An Analysis on DVI SBLOCA for BANDI-60

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1. Introduction

Korea Electrical Power Corporation Engineering & Construction, Inc. (KEPCO E&C) has been developing a block-type Small Modular Reactor (SMR) with 200MWt (60MWe) power, named as BANDI-60, based on PWR (Pressurized Water Reactor) technology. Its conceptual design was set up in 2019 as shown in Figure 1, and currently performance and safety analyses are under way to optimize the systems and components.
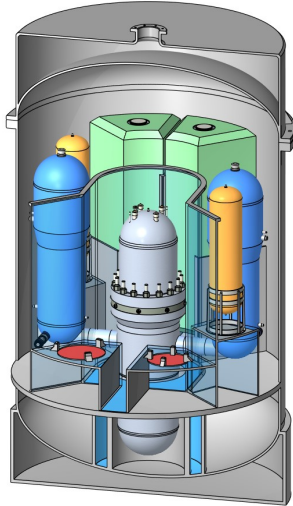

Fig. 1. Configuraton of BANDI-60 NSSS

BANDI-60 is a full passive reactor designed to be mounted on a floating power plant in the sea. Its reactor vessel block and steam generator block are directly connected, nozzle-to-nozzle, without large connecting pipes. As such, Large Break Loss of Coolant Accident (LBLOCA) can be eliminated from the design basis accident scenario. Including it, as compared to the conventional PWR plants, BANDI-60 provides more advanced design features as follows [1]:

1) Block-type reactor coolant system arrangement to eliminate LBLOCA
2) Soluble Boron-Free (SBF) operation
3) In-Vessel Control Element Drive Mechanism (IV-CEDM)
4) In-Core Instrumentations mounted on the reactor vessel head (Top-mounted ICI)
5) Passive Safety Injection System (PSIS), Passive Containment Cooling System (PCCS) and Passive Residual Heat Removal System (PRHRS)

6) Canned-motor Reactor Coolant Pumps (RCPs)
7) Integrated pressurizer inside the reactor vessel

Currently, KEPCO E&C is analyzing and evaluating the performance of passive safety systems for optimization. A Small Break Loss of Coolant Accident due to the double-ended guillotine break in the Direct Vessel Injection line (DVI SBLOCA) is selected as the limiting design basis accident in assessing the performance of passive safety systems. This paper presents the results on DVI SBLOCA analyses for BANDI-60 to demonstrate that its passive safety systems are adequately designed.

2. Passive Safety Systems of BANDI-60

Inherent passive safety features of BANDI-60 are shown in Figure 2 as a simplified diagram. The passive safety systems consist of the PSIS, PCCS, and PRHRS, which rely on natural forces and battery power only to enhance safety in case of a postulated accident [1].
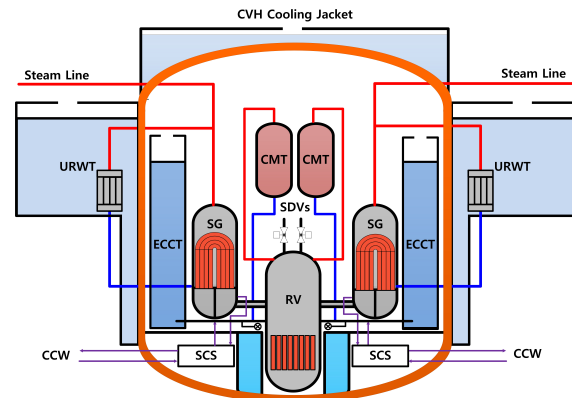

