THE CONCEPT OF A PASSIVE WATER-COOLED TUBE REACTOR WITHOUT EMERGENCY CORE COOLING SYSTEM

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ABSTRACT

An ECCS-free passive water-cooled tube reactor concept is being studied to assess the feasibility and to determine basic conceptual design features. It is a loop-type heavy water moderated (and heavy or light water cooled) reactor with matrix-type fuel and passive moderator cooling system. Among several options for fuel channel design, special attention is given to two types: the fuel channel with metallic fuel matrix and the fuel channel with Zircaloy matrix. Preliminary analysis shows that the fuel channel temperature can be maintained within the permissible range for both normal operation and complete LOCA conditions.

1. INTRODUCTION

There is a world-wide effort to develop passive or inherently safe nuclear reactors which are expected to improve the safety, economy, and public acceptance of the nuclear power plant [1-3]. Among various reactor types including light water reactors (LWRs) [4-7], heavy water reactors[8], liquid metal reactors [9], and high temperature gas-cooled reactors [10], the LWR design concept is the most actively studied primarily due to its much greater operating experience compared with the other types.

Severe accident can be prevented in water-cooled reactors as long as the reactor is properly tripped and sufficient cooling water is provided to the reactor core. Therefore most revolutionary water cooled reactors are designed with a primary safety objective to minimize the possibility of core uncovery adopting the passive emergency core cooling system (ECCS) instead of the current active ECCS. But the passive ECCS in most LWRs still requires an active depressurization system, the reliability of which is a matter of great concern now. Nevertheless the loop-type passive safety water-cooled reactor is considered as the most promising candidate for the next generation reactors before commercialization of liquid metal fast breeder reactors.

It is natural to consider the concept of water cooled reactors not requiring the ECCS. Several pool-type LWR concepts seem to achieve this objective by eliminating the possibility of the loss-of-coolant accident(LOCA). However problems related to operation and maintenance make it difficult to adopt the pool-type concept. In this regard, a loop-type water-cooled reactor not requiring the

ECCS would be the most attractive solution to overcome problems related to safety, licensibility and public acceptance.

The pressure tube concept used in most heavy water reactor designs has been considered good in the viewpoint of decay heat removal in case of LOCA. This fact was theoretically confirmed by Hejzlar et al.[11]. They investigated various alternatives of passive decay heat removal from the core to the ultimate heat sink and suggested the system of solid matrix pressure tubes dispersed in a low pressure calandria as the most promising one, especially focusing on the use of graphite matrix. The thermal switch concept - switch of the cooling mode between coolant cooling in normal operation and moderator cooling in accident condition - was shown to be practically applicable. Their efforts are presently concentrated to design a pressure tube light water reactor[12]. Spinks et al. at Chalk River Laboratories are also investigating an advanced CANDU concept with passive moderator cooling system[8].

Based on the above considerations, conceptual design work are being performed by a small group at Center for Advanced Reactor Research (CARR) in Korea Advanced Institute of Science and Technology (KAIST) to remove the ECCS by adopting the tube reactor concept with innovative fuel channel design[13, 14]. This paper describes and discusses the concept of the ECCS-free Inherently Safe and Simple Tube Reactor (ISSTER) under study at CARR.

2. CONCEPTUAL DESIGN FEATURES

The primary design objective of the ISSTER is to achieve passive decay heat removal through moderator cooling at loss-of-cooling accident including LOCA by introducing the thermal switch concept.

The concept of the ISSTER is shown in Figs. 1 and 2. The major differences with the present CANDU are matrix-type fuel and passive moderator cooling system. There are several design options for the fuel matrix in the aspects of material and geometry, but two types are considered in this work as illustrated in Figure 1: (a) the metallic fuel matrix with dispersed coolant holes (Type-A) and (b) the Zircaloy matrix with dispersed fuel elements and coolant holes (Type-B). Attention on the metallic fuel matrix of Type-A is due to its advantages over Type-B in thermal, nuclear and manufacturing aspects. The selection of Zircaloy matrix for Type-B is due to its good nuclear and mechanical properties and much available information.

