Prediction of Heat Removal Performance for Passive Containment Cooling System using MARS-KS Code Version 1.14

Sang-Gyu Lim[ab*], Dae-Hun Kim[a], Jae-Min Lee[a], Sang-Won Lee[a], Han-Gon Kim[a], Hee-Cheon No[b]

NSSS Design Group, Advanced Reactor Development Laboratory, Central Research Institute, KHNP, Ltd.,
70, 1312-gil, Yuseong-daerom Yuseong-gu, Daejeon 34101, Republic of Korea
[b]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291,*
Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea
[*]*Corresponding author: sanggyu.lim@khnp.co.kr*

1. Introduction

After Fukushima accident, the importance of the passive safety system against the prolong Station Black-Out (SBO) has been re-confirmed. Especially, the containment is the last barrier to protect the large release of the radioactive material to the environment. To protect the containment integrity against such as the prolong SBO, many different type of the passive containment cooling systems (PCCS) has been developed in many countries.

AP1000 has steel containment which resides inside of a concrete structure with ducts that allow cool outside air to come in contact with the outside surface of the steel containment vessel. When the accident comes, two large water tank located in the top of concrete structure start to drain water into the outside surface the steel containment vessel [1]. AP1000 PCCS cools outer surface of steel containment shell using natural circulation of air and water evaporation.

ESBWR has the heat exchanger type of PCCS condenser. The PCCS condensers are located in a large pool (PCC pool) positioned above, and outside the containment. PCCS loops receive a steam-gas mixture supply directly from the containment. The heat removal process made by the internal condensation in the PCCS condenser located in PCC pool [2].

AES-2006 is an abbreviated name of an evolutionary nuclear power plant of VVER-1200 design. AES-2006 has the heat exchanger type of PCCS located in the containment. The heat exchanger is connected with the passive cooling system tank located in the outside of containment. The external condensation in the outer surface of the heat exchanger is occurred during the design bases accidents (DBA). Fluid inside the heat exchangers removes the heat of the containment using natural circulation [3].

KHNP is now developing iPOWER which is standing for Innovative Passive Optimized World-wide Economical Reactor. iPOWER has the heat exchanger type of PCCS which is similar with AES-2006. The heat exchanger tube assemblies located in the high elevation of the containment. The passive condensation cooling tank (PCCT) positioned above the auxiliary building, and outside of containment as shown in Fig. 1 [4]. When DBA comes, the steam is condensed in the outer surface of the heat exchangers. The containment heat moves into the coolant in the heat exchangers tubes. In the tube side, temperature of the coolant increased due to the heat transfer, and the density of the coolant in the tubes is lighter than the PCCT fluid. Due to this density difference, natural circulation flow is taken place in PCCS loops.

The heat removal performance of the PCCS is very important because the reactor nominal power can be determined by the PCCS performance (The reactor power of iPOWER is not determined yet). The PCCS performance can be evaluated by the containment pressure-temperature (P-T) analysis under DBAs conditions. Generally, CONTEMPT and GOTHIC codes are used as the containment P-T analysis code. The modeling methodology of the containment P-T analysis in the conventional spray system is lumped approach. Containment is modeled as single node and heat transfer from passive heat sink and spray are occurred in the single node of containment. This conventional methodology is quite reasonable because containment state goes into homogenous state after the actuation of the spray system. In PCCS case, however, flow behaviors in the containment and inside the heat exchanger tubes are governed by natural circulation. Therefore, the conventional methodology may not be valid in the PCCS case.

GOTHIC code has a capability for multi-node approach. In the domestic licensing, the P-T analysis methodology using the multi-node approach is not developed yet.

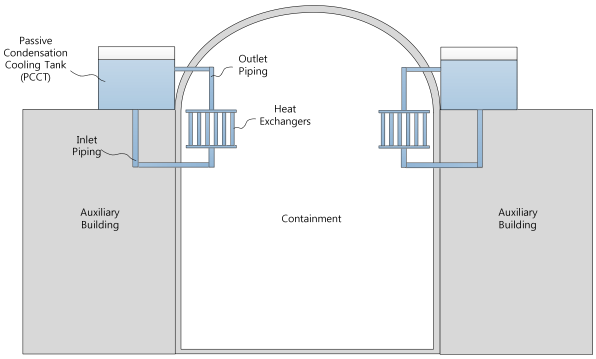

Fig. 1. Design concept of PCCS.

