CANDU ORIGINS AND EVOLUTION – PART 4 OF 5

EMERGENCY CORE COOLING SYSTEMS

by
G.L. Brooks[1] - 2001 February

Prepared as a contribution to a project sponsored by AECL, and carried out by the AECL Retirees Group, in the period of the 1990's. Published with permission of the authors.

[1] Former Chief Engineer, AECL

Summary:

This monograph discusses the origins and evolution of the emergency core cooling systems provided for CANDU reactors.

Table of Contents

CANDU ORIGINS AND EVOLUTION – Part 4 of 5 1

Introduction & the Early Days 2

Douglas Point 3

Pickering - A 5

Bruce - A 6

CANDU 6 Reactors 7

Later Ontario Hydro Reactors 7

INTRODUCTION & THE EARLY DAYS

This monograph discusses the origins and evolution of the emergency core cooling systems provided for CANDU reactors.

Starting with the design of the NRX research reactor in the 1940's, Canadian designers recognized that the presence of fission products in the fuel of any nuclear reactor, which operated at a significant power level, unavoidably meant that fission product decay heat would continue to be generated in the fuel following a shutdown of the reactor. This imposed a requirement that adequate cooling of the fuel must, with a high degree of certainty, be continued for an extended period after shutdown if fuel damage through overheating was to be avoided. If, therefore, the normal cooling system was disabled for any reason then the reactor must be promptly shut down and some alternative means must be brought into action for continued fuel heat removal.

The need for such alternative means continued to be recognized in the early evolution of the Canadian nuclear power program. This is illustrated by the following excerpt from a paper "Safety in the Use of Nuclear Reactors" presented by Dr. George C. Laurence at the Atomic Power Symposium held at Chalk River, May 4 and 5, 1959 (AECL-799). Dr. Laurence was at that time Director of AECL's Reactor Research and Development Division and a leading pioneer in developing Canada's approach to reactor safety.

"A break in the piping or equipment of the cooling system that allows the coolant to escape is another kind of accident that can result in disaster if the reactor is not shut down automatically by the protective trip system. Emergency cooling should be provided for the fuel if necessary. The section of the cooling system outside the reactor is made of equipment and parts that are very familiar in other industries also. There are very few disastrous failures in equipment of this kind that has been constructed and maintained in accordance with modern safety codes for boilers and high-pressure piping. However, we cannot afford to be so confident about those parts of the cooling system which are inside the reactor. These parts and very difficult to inspect periodically because they become highly radioactive as a result of bombardment by neutrons which they undergo inside the reactor. Also, exposure to neutrons and to radiation changes the properties of many materials. For example, generally speaking, annealed metals become hardened and embrittled and work-hardened materials may become somewhat softer. We are beginning to learn about these effects and understand them. We must allow for changes of this kind in the design of equipment."

The foregoing passage is of interest in several regards. It is noteworthy that Dr. Laurence gives particular prominence to the importance of the protective trip system - a result, no doubt, of the 1952 NRX accident. This emphasis on the protective trip system is repeated several times throughout the paper. In contrast, Dr. Laurence appears to give lesser prominence to the need for an ECC system. This probably was the result of his stated view that major out-reactor LOCA's presented a relatively minor risk because of their improbability. His highlighted concern about possible in-reactor failures of the coolant system boundary was eventually shown to be valid by the 1983 pressure tube failure in Pickering Unit-2.

In another paper presented at the same symposium, "Design of NPD-2 and CANDU", I.L. (Willy) Wilson, who was Head of the Reactor Design Branch of AECL's Nuclear Power Plant Division, has the following to say with respect to the need for an ECC system:

"The engineering of nuclear plants differs from that of conventional plants not only because of the difference in equipment and process but also because special measures must be taken to satisfy safety requirements. A reactor cannot be completely turned off. Once it has operated for a while there is a considerable production of heat in the fuel even when shut down. This may be only one percent or so, depending on how long the reactor has been down, but one percent of CANDU (the name adopted at the time for what became Douglas Point) heat is still over 7000 KW. Further the fuel contains enough radioactive fission products at all times to be injurious to persons or property over an area of several square miles if somehow they became distributed around the countryside. Thus a type of accident, which would be more or less ignored as a risk in a conventional plant, may require more serious consideration in a nuclear plant. The probability of failure of a steam or water pipe designed to the code is very small and of no great concern in a normal plant but if the result of such a failure in NPD is considered to be the loss of cooling on the fuel and the possible release of fission products, then some backup action is considered necessary. A large water-storage tank is provided for possible emergencies in NPD. If a main pipe in the primary heavy-water circuit should break, the circuit would blow dry fairly quickly. An emergency cooling connection is provided to admit ordinary water to the reactor circuit in such an unlikely circumstance, and water sprays throughout the process area will be called into play at the time of the break to condense escaping steam."