Fig. 2. Passive Safety Systems of BANDI-60

The PSIS provides a Reactor Coolant System (RCS) inventory makeup for any loss of coolant events using a gravity driven flow. The PSIS consists of the Core Makeup Tanks (CMTs), Emergency Core Cooling Tanks (ECCTs) and Safety Depressurization Valves (SDVs). CMTs are connected to the DVI nozzle and pressurizer with Pressure Balance Line (PBL), and are normally pressurized to the RCS pressure during operation. The CMT isolation valves on the DVI line are opened on low pressurizer pressure/level or high containment pressure to inject coolant by gravity. When the CMT water level decreases to the low level setpoint,

the ECCT isolation valves in the DVI line are opened to initiate coolant injection by gravity. Because the top of ECCTs is open to the containment and its pressure at the top is equal to the containment pressure, a rapid depressurization of RCS may be required to initiate the ECCT injection. Thus, the SDVs on the pressurizer are designed to be opened for a rapid depressurize of the RCS. The spilled water through the break is collected from the bottom of the containment and, eventually, the reactor vessel and the broken DVI nozzle become submerged in the spilled water. This enables a continuous coolant supply to RCS through the broken DVI nozzle while venting through the SDVs. Recirculation lines are also connected to the DVI nozzles to recirculate the spilled water through the intact DVI line without pump.

There are the Ultimate heat sink and Refueling Water Tank (URWT), the Containment Vessel Head (CVH) cooling jacket, and the metal containment vessel in the PCCS. The energy released to the containment is removed to the water stored in the URWT and CVH cooling jacket by heat transfer through the containment metal wall. The URWT and CVH cooling jacket are located outside the containment vessel and are in contact with the metal wall of the containment. The URWT capacity is sufficiently large enough for containment cooldown and decay heat removal for more than one month without refill.

The PRHRS removes the decay heat and the RCS sensible heat after reactor trip. The steam from the SGs condenses in the PRHRS heat exchangers which are submerged in the URWT. The condensed water returns to the SGs by gravity.

3. Description of DVI SBLOCA Analysis

3.1 Analysis Software

Analyses on DVI SBLOCA are performed using MARS-KS 1.5 computer code which has been developed for a realistic multi-dimensional thermal-hydraulic system analysis of light water reactor transients. MARS-KS employs one-dimensional, two-fluid, two-phase flow transient model with eight field equations [2].

Considering that BANDI-60 is designed for a floating power plant in the sea, it is required to simulate the moving reactor like a ship. MARS-KS 1.5 has capability to simulate the thermal-hydraulic phenomena with six degrees of freedom of motion such as surging, swaying, heaving, rolling, pitching and yawing. Although the simulation for moving reactor is not included in this paper, MARS-KS 1.5 is selected to perform simulations with the translational and angular motions in the future.

3.2 Input Model

Figure 3 presents the MARS-KS nodalization of the primary and secondary systems, the containment, and the passive safety systems of BANDI-60. Only the break and the passive safety systems are labeled in the nodalization diagram as shown in this figure.
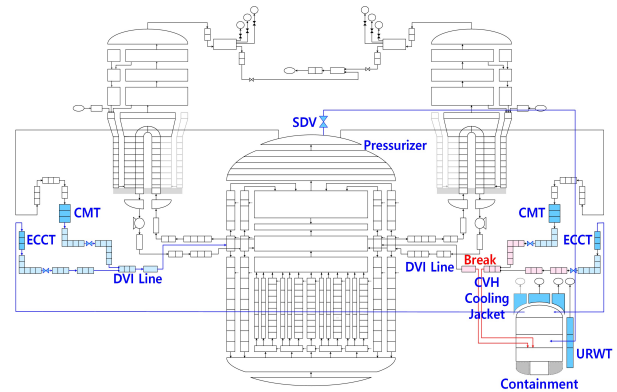

Fig. 3. MARS-KS Nodalization of BANDI-60

The reactor core is modeled as four-divided average cores and one hot channel considering the motion in the sea. Since the pressurizer is integrated into the reactor vessel upper head, it is modeled to be located at the top of reactor vessel as shown in Figure 3. The secondary system model includes two steam generators, main feedwater lines modeled as boundary conditions, main steam lines, Main Steam Isolation Valves (MSIVs), Main Steam Safety Valves (MSSVs), and the turbine.

The broken DVI line is modeled to be connected to the containment to calculate pressure interactions between the RCS and the containment. The containment is modeled with the containment vessel wall as a heat structure to simulate containment cooling phenomena. The containment is assumed to be filled with room temperature air initially.

