Analyses on Containment Peak Pressure 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.

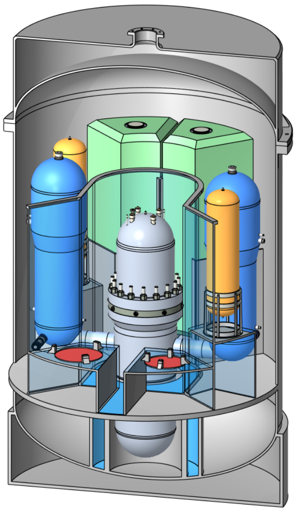

Fig. 1. Configuraton of BANDI-60 NSSS

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 finalizing the steel containment design including its design pressure and wall thickness. The thickness of containment steel wall can be calculated according to its geometry and design pressure which is determined based on the peak containment pressure during the design basis accidents. For BANDI-60, three accidents that can result in a containment pressurization are selected for quantitative analyses such as Inadvertent Opening of Safety Depressurization Valve (IOSDV), Direct Vessel Injection Small Break Loss of Coolant Accident (DVI SBLOCA), and Steam Line Break (SLB) inside containment. This paper presents the peak containment pressure analysis results for those candidate design basis accidents.

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. [1]

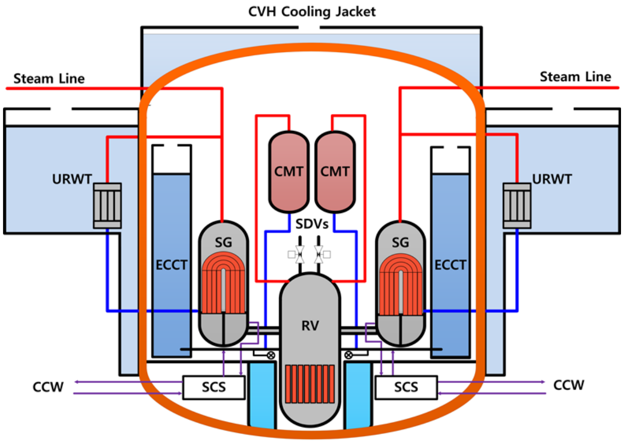

Fig. 2. Passive Safety Systems of BANDI-60

The PSIS consists of the Core Makeup Tanks (CMTs), Emergency Core Cooling Tanks (ECCTs) and Safety Depressurization Valves (SDVs). The CMTs are designed to be pressurized at the Reactor Coolant System (RCS) pressure during normal operation via the Pressure Balance Line (PBL) to the pressurizer. The CMT isolation valves in 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 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 SDVs on the pressurizer are designed to be opened for a rapid RCS depressurization.

The discharged 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 discharged 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 containment wall. 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 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 Peak Pressure Analysis

3.1 Analysis Program

Analyses on the containment peak pressure 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 considered 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 nodalization of the primary 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 these figures. Portions of the primary and the secondary systems that are not important to this analysis is omitted in Figure 3 for convenience.

As shown in Figure 3, the break in the DVI line is modeled to be connected to the containment with two flow paths: one from RV and the other from CMT/ECCT (marked with ‘DVI Break’). In cases of IOSDV and SLB analyses, ‘DVI Break’ portion is replaced with the ‘Recirculation’ portion in which the recirculation valve is modeled to be connected to the containment on both loops.

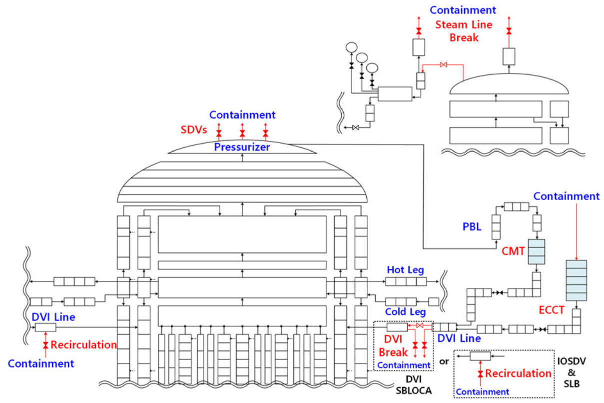

Fig. 3. MARS-KS Nodalization of BANDI-60 PSIS and SG

The containment is modeled with the containment vessel wall as a heat structure to simulate containment cooling phenomena as shown in Figure 4. Heat structures for CMT and ECCT walls are also included in the modeling to consider the passive heat sink. To evaluate the containment peak pressure conservatively, the PRHRS and CVH cooling jacket are not included. The containment is assumed to be filled with room temperature air initially.

