DESIGN CONCEPTS FOR PASSIVE HEAT REJECTION IN CANDU REACTORS

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ABSTRACT

A study has started at AECL to assess the safety and capital cost implications of a more extensive use of passive safety design features in CANDU reactors. The passive designs avoid reliance on electrical power and on operator action for three days following an accident. A further goal is to minimize periodic testing by designing systems that function during normal operation, and therefore continually demonstrate their availability.

At this stage, a number of concepts have been identified for passive heat removal and some preliminary sizing has been completed based on a CANDU 6 reactor design. The paper describes the more attractive concepts and the results of preliminary performance assessments.

The next step in the study is to prepare cost and safety assessments. The latter will include an estimate of the improvement in core melt frequency. A positive assessment would lead to a more detailed design study.

1.0 INTRODUCTION

Passive designs offer the potential for plant simplification leading to improvements in capital cost and safety. Safety would be expected to improve through a lower probability of failure of safety systems. Capital cost might be reduced through the elimination of systems such as standby power and pumped cooling water. For these reasons, a study has started at AECL to assess the safety and capital cost implications of a more extensive use of passive design features in CANDU reactors. A positive assessment would lead to a more detailed design study.

CANDU reactors incorporate a mixture of passive and active design features in protecting against a wide variety of accident scenarios. The containment building is, of course, passive. Reactor shutdown is achieved by two independent passive systems. One shutdown system uses rods which drop under spring assistance, while the second uses pressurized helium to inject a gadolinium nitrate solution into the moderator.

Heat rejection also has several passive features including the ability of the reactor coolant to thermosyphon on loss of forced circulation, a pressurized gas driven option for emergency coolant injection and, for low probability accidents involving loss of emergency coolant injection, the ability of the low pressure moderator to maintain fuel channel integrity. Some CANDU reactor designs incorporate a dousing tank. The water in the dousing tank can also be used to provide a gravity feed of water for emergency feedwater following depressurization of the steam generators.

The intent of the study is to identify and evaluate passive design concepts that would replace active systems or reduce the reliance on operator action and electrical power. The CANDU 6 was used as the baseline design for this assessment.

2.0 "PASSIVE"

The term "passive" has been taken to mean the exclusion of operator action and any reliance on electrical power supplies (except batteries) during an accident. Consistent with the EPRI requirements [1] for passive design, the use of signals and the repositioning of valves is allowed. After 72 hours, limited (straightforward) operator actions and easily installed electrical supplies are allowed. To ensure protection against systems being impaired or unavailable when called upon, preference is given to designs that function during normal operation, continuously demonstrating their availability. This goes beyond the EPRI requirements.

3.0 COOLING CONCEPTS

For CANDU, as for light water reactors, the loss of coolant and the loss of heat sink accidents dominate the cooling requirements. Considering these accidents, cooling can be done at three levels of increasing severity.

The first level protects the primary heat transport system from loss of the normal steam generator heat sink.

The second level provides emergency coolant injection and heat rejection when the primary heat transport system has failed.

The third level provides emergency core cooling if the emergency coolant injection system has also failed.

Some CANDU designs have two isolable primary coolant loops. Only the failed loop for a two loop plant is cooled at level 2 or 3. The unbroken loop is cooled at level 1.

4.3 Level 3: Moderator Cooling

The third level provides protection if the primary and the emergency coolant injection systems fail. It has been shown that the moderator system can be utilized to protect the fuel channels from failure [3] for these scenarios. The distributed geometry of the CANDU core submerged in a large volume of cool liquid (moderator) lends itself well to passive design concepts.

During normal operation, the heat transfer to the moderator is minimized by a gas filled annulus. Following an accident with loss of ECI, the pressure tubes sag and make contact with the calandria tubes. A path for heat conduction from the fuel to the moderator is established, however fuel failures occur.

In current CANDU designs, a forced convection system for moderator heat rejection maintains a moderator subcooling of 30°C which is sufficient to prevent fuel channel failures during a loss of coolant accident with loss of emergency coolant. It is expected that R&D, which is currently underway to improve the fuel channel design, will reduce the required subcooling to less than 5°C.

The limiting accident for moderator heat rejection is the in-core LOCA with loss of emergency coolant injection. It is an unlikely occurrence, not only because of the presumed coincident failure of emergency injection but also because the failure of a pressure tube is not expected to lead to failure of the associated calandria tube. It is a limiting case for moderator heat rejection because of the heat load from the break discharge. This is imposed in addition to the direct heat load due to gamma radiation from the fuel plus the heat load transferred from the fuel by conduction through pressure tubes and calandria tubes.