The isolation valves of CMT and ECCT at the broken side are opened simultaneously with the intact side valves. Therefore, the water in CMT and ECCT at the broken side is modeled to be spilled to the containment during the accident. The PRHRS is not included in this model because the coolant in the U-tubes are drained in the early phase of accident.

3.3 Assumptions for Analysis

A double-ended guillotine break in one DVI line is assumed to occur at full power. The break sizes of DVI line used in this analysis are 2 and 3 inches in diameter to assess the performance of the passive safety systems.

The CMT isolation valves are assumed to be opened by the low pressurizer pressure or level. The SDV and ECCT isolation valves are assumed to be opened by the low water level signal from the CMT at intact side.

Only one SDV with 3 inches in diameter is opened to depressurize the RCS before the ECCT injection assuming that the other one fails to open. On reactor trip,

it is assumed that turbine trip, Loss of Offsite Power (LOOP), feedwater isolation, and main steam line isolation occur simultaneously. The analyses were performed until the spilled water fills the containment above the elevation of DVI nozzle, beyond which the passive containment recirculation is assumed to start for a long term cooling.

4. Results of DVI SBLOCA Analysis

The double ended guillotine break LOCA at DVI line has been analyzed for 2 and 3 inches in diameter breaks and the results are presented in Table 1 and Figures 4 through 11. When the accident occurs, the RCS pressure and the pressurizer level decrease rapidly as the liquid phase coolant discharges in early phase. The reactor trip occurs by the low pressurizer pressure and the control rods start to drop.

Table 1: Sequence of Event

Event	Time after break	
	2" Break	3" Break
DVI line break	0.0 sec	0.0 sec
CMT isolation valves open	12.0 sec	5.4 sec
Containment peak pressure	9.67 min	4.75 min
SDV and ECCT isolation valves open	27.8 min	13.4 min
Intact CMT empties	43.7 min	22.5 min
Passive recirculation phase starts	11.1 hr	5.99 hr

As shown in Figures 4 and 5, while the pressurizer pressure decreases continuously, the discharged coolant vaporizes and pressurizes the containment. As the containment pressure and temperature increases, the containment heat removal by the URWT and the CVH cooling jacket also increases limiting further containment pressurization. The peak containment pressure for the larger break case occurs earlier with higher peak value as compared to the smaller break case. After the peak containment pressure, a continued containment cooling depressurizes the containment and results in a quasi-equilibrium state between the pressurizer and containment pressures as depicted in Figures 4 and 5.
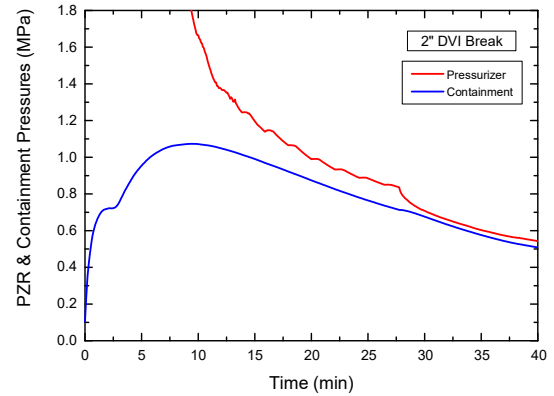

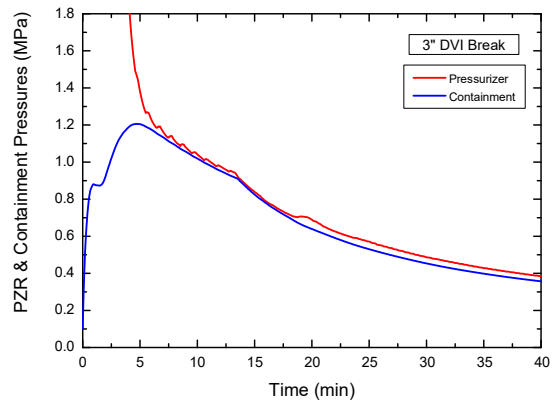Fig. 4. Pressurizer & Containment Pressure (2" Break)

Fig. 5. Pressurizer & Containment Pressures (3" Break)

