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UK ABWR Generic Design Assessment

Generic PCSR Sub-chapter 13.3 : Emergency Core Cooling System

Hitachi-GE Nuclear Energy, Ltd.

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13.3.1. System Summary Description

This section is a general introduction to the Emergency Core Cooling System (ECCS) where the system roles, system functions, system configuration and modes of operation are briefly described.

13.3.1.1 System Roles

The main roles of the ECCS are to prevent serious damage to the core fuel, suppress the zirconium-water reaction as much as possible and provide long-term decay heat removal in the event of a Loss of Coolant Accident (LOCA). The ECCS consists of the Low Pressure Flooder mode (LPFL) of the Residual Heat Removal System (RHR), the High Pressure Core Flooder System (HPCF), the Reactor Core Isolation Cooling System (RCIC) and the Automatic Depressurisation System (ADS).

13.3.1.2 Functions Delivered

The ECCS is designed to perform the following functions:
(1) The HPCF provides high pressure core cooling water supply to the Reactor Pressure Vessel (RPV) to compensate for water loss during transitional states and LOCA events.
(2) The RCIC provides high pressure core cooling water supply to the RPV to compensate for water loss during transitional states and LOCA events.
(3) The ADS depressurises the RPV in the event of small pipe breaks to provide core cooling in conjunction with the LPFL.
(4) The LPFL provides low pressure core cooling water supply to the RPV to compensate for water loss and removes decay heat in the event of LOCA.

13.3.1.3 Basic Configuration

The ECCS network consists of three independent divisions, I, II, and III as shown on Figure 13.3-1. Each division has high pressure and low pressure water injection function into the RPV. The ADS operates in conjunction with all divisions. The necessary piping, valves, pumps and heat exchangers are included in each division. The configuration is summarised as follows.
Division I: RCIC + LPFL (A)
Division II: HPCF (B) + LPFL (B)
Division III: HPCF (C) + LPFL (C)
All divisions: ADS

The configuration of the HPCF is shown on Figure 13.3-2.
The configuration of the RCIC is shown on Figure 13.3-3.
The configuration of the LPFL is shown on Figure 13.3-4.
The configuration of the ADS is shown on Figure 13.3-5.

13.3.1.4 Modes of Operation

The systems integrating the ECCS network operation are summarised as follows.

13.3.1.4.1 HPCF

The HPCF pumps water through a flooder sparger mounted within the RPV above the reactor core. Coolant is supplied over the entire range of system operation pressures. The primary purpose of the HPCF is to maintain reactor vessel inventory after small breaks which do not depressurise the RPV. The HPCF starts operating automatically in the event of LOCA upon the reactor low water level signal or the drywell high pressure signal in order to maintain the core covered with water in conjunction with the RCIC and the RHR.

13.3.1.4.2 RCIC

The RCIC injects water into one of the two feedwater lines, using a pump driven by a steam turbine. The RCIC steam supply line branches off one of the Main Steam (MS) lines leaving the RPV and goes to the RCIC turbine. The RCIC, in conjunction with the two HPCF divisions, is designed to supply cooling water into the RPV upon high pressure until the vessel pressure drops to the point at which the LPFL can be placed in operation, in the event of a LOCA. The RCIC is initiated automatically upon a predetermined reactor low water level or high drywell pressure signal during LOCA.

13.3.1.4.3 ADS

The ADS utilises a number of the reactor Safety Relief Valves (SRVs) to reduce reactor pressure during small breaks in the event that the HPCF and the RCIC cannot maintain cooling or reactor water level. When the RPV pressure is reduced to within the injection capacity of the LPFL, this system provides inventory makeup so that acceptable post-accident temperatures are maintained. Specifically, the piston actuator of the SRVs is driven by the simultaneous signal of low reactor water level and high drywell pressure to forcibly open the SRVs and quickly reduce the nuclear reactor pressure upon small and medium piping breaks. Thus, makeup from the LPFL can be provided into the RPV. Seven valves out of the 16 SRVs are provided with this function.

13.3.1.4.4 LPFL

The LPFL has three independent loops and delivers water to the core at relatively low reactor pressures. The primary purpose of the LPFL is to provide inventory makeup and core cooling during large breaks and to provide containment cooling. Following ADS initiation, the LPFL can also provide inventory makeup and core cooling in the event of small breaks.