Wilson's comments are of interest in confirming that, as of 1959, the designers of NPD had decided to incorporate an ECC system, albeit of a rather rudimentary form.

One of the major problems facing designers of ECC systems at the time was the lack of comprehensive analytical tools that could properly model the complex thermal hydraulic phenomena involved in the coolant blowdown and ECC refill phases. Blowdown tests were carried out using high pressure, high temperature water loops but these early tests did not include the effects of residual heat in the reactor fuel which was later determined to be of considerable importance. Experimentally based analytical tools to predict the refill phase were simply not available. The NPD designers therefore had to proceed on the basis of simple engineering judgment, hand calculations, and limited experimental studies (ref. "Experimental Investigation of Water Injection Emergency Cooling in a Simulated NPD-2 Coolant Channel - E. Brundrett - NEI-133 revised). Fortunately, the low power rating of the NPD fuel did not impose particularly arduous performance requirements on the ECC system, as the decay power level was relatively low.

DOUGLAS POINT

As the writer recalls from discussions with the AECL Nuclear Power Plant Division designers in late 1958, a number of alternative ECC system arrangements were being studied for what was then called CANDU - this became a generic name when the Douglas Point site was chosen for the prototype reactor. While a gravity-driven light water injection system, such as that provided for NPD, was attractive in terms of simplicity, it suffered from the obvious disadvantage of downgrading of the heavy water coolant in the event that it was actuated (either accidentally or "in anger"). It was also recognized that a gravity-driven system could not prevent fuel failures in all LOCA situations because of the limited emergency coolant injection pressure. High pressure coolant injection was considered but discarded at the time as reported in Appendix K.1 of Volume II of the original "final" Douglas Point Safety Report which contains the following statement: "In these preliminary studies complete loss of cooling over the fuel in the maximum rated channels of one-half of the reactor was assumed two seconds after the piping accident."

(*An accident which would lead to flow stagnation in one core pass*). "The sheath temperature at which failure was assumed to occur was 1700 degrees F. Since the time between piping failure and fuel failure was predicted to be only about eight seconds and as the system circulation could be 'blocked' by coolant at 1000 psi at this time, it appeared impractical to attempt to prevent possible fuel failures by high pressure emergency injection." It is interesting to note that this judgment was eventually to be shown to be incorrect as noted later in this monograph.

The alternative, which was eventually chosen for Douglas Point, employed the moderator system. In the Douglas Point design, the single reactor safety shutdown system utilized "moderator dump". Upon actuation, the moderator heavy water was drained rapidly by gravity to a tank (the dump tank) located immediately below the calandria vessel. In the case of a LOCA, moderator dump would be actuated automatically by the reactor trip system and the moderator heavy water would be transferred to the dump tank. This water would then be available for injection into the reactor heat transport system via the moderator pumps which would continue to operate. The above referenced Appendix K.1 contains the following statement regarding the choice of this alternative: "Instead, an emergency coolant injection system was selected (using the moderator pumps to inject moderator into the primary system at 30 psia) which would prevent fuel failures in the event of all 'small' piping accidents and would limit the fuel damage to a small fraction of the fuel in the core for any conceivable accident in the primary circuit. The preliminary accident analysis indicated the maximum number of fuel failures following a loss of coolant accident would be 16 percent of the fuel in the core."

This fuel failure estimate was then modified by the following statement: "After completion of the preliminary accident analysis, pressure testing of the fuel at high temperatures indicated that the minimum sheath temperature which would result in failure due to internal gas pressure is above 2000 degrees F. In addition, the preliminary assumption of no heat removal from the fuel after two seconds following certain piping failures appears to be too severe. The appropriate cooling rates for several piping accidents were examined as discussed in Appendix C. Assuming effective emergency injection when the system pressure reaches 30 psia, the maximum fuel temperature following any conceivable loss of coolant accident would not be more than 2000 degrees F., provided that the reactor trips out at the instant of the pipe failure. Therefore, no fuel failures would be expected as a result of a failure in the primary piping system." This conclusion was eventually shown to be incorrect as improved analytical tools became available and resulted in changes to the ECC system which increased the emergency coolant injection pressure substantially. These changes were made some years later in the life of Douglas Point.