In the passive design, the moderator heat is rejected through a heat exchanger to the water jacket (see Figure 1). Natural circulation drives the flow on both sides of the heat exchanger. D_2O is used as the moderator in CANDU reactors. The high cost of D_2O severely penalizes the obvious passive design options such as increased moderator inventory and oversized heat exchangers. Even the requirement to locate the heat exchanger above the calandria to allow natural circulation incurs a significant cost.

Figure 2 shows the total heat load and predicted D_2O and H_2O temperatures for an in-core LOCA as a function of time. Thermosyphoning in the moderator is enhanced by boiling at the heat exchanger inlet. The 5°C subcooling at the upper row of fuel channels is achieved by the static head of D_2O in the piping above the calandria. After about an hour, the heat load decreases and the moderator outlet temperature reduces from a maximum of about 125°C. The temperature of jacket water, initially at 55°C, reaches a maximum of about 82°C in about a day. At this time the heat from the moderator equals the heat transferred to the air (approximately 8 MW).

4.4 Water Jacket

The water jacket is a water filled annulus forming the vertical cylindrical walls of the steel containment vessel. The water jacket absorbs, stores and rejects heat at levels 2 and 3.

The jacket is divided into two independent compartments for long term reliability. Each compartment would serve both levels 2 and 3. Although both compartments may be required for the initial heat load after a loss of coolant accident, one compartment would have sufficient capacity after one to two days in the event of the other compartment being disabled.

The passive cooling loop is functional during normal operation. The jacket rejects approximately 3 MW with an outside air temperature of 40°C and a steady state jacket temperature of about 55°C. This continual removal of heat from the moderator demonstrates that the cooling loop is available at all times. No special performance testing is required for this loop, achieving increased reliability at reduced cost.

Sensitivity analysis showed that the transients were not significantly affected by changes in the water jacket volume (1 m or 0.5 m thickness). Therefore, an annulus thickness of 0.5 m (about 3000 m^3 of water) was selected to reduce the seismic stresses on the building. Furthermore the analysis demonstrated that the water jacket is effective in maintaining a maximum temperature differential across the heat exchanger, and that the limiting factor in the system performance is the ability to transport heat to the water jacket.

5.0 DISCUSSION

Current CANDU designs have many passive safety features and the present study has indicated that several passive design concepts can be introduced to enhance heat rejection as well. The modifications discussed provide safety related heat removal that is less reliant on electrical power, is not dependent on operator action and has improved reliability through additional redundancy, simplification or continuously demonstrated availability. It is estimated that these changes could produce a 5 to 10 fold improvement is the core melt frequency of the plant.

While cost reductions are achieved through the deletion or downsizing of some systems, the cost of heavy water, and the high cost of a containment building with both a steel vessel and a concrete shroud are likely to have a significant impact on the overall cost of the plant.

The initial approach to this study was to incorporate a large volumes of light water to store heat. Since heat transport rates are poor in passive loops with small temperature changes, the more effective heat reservoirs are those in close contact with

