# Long Term Cooling Analysis on DVI SBLOCA for BANDI-60

Jeong Ju Kim*, Jong Tae Seo, Han Rim Choi, Byung Jin Lee
*NSSS Division, KEPCO Engineering & Construction Company, Inc.,*
*111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon, Korea*
**Corresponding author: jeongjukim@kepco-enc.com*

## 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.

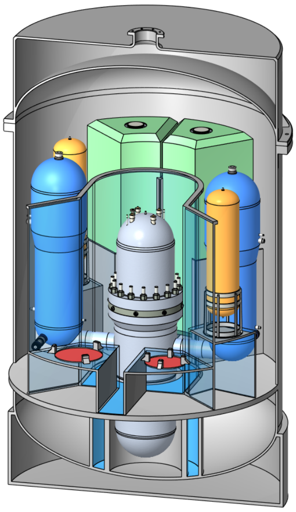

Fig. 1. Configuraton of BANDI-60 NSSS

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.

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.

The previous paper showed that the passive safety systems of BANDI-60 are adequately designed to prevent fuel failure during early phase of DVI SBLOCA before the initiating of containment recirculation. [1] This paper presents the results on DVI SBLOCA analyses for containment recirculation phase to demonstrate its passive long term cooling capability.

## 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 Passive Safety Injection System (PSIS), Passive Containment Cooling System (PCCS), and Passive Residual Heat Removal System (PRHRS) which rely on natural forces and battery power only to enhance safety in case of a postulated accident. [2]

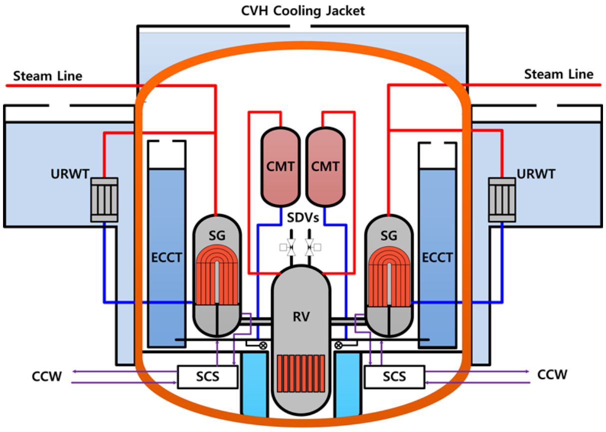

Fig. 2. Passive Safety Systems of BANDI-60

The Core Makeup Tanks (CMTs) are designed to be pressurized at the Reactor Coolant System (RCS) pressure during normal operation. The CMT isolation valves in the DVI line are opened on low pressurizer pressure/level or high containment pressure to inject cooling water by gravity. When the CMT water level decreases to the low level setpoint, the Emergency Core Cooling Tank (ECCT) isolation valves in the DVI line are opened to initiate coolant injection by gravity. Because the ECCTs are open to the containment and their pressure at the top is in equilibrium with the containment pressure, a rapid depressurization of the RCS is required to initiate the ECCT injection. Thus, the Safety Depressurization Valves (SDVs) on the pressurizer are designed to be opened for a rapid RCS depressurization. The spilled water through the break from the reactor vessel and CMT/ECCT is collected at the bottom of the containment. Also, the steam released through the SDVs is condensed on the containment wall and other structures flows down to the containment bottom and, eventually, the reactor vessel and the broken DVI nozzle become submerged in the water collected at the containment bottom. 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. When the ECCT water level decreases to the low level setpoint, the recirculation valves in the DVI lines are opened to initiate the containment recirculation for a long term cooling. The spilled water level above the DVI nozzle elevation is designed to provide enough elevation head for a continued containment recirculation through the DVI nozzles.

The PCCS consists of Ultimate heat sink and Refueling Water Tank (URWT), the Containment Vessel Head (CVH) cooling jacket, and the metal containment vessel. The released energy to the containment is removed by the water stored in the URWT and CVH cooling jacket via heat transfer through the containment metal wall as presented in Figure 2. The URWT and CVH cooling jacket are located outside the containment vessel and are in contact with the containment wall. The URWT capacity is sufficiently large enough to cooldown containment and to remove decay heat for more than one month without refill.

The PRHRS removes the decay heat and the RCS sensible heat after reactor trip during non-LOCA accidents. 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. [3]

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 and 4 present the MARS-KS nodalizations of the primary system, 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 these figures. The secondary system model is omitted in Figure 3 for convenience.