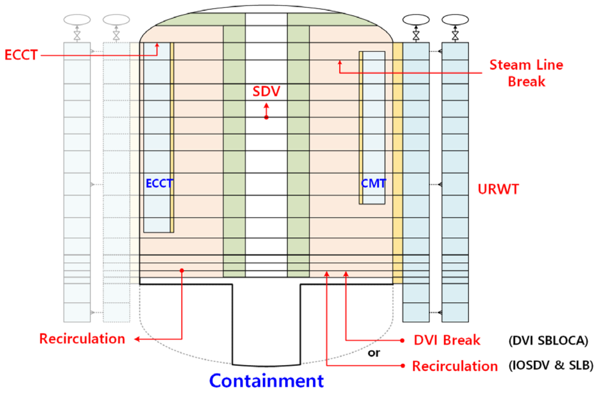

Fig. 4. MARS-KS Nodalization of BANDI-60 PCCS

3.3 Assumptions

In case of IOSDV, one of the three SDVs is assumed to open inadvertently. The inner diameter of SDV is 2.5

inches. The other two SDVs are opened later to depressurize the RCS before the ECCT injection.

For the DVI SBLOCA analysis, 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 3.0 inch inner diameter. The CMT isolation valves are assumed to be opened by the low pressurizer pressure or level. The SDVs and ECCT isolation valves are assumed to be opened by the low water level signal from the CMT at intact side. Three SDVs are opened to depressurize the RCS before ECCT injection.

In case of SLB, a double-ended guillotine break in the main steam line inside containment is assumed to occur at nominal condition. However, the initial SG level is assumed to be maximum to evaluate the containment peak pressure conservatively.

4. Results of Containment Peak Pressure Analyses

The containment peak pressure analyses for three accidents have been performed and the results are presented in Figures 5 through 9 and Table 1. The containment peak pressure is determined by the energy balance between the energy released to the containment and the energy removed to the passive heat sink including containment wall and URWT.

Figure 5 shows the integrated discharged steam flow to the containment. The discharged steam flow represents the total steam flow through the affected and intact SDVs for IOSDV, DVI break and the SDVs for DVI SBLOCA, and the steam line break and the SDVs for SLB.

In case of SLB, after initial fast increase, the steam discharge to the containment ceases to increase after the depletion of the affected SG as presented in Figures 5. For IOSDV case, the steam discharge through 2.5 inch valve continues longer at a lower rate. Although, the steam discharge for DVI SBLOCA is smaller than the other two cases, the discharged water is vaporized under the low containment pressure environment adding additional energy to the containment atmosphere.

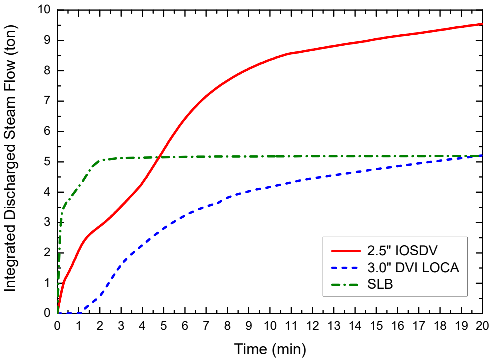

Fig. 5. Integrated Discharged Steam Flow

Figure 6 shows the heat removed from the containment atmosphere to the containment wall inner surface which is the dominant passive heat sink for BANDI-60. As shown in this figure, large amount of steam released to the containment during SLB condenses on the containment wall resulting in the highest value as compared with the other cases. However, the heat removed by the containment wall for IOSDV and DVI SBLOCA also contributes significantly in limiting containment pressurization during early phase of accident.

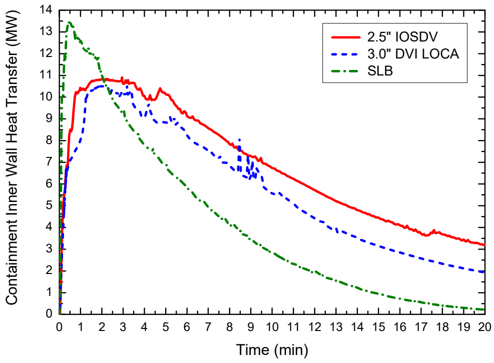

Fig. 6. Containment Wall Heat Transfer

Figures 7 presents the heat transfer to metal wall of ECCTs and CMTs that are large water tanks in containment containing cold water. As shown in this figure, the peak heat transfer is smaller than that for the containment wall but increases slowly and continues longer. Considering the decay heat level is about from 7.1 to 5.5 MW from 1.8 to 7.0 minutes after reactor trip, the amount of ECCT wall heat transfer is considerable.