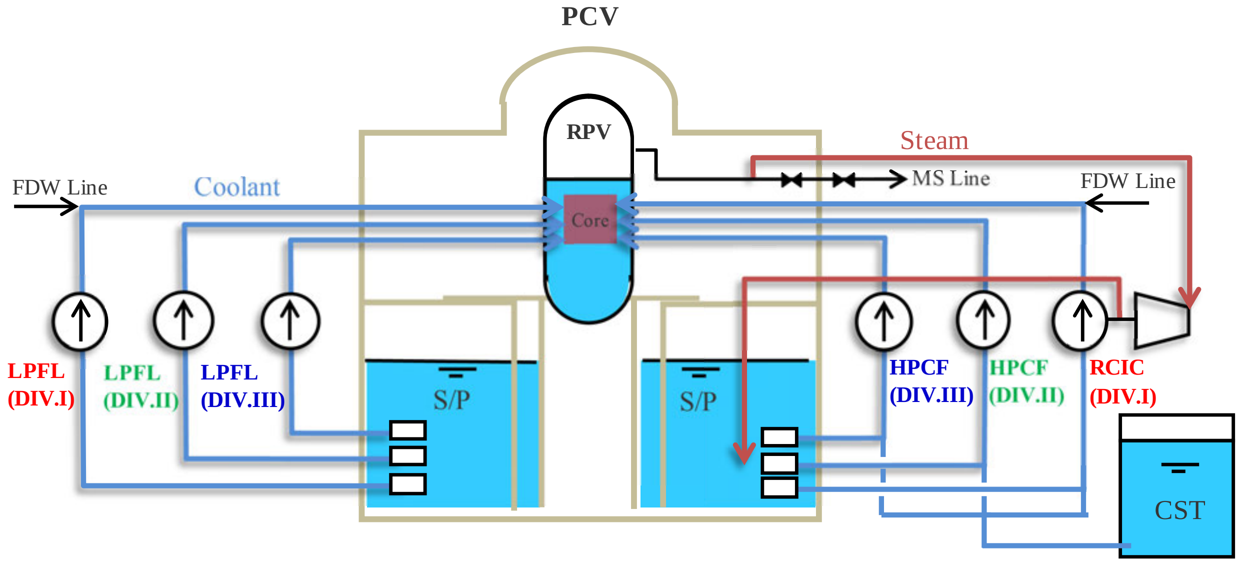

Figure 13.3-1 : Outline of the ECCS Network

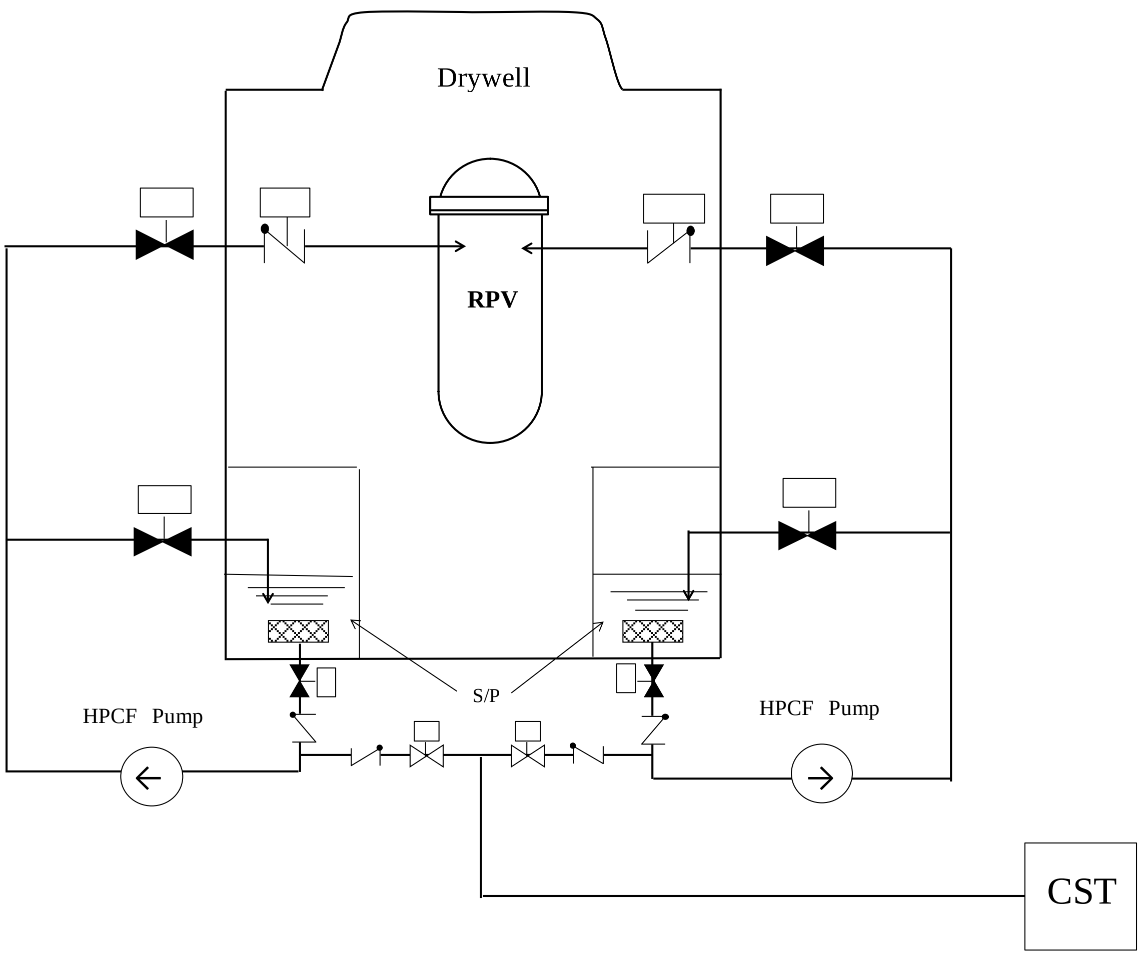

Figure 13.3-2 : Outline of the HPCF

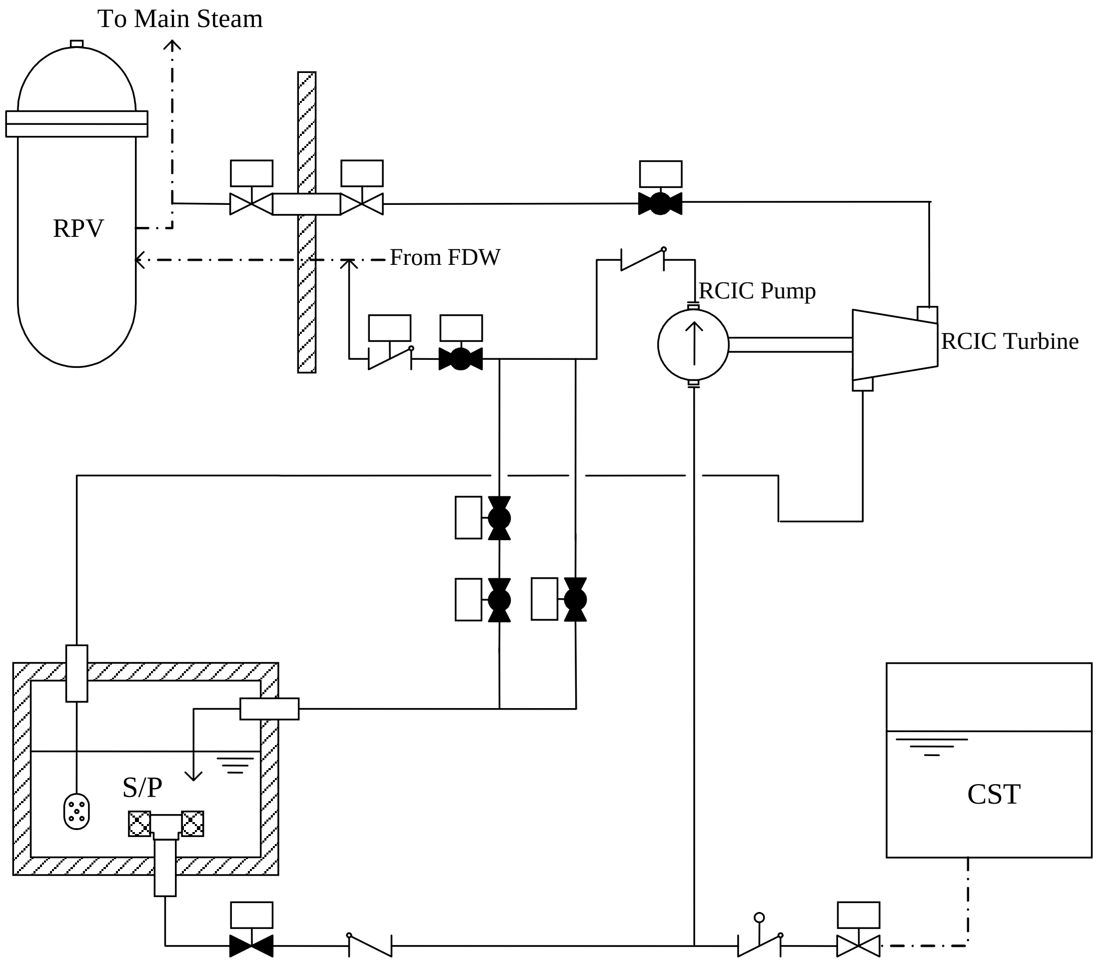

Figure 13.3-3 : Outline of the RCIC

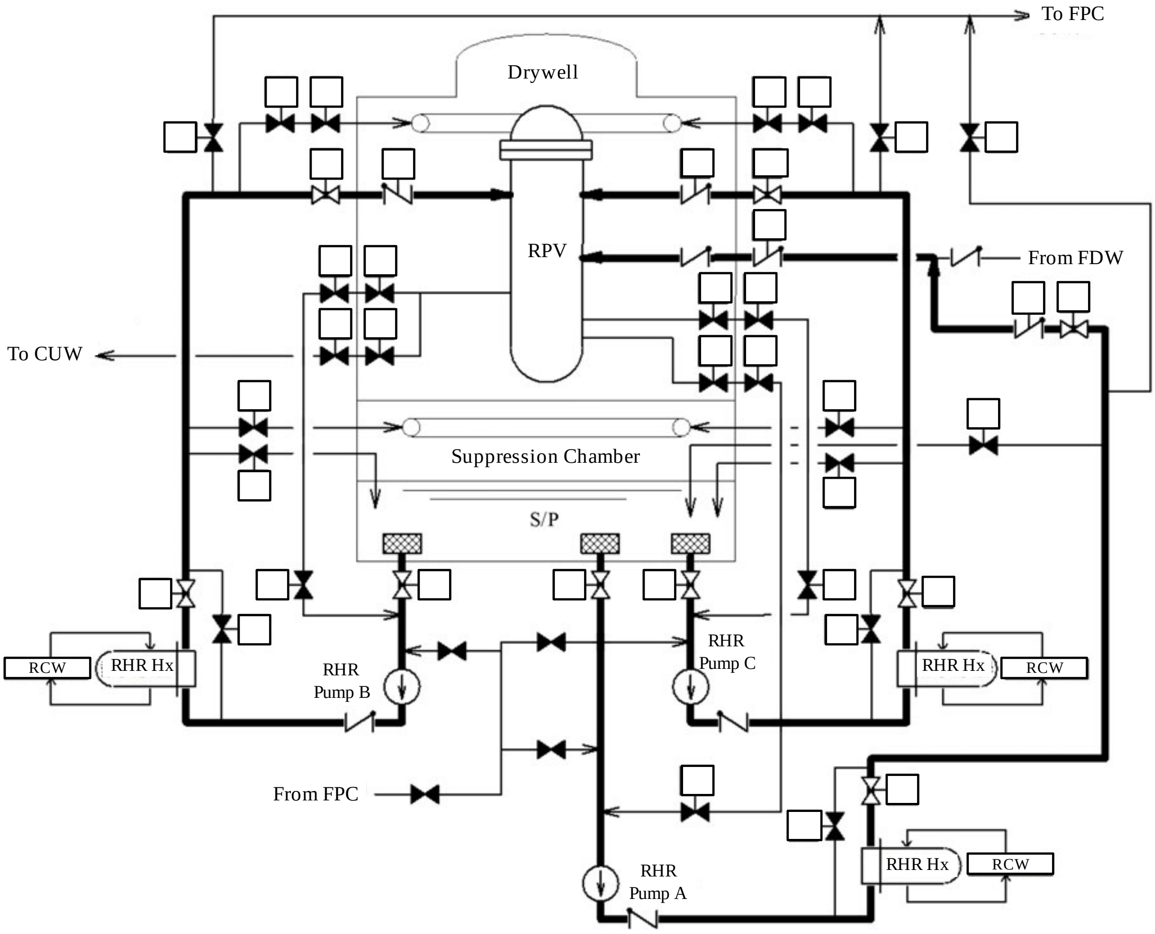

Figure 13.3-4 : Outline of the LPFL

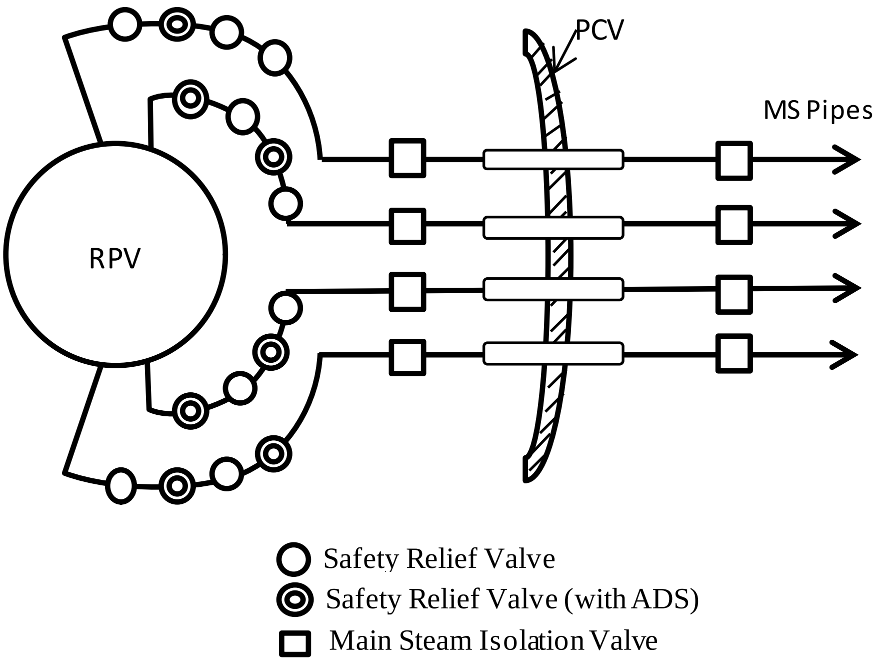

Figure 13.3-5 : Outline of the ADS

13.3.2. Design Bases

(1) Part of the ECCS forms the Reactor Coolant Pressure Boundary (RCPB). Therefore, the components within the RCPB ensure the pressure integrity of the boundary and preserve reactor coolant, loss of which would lead to consequences above the Basic Safety Level (BSL). From this perspective, the ECCS delivers a Category A safety function (confinement) and the components necessary to deliver this function are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.
This safety function is developed and justified in the section 12.1.3 related to the RCPB in chapter 12.

(2) The ECCS is the principal means to provide reactor core cooling so that significant damage to the fuel is prevented and the reaction between the fuel cladding and the reactor coolant is sufficiently minimised in the event of frequent and infrequent faults such as LOCA. From this perspective, the ECCS delivers a Category A mitigation function, and as principal means, the components necessary to deliver core cooling are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.

(a) The HPCF is a principal means to provide reactor core cooling as part of the ECCS so that significant damage to the fuel is prevented and the reaction between the fuel cladding and the reactor coolant is sufficiently minimised in the event of frequent and infrequent faults such as LOCA. From this perspective, the HPCF delivers a Category A mitigation function, and as principal means, the components necessary to deliver core cooling are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.

(b) The RCIC is a principal means to provide reactor core cooling as part of the ECCS so that significant damage to the fuel is prevented and the reaction between the fuel cladding and the reactor coolant is sufficiently minimised in the event of frequent and infrequent faults such as LOCA. From this perspective, the RCIC delivers a Category A mitigation function, and as principal means, the components necessary to deliver core cooling are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.