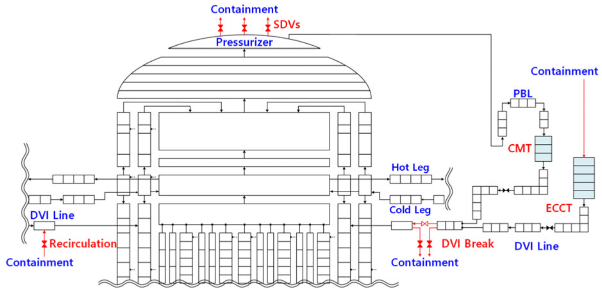

Fig. 3. MARS-KS Nodalization of BANDI-60 PSIS

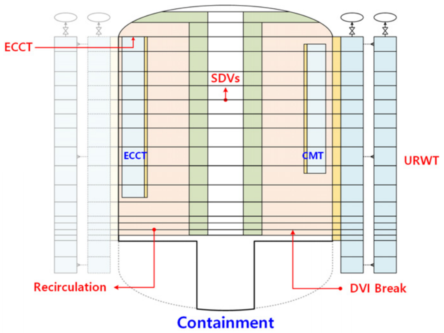

Fig. 4. MARS-KS Nodalization of BANDI-60 PCCS

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 broken DVI line is modeled to be connected to the containment to calculate pressure interactions between the RCS and the containment as shown in Figures 3 and 4

The containment is modeled with the containment vessel wall as a heat structure to simulate containment cooling phenomena in Figure 4. The containment is assumed to be filled with room temperature air initially.

The isolation valves of CMT and ECCT at the broken side of the DVI line are opened simultaneously with the intact side valves. Therefore, the water in CMT and ECCT at the broken side is modeled to be directly spilled to the containment during the accident.

For conservatism, the PRHRS is not included in this model because the coolant in the U-tubes are drained in the early phase of accident. Also, the CVH cooling jacket is also excluded in the input model for a conservative long term cooling analysis, and the decay heat is removed only through the URWT.

### *3.3 Assumptions*

A double-ended guillotine break in one DVI line is assumed to occur at full power. The break size of DVI line used in this analysis is 3 inch in diameter. 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.

Three SDVs with 2.5 inches in diameter are opened to depressurize the RCS before the ECCT injection. On reactor trip, it is assumed that turbine trip, Loss of Offsite Power (LOOP), feedwater isolation, and main steam line isolation occur simultaneously.

The recirculation valve with 3.0 inches in diameter is assumed to be opened by the low level signal from the ECCT at intact side. At the affected side, since the spilled water in the containment may flow back into the reactor vessel through the break, it is assumed that the recirculation valve at the affected side is not opened.

## 4. Results of DVI SBLOCA Analysis

A double ended guillotine break LOCA at one DVI line with 3 inch in diameter has been analyzed for 10 days after the accident initiation, and the results are presented Table 1 and Figures 5 through 9. Because there are minor changes in the system designs, assumptions, input models, and setpoints after the previous analysis, the sequence of event in Table 1 is slightly different as compared to the previous analysis. [1]

Table 1: Sequence of Event

| Event | Time |
|---|---|
| DVI line break | 0.0 sec |
| CMT isolation valves open | 12.4 sec |
| Containment peak pressure | 4.67 min |
| SDV isolation valves open | 7.60 min |
| ECCT isolation valves open | 8.93 min |
| Intact CMT empties | 13.0 min |
| Passive recirculation phase starts | 3.43 hr |

The spilled water from RV and discharged from CMT/ECCT through broken DVI line as well as the steam released through SDVs and condensed on the containment wall start to fill the containment, and the containment water level increases to the maximum level within 4 hours and remains steady thereafter as shown in Figure 5. Since the containment water level is maintained above DVI line elevation, the passive recirculation starts to circulate the water in the containment to the RCS for long term cooling. As shown in Figure 5, the containment water elevation head is sufficient to maintain the recirculation during 10 days and beyond as long as the PCCT tank water cools the containment.

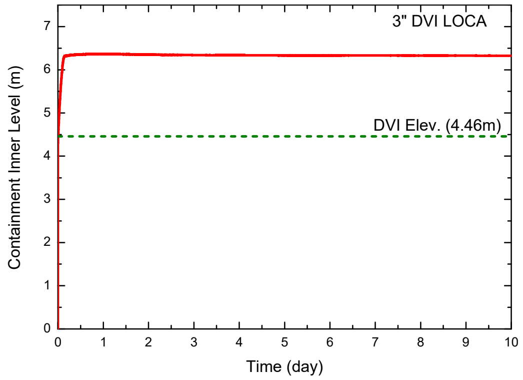

Fig. 5. Containment Water Level

Figure 6 shows the integrated flows through the broken and intact DVI lines. In early phase, the RCS coolant continues to discharge through the break as shown in this figure with negatively increasing value. As the containment level increases, the elevation head between the DVI and the containment water increases and reverses the flow direction at the break resulting in a recirculation. Meanwhile, the recirculation valve at the intact side is opened by the low ECCT level signal and the water in the containment flows into the RV through the recirculation valve as shown in Figure 6.

