

ADVANCED DVI+

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A new advanced safety feature of DVI+ (Direct Vessel Injection Plus) for the APR+ (Advanced Power Reactor Plus), to mitigate the ECC (Emergency Core Cooling) bypass fraction and to prevent switching an ECC outlet to a break flow inlet during a DVI line break, is presented for an advanced DVI system. In the current DVI system, the ECC water injected into the downcomer is easily shifted to the broken cold leg by a high steam cross flow which comes from the intact cold legs during the late reflood phase of a LBLOCA (Large Break Loss Of Coolant Accident). For the new DVI+ system, an ECBD (Emergency Core Barrel Duct) is installed on the outside of a core barrel cylinder. The ECBD has a gap (From the core barrel wall to the ECBD inner wall to the radial direction) of $3/25 \sim 7/25$ of the downcomer annulus gap. The DVI nozzle and the ECBD are only connected by the ECC water jet, which is called a hydrodynamic water bridge, during the ECC injection period. Otherwise these two components are disconnected from each other without any pipes inside the downcomer. The ECBD is an ECC downward isolation flow sub-channel which protects the ECC water from the high speed steam crossflow in the downcomer annulus during a LOCA event. The injected ECC water flows downward into the lower downcomer through the ECBD without a strong entrainment to a steam cross flow. The outer downcomer annulus of the ECBD is the major steam flow zone coming from the intact cold leg during a LBLOCA. During a DVI line break, the separated DVI nozzle and ECBD have the effect of preventing the level of the cooling water from being lowered in the downcomer due to an inlet-outlet reverse phenomenon at the lowest position of the outlet of the ECBD.

KEYWORDS : APR+, Direct Vessel Injection, DVI+, ECBD, ECC Duct, ECC bypass

1. INTRODUCTION

In some advanced pressurized water reactors, a Direct Vessel Injection (DVI) system of Emergency Core Cooling (ECC) water is widely used as a new design feature. APR1400 and AP1000 use a fully DVI system while the US-APWR uses a combined injection system with both a DVI and a Cold Leg Injection (CLI) system. The ECC direct bypass fraction during the late reflood phase of a LBLOCA is strongly dependent on the break suction flow, downcomer cross flow from intact cold legs, and the geometrical configuration of the DVI nozzle and its location in the downcomer (T.S. Kwon et al., 2003, H. Glaeser, 1992, 1993). In the current DVI system, the ECC bypass which occurs near the break suction flow is not controllable because the smooth downcomer wall has no resistance against the highly increased pressure difference of the break flow, and has no roles to prevent a high steam-water interaction near the break nozzle. One of the major design parameters of the DVI system to mitigate the direct ECC bypass is the azimuthal angle of the DVI nozzle from each cold leg (T.S. Kwon et al., 2003). The relative

azimuthal injection angle of a DVI nozzle is measured from the broken cold leg to the hot leg. The current DVI azimuthal injection angle of APR1400 is 15 degrees. In general, a high relative azimuthal gives a low ECC bypass fraction (T.S. Kwon et al., 2003, 2004). A dual core barrel cylinder as an ECC flow separator, located between the reactor vessel and the core barrel outer wall in the downcomer annulus, has been suggested by Kwon et al. (2004).

To prevent the direct ECC bypass near a broken cold leg, the injection location of ECC water should be as far away as possible from the broken cold leg. However, the relative angle between the cold leg nozzle and the DVI nozzle is limited. The nozzle-to-nozzle angle is small. For these cases, an ECC flow sub-channel using ECBD to prevent a steam-water interaction is one of the important design features for an advanced DVI system to mitigate the direct ECC bypass phenomena. Without the ECBD, the flow zone around a broken cold leg in the downcomer plays the role of a high ECC direct bypass due to the strong suction force.

2. DESIGN CONCEPT OF DVI+

2.1 Design Requirements of ECBD

As shown in Figure 1, a strong suction force and a high entrainment around a broken cold leg due to a high speed cross flow of the downcomer are induced by a break flow during the reflood phase of a LBLOCA. However, if the ECBD prevents high steam-water interactions in the downcomer, the ECBD could be installed at a wide range of azimuthal angles though it should be close to the broken cold leg. As a result, the direct ECC bypass fraction for the ECBD will be decreased when compared to the typical DVI design. In the design of the ECBD, to minimize the side force or flow induced vibration acting on the ECBD, a large azimuthal angle from an impinging jet of the cold legs is also a considerable design parameter.