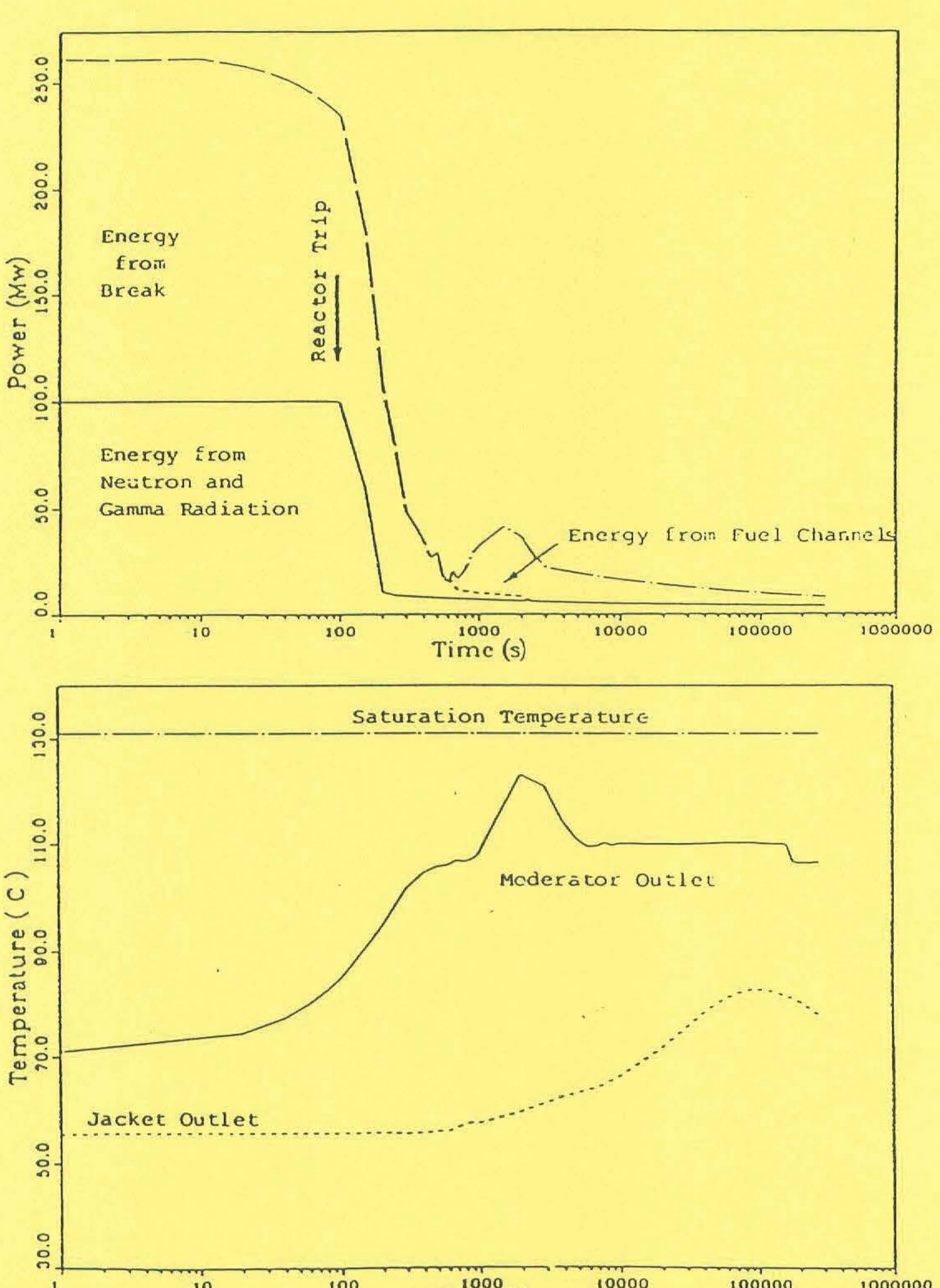


FIGURE 2 Moderator Response To In-Core LOCA
(Without Emergency Coolant Injection)

the heat source. The ECI sump and the moderator inventory are examples of this principle. Although the proposed passive concepts provide adequate heat removal capacity, more cost effective options should be investigated (e.g. an intermediate loop with a low boiling point fluid).

6. CONCLUSIONS

The key to passive design is the ability to absorb large quantities of heat for rejection at a lower rate over an extended period of time. The counteracting goals of increased thermal inertia and reduced heavy water holdup add an extra challenge to the design of passive systems for CANDU.

The passive design concepts presented can provide significant improvements in reliability. An equally important benefit is the improved public perception of plant safety through the elimination of operator action for 72 hours and reduced reliance on electrical power supplies.

The next phase of the study must investigate options to reduce the capital cost. It is also noted that with further research and development of advanced fuel and fuel channel designs it may be possible to make the moderator as effective as the ECI system for fuel cooling.