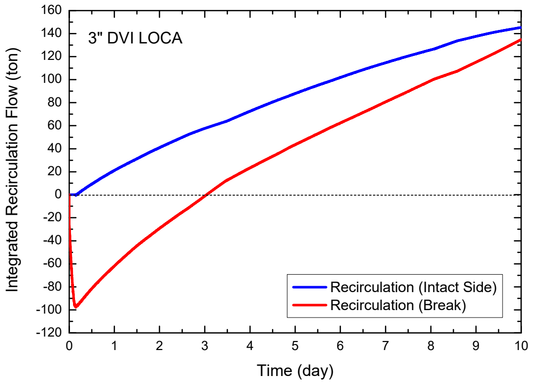

Fig. 6. Integrated Recirculation Flow

The difference between the core power and the heat removal rate through the containment wall to URWT is integrated to evaluate the long term cooling capability. Figure 7 presents the integrated energy balance in the containment based on the total heat addition from RCS and removal through the containment wall. As shown in this figure, the initial rapid increase is mainly caused by the hot RCS coolant discharge through the break and SDVs. As the coolant discharge ends and the containment recirculation starts, the total containment energy increase slows down and reaches peak value at around 1 day after accident initiation at which the decay heat balances with containment heat removal. Beyond this point, the decay heat addition is less than the heat removal through the containment wall to URWT showing a continues decrease in total containment energy in Figure 7.

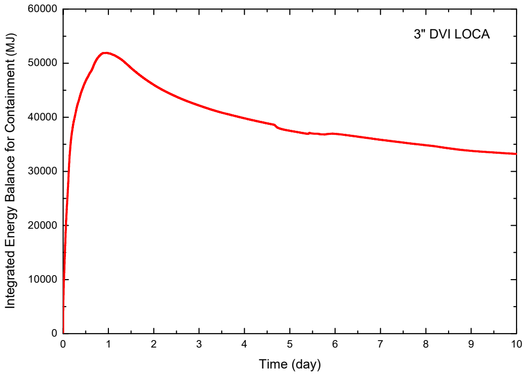

Fig. 7. Integrated Energy Balance for Containment

Figure 8 shows the hot channel fuel cladding temperature behavior. Throughout the transient, the reactor core was covered with coolant demonstrating successful decay heat removal capability by the passive containment recirculation without resulting in a fuel failure.

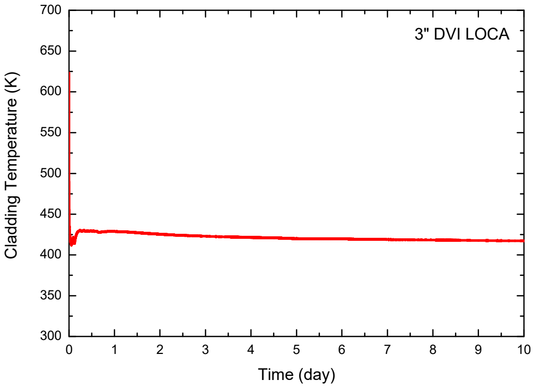

Fig. 8. Cladding Temperature

Finally, the containment pressure reaches peak value of about 11 atm in early phase due to the rapid coolant discharge as shown in Figure 9. As shown in this figure, the containment pressure is maintained at around 5 atm after the initial peak and stably decreases as the decay heat decreases and the sufficient containment heat removal continues.

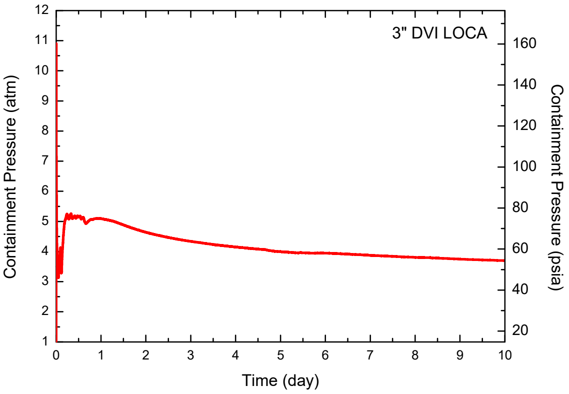

Fig. 9. Containment Pressure

## 5. Conclusions

DVI SBLOCA for BANDI-60 was analyzed using MARS-KS 1.5 computer code to assess the performance of passive long term cooling capability of BANDI-60. The analysis results demonstrated that the passive safety systems of BANSI-60 are adequately designed to prevent the core damage throughout the transient including long term cooling. Also, the cooldown by PCCS through the containment steel wall is sufficient to remove decay heat and RCS sensible heat as long as the water in URWT maintains containment cooling.

## REFERENCES

[1] Jeong Ju Kim et al., “An Analysis on DVI SBLOCA for BANDI-60,” Transaction of the Korea Nuclear Society Spring Meeting, 2021.

[2] 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.

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