An emergency core cooling water direct vessel injection system should comply with the following design requirements of the DVI+.

- (1) The DVI+ system should be able to supply a larger quantity of emergency core cooling water to a core inlet during a LBLOCA.
- (2) The internal coolant should flow well during a steady-state with the RCP running.
- (3) The collapsed water level in the reactor vessel should not be significantly reduced because an emergency core cooling water outlet at the lowest position of the ECBD functions as an inlet for a break flow when the DVI line is broken.
- (4) The cross flow resistance should not be increased excessively, and the flow induced vibration should not be increased excessively.
- (5) A connector for the ECBD and the direct vessel injection nozzle should not cause interference when the reactor vessel is assembled with a core barrel or a withdrawal hole for a neutron monitoring capsule.

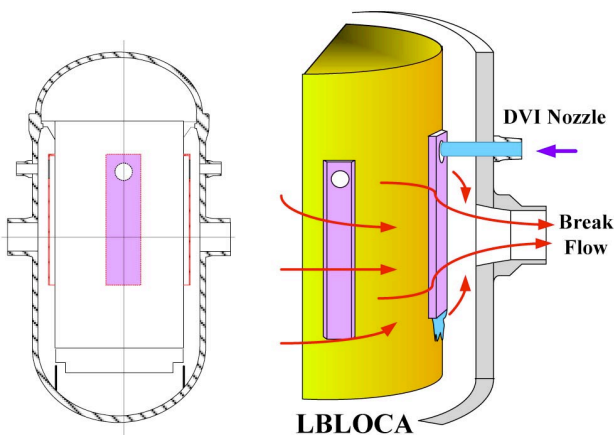


Fig. 1. Overview of DVI+

2.2 ECBD Shape

In the DVI+, the DVI nozzle outlet and the ECBD inlet, which are opposite each other, are designed to open without any mechanical connections in the downcomer. As illustrated in Figure 1, although the DVI nozzle is not connected mechanically with the ECBD by means of a pipe, the emergency core cooling water is injected into the intact hole of the ECBD from the direct vessel injection nozzle by a hydraulic flow momentum.

As shown in Figure 2, the lowest outlet of the ECBD is open, and the highest cap of the ECBD is closed, and it includes at least one air vent so that gas can be discharged when the nuclear reactor vessel is filled with water. The ECC water intake port is located on the axial line of the DVI nozzles. The diameter of the emergency core cooling water intake port is about one to two times the inner diameter of the DVI nozzle in consideration of deflection of the jet by means of gravity in the case in which the jet of the DVI nozzle has a small spreading and flow rate. Thereby, the emergency core cooling water is introduced more easily into the ECBD.

2.3 ECBD Flow Area

The ECBD is designed for the reflood phase of a LOCA. Therefore, the flow area of the ECBD would be considered only for the condition of a SIT fluidic device (F/D) activation or HPSI injection situations. In these

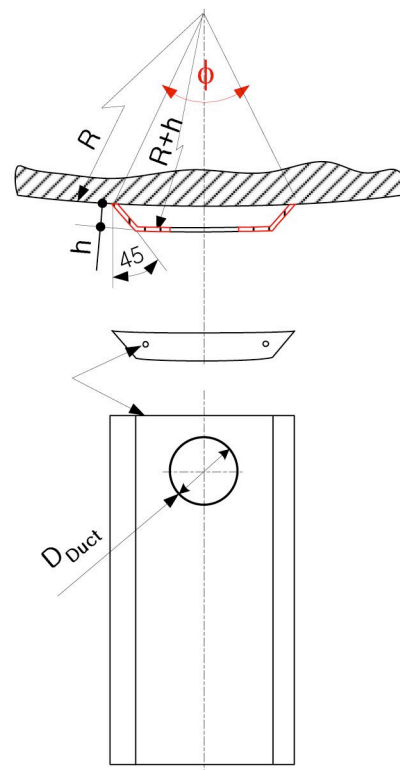


Fig. 2. Overview of ECC Duct

cases, the equivalent flow area of the DVI nozzle is considered as an inner flow area of the ECBD.