Figure 2 illustrates the typical configuration of the nuclear steam supply system (NSSS), respectively, admitting that there are many other possible options. Note that special moderator system is designed to passively transfer the decay heat to the containment atmosphere at loss of normal moderator cooling.

In normal operation, the fission heat generated in fuel elements is transferred to coolant and used to generate steam in steam generators as in the present PWRs or PHWRs. The moderator is cooled through forced circulation. In Type-A, the metallic fuel matrix temperature is rather uniform and strongly dependent on the gap characteristics between the fuel and coolant hole tubes. In Type-B, the Zircaloy matrix temperature has considerable variation according to location, and the maximum occurs near the fuel element where distance from coolant holes is long.

At loss of coolant cooling including the complete LOCA, however, the decay heat is transferred to the moderator through the gap between fuel channel tube and fuel matrix. The fuel matrix temperature is strongly dependent on the heat transfer characteristics of the gap for both types. The heat transferred to moderator can be transferred to the containment atmosphere through natural circulation of moderator and opening of safety valves, and finally cooled by the passive containment cooling system. In case of the loss of normal moderator cooling, safety valves of the moderator tank will open due to the pressure build-up in the moderator system by boiling.

Many options are also possible for the design parameters of the reactor coolant system including the moderator/coolant material, orientation of reactor, etc. For moderator/coolant materials, D2O / D2O or D2O / H2O options are considered to be the most promising in consideration of reactor physics characteristics. Reactor orientation, refueling strategy, arrangement of NSSS equipments are under discussion. Passive containment concepts proposed in AP600 et al. can be directly applied to the ISSTER.

3. DISCUSSION

In the proposed concept, the decay heat removal capability at complete LOCA depends on the following heat transfer rates: (a) heat transfer from fuel to moderator, and (b) heat transfer from moderator to ultimate heat sink. Passive moderator cooling can be achieved in several ways including the approach of Fig. 2 and Spinks et al.[8]. So the main problem is how to achieve passive heat transfer from fuel to moderator.

A preliminary calculation of the temperature distribution in fuel matrix has been performed assuming the peak linear heat generation rate of a fuel channel is 400 kW/m (approximately equivalent to 8 fuel rods in CANDU). The estimated temperature rise in fuel matrix is given in Table 1.

Table 1
Temperature Rise in Fuel Matrix in Decay Heat Removal Condition

	Decay Power Level		
	6%	4%	2%
Metallic Fuel (Type A)	102	68	34
Zircaloy Matrix (Type B)	320	215	107

Table 1 shows that the temperature rise in the fuel matrix is not large especially in case of metallic fuel. So the real problem is the gap heat transfer. Though only one gap is represented in Fig. 1, two gaps(fuel matrix - pressure tube and pressure tube - calcndria tube) are more desirable in the aspect of refueling procedure. In that case two gaps in series give much temperature rise between moderator and fuel matrix outside surface. Therefore an engineered but passive thermal switch should be provided to increase the heat transfer in one gap. Now the effort is concentrated to figure out appropriate thermal switch concept.

The specific design details would be quite different between power reactors and district heating reactors. But it has been confirmed by calculation that inherently safe decay heat removal can be achieved by the moderator system without the ECCS. The ISSTER presented in this paper are expected to have several advantages over existing LWRs or suggested passive LWRs as follows:

a) The safety of reactor can be remarkably improved since no active system is required to cool the core after LOCA. Core damage could occur only at the simultaneous loss of coolant and moderator which constitute separate loops.

b) Selection of the loop-type NSSS maximizes the use of proven technology and existing design of NSSS components.

c) Elimination of the ECCS would make the plant be rather simple, economical, and easy to design, analyze and operate. Adverse effect due to human error can also be minimized.

d) Design verification test is expected to be remarkably simple. Two important subjects to be tested are the heat removal from a separate fuel channel and passive cooling of the moderator system.

e) Change of reactor power is easily achievable by changing the number of fuel channels and re-sizing of the coolant loop and the moderator cooling loop.