(c) The ADS is a principal means to depressurise the RPV in order to provide reactor core cooling as part of the ECCS so that significant damage to the fuel is prevented and the reaction between the fuel cladding and the reactor coolant is sufficiently minimised in the event of infrequent faults such as LOCA. From this perspective, the ADS delivers a Category A mitigation function, and as a principal means, the components necessary to deliver reactor core cooling are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.

(d) The LPFL is a principal means to provide reactor core cooling as part of the ECCS so that significant damage to the fuel is prevented and the reaction between the fuel cladding and the reactor coolant is sufficiently minimised in the event of infrequent faults such as LOCA. From this perspective, the LPFL delivers a Category A mitigation function, and as principal means, the components necessary to deliver core cooling are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.

(3) Part of the ECCS forms the Primary Containment Vessel Boundary (PCV Boundary). Therefore, the components within the PCV boundary form a barrier to maintain the integrity of the boundary and thus prevent the dispersion of radioactive material. From this perspective, the ECCS delivers a Category A safety function (confinement) and the components necessary to deliver this function are classified as Class 1 safety components according to the safety categorisation and classification of UK ABWR.
This safety function is developed and justified in the section 13.2.3.1 related to the Primary Containment Facility in chapter 13.

13.3.3. System Design

This section describes the design of the ECCS to satisfy the design bases.

13.3.3.1 Overall Design and Operation

13.3.3.1.1 HPCF

The HPCF is composed of two electrical and mechanically independent and separated HPCF divisions designated B and C. The two divisions are both high pressure pumping systems (i.e., they are capable of injecting water into the RPV over the entire operating pressure range) with the necessary piping, pumps, valves, instrumentation and controllers each. Rated flow at both high and low pressure is the same for each division.

The HPCF is on standby during normal reactor operation and each motor-operated valve remains at their normal position (open/closed). Condensate water is continuously supplied by the Makeup Water Condensate System (MUWC) to maintain the pumps discharge line filled with water during this mode and thus minimise the time lag between a starting signal and initiation of flow into the RPV and to minimise momentum forces associated with accelerating fluid into an empty pipe.