2.4 Design Concept for Reducing Flow Vibration

The flow induced vibration of the ECBD is also strongly dependent on the relative azimuthal angle of the DVI nozzle from the cold leg because the impinging jet force of each cold leg flow is decreased with the distance from the centerline of the impinging jet. In the APR1400, the DVI nozzles have a relative angle of 15 degrees with a cold leg. If the relative angle between the cold leg and the DVI nozzle is increased from the current relative angle of 15 degrees as shown in Figure 3, the impinging jet force is also considerably reduced when compared to

the current design of the APR1400. If the arrangement angle of the DVI nozzles is shifted to a hot leg, the ECC penetration will be increased with the relative azimuthal injection angle increasing.

In the current design without the ECBD, the relative azimuthal angle of the DVI nozzle from the broken cold leg is a considerable design parameter to reduce the ECC bypass. A large azimuthal angle from a cold leg to a hot leg causes a high suction flow zone when ECC water is injected during a LBLOCA reflow phase.

As shown in Figure 4, the ECBD includes lateral faces inclined in a transverse direction at an angle of about 45° on opposite sides thereof, so that it can reduce the resistance and flow vortex of the cross flow when compared to a rectangular shaped ECBD, the lateral faces of which are formed at an angle of 90°.

A leading edge flow deflector installed at the bottom of the ECBD, as shown in Figure 5, is a considerable design feature to mitigate the flow reversal force on the

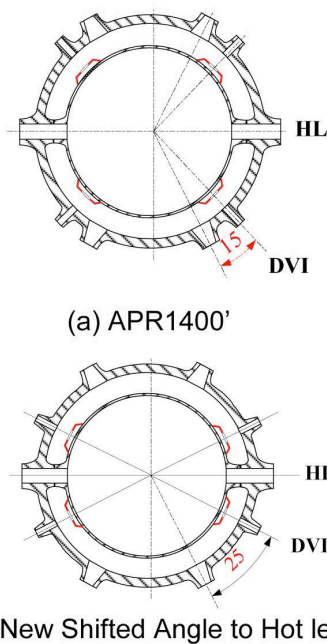


Fig. 3. Azimuthal Angle of the ECC Duct

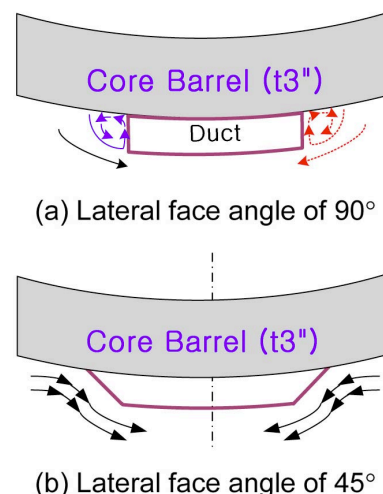


Fig. 4. Side Angle of the DVI+ Duct

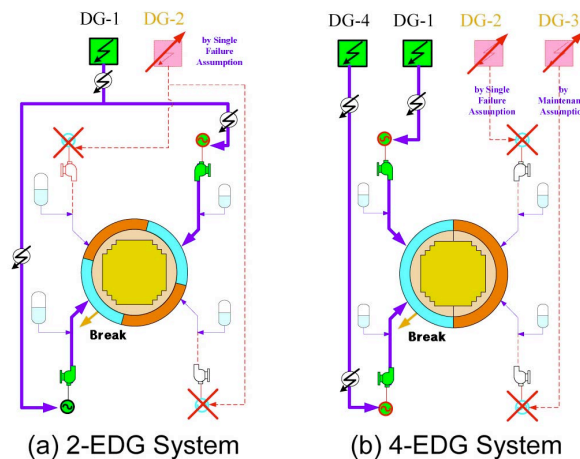


Fig. 5. Activation HPSI Train by EDG during LOCA

ECBD during the blowdown phase of a LBLOCA.