Besides the thermal switch, the proposed ISSTER concept requires extensive optimization studies in the aspects of fuel channel, reactor, moderator system, etc., among which the most important subject is the optimization of fuel channel design. The fuel channel of Type-A is preferred if high gap conductance between the metallic fuel and coolant hole tubes comparable to that in PWR fuel rods is achievable. Use of metallic fuel would give us several advantages over the Type-B including:

a) Metallic fuel gives larger negative reactivity feedback against power excursion.

b) Larger fuel-to-moderator ratio lowers required fuel enrichment and improves moderator reactivity feedback.

c) The temperature in normal operation is much lower than the fuel temperature in Type-B so that redistribution of temperature due to the stored energy brings little problem at initial stage of LOCA.

d) Fabrication of Type-A is relatively simpler than Type-B.

The available information is very limited for the metallic fuel compared with ceramic fuel or Zircaloy. Especially the behavior of the large irradiated metallic fuel is complex and difficult to predict. Therfore much more experimental investigation is required to finalize the design details of the Type-A fuel channel.

The concept of ISSTER suggests us several research topics in thermal hydraulics (T/H), reactor physics, and material engineering. In the T/H area, the most important problem would be the gap design. Another important problem is the heat transfer to the ultimate heat sink, which includes the design of the passive moderator cooling system and the containment system. Low pressure boiling, natural circulation (or convection), and condensation are the typical phenomena.

It is also necessary to assess the various options (for materials of coolant and fuel matrix, configuration of fuel channels, arrangement of fuel channels in the moderator pool) in the viewpoint of reactor physics. Especially achievement of the negative reactivity feedback and effective fuel reloading would be of important consideration.

The practical applicability of the ISSTER concept strongly depends on the material problem. Investigation should be performed for selection of the fuel channel material, determination of the properties and manufacturing process of the selected materials, etc.

Now efforts are concentrated on optimization of fuel channel and the design of the engineered (but passive) thermal switch. District heating reactors and power reactors are being studied in parallel.

4. CONCLUSION

The concept of the Inherently Safe and Simple Tube Reactor (ISSTER) is briefly introduced in this paper. It is shown that an ECCS-free and economical loop-type water reactor is feasible with maximizing the use of existing technology. Easy verification test, simple accident analysis, easy operation and accident management would be additional advantages. However it should be clearly stated that the ISSTER concept is just an infant and is open to many creative thinkings. The passive thermal switch concept would be the most important one.

REFERENCES

(1) "Feasibility Study on Development of an Advanced Reactor," KAERI/KAIST/SNU Report, July 1991 (in Korean).

(2) "Study on the Advanced Reactor Developments," KOPEC/90-T-017, December 1990 (in Korean).

(3) "The Feasibility Study on the Advanced Reactors in Korea," KEPCO Report KRC-88N-J06, October 1989 (in Korean).

(4) Hannerz,K., "Making Progress on PIUS Design and Verification," Nucl. Eng. Int'l, 29-31, November 1989.

(5) Tower, S.N. et al., "Passive and Simplified System Features for the Westinghouse 600MWe PWR," Nucl. Eng. Des., Vol.109, 147-154, 1988.

(6) Bradbury, R.J. and Redding, J.R., "The Design Goals and Significant Features of the Safe Integral Reactor," Presented at ANS 1989 Annual Meeting, Atlanta, June 1989.

(7) McCandless, R.J. and Redding, J.R., "Simplicity: the Key to Improved Safety, Performance and Economics," Nucl. Eng. Int'l, 20-24, November 1988.

(8) Spinks, N.J. and Dick, J.E., "Passive Heat Rejection Concepts for CANDU Reactors," Proc. 7th KAIF/KNS Annual Conf, Seoul, Korea, 387-395, April 1992.

(9) Kwant, W. et al., "PRISM Reactor Design and Development," Proc. Int. Topical Mtg on Safety of the Next Generation Power Reactors, Seattle, 130-135, May 1988.

(10) Varley, J., "Interest Grows in the Modular HTGR," Nucl. Eng. Int'l, 25-28, November 1989.

(11) Hejzlar, P., Todreas, N.E. and Driscoll, M.J., "Passive Decay Heat Removal in Advanced Reactor Concepts," MIT Report No. MIT-ANP-TR-003, May 1991.