The HPCF starts operating automatically upon detection of reactor low water level (Level 1.5) or drywell high pressure (13.7kPa [gauge]) from four independent and redundant sensors (two-out-of-four logic). The HPCF is capable of manual initiation as well. Suction is taken from the normal suction source with the pump discharge diverted through the minimum flow lines to the Suppression Pool (S/P) until sufficient pump flow rate and pressure has been developed to discharge into the RPV. The HPCF Pump and injection valve are designed to inject flow into the RPV within the time required by the safety analysis after receipt of initiation signal. The injection valves on the discharge lines will automatically close after automatic initiation if the RPV water level increases to a determined high level (Level 8). The valves reopen if the reactor water level decreases to a low level again (Level 1.5). Each minimum flow valve opens automatically if the main line flow rate is low, allowing the HPCF Pump to discharge at minimum flow rate into the S/P. Once the HPCF emergency mode is initiated, the system remains operating until manually stopped by the operator.

The HPCF takes primary suction from the Condensate Storage Tank (CST) and secondary suction from the S/P. In the event CST water level falls below a predetermined setpoint or S/P water level rises above a predetermined setpoint, the pump suction will automatically transfer from the CST to the S/P. The HPCF suction lines are independent from the RHR.

The HPCF discharges water into the core via a separate flooder sparger within the RPV. Internal piping connects each sparger to the vessel nozzle. The HPCF is provided with a test line which discharges to the S/P to allow testing of pump function.

13.3.3.1.2 RCIC

The RCIC consists of a steam-driven turbine which drives a pump assembly. The system also includes piping, valves, and instrumentation necessary to implement several flow paths. The RCIC steam supply line branches off one of the MS lines (leaving the RPV) within the PCV and goes to the RCIC turbine with drainage provision to the Main Condenser. The turbine exhausts to the S/P with vacuum breaking protection. Makeup water is supplied from the CST and the S/P with the preferred source being the CST. RCIC Pump discharge lines include the main discharge line to the feedwater line, a test return line to the S/P and a minimum flow bypass line to the S/P.

During normal plant operation, the RCIC is on standby with the motor-operated valves in their normal positions (open/closed). The MUWC is operating to keep the RCIC Pump discharge line filled during this mode to minimise the time lag between a starting signal and initiation of flow into the RPV and to minimise momentum forces associated with accelerating fluid into an empty pipe.

Following the reactor scram, steam generation in the reactor core will continue at a reduced rate due to the core fission product decay heat. The turbine bypass system will divert the steam to the Main Condenser, and the Feedwater System (FDW) will supply the makeup water required to maintain the RPV inventory. In the event that the RPV is isolated (Main Condenser unavailable), and the feedwater supply is unavailable, the SRVs are provided to automatically (or remote manually) maintain reactor pressure within desired limits. The water level in the RPV will drop due to continued steam generation by decay heat. Upon reaching a predetermined low level (Level 2, auxiliary feedwater mode operating signal), the RCIC is initiated automatically. The turbine-driven pump will supply water from the CST to the RPV. The turbine will be driven with a portion of the decay heat steam from the RPV, and will exhaust to the S/P until the RPV is depressurised to a level at which the RHR Shutdown Cooling mode can start operation. If the water level drops to Level 1.5 the HPCF will be initiated as a backup.

In the event that there is a LOCA, the RCIC, in conjunction with the HPCF, automatically starts, and delivers the design flow rate within the time required by the safety analysis upon receipt of the accident mode operating signal (low reactor water level (Level 1.5) or high drywell pressure signal (13.7kPa [gauge]) if not already initiated by the feedwater mode operating signal) from four independent and redundant sensors (two-out-of-four logic). The RCIC is designed to pump water into the RPV while it is fully pressurised. This combination of systems will provide adequate core cooling until vessel pressure drops to the point at which the LPFL can be placed in operation (Level 1).

The RCIC turbine shuts off automatically upon receipt of any of high water level in the RPV (Level 8). The valves reopen to restart RCIC operation if the reactor water level decreases to a low level again (Level 1.5). The RCIC is capable of manual initiation by the operator in case initiation or shutoff signals are not initiated.

During RCIC operation, the S/P acts as the heat sink for steam generated by reactor decay heat.

13.3.3.1.3 ADS

If the RCIC and HPCF cannot maintain the reactor water level, the ADS, which is independent of any other ECCS, reduces the reactor pressure so that flow from the RHR operating in the LPFL enters the RPV in time to cool the core and limit fuel cladding temperature.

The ADS employs seven out of 16 SRVs which are provided with ADS function of the Nuclear Boiler System (NB) to relieve high pressure steam directly to the S/P and condense it. The SRVs with ADS function are provided with and additional accumulator dedicated for ADS operation in addition to the accumulator for SRV relief operation. Like the accumulator for relief operation, the ADS accumulator of the SRVs with ADS function is also connected to High Pressure Nitrogen Gas Supply System (HPIN) through the normal nitrogen gas evaporator and the nitrogen gas cylinder rack for backup as additional supply. The SRVs are designed to be able to open by the nitrogen gas stored in the accumulators even if the nitrogen gas supply system in the PCV was damaged. A check valve is mounted on the nitrogen supply line to each accumulator so that the internal pressure of the accumulator does not drop rapidly in the event that the supply system on the upstream side of the accumulator was damaged.

SRVs with ADS function are provided with three solenoid valves to control them from the Main Control Room (MCR), one for operation of the accumulator for SRV relief function and two for operation of the accumulator for ADS function. The solenoid valves are remotely and independently operated.

The SRVs forming ADS are actuated automatically upon LOCA and maintained opened by the ADS accumulator to depressurise the RPV even if the pressure drops below the closing set pressure of the valves. The actuation signal is initiated by the simultaneous high drywell pressure and low reactor water level (Level 1) signals in conjunction with signal that one RHR or HPCF Pump is in operation. The SRVs are designed to open with a sufficient delay after receiving an accident signal to prevent unnecessary operation by a false signal etc., since the actuation of this function involves a loss of reactor water to the S/P.

13.3.3.1.4 LPFL

The LPFL is composed of three electrical and mechanically independent and separated RHR divisions designated A, B, and C. Each division contains the necessary piping, pumps, valves, heat exchangers, instrumentation and controllers.
The LPFL is an operation mode of the RHR, which by switching the position of the valves, can operate to deliver low pressure core cooling function as described below. Common design aspects with the rest of RHR modes are described in chapter 12.

The RHR is on standby and the motor-operated valves are at their normal positions (close/open) during plant normal operation. The pump discharge lines are continuously kept filled with condensate water via the MUWC during standby to minimise the time lag between a starting signal and initiation of flow into the RPV and to minimise momentum forces associated with accelerating fluid into an empty pipe.

The LPFL supplies sufficient coolant to maintain the fuel cladding temperature below the design basis criteria and remove the core decay heat during LOCA. During this mode, the RHR draws water from the S/P and injects the water into the RPV outside the core shroud (RHR division A injects water via the feedwater line A and divisions B and C via their respective low pressure lines into the RPV).

The LPFL is initiated automatically upon drywell high pressure or reactor low water level (Level 1) starting signals from four independent and redundant sensors (two-out-of-four logic), and therefore no operator action is required during the first 30 minutes following an accident. The RHR Pump and injection valve are designed to allow water injection into the reactor in less than the time required by the safety analysis after receiving the automatic initiation and reactor low pressure permissive signals, which is the time required for the pump to reach rated revolutions and the injection valve to fully open.
This mode can also be initiated manually. Once the LPFL starts, the operation continues until the mode is manually shut off by the operator.