To remove the reactor vessel assembly interference, the height of the ECBD, in the radial direction in the downcomer, preferably has a radial distance (h) limited to a range from about $3/25$ to about $7/25$ of the width of the diametrical gap of the downcomer. This is because, in the case in which the radial distance (h) must be smaller than the minimum inner diameters of the upper alignment, key portion of the reactor vessel, and the inner diameter of the hot leg, no interference occurs when the reactor vessel and the core barrel are assembled or when the neutron monitoring capsule is withdrawn.

Thus, as for the cross-sectional shape of the ECBD, the radius of the curvature of the outer surface of the ECBD protruding into the downcomer is equal to the sum of the radius (R) of the core barrel and the radial distance (h) of the ECBD. The opposite lateral faces of the ECBD are similar to the non-parallel opposite sides of an isosceles trapezoid.

The length of the ECBD installed on the core barrel starts from the DVI nozzle to a lower downcomer. Considering that the surrounding cooling water is swept out by a strong break flow formed around a broken cold leg in the down-comer, the lowest position of the outlet of the ECBD preferably extends toward a lower portion of the down-comer from the central axis of the cold leg within a range about two times that of the inner diameter of the cold leg, thereby being effective in preventing a direct bypass of the emergency core cooling water.

3. COMPARISON OF 2-EDG AND 4-EDG SYSTEM

The ECC direct bypass performances test for a 4-EDG system has been compared with that of the standard type of the APR1400's 2-EDG system. The EDG arrangements for DVI-2 and DVI-4 HPSI pumps are shown in Figure 5(a) and 5(b). The corresponding DVI injection nozzle arrangements are also shown in Figure 6(a) and 6(b). The DVI-2 and DVI-4 injection is the worst case of HPSI

injection of the 2-EDG system during a LBLOCA late reflood phase. The DVI-4 has the highest ECC bypass fraction among the 4 DVI nozzles because the DVI-4 is located near the broken cold leg. Thus, the ECC water injected in the downcomer annulus is easily bypassed through the broken cold leg due to its strong suction force (T.S. Kwon et al., 2009). The combination of DVI-2 and DVI-4 injection in the 2-EDG system has generally higher ECC bypass than that of any other DVI combination. Therefore, the DVI-2 and DVI-4 injection is assumed while the DVI-1 and DVI-3 have failed in the LOCA analysis when the single failure assumption is applied to the 2-EDG system. In the 2-EDG system, the cross pairs of DVI nozzles should be considered for ECC injection. Because the 2 HPSI pumps, which are connected to an active EDG, are arranged with a relative angle of 180 degrees opposite from each other while the other EDG (one of two) is assumed to have failed.

In the 4-EDG system as shown in Figure 6 (b), the 4 HPSI pumps are activated by a separate EDG electric power supply system. However, a total 3 of 4 HPSI pumps are available when the single failure assumption is applied. The DVI-2 failure is assumed by the single failure assumption because the DVI-2 has the lowest ECC bypass fraction among the 4 DVI nozzles in Figure 6 (b). If the additional maintenance concept is applied, one more HPSI should be assumed as a failed one. The DVI-1 or DVI-3 should be failed by the maintenance concept. Thus, the active DVI combination is "DVI-4 and DVI-1" or "DVI-4 and DVI-3" in the 4-EDG system when both the single failure assumption and the maintenance concept are applied at the same time.

4. PERFORMANCE TEST RESULTS

4.1 Air-Water ECC Bypass Test

4.1.1 Test Conditions

To evaluate the ECC bypass performance of the 2-

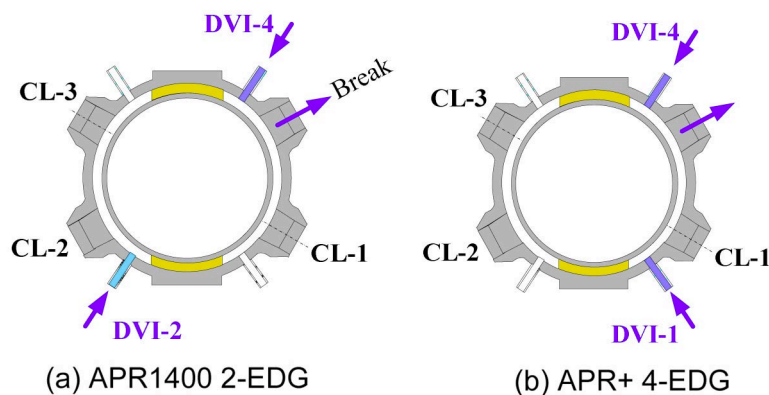


Fig. 6. ECC Injection of 2-EDG and 4-EDG System.