(12) Tang, J.R., Todreas, N.E. and Driscoll, M.J., "Concepts of a Pressure Tube Light Water Reactor with Passive Safety Features," MIT-ANP-TR-008, September 1991.

(13) Baek, W.-P. and Chang, S.H., "Proposed Concept of a Water-Cooled Reactor with Passive Decay Heat Removal Capability," Presented at the IAEA TCM to Review the Safety Features of New Reactor Designs, Vienna, Austria, November 1991.

(14) Chang, S.H. et al., "Conceptual Design Study for Advanced Reactors," CARR/SASA-9201, February 1992.

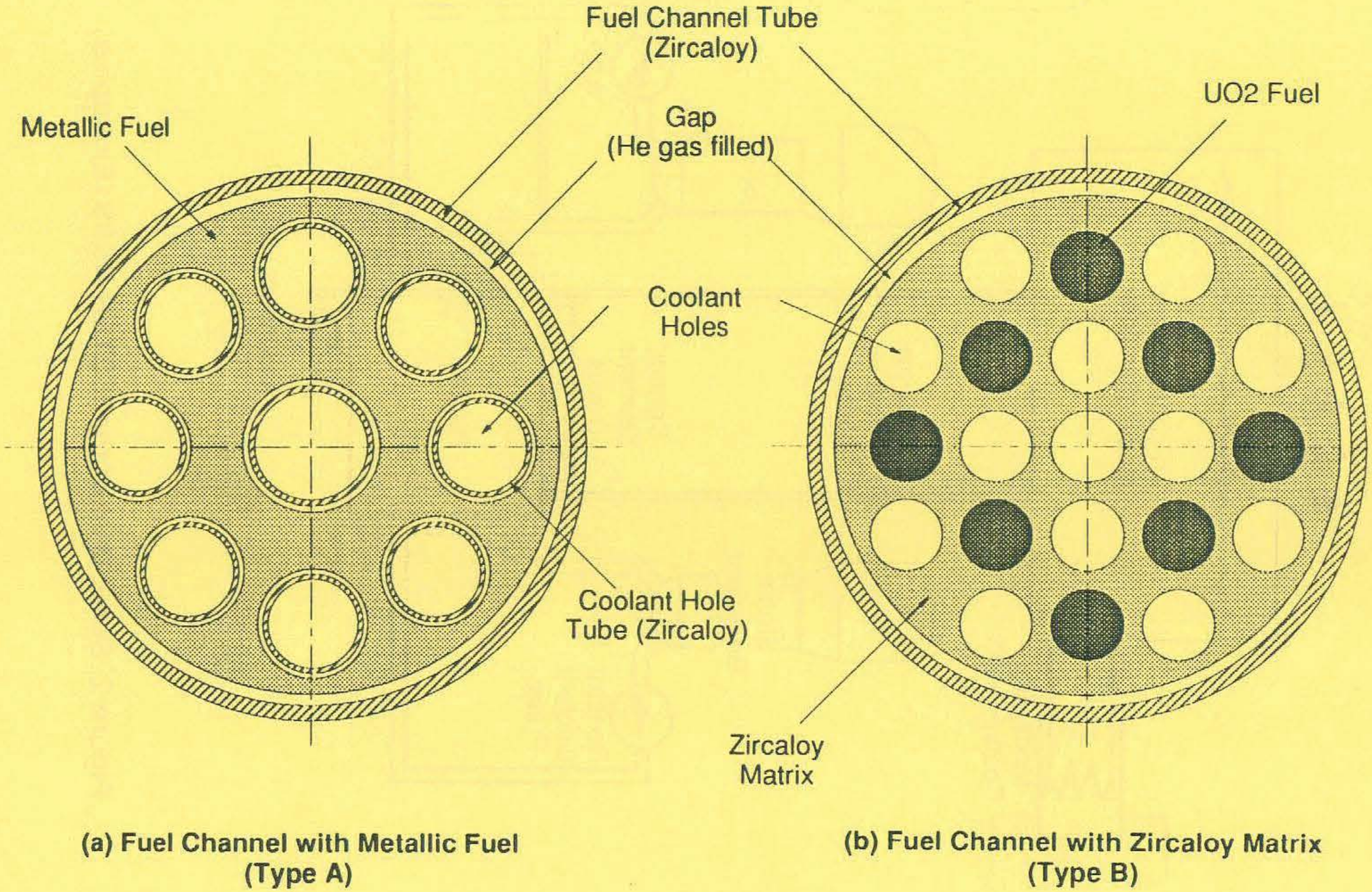

Figure 1. Examples of Fuel Channel Design

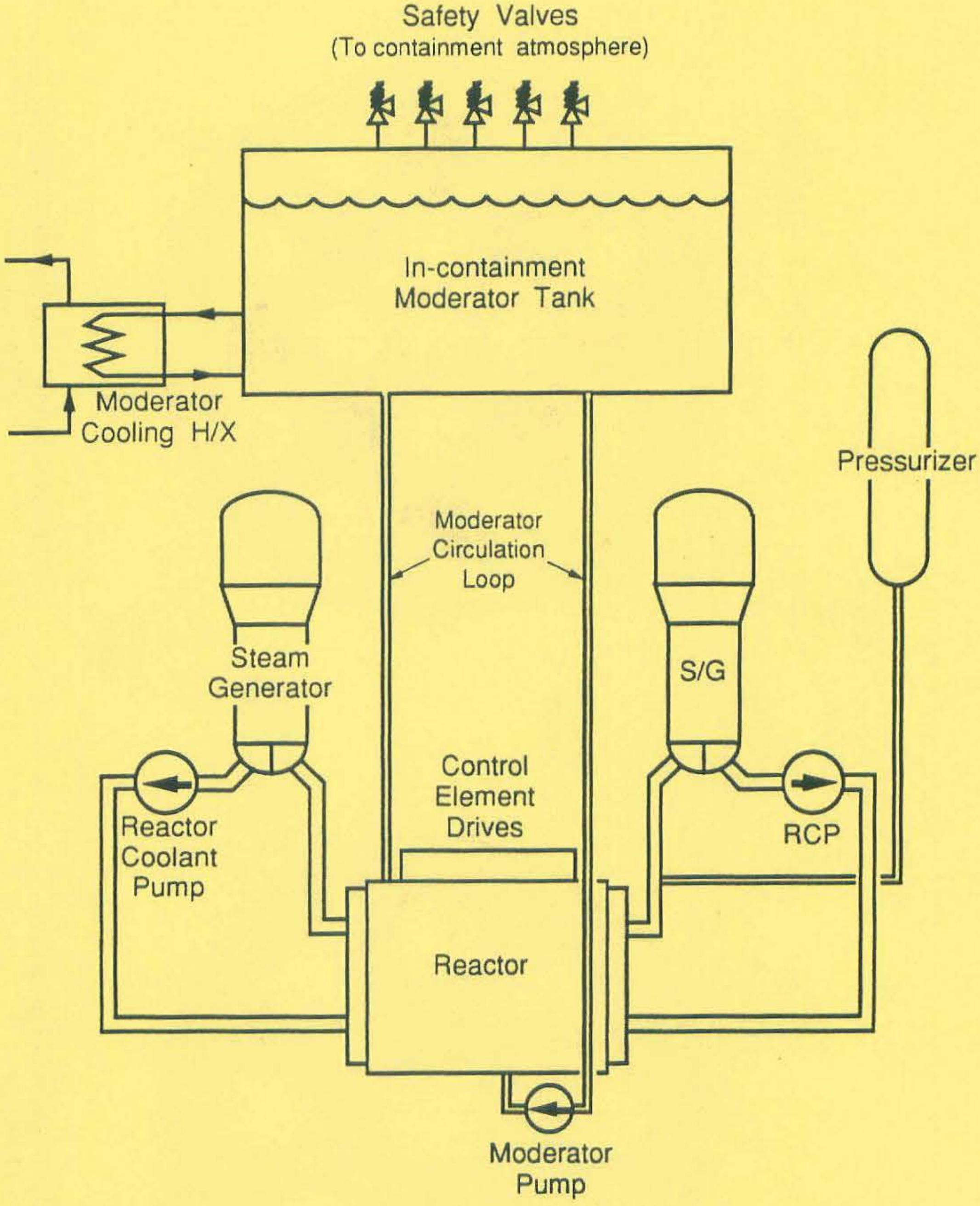

Figure 2 Schematic of the ISSTER NSSS (Examples)

Containment cooling is needed at all levels.