In choosing the moderator system as the source of emergency coolant injection, the Douglas Point designers were influenced by reliability considerations. Appendix K.1 of the above noted reference contains the following statement: "The low pressure emergency injection system is considered to be highly reliable. The moderator pumps operate continuously and would be immediately available in the event of an accident." From a reliability standpoint, the chief weakness in the Douglas Point ECC system design arose from the relative complexity of the valving arrangements needed to connect the outlet flow from the moderator heat exchangers to the primary heat transport system and to switch the suction side of the moderator pumps from the calandria to the dump tank and later to the floor sumps. However, at the time of the original design, the claimed unavailability of the system (Section 4.1 of the Safety Report) was only 10^{-2} per year.

The designers recognized, of course, that in the longer term a means must be provided to recover coolant lost through the break in the primary circuit once most of the moderator water in the dump tank had been injected into the primary circuit. To accomplish this, Appendix K.1 of the above noted reference describes the following provisions: "The floor drainage is so arranged that if the moderator water which is pumped into the primary circuit flows out of the opening in the circuit, it will be returned to the pump inlet regardless of the location of the failure. Leakage in the calandria or fuelling machine vaults will be returned to the primary system via the moderator pumps through drains in the floors of these areas.

A piping failure in the boiler room would result in water spilling on the boiler room floor. It would then flow along the depressions in the floor under the boilers, and down onto the ceilings of the east and west ground floor passageways, adjacent to the fuelling machine vault breakout panels. Drains from these ceilings would conduct the water under the breakout panels and into the fuelling machine vaults. The water would then enter the floor drains in the fuelling machine vaults and be returned via the moderator pumps and coolers to the primary system."

PICKERING - A

The "as originally constructed" design of the ECC system for Pickering-A was closely patterned on the "as originally constructed" Douglas Point design discussed in the preceding section. The moderator pumps were employed to provide low pressure injection of moderator heavy water, drawn from the dump tank, into certain reactor headers, the choice of headers being dependent on the location of the break in the primary heat transport system. The design called for the location of the break to be identified by the relative rate of post-LOCA depressurization as measured by pressure sensors located at various points in the system.

Subsequently, and during the design of the Bruce-A reactors, the then available, more advanced version of the "Firebird" analytical code identified that the relative rate of depressurization algorithm was not, in fact, reliable and that, for certain break sizes and locations, could lead to an error in selecting the appropriate points for emergency coolant injection. The Pickering-A design was, therefore, immediately reanalyzed, confirming the existence of this problem for Pickering-A. In dealing with this problem, consideration was firstly given to whether or not a more reliable means of identifying break location could be devised. These efforts were unsuccessful so the alternative of employing what was termed "all points injection" was investigated. In this approach, emergency coolant injection is provided to both inlet and outlet headers irrespective of the location of the primary system break. While the ECC system performance with this approach was inferior, with certain break sizes and locations, to "properly selected" directed injection, analysis at the time indicated that performance would be acceptable. The system was therefore modified to utilize the "all points injection" approach.

As noted later in this monograph, and in conjunction with the construction of Pickering-B, the Pickering-A ECC system was later modified to incorporate a high-pressure light water injection system.

BRUCE - A

The initial design of the Bruce - A reactors incorporated several features which impacted on the design of an appropriate ECC system. Firstly, the reactor design did not employ moderator dump - the design called for the calandria to remain full at all times. Secondly, the reactor was to be fitted with a large number of highly enriched uranium booster rods to provide excess reactivity to override a xenon poison transient at any time. These high-power booster rods were to be cooled by moderator flow provided from the moderator pumps and coolers. Thirdly, the main moderator system components were located outside of the primary reactor containment envelope. These changes led the designers to conclude that the use of the moderator system to provide emergency coolant injection was, no longer, a desirable choice. The choice initially adopted was similar to that adopted for NPD, viz., gravity-driven light water injection. However, instead of using a dedicated elevated light water storage tank, as in the case of NPD, the initial design concept for Bruce-A utilized the vacuum building dousing water storage tank as the source of emergency injection water. A line from this tank fed a common supply header which extended across the four units. As noted in the preceding section, post-LOCA blowdown analysis performed for Bruce showed that local pressure measurements in the primary heat transport circuit would not provide unambiguous indication of the location of the LOCA-initiating break and, hence, "all points" injection was adopted.