EDG and the 4-EDG systems, the air-water 1/5-scale reactor downcomer model of the APR1400 is applied. The cross sectional arrangement of the air-water test facility is shown in Figure 7. The test loop has a 4 cold leg, 2 hot leg blunt body, and 4 DVI nozzles. The reference plant is the APR1400 which is a 2-loop pressurized light water reactor. The RCS of the APR1400 consists of 2 hot legs and 4 cold legs. The test condition is assumed as an air-water flow condition at atmospheric temperature and pressure. The DVI water injection velocity is fixed at about 0.72 m/sec. The air velocities of 3 cold legs are varied from 5 m/sec to 20 m/sec. The water level of the downcomer was controlled at low level. The DVI injection and cold leg flow conditions are summarized in Table 1.

In this test, the relative azimuthal angle of the DVI-1 and DVI-3 from a broken cold leg has an effect on the ECC bypass. The hot leg blunt body is also very important to mitigate an ECC bypass. If the hot leg blunt body is located between the broken cold leg and the DVI-1 or DVI-3, the ECC bypass fraction is mitigated due to the effect of hot leg wakes.

The bypass fraction is defined as equation (1). The

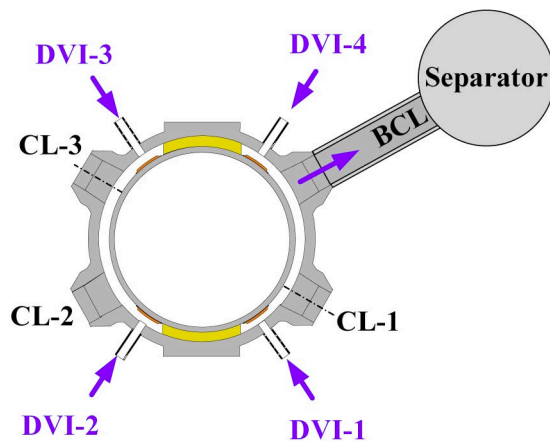


Fig. 7. Tested DVI Nozzle Allocation

Table 1. Test Conditions

Description	Condition	
Cold leg Fluid	Air (CL 1~3)	
Cole leg Temp.	15°C	
Cold leg Velocity	10, 15, 18, 20 m/sec	
DVI Conditions	Water Temp	15°C
	Injection Nozzle	DVI-1,-3, and -4
	Velocity	0.72 m/sec
	Single failure assumption	DVI-2 : no injection

entrained water into the break flow is calculated as a total water fraction.

$$ECC_bypass_fraction = \frac{m_{BrokenCL_WaterFraction}}{\sum_{DVI=1,3,4} m_{DVI_Water}} \quad (1)$$

4.1.2 Test Results

The ECC direct bypass fractions with injection nozzle variation are compared in Figure 8. The red open squared and black open triangle symbols represent the DVI-2 and DVI-4 combination for the 1/5-scale air-water model of the original APR1400 without the DVI+ DCBD. The total ECC bypass fraction is about 42 % at the cold leg velocity of 20 m/sec. The ECC direct bypass fraction hits about 68 % for the combination of the DVI-1 and DVI-4 of 4-EDG system at a cold leg velocity of 18 m/sec. The ECC direct bypass is strongly mitigated when compared to the combination of the DVI-1 and DVI-4 injection. The hot leg blunt body is located between the DVI-4 and the DVI-3, therefore, the ECC direct bypass is strongly mitigated when compared to the combination of the DVI-1 and DVI-4 injection.

The results for the DVI+ ECBD system show that the ECC bypass performance of the 4-EDG system is lower than that of the 2-EDG system when the single failure assumption and the maintenance concept are applied at the same time during LOCA.

Figure 9 shows the ECC deflector system. Figure 10 represents the ECC bypass performance of the ECC deflector system. The ECC deflector has the role of an ECC momentum directional controller. The direct bypass fraction of the ECBD is about 10 % for the velocity range of 0~15 m/sec. while the ECC bypass fraction increases very sharply over 50~60 %.