Since the CMTs are already pressurized at system pressure through the PBL connected to the pressurizer, the CMT water injection starts when isolation valves open by the CMT actuation signal as shown in Figures 6 and 7. The broken side CMT discharges to the containment and empties quickly while the intact side CMT injects water into the RCS, and its water level decreases over a period depending on the break sizes. The intact side CMT injection continues over 43.5 and 22.4 minutes for 2 and 3 inches breaks, respectively.
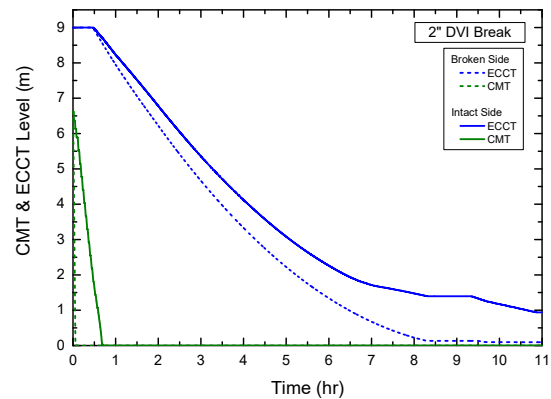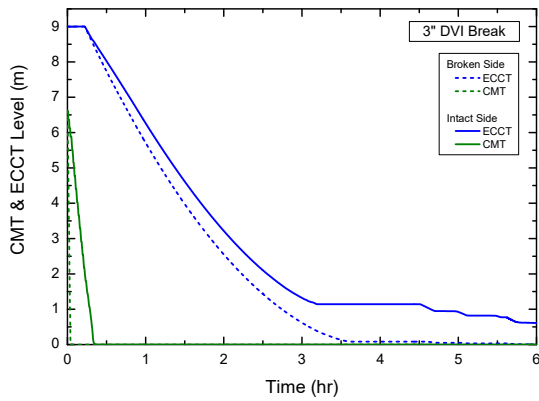

Fig. 6. CMT and ECCT Levels (2" Break)

Fig. 7. CMT and ECCT Levels (3" Break)

As the intact side CMT level decreases below the predetermined value of 2 meters, the SDV and ECCT isolation valves are opened simultaneously. In case of 2 inches break, due to a smaller coolant discharge, the pressure difference between pressurizer and containment exists before the SDV opening as shown in Figure 4. After opening of SDV at about 28 minutes after accident, the pressure difference decreases as shown in the figure facilitating ECCT injection. However, in case of 3 inches break, the influence of SDV opening is much smaller as shown in Figure 5 because the pressure difference between pressurizer and containment is small at the time of SDV opening (about 13 minutes after accident) due to the larger break area.

Because the ECCT pressure is balanced with the containment pressure, the ECCT injection through the intact DVI line depends on the system pressure, ECCT hydrostatic head, and the friction in the injection lines while the broken side ECCT discharges to the containment directly. As shown in Figures 6 and 7, ECCT injection continues over about 8 and 3 hours after accident for 2 and 3 inches breaks, respectively, demonstrating the effectiveness of ECCT injection for core decay heat removal. Figures 8 and 9 show the hot channel fuel cladding temperature. For both cases, a successful core decay heat removal by the passive safety systems throughout the transient without resulting in a fuel failure is demonstrated. Although, in the 2 inches break case, a slight cladding temperature rise occurs in early phase caused by a not enough CMT water injection and a delayed ECCT injection, the fuel cooling recovers thereafter.
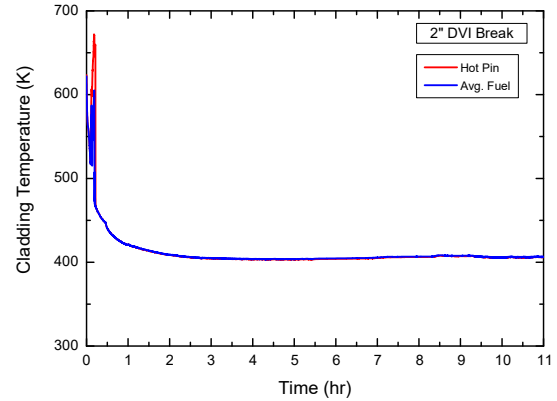