4.0 PASSIVE COOLING CONCEPTS

For the passive design, the containment vessel is a steel shell supporting a water storage tank on the roof and having a water annulus in the walls as shown in Figure 1. The reactor building has the same dimensions as the CANDU 6 containment, with 50 mm walls to withstand the internal pressure of a steam main failure and fins on the outer surface to enhance heat transfer from the water jacket.

Water from the overhead tank flows by gravity to provide make up to the secondary side of the steam generators. The water jacket provides heat storage and rejection for cooling at levels 2 and 3. Water from the jacket flows in natural circulation loops to these heat loads.

The concrete shroud around the reactor building provides a flow path to enhance the natural convection of air for heat rejection from the water jacket. The concrete structure also serves to shield the environment from radiation and to shield the containment vessel from external events. The inner walls of the water jacket and water storage tank are also available to remove heat from the containment atmosphere following an accident.

4.1 <u>Level 1: Emergency Feedwater Supply</u>

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

Operating CANDU reactors have several alternative systems at this level. An auxiliary feedwater system, a low pressure steam generator cooling system and a shutdown cooling system are active systems providing this protection. Current stations also take advantage of the demonstrated ability of the primary coolant to thermosyphon on loss of forced circulation[2]. In addition to level 1 cooling, the steam generators are used for depressurization and cooling of the primary system to support cooling at levels 2 and 3 following a LOCA.

For the passive plant, the low pressure steam generator water supply is designed to be fully passive. Depressurization of the steam generators is initiated automatically and there is sufficient water in the tank to remove decay heat for three days. The active systems (auxiliary feedwater and shutdown cooling) are retained for ease of operation and investment protection.

As shown in Figure 1, each steam generator has an independent connection to the overhead water storage tank, with a check valve and two parallel isolation valves. The storage tank is divided to provide a separate compartment for each steam generator, with sufficient capacity to ensure adequate cooling assuming one steam generator is unavailable. The CANDU 6 has two independent loops in the primary system. As a result each of the four steam generators must have the capacity to remove heat from half the core (approximately 600 m^3 of water in each compartment). The overhead tank is about the same size as the current dousing tank. Work is currently underway to verify that natural circulation cooling of the primary coolant is effective using one of the two steam generators per loop.

4.2 Level 2: Emergency Coolant Injection (ECI)

The second level provides protection if the primary heat transport system fails. Fuel cooling is provided by the emergency coolant injection system.

The CANDU 6 ECI design has a passive high pressure phase and an active low pressure recovery phase. The initial high pressure phase is activated by opening valves which connect a vessel of high pressure gas to a vessel of light water which is thereby injected into the headers of the primary heat transport system. A mixture of light and heavy water collects in a sump in the reactor building basement from which it is pumped through a heat exchanger back to the reactor.

Further simplifications of the CANDU 6 ECI system, as shown in Figure 1, were considered in this study. The elimination of the dousing tank required that a new source of water be found for pumped injection. Providing 600 m^3 of water in the ECI sumps in the basement of the reactor building has several advantages.

- the high energy discharge from the break mixes directly with the sump water
- immediate initiation of the recirculation phase at the end of high pressure injection eliminates the need for medium pressure injection (operator action)
- it may be possible to have the isolation valves in the pump suction line normally open.

The system retains the recovery pumps. The pumps have the same flow as the CANDU 6 pumps but have a 30% higher head to compensate for the static head of the dousing tank. Heat rejection is made passive via a natural circulation loop to the water jacket.

The performance evaluation of the modified ECI system showed that the proposed configuration was capable of cooling the core while maintaining sump temperatures below 75°C for both small and large breaks.