In the figures, the ECC bypass performance between the ECC deflector and the DVI+ ECBD are compared.

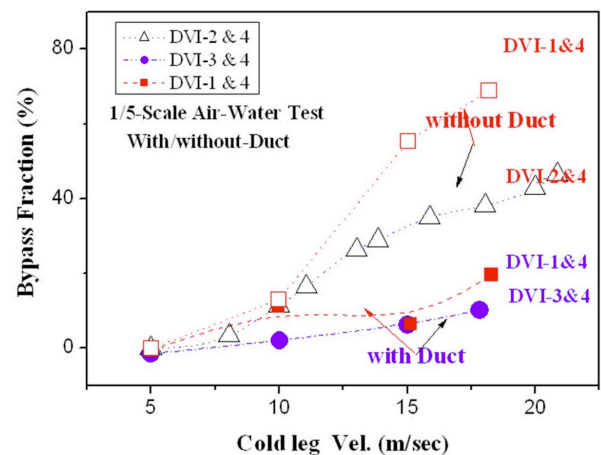


Fig. 8. Comparison of ECC bypass Fraction for Duct (DVI+)

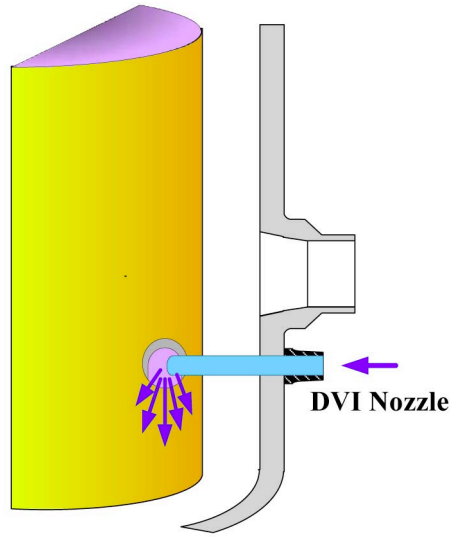


Fig. 9. ECC Deflector

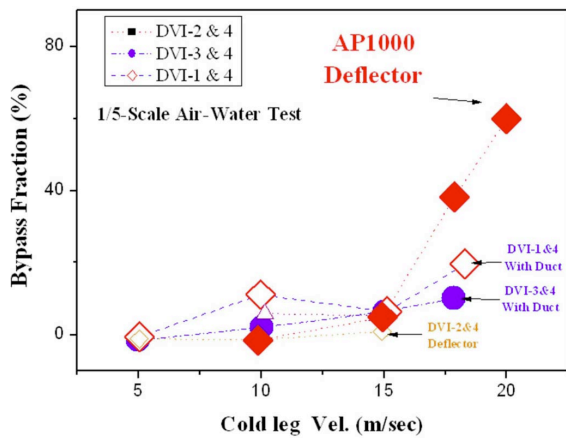


Fig. 10. ECC Bypass of ECC Deflector

As shown in the figures, the ECC bypass fraction of the ECC deflector is higher than that of the DVI+ ECBD in the velocity range of 15~20 m/sec.

4.2 Full Scale ECBD Injection Test

4.2.1 Test Conditions

A full scale ECBD injection test was performed to evaluate the spillage fraction of ECC water for the DVI+ ECBD. The steady-state cold water injection test was performed under conditions of atmospheric pressure and room temperature. The full scale ECBD cold water injection test facility is shown in Figure 11. The inner diameter of the DVI nozzle is 8.5 inches. The gap (inside gap) between the core barrel and the DVI+ ECBD is 5 cm. The height of the DVI+ ECBD is about 4 m (full length). The injection velocity of the ECC water was controlled