7.0 REFERENCES

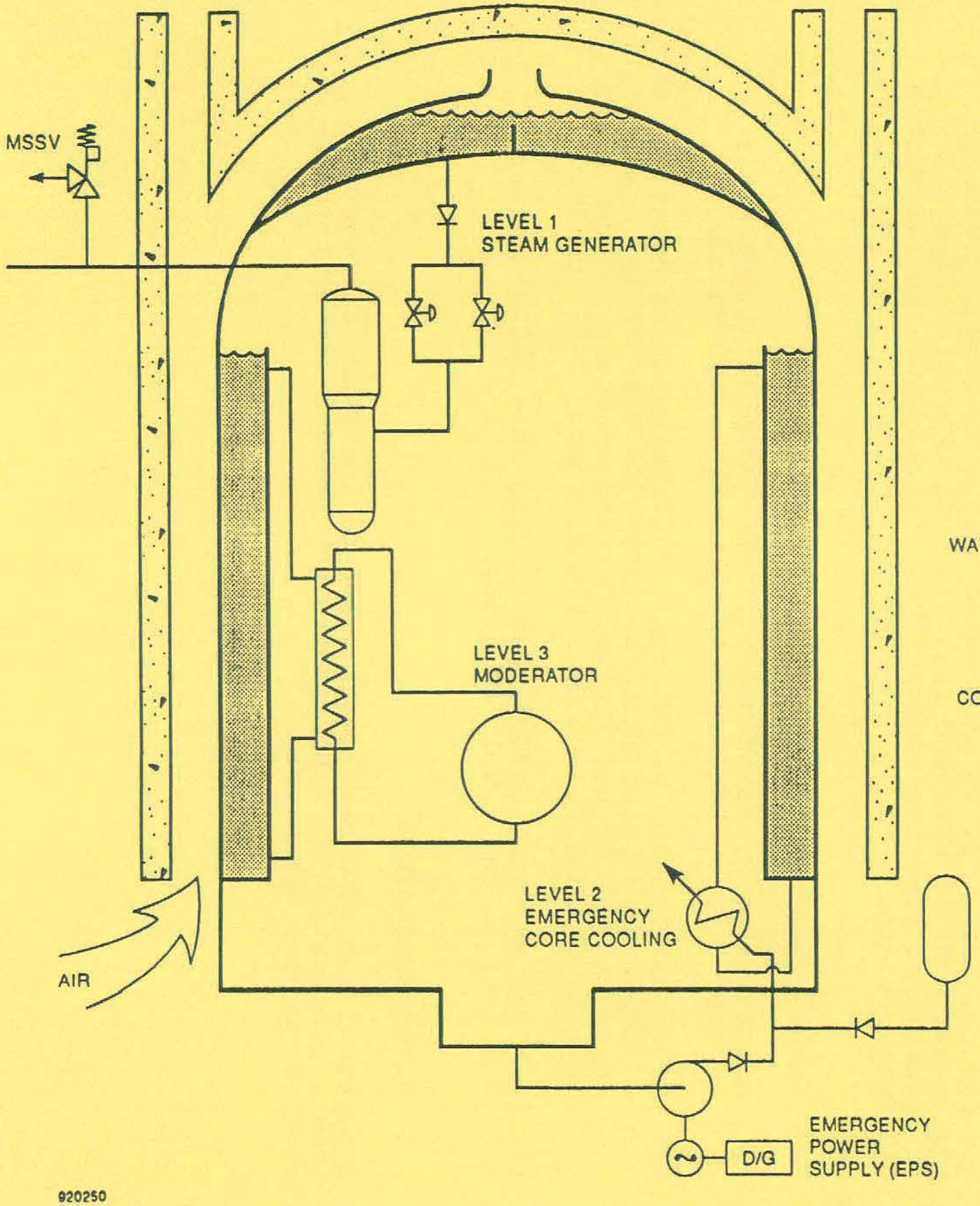
(1) ELECTRIC POWER RESEARCH INSTITUTE, "Advanced Light Water Reactor Utility Requirements Document", 1990 March.

(2) V.S. KRISHNAN AND P. GULSHANI, "Thermosyphoning Behaviour of a Pressurized-Water Test Facility with CANDU-PHTS Geometry", Second International Topical Meeting on Nuclear Power Plant Thermal Hydraulics and Operations, Tokyo, 1986 April.

(3) R.A. BROWN ET AL., "Degraded Cooling in a CANDU Reactor", Nuc. Sci. & Eng., Vol. 88, 1984.

8.0 ACKNOWLEDGEMENTS

Many people at AECL have contributed to the CANDU passive design study. In particular, the authors acknowledge the contributions of P. Soedijono and R. Mak.



LEVEL 1	STEAM GENERATORS BOIL STORED WATER TO ATMOSPHERE VIA MAIN STEAM SAFETY VALVES (MSSV).
LEVEL 2	PASSIVE HIGH PRESSURE INJECTION FOLLOWED BY PUMPED RECOVERY OF EMERGENCY COOLANT. HEAT TRANSFERRED TO COOLING WATER FROM WATER JACKET.
LEVEL 3	MODERATOR THERMOSYPHONS THROUGH HEAT EXCHANGER. HEAT TRANSFERRED TO COOLING WATER FROM WATER JACKET.
WATER JACKET	CONTAINMENT WALL CONTAINS 0.5 m WATER FILLED ANNULUS. WATER THERMOSYPHONS THROUGH HEAT EXCHANGERS FOR LEVEL 2 AND 3 COOLING. HEAT TRANSFERRED TO AIR FLOWING UPWARDS BY NATURAL CONVECTION.
CONTAINMENT	5 cm STEEL SHELL DESIGNED FOR PRESSURE AND TEMPERATURE OF STEAM MAIN BREAK.

FIGURE 1 INTEGRATED SAFETY HEAT SINKS