The RHR is provided with a minimum flow bypass line to return the water to the S/P to prevent pump damage until the pump reaches the necessary injection flow and pressure while the injection valve is closed. A motor-operated valve on the bypass line automatically closes when the flow in the main discharge line is sufficient to provide reactor core cooling.
The RHR is provided with a test line which discharges to the S/P to allow testing of pump function.

13.3.3.2 Equipment Design and Operation

13.3.3.2.1 HPCF Pump

(1) Configuration
Each division of the HPCF is provided with one turbo type pump of approximately 182m^3/h of design flow rate driven by an induction motor to deliver high pressure core flooding for reactor cooling. This flow rate satisfies the required minimum flow rate to maintain reactor water level according to the safety analysis. Therefore, a total of two pumps delivering approx. 182m^3/h each are provided.

(2) Performance
The HPCF Pump is designed to perform as follows:

Table 13.3-1 : HPCF Pump Capacity

Item	Flow Rate	
	High Pressure	Low Pressure
Flow (m^3/h)	approx. 182	approx.727
Total Head (m)	approx.890 (provisional)	approx.190 (provisional)

The HPCF Pumps are designed such that they can be initiated with the injection valves closed and reach rated flow within the time required by the safety analysis after receiving the initiation signal.

13.3.3.2.2 RCIC Pump

(1) Configuration
The RCIC is provided with one steam-driven turbine which drives a pump assembly (provisional) of approximately 182m^3/h (provisional) of design flow rate to deliver high pressure core flooding for reactor cooling. This flow rate satisfies the required minimum flow rate to maintain reactor water level according to the safety analysis. Therefore, one pump delivering approx. 182m^3/h (provisional) is provided.

(2) Performance
The RCIC Pump is designed to perform as follows:

Table 13.3-2 : RCIC Pump Capacity

Item	Flow Rate
Flow (m^3/h)	approx.182 (provisional)
Total Head (m)	approx. 900 to 186 (provisional)

The RCIC Pump is designed such that it can be initiated with the discharge valves closed and reach rated flow within the time required by the safety analysis after receiving the initiation signal.

13.3.3.2.3 SRVs with ADS Function

(1) Configuration
A total of seven SRVs are provided on the MS lines between the RPV and the inboard MSIV within the drywell to deliver RPV depressurisation by ADS function.
The SRVs are spring loaded safety valves to which an actuator is attached to remotely force them to open and close by supplying nitrogen to the piston of the actuator. Nitrogen is supplied

by an accumulator which is kept charged during normal operation and the SRV valve is opened by energising any of the two solenoid pilot valves to discharge nitrogen from the accumulator into the pneumatic cylinder.

(2) Performance

Seven large capacity SRVs with a discharge flow rate per valve of approx. 460t/h under reactor pressure at approx. 7.92MPa [gauge] (minimum discharge pressure for safety operation) are provided for ADS, with a total discharge capacity of approximately 3,100t/h sufficient to satisfy the discharge capacity required by the safety analysis.

The SRV accumulators for ADS operation are designed with approximately 220L of capacity each to hold the SRVs open following loss of the nitrogen supply to the accumulators and perform ADS actuation.

The SRVs are designed such that the time delay until the SRV initiates operation after reception of the open signal at the solenoid valve and the response time until the SRV fully opens is sufficient to perform depressurisation within the time required by the safety analysis.

13.3.3.2.4 RHR Pump

(1) Configuration

Each division of the LPFL is provided with one turbo type pump of approximately 954m^3/h design flow rate driven by an induction motor to deliver heat removal after reactor shutdown and low pressure core flooding for reactor cooling. This flow rate satisfies the required minimum flow rate to maintain reactor water level according the safety analysis. Therefore, a total of three pumps delivering 954m^3/h each are provided.

(2) Performance

The RHR Pump is designed to perform as follows:

Table 13.3-3 : RHR Pump Capacity

Item	Flow Rate
Flow (m^3/h)	approx. 954
Total Head (m)	approx. 125 (provisional)

The RHR Pumps are designed such that they can be initiated with the injection valves closed and reach rated flow within the time required by the safety analysis after receiving the initiation signal.

13.3.3.3 Main Support Systems

13.3.3.3.1 Instrumentation and Control

(1) Instrumentation

Instrumentation is provided to measure and monitor the operating conditions of the ECCS components necessary for the delivery of reactor core cooling. The main provisions for instrumentation are described as follows.

(a) ECCS control devices are centralised in one area inside the MCR such that the minimum number of operators can control the system operation and the pump operating conditions, the position of valves, etc. can be easily understood

(b) Pressure detectors are provided in the pump discharge lines in order to verify the seal water conditions and to raise an alarm if low pressure is detected.

(c) Local pressure indicators are installed at the pump suction lines to monitor the pump NPSH and head.

(d) Flow-meters are mounted to monitor system flow rate.

(e) Instruments to detect the water level in the CST and S/P are provided to control suction valves switch.

(2) Control

The main control provisions related to the delivery of the reactor core cooling are summarised as follows.

(a) General
   (i) Reactor Water Level 8: the RCIC Turbine is tripped and the HPCF injection valve closed if RCIC or HPCF divisions are operating.
   (ii) Reactor Water Level 2: initiation of RCIC water supply at this level, which is set at a sufficiently low level to prevent RCIC spurious initiation if the feedwater supply is still available after reactor scram at Level 3 (auxiliary feedwater mode).
   (iii) Reactor Water Level 1.5: initiation of RCIC emergency core cooling operation and HPCF.
   (iv) Reactor Water Level 1: ADS is initiated (simultaneously with high drywell pressure signal) and water is supplied into the RPV by operating the LPFL mode of the RHR, which is also initiated at Level 1.

(b) HPCF
   (i) The water source is switched to the S/P upon low CST level or a high S/P level.
   (ii) HPCF is switched from the test flow mode to the emergency mode upon receipt of the initiation signal.

(c) RCIC

The cooling water source is automatically switched to the S/P if the water level in the CST is low or the water level in the S/P is high after RCIC initiation.

(d) LPFL
   (i) Pressure transmitters are mounted on the RHR Pump discharge lines for transmission of the signal allowing ADS operation.
   (ii) The RHR Pumps start automatically after confirmation of power supply once the initiation signal has been received.
   (iii) An interlock is provided to prevent LPFL injection valve opening whenever pressure is above the high pressure limits. These valves are closed if the pressure increases during operation.

13.3.3.3.2 Power Supply System

(1) Power supply for ECCS components, valves, instrumentation and controllers come from the Electrical Power Distribution System.

(2) The ECCS is connected to separated and independent divisions of AC and DC power sources supplying the required power to all electrical components in each division (Division I is connected to power Division I, Division II is connected to power Division II and Division III is connected to power Division III).

(3) The normal AC and DC power supply to the ECCS electrical components is provided by an independent and reliable off-site source (external grid). In addition, independent divisional power sources such as standby diesel generators provide a reliable source of electrical power in the event of Loss of Off-site Power (LOOP).

(4) The Emergency Diesel Generator of each division provides power for all ECCS components in the corresponding division which require electrical supply when normal AC and DC power sources are not available.

13.3.3.3.3 Reactor Building Cooling Water System (RCW)

The RCW supplies water to the HPCF Pump mechanical seal and the motor bearing coolers, the RHR Heat Exchangers, RHR Pumps, motors, bearings and seal water cooling equipment. The RHR and HPCF are connected to independent and separated RCW divisions. RHR division A components are supplied cooling water by RCW division A, RHR division B and HPCF division B components are supplied cooling water by RCW division B and RHR division C and HPCF division C components are supplied cooling water by RCW division C.