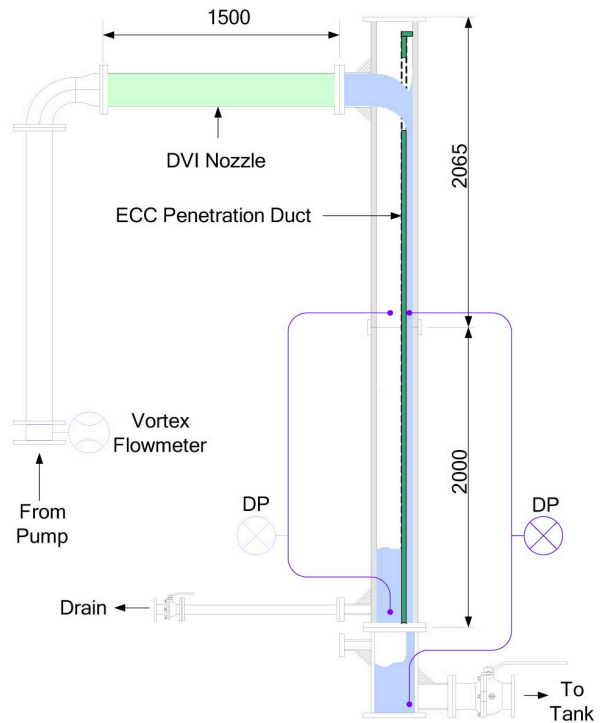


Fig. 11. Full Scale Duct Injection Test Facility

to be about 1.6 m/sec. The injected water flow rate was set at desired values by controlling the speed of the injection pump. When the desired ECC water injection velocity reached steady conditions, data logging started for the total ECC water injection and the accumulated water level at the spillage region of the ECBD. Then, the total ECC water spillage to outside the ECBD (spillage region) could be measured.

The spillage fraction of ECC water is defined as equation (2). The spillage water outside the ECBD flows into the downcomer.

$$Spillage_fraction = \frac{m_{Spillage_Outside_ECBD}}{\sum m_{DVI,Injection}} \quad (2)$$

4.2.2 Test Result

The injection flow shape of ECC water is shown in Figure 12. The spillage fraction is summarized in Table 2. The ECC water spillage fraction increased with the ECC water injection velocity. The circular shaped intake hole had a lower spillage fraction than that of the elliptical shaped intake hole. The reflection of the ECC water at the core barrel surface was increased when the ECC injection velocity was increased. This phenomenon increased the ECC spillage fraction. In the case of the circular shaped intake hole, the ECC water spillage fraction of the ECBD was reduced due to the minimized water reflection from

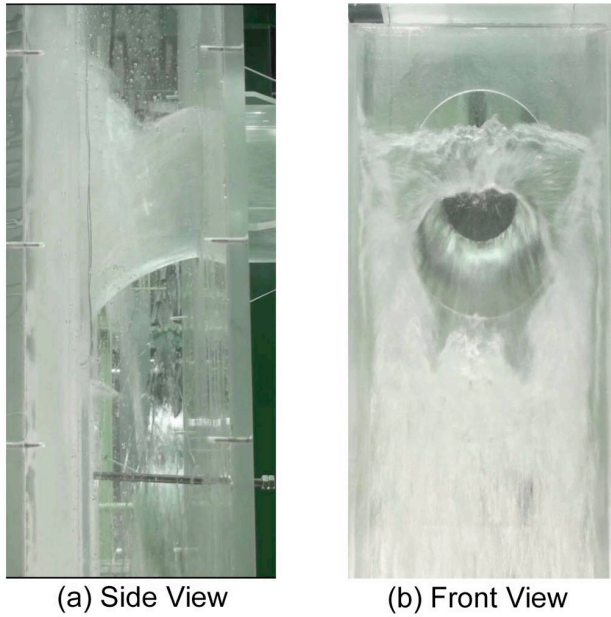


Fig. 12. ECC flow pattern (Circular, $V_{DVI} = 1.58$ m/s)

Table 2. Spillage Ratio of ECC Water

DVI Duct intake shape	DVI Nozzle Average Injection Velocity (m/sec)	Spillage Fraction (to duct outside) (%)
Elliptical	1.792	12.102
	1.641	5.886
	1.566	4.77
Circular	1.757	4.013
	1.584	3.181

the ECBD when compared with the elliptical shaped intake hole. To minimize the ECC water spillage fraction, the elevation and shape of the intake hole should be adjusted to a circular shape.