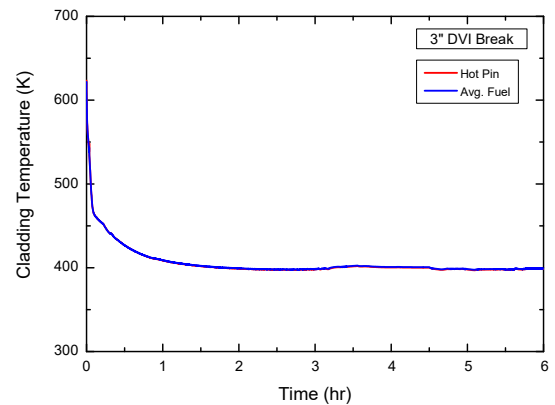Fig. 8. Cladding Temperature (2" Break)

Fig. 9. Cladding Temperature (3" Break)

The total heat removal through the containment wall is greater than the decay heat generation as shown in Figures 10 and 11. The containment heat removal which is directly proportional to the temperature difference between the water in the PCCS tanks and the vapor in the containment increases to the maximum value before 30 minutes into the accident. The fraction of heat removed through the containment vessel head is much smaller than that through the vertical wall to the URWT in the early phase but increases with time.

After about 11 hours (2" break case) and 6 hours (3" break case), the spilled water to the containment fills the containment to above the broken DVI line elevation. Thereafter, the passive recirculation starts to circulate the water in the containment to the RCS for long term cooling as long as the PCCT tank water cools the containment.
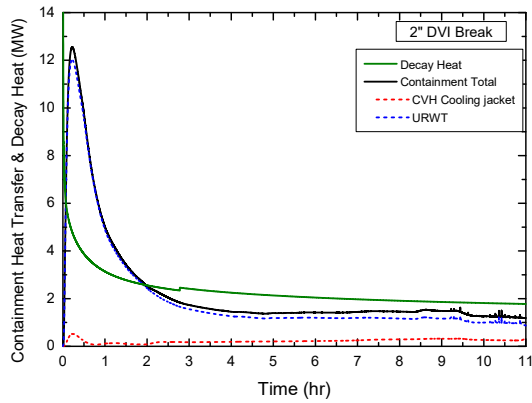
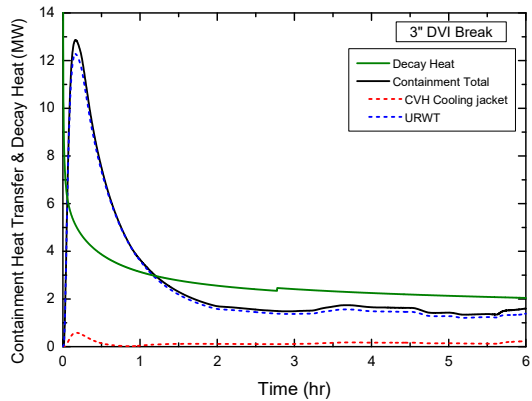Fig. 10. Containment Heat Transfer & Decay Heat (2" Break)

Fig. 11. Containment Heat Transfer & Decay Heat (3" Break)

5. Conclusions

DVI SBLOCA for BANDI-60 was analyzed using MARS-KS 1.5 computer code to assess the performance of passive safety systems of BANDI-60. The analysis results demonstrated that the passive safety systems of BANSI-60 are able to prevent the core damage. Also, the cooldown by PCCS through the containment steel wall is sufficient to remove decay heat and RCS sensible heat before the depletion of the water in PCCS tanks.

REFERENCES

[1] International Atomic Energy Agency, "Advances in Small Modular Reactor Technology Developments, Supplement to IAEA Advanced Reactors Information System (ARIS)," In progress to the revision of 2020 Edition, 2020.

[2] Korea Institute of Nuclear Safety, "MARS-KS Code Manual; Volume 1: Theory Manual," KINS/RR-1822, 2018.