13.3.3.4 System Architecture

13.3.3.4.1 Redundancy

The ECCS consists of three redundant divisions I, II, and III, each one of them is provided with high pressure and low pressure core cooling systems and with their respective pumps, heat exchangers, strainers, piping, valves, test line, minimum flow line and instrumentation. In addition, the ADS working in conjunction with all divisions is provided with redundant SRVs, accumulators and solenoid pilot valves. Furthermore, the systems supporting ECCS functions such as the C&I for initiation signals (two-out-of-four logic), power supply, cooling water, HVAC, etc. are also redundant and dedicated for the corresponding ECCS division. The configuration is such that, single failure of any dynamic mechanical or electrical component under the worst permissible availability state does not prevent the delivery of the safety function. The configuration is as shown below:
Division I: RCIC + LPFL (A)
Division II: HPCF (B) + LPFL (B)
Division III: HPCF (C) + LPFL (C)
All divisions: ADS

13.3.3.4.2 Independence

The three divisions forming the ECCS are independent and separately arranged in different locations within the Reactor Building (R/B) to prevent failure of a component in one of the divisions from leading to a common cause failure of all divisions. The components forming the ADS are independent and are separated as far as practicable within the PCV to prevent failure of a single component affecting other or leading to common cause failure. Furthermore, the redundant supporting systems for each division of ECCS and ADS (C&I, power supply, cooling water, etc.) are independent and separated as well.

13.3.4. System Design Evaluation

Performance of the ECCS is determined by evaluating the system response to an instantaneous break of a pipe (LOCA). The analyses included in this subsection demonstrate the ABWR ECCS performance for the entire spectrum of postulated break sizes.

13.3.4.1 Evaluating Event

The key events evaluated assume that reactor coolant flows out of system and cooling capacity of reactor core is reduced, due to damage to piping which is part of the RCPB and associated equipment during rated power operation of the reactor.

As pipe breaks, breaks of MS line, FDW line, RHR outlet line, LPFL line, HPCF line, and Drain line which connect to RPV are analysed and evaluated.

For all piping breaks in ABWR, Peak Cladding Temperature (PCT) during all piping break events is almost the same, and the inventory of the coolant reduces the most during the HPCF piping break event. Therefore, the HPCF piping break is selected as representative break and evaluated in the following subsection.

13.3.4.2 Analysis Method

The following three analysis codes are used in the analysis:

(a) LAMB: short-term thermal hydraulic transient analysis code
(b) TASC: single-channel thermal hydraulic analysis code
(c) SAFER: long-term thermal hydraulic transient analysis code

Core flow transient and critical power transient should be analyzed using LAMB and TASC immediately after the accident, due to rapid change of thermal hydraulic behaviour after the accident. Thereafter, long-term core pressure, water level transient, and core heat-up are evaluated by using SAFER. Detailed descriptions of these computer codes and the modelling of LOCA cases can be found in section 24.3.3.2 of chapter 24.

Figure 13.3-6 shows the flow chart of the above analysis.

13.3.4.3 Acceptance Criteria

Acceptance criteria to prevent significant damage to the fuel and to sufficiently minimize the reaction between the fuel cladding and the reactor coolant are as follows:

(a) The calculated maximum fuel element cladding temperature shall not exceed 1,200 °C.
(b) The calculated total local oxidation of fuel cladding shall nowhere exceed 15% of the total thickness of cladding before oxidation.

The basis of above criteria is presented in section 11.2.1.1.12 of chapter 11.

13.3.4.4 Analysis Conditions

Following analysis conditions are assumed.

(1) The reactor is assumed to operate at about 102% of rated power (thermal power: 4,005 MW) and 100% of rated core flow (52.2 x 10^3 t/h) before the accident. Initial reactor pressure is 7.17MPa [gauge].
(2) Peak linear heat generation ratio of a fuel rod is 102% of 44.0kW/m, which is the operating limit. Also, for gap conductance between fuel cladding and pellet, the value to make the analysis result more conservative is used in consideration of responses during the cycle exposure.
(3) For decay heat after the shutdown of the reactor, 1.2 times the values of 1971 ANS Standard is used.
(4) Off-site power is lost concurrently with the occurrence of the accident and the ten units of recirculation pumps trip simultaneously.
(5) It is assumed that initial water level is at low reactor water level (Level 3) to conservatively reduce the inventory of the coolant, and reactor scram is initiated concurrently with the occurrence of the accident.
(6) It is considered that a signal for high drywell pressure as an ECCS start-up signal is given earlier than a signal for a low reactor water level (Level 1.5 or 1), but ECCS is assumed to conservatively start up at the signal for the low reactor water level.
(7) The most conservative single failure is assumed in the ECCS network from the viewpoint of the capability of reactor cooling. The most conservative single failure in the case of the HPCF pipe break accident is a failure of an emergency diesel generator that supplies power to an intact HPCF.
(8) The leakage of coolant from the break is calculated based on the homogeneous critical flow model.
(9) The opening pressure of the safety relief valves is 1.03 times higher than the setpoint in consideration of setting error.
(10) For heat transfer coefficient between fuel cladding and coolant in the calculation of the fuel cladding temperature, the following correlations are used:
    (a) Nucleate boiling cooling: correlation used as a function of void fraction
    (b) Film boiling cooling: mist cooling correlation and the Modified Bromley correlation are used as functions of void fraction
    (c) Transition boiling cooling: correlation in which heat transfer coefficients of nucleate boiling and film boiling are interpolated with the fuel cladding superheat
    (d) Steam cooling: Dittus-Boelter correlation
    (e) Mist cooling: Dittus-Boelter correlation and dispersed droplet flow film boiling
(11) The volume of oxidation of fuel cladding produced by zirconium-water reaction is calculated using Baker-Just equation.

Table 13.3-4 shows the main calculation conditions used for the analysis.

13.3.4.5 Analysis Results

(1) Responses of core flow, reactor pressure, reactor water level and fuel cladding temperature

After the occurrence of the double-ended break of HPCF line, critical flow occurs at HPCF sparger nozzle having the smallest area within the flow path from the HPCF sparger to the break.

In the assumption of the loss of off-site power occurring concurrently with the accident, core flow rapidly decreases because of trip of the recirculation pumps.

Due to the rapid decrease of core flow, MCPR decreases below 1.0 in about 1 second after the accident, and boiling transition occurs as far as the fourth spacer position from the top of the fuel assembly. Consequently, heat transfer coefficient from fuel cladding to coolant decreases, and fuel cladding temperature increases. However, the increase of fuel cladding temperature subsides within a short time because of the decrease of power due to reactor scram.

On the other hand, water level inside the core shroud starts to decrease. However, RCIC is activated by signal of low reactor water level (Level 1.5) and starts water injection in about 106 seconds after the accident. ADS is also activated to lower the reactor pressure by signal of high drywell pressure and signal of low reactor water level (Level 1) in about 185 seconds after the accident, and two LPFL actuated by signal of low reactor water level (Level 1) begin to inject water in about 373 seconds. Water level inside the core shroud does not decrease below top of active fuel, and the core is kept flooded. Therefore, temperature increase of fuel cladding because of core uncovering does not occur. That is, fuel cladding temperature does not increase above the temperature increase due to the boiling transition immediately after the accident.

Figure 13.3-7 shows the reactor water level transient, and Figure 13.3-8 shows the reactor pressure transient during accident. Figure 13.3-9 shows the heat transfer coefficient transient at the position where fuel cladding temperature is maximum, and Figure 13.3-10 shows the fuel cladding temperature transient. Peak fuel cladding temperature during accident is about 640 °C.

(2) Perforation and oxidation of fuel cladding

Fuel rods can be perforated when fuel cladding temperature increases after an accident if the hoop stress of fuel cladding due to internal pressure exceeds the perforation stress at that temperature.