However, CMT wall heat transfer is relatively smaller because of its smaller size. The negative heat transfer in Figure 7 means that heat is transferred from the CMTs to the containment. In case of IOSDV and DVI SBLOCA, the water in the CMTs are discharged to RV early and the hot steam in the pressurizer replaces the CMT water through the PBL and heats up CMT wall causing heat addition to the containment. On the contrary, for SLB, the pressurizer pressure does not decrease to the CMT actuation setpoint, and the CMT remains cold as a heat sink.

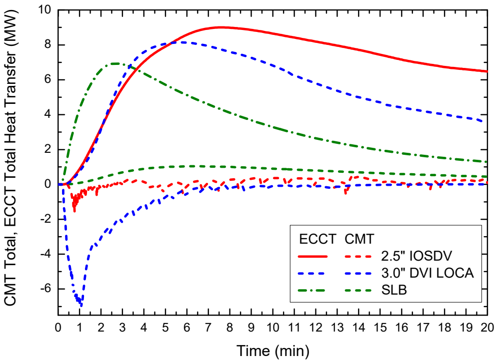

Fig. 7. ECCT and CMT Wall Heat Transfer

Although heat transfer to the containment wall inner surface increases fast (see Figure 6), heat transfer to the URWT on the containment outer surface increases slowly with time delay as shown in Figure 8. The difference between the inner and outer wall heat transfer is used in increasing the containment wall temperature. The amount of the URWT heat transfer is negligible at the time of the containment peak pressure (see Figure 9). Therefore, the major parameters affecting the containment peak pressure are the released mass and energy to the containment and the heat transfer to the containment, ECCT, and CMT walls.

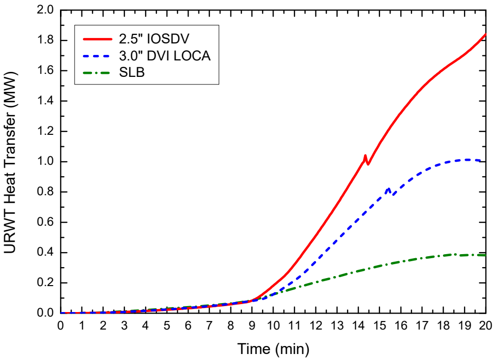

Fig. 8. URWT Heat Transfer

Finally, the containment pressures for each accident are shown in Figure 9, and the peak pressures are summarized in Table 1. As these results shows, IOSDV is identified as the limiting case with the containment peak pressure of 12.4 atm occurring at about 7 minutes into transient. Based on this conservative containment peak pressure analysis, the containment design pressure for BANDI-60 can be determined at around 15 atm (about 220 psia) considering additional margin.

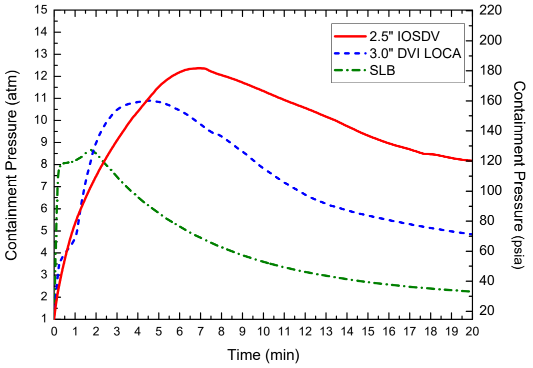

Fig. 9. Containment Pressure

Table 1. Containment Peak Pressure

Accident	Peak Pressure (atm)	Time (min)
2.5” IOSDV	12.4	7.0
3.0” DVI SBLOCA	11.1	4.7
SLB	8.80	1.8

5. Conclusions

The containment peak pressure was evaluated using MARS-KS 1.5 computer code to determine the design pressure of the containment. The analysis results showed that IOSDV is the limiting event in view of the containment pressure, and the containment design pressure for BANDI 60-can be determined at around 15 atm. The major parameters affecting the containment pressure are the mass and energy release and the passive heat removal to the containment, ECCT, and CMT walls. The heat transfer to the URWT did not affect the containment peak pressure significantly.

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.