As the Bruce design proceeded and improved analytical codes and evidence from single channel refill tests became available, it became apparent that the emergency coolant injection pressure available from the vacuum building dousing tank was inadequate to refill the primary circuit within the time frame necessary to prevent "significant" fuel failures for all break sizes and locations, the original design intent. This situation also applied to the first CANDU 6 reactors which were being designed at the same time. To deal with this situation, it was recognized that the emergency coolant injection pressure would have to be increased substantially. To achieve this, the CANDU 6 designers evolved a high-pressure emergency injection system which utilized two dedicated light water storage tanks, operating in parallel, which could be rapidly pressurized by gas to pressures of the order of 800 psi. This system was, in effect, a major scale-up of the liquid poison injection system concept developed for SDS-2 (see Part 5 of this series). The basic system as evolved for the CANDU 6 reactors was accepted by Ontario Hydro for application to the Bruce reactors. The system operates as follows: Upon receipt of a LOCA signal from any of the four reactor units, valves in the gas line to the water storage tanks automatically open, thereby "arming" the system by pressurizing the water storage tanks. The same signal opens motorized valves in the lines from the water storage tanks to each of the primary system headers in the affected reactor unit. In addition to the motorized valves, these lines are provided with normally-closed check valves which prevent "blow-back" of primary coolant during the transient period when the primary coolant pressure is greater than that of the water storage tanks. When the pressures become equal, the check valves open and allow emergency coolant to enter the primary system as it is further depressurized via the break and/or by heat rejection via the steam generators. The automatic opening of the main steam safety valves on the steam generator secondary side, also in response to the LOCA signal, enhances the latter. This latter feature is necessary in the case of "small-break" LOCA's where the primary system pressure would remain high until most of the primary coolant had been lost through the break, thereby delaying emergency coolant injection.

The final selection of the operating pressure for the emergency injection system was determined by two considerations. Firstly, the higher the pressure, the shorter the delay time until emergency injection would commence in the case of a LOCA. On the other hand, too high a pressure could lead to unwanted injection in the case of non-LOCA operating upsets which result in transient decreases in primary coolant pressure and in any case, because of the unavoidable delay in valve opening time, the advantages of higher pressure would not be large. Design studies indicated that an ECC initiating signal "arming pressure" of about 1000 psi in the primary coolant system combined with an injection pressure of about 800 psi represented an appropriate compromise between these two considerations.

While the high-pressure water storage tanks provided emergency coolant for the initial refill of the heat transport system, there was, of course, a need to provide an ongoing supply of injection water, albeit at a lower pressure. Emergency coolant injection pumps provided this ongoing supply. These pumps initially drew water from the vacuum building dousing tank via the header discussed above. Once the water available from the dousing tank was exhausted, the pumps were switched to draw water which had collected on the floor of the fuelling machine tunnel. This collected water would include both the heavy water which had escaped initially from the break in the heat transport system plus the escaping emergency coolant injected from the earlier stages of ECC operation.

CANDU 6 REACTORS

As noted earlier, the ECC system design adopted for the CANDU 6 reactors was basically the same as that adopted for Bruce-A. The only significant differences involved firstly, the location of the dousing tank which in the CANDU 6 design is located within the reactor building and, secondly, the "arming" and injection pressures were reduced somewhat - to 800 and 600 psi respectively.

LATER ONTARIO HYDRO REACTORS

For Bruce-B, Ontario Hydro decided to retain the same ECC system design as for Bruce-A in the interests of design replication.

For Pickering-B, Ontario Hydro decided to use a high pressure pumped system rather than the gas-pressurized storage tank system used for the Bruce and CANDU 6 reactors. They also decided to backfit such a high-pressure system to Pickering-A when it became apparent through contemporary analytical codes that the original low-pressure system was inadequate. The high pressure pumped system appeared to their designers to offer some advantages. These included a reduction in the potential for water-hammer damage to the pipework, as the high pressure would be more gradually applied to the pipework as the pumps came up to speed. A second advantage was that the high-pressure injection mode could be extended further in time relative to the limited volume of water available from reasonably sized high-pressure injection tanks. The disadvantage with the high pressure pumped approach lies in providing a highly reliable electricity supply to the pumps which necessarily have heavy power demands, particularly on starting. With multi-unit stations, Hydro designers were able to demonstrate the necessary reliability within the normal overall station power system. This would not be the case for single-unit CANDU 6 reactors without the provision of very costly high powered diesel or gas turbine backup generators.

For Darlington, Ontario Hydro designers decided to adopt the Pickering high pressure pump arrangement for the same general reasons.