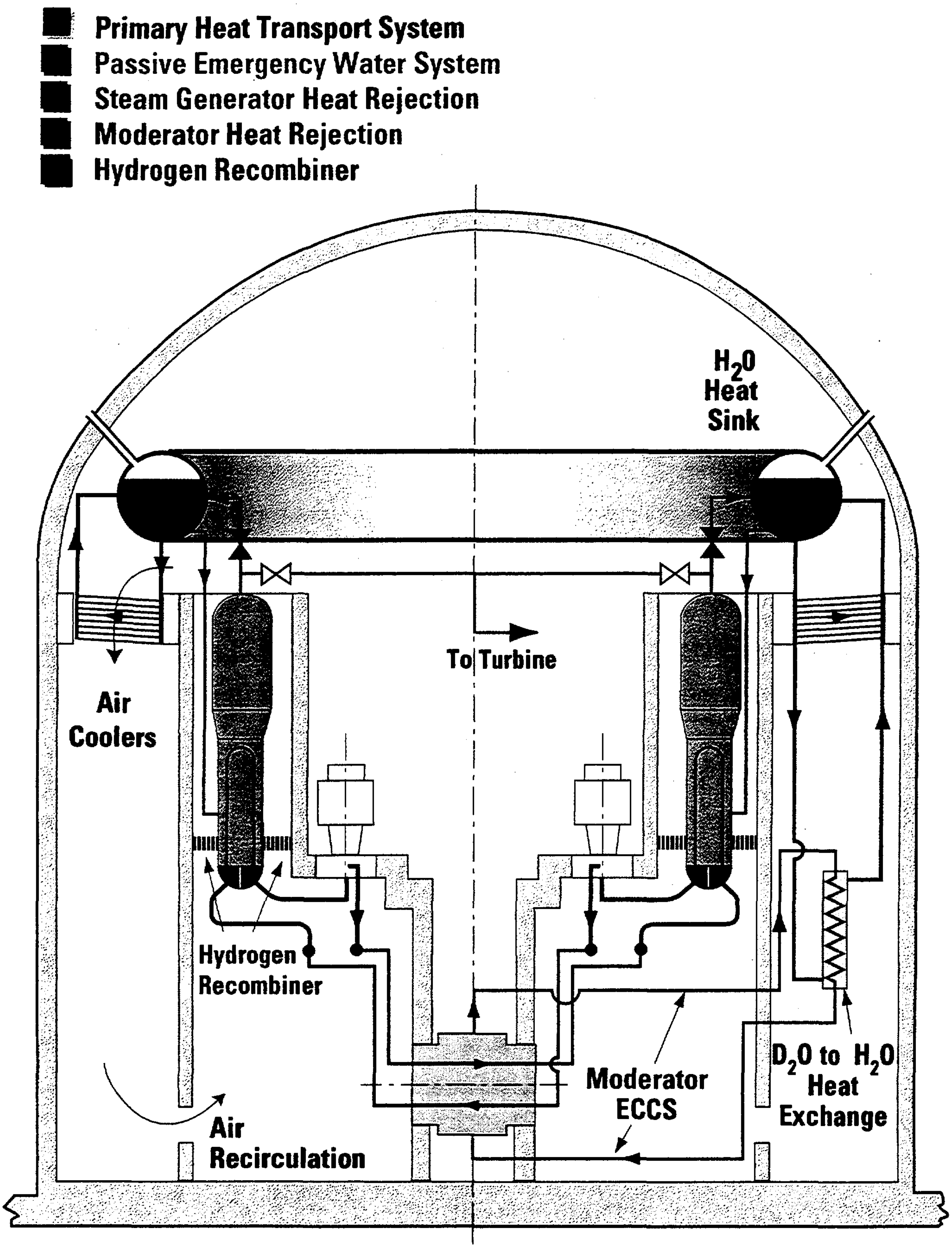

**Passive Emergency Water System**