Fuel cladding temperature in this reactor is about 640 °C or less during the double-ended break accident of HPCF line. In the postulated accident, the calculated hoop stress of fuel cladding is less than the value at which fuel cladding is perforated. Therefore, fuel rods are not perforated at LOCA.

Increase of oxide layer thickness on the fuel cladding is very small because fuel cladding temperature is relatively low.

(3) Summary of analysis results

In the assumption of the most conservative single failure at LOCA, the peak cladding temperature in the case of the double-ended break of HPCF line is about 640°C and is below 1,200°C. Therefore, the acceptance criteria (a) are satisfied.

Increase of oxide layer thickness on the fuel cladding is very small and does not exceed 15% of the thickness of fuel cladding before the oxidation reaction gets significant. Therefore, the acceptance criteria (b) are satisfied.

The fuel cladding does not lose its ductility, and there is no fuel rod rupture.

In the case of the split breaks of HPCF line or the breaks of various other lines, fuel cladding temperature is the same as in the case of the double-ended break of HPCF line.

Table 13.3-4 : Main Calculation Conditions for LOCA

Items	Values
Reactor thermal power	About 102% of the rated power (4,005MW)
Peak linear heat generation ratio	44.0 kW/m x 1.02
Core flow	100% of the rated flow rate (52.2 x 10^3 t/h)
Reactor pressure	7.17 MPa[gage]
Core inlet enthalpy	1.23 MJ/kg
High Pressure Core Flooder System (HPCF) flow (rated value)	727 m^3/h (at 0.689 MPa[dif] per pump)*
Low Pressure Flooder System (LPFL) flow (rated value)	954 m^3/h (at 0.276 MPa[dif] per pump)*
Reactor Core Isolation Cooling System (RCIC) flow (rated value)	182 m^3/h (at 8.115 to 1.034 MPa[dif] per pump)*
Setpoints for low reactor water level (main steam isolation valve closing, and HPCF, RCIC (ECCS function) and emergency diesel generator (divisions II and III) starting)	Level 1.5
Setpoints for low reactor water level (LPFL, emergency diesel generator (division I) and Automatic Depressurization System (ADS) starting)	Level 1

*: MPa[dif] : differential pressure between reactor pressure vessel and water source

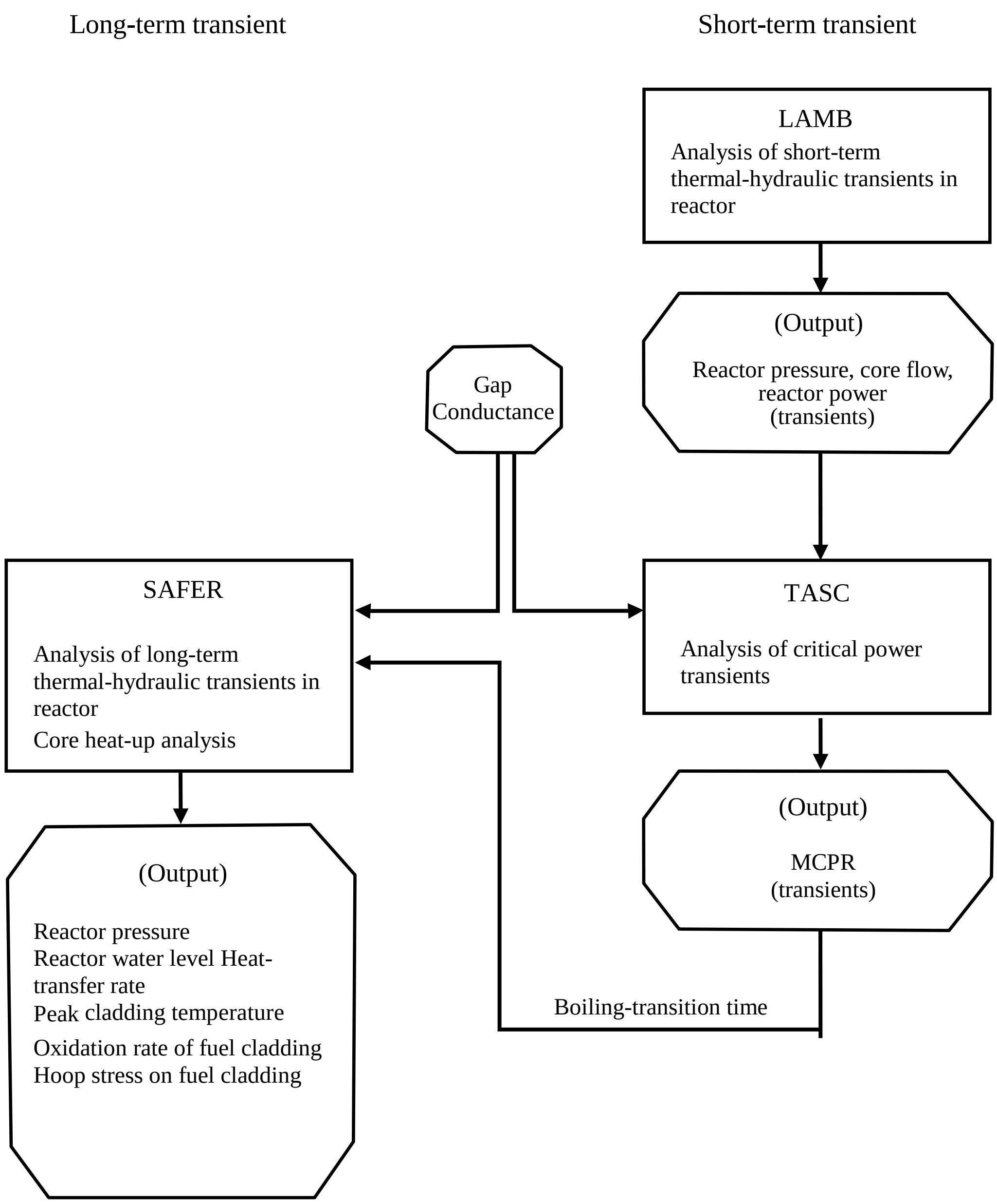

Figure 13.3-6 : Flow Chart of LOCA Analysis

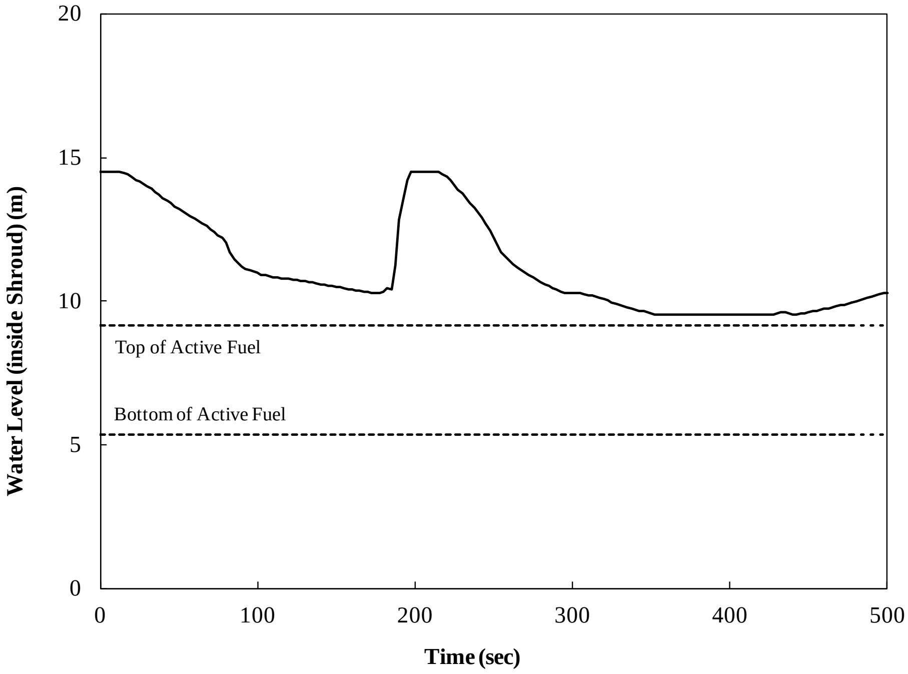

Figure 13.3-7 : Reactor Water Level during the Double-ended Break Accident of HPCF Line (with actuation of RCIC, two LPFL pumps)