4.3 APR+ Application

The direct ECC bypass and sweep out behaviors in the reactor downcomer annulus are strongly dependent on the Wallis parameter. Because the downcomer gap of the APR+ is reduced by the ECBD in the downcomer annulus, the circumferential steam velocity is increased when compared to that of the APR1400. However, the developing test of DVI+ was performed on the 1/5-Scale air-water test facility DIVA for the APR1400. Therefore, to evaluate the ECC bypass behavior for the APR+ based on the 1/5-scale DIVA air water test results, the Wallis

parameters for each plant is compared. The increased Wallis parameter for APR+ drives the ECC bypass. In the APR+, the downcomer gap and its height, pipe diameter of hot legs and cold legs, and the break size are not changed except the core power is increased by 7 %. However, the ECC bypass fraction of the APR+ does not increase because the DVI+ ECBD prevents the steam-water interaction in the downcomer annulus. In this scaling parameter comparison, the dimensionless circumferential velocity $j_{g,ent}^*$ and $j_{l,ent}^*$ are compared by equation(3).

$$\begin{aligned}
 (j_{g,eff}^*)_R &= \frac{\left(\frac{\dot{M}_{g,eff}}{\rho_g \cdot A_{Flow}} \left[\frac{\rho_g}{(\rho_f - \rho_g) \cdot g \cdot L_{DC}} \right]^{1/2} \right)_{APR+}}{\left(\frac{\dot{M}_{g,eff}}{\rho_g \cdot A_{Flow}} \left[\frac{\rho_g}{(\rho_f - \rho_g) \cdot g \cdot L_{DC}} \right]^{1/2} \right)_{APR1400}} \\
 &= (\dot{M}_{g,eff})_R * \frac{1}{(Gap_{D/C})_R} = 1.07 * \left(\frac{1}{0.8} \right) \\
 &= 1.3375
 \end{aligned} \tag{3}$$

where,

$$(\dot{M}_{g,eff})_R = \frac{(CoreSteamFlow)_{APR+}}{(CoreSteamFlow)_{APR1400}} = 1.07$$

$$(L_{DC})_R = \frac{(D_{CL})_{APR+}}{(D_{CL})_{APR1400}} = 1$$

$$\begin{aligned}
 (A_{Flow})_R &= \frac{(L_{D/C} * Gap_{D/C})_{APR+}}{(L_{D/C} * Gap_{D/C})_{APR1400}} \\
 &= \frac{(Gap_{D/C})_{APR+}}{(Gap_{D/C})_{APR1400}} \\
 &= \frac{20}{25} = 0.8
 \end{aligned}$$

5. CONCLUSION

The ECC bypass fraction tests were performed using the ECBD with 1/5-scale air-water test facility for the APR1400 reactor. The test results show that the ECC bypass fraction of the 4-EDG system is higher than that of the 2-EDG system under a single failure assumption. For the 4-EDG system, one EDG maintenance stop assumption was added with a single failure assumption. Therefore, the adjacent DVI injection nozzle and azimuthal angle was shifted to the broken cold leg. The ECC bypass fraction was very low when the DVI+ ECBD was applied at the core barrel on the opposite side of the DVI nozzle. The strong air-water interaction in the downcomer annulus disappeared due to the DVI+ ECBD. The DVI+ ECBD

can be considered as an advanced design feature for the DVI system, which significantly reduces the ECC direct bypass fraction induced by the high cross steam flow in the downcomer during the LBLOCA reflood phase.

The new safety concept of the DVI+ was implemented to the standard design of the APR+ safety system.

ACKNOWLEDGEMENT

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NOMENCLATURE

<i>m</i>	<i>mass flow rate(kg/sec)</i>
<i>HL</i>	<i>hot leg</i>
<i>CL</i>	<i>cold leg</i>
<i>EDG</i>	<i>emergency diesel generator</i>

Subscripts

<i>1,2,3,4</i>	<i>number of DVI or cold leg</i>
<i>water</i>	<i>water phase</i>
<i>DVI</i>	<i>direct vessel injection(nozzle)</i>
<i>g</i>	<i>gas phase</i>
<i>f</i>	<i>fluid</i>
<i>CL</i>	<i>cold leg</i>
<i>D/C</i>	<i>downcomer</i>

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