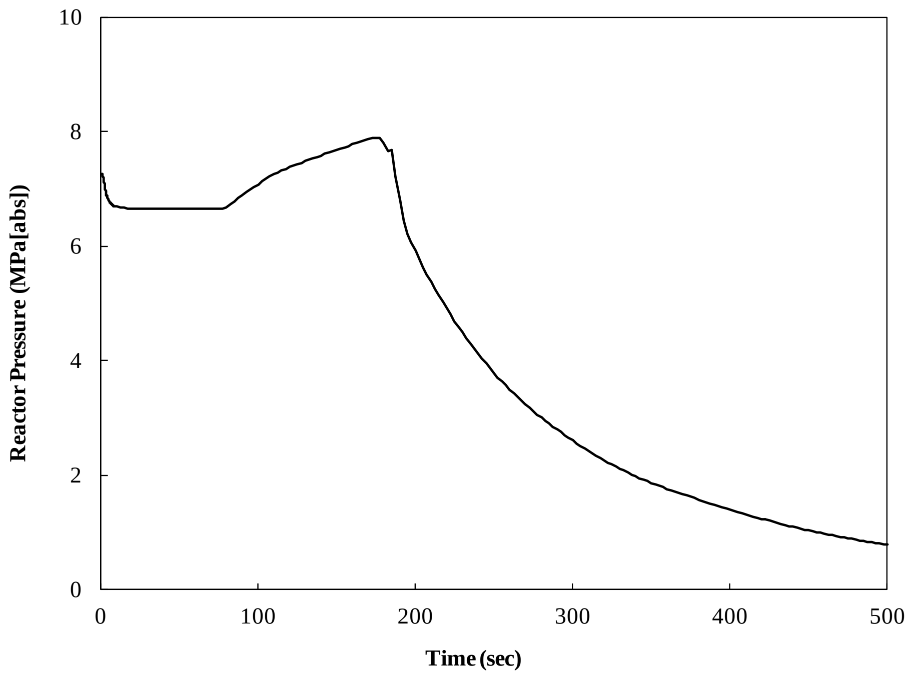

Figure 13.3-8 : Reactor Pressure during the Double-ended Break Accident of HPCF Line (with actuation of RCIC, two LPFL pumps)

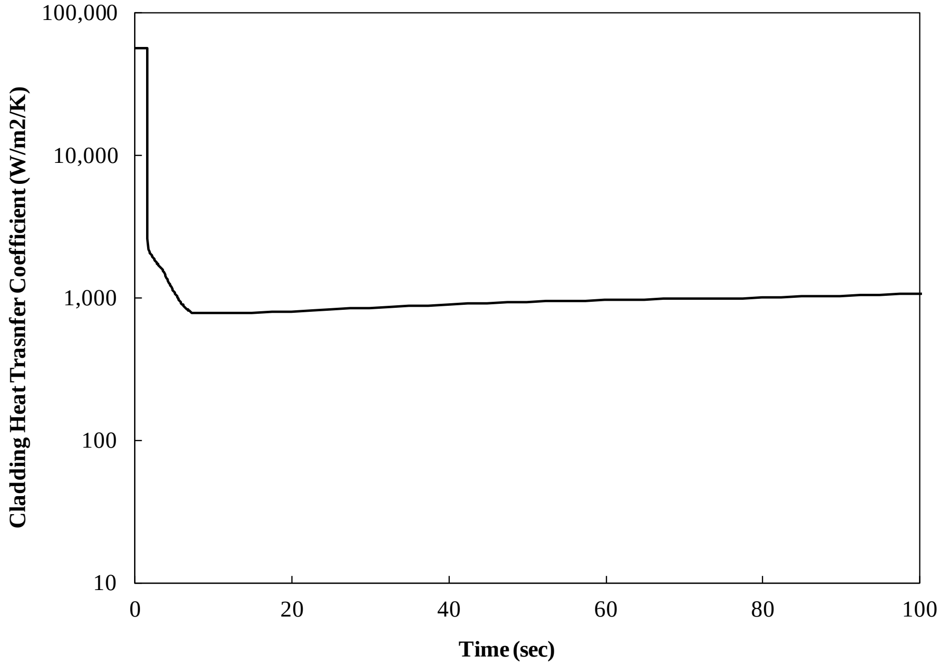

Figure 13.3-9 : Heat Transfer Coefficient at the Position where Fuel Cladding Temperature is Maximum during the Double-ended Break Accident of HPCF Line (with actuation of RCIC, two LPFL pumps)

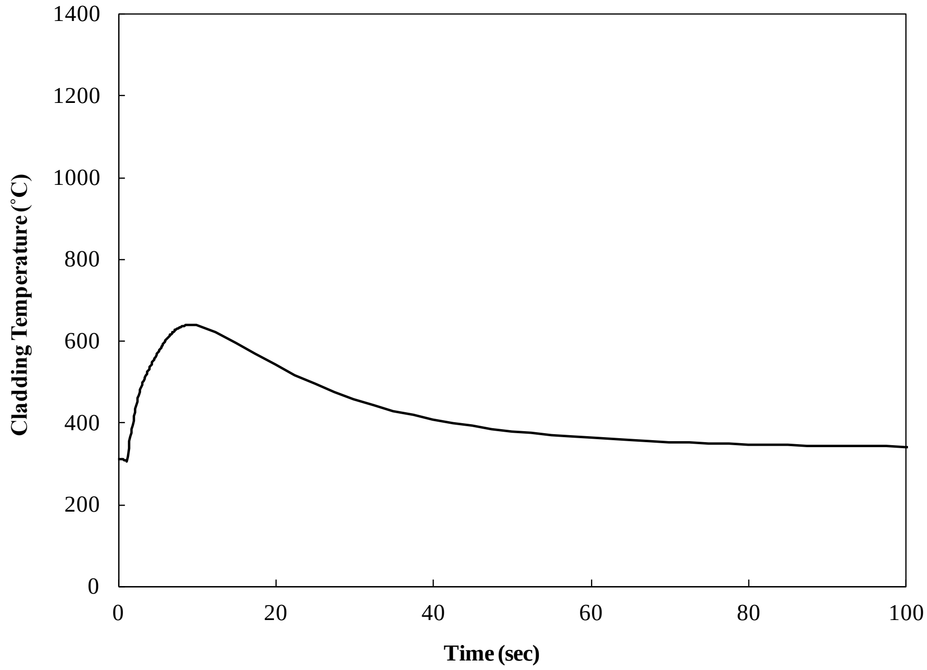

Figure 13.3-10 : Fuel Cladding Temperature at the Position where Fuel Cladding Temperature is Maximum during the Double-ended Break Accident of HPCF Line (with actuation of RCIC, two LPFL pumps)

13.3.5. References

[Ref-1] GA91-9201-0002-00015 Rev. 0, Basis of Safety Cases on Residual Heat Removal System, Hitachi-GE

[Ref-2] GA91-9201-0002-00016 Rev. 0, Basis of Safety Cases on Nuclear Boiler System, Hitachi-GE