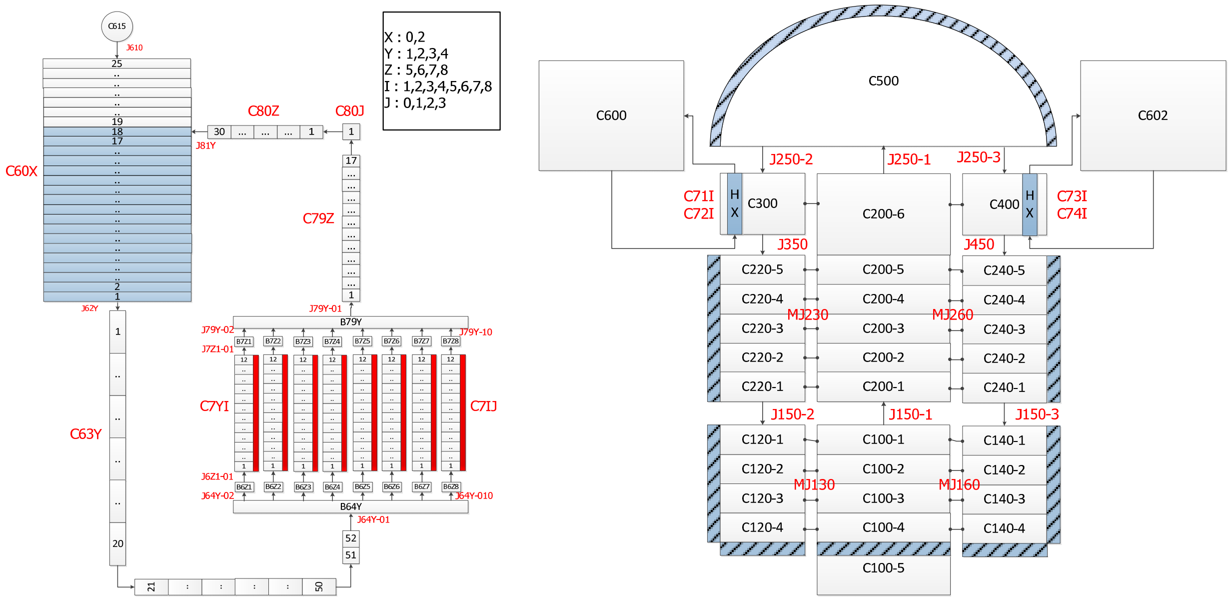

Fig. 2. Nodalization Scheme for PCCS.
(Left : PCCT, Inlet piping, PCC heat exchangers and Outlet pipe, Right : Containment with PCCS)

GOTHIC code has an advantage for analysis of containment behavior but fluid flow in the piping system and boiling phenomena are not widely validated yet.

MARS-KS code is widely used in the safety and performance analysis of nuclear system, and can deal with boiling and condensation phenomena, which are validated intensively using various experiments.

In this paper, prediction results of performance for the conceptual PCCS design are suggested using MARS-KS code version 1.14. Based on the analysis results, the thermo-hydraulic behavior in the system will be discussed focusing on the PCCS loops. The sensitivity analysis results under various design options will be suggested with the advantage and disadvantage in each design options. Also, these results can help us to advance our understanding of the physics in PCCS and to prepare the experiments.

2. Analysis Results for Bases Model

In this section nodalization scheme for base design of PCCS is described, and boundary and initial conditions are explained. MARS analysis results are provided in terms of global and local thermo-hydraulic behavior of the PCCS loops and the performance of PCCS.

2.1 Models and Conditions

Before stating the discussion about MARS analysis models, summary of design configurations for the prototype of PCCS and its related designs are provided but the detailed design information will not be discussed here because the detail design values are propriety information.

- PCCT
  - No. of train : 2 train
  - Height of water level : 8.83m
  - Water volume : 734,400 gallon
- PCC Heat Exchanger (PCCHX)
  - No. of train : 4 train
  - No. of heat exchanger bundle per 1 train : 8
  - No. of tubes per 1 bundle : 252
  - Height of tube : 6m
- Containment
  - Reference plant : Shin-Hanul 3,4 (APR1400)
  - Containment Free volume : 8.9 x 10^4 m^3
  - Accident Condition: LBLOCA with Max. SI.

As shown in Fig. 2, PCCT is modeled as a pipe component with 25 vertical volumes. During the accident analysis, local thermal mixing is taken place in the tank but this model neglects the local thermal mixing effect for conservatism. The inlet piping connects from the bottom of the PCCT to the bottom train header of PCCHX. The 1 train of PCCS has 8 bundle of PCCHX with each bundle header. The 1 bundle of PCCHX has 252 tubes. In the model, the 1 bundle of PCCHX is modeled as 1 lumped pipe component with 12 vertical volumes. The outlet pipe connects from the top of train header to the PCCT tank. The connection point between the PCCT tank and the outlet pipe is positioned below the water free surface of the PCCT.

Containment dome is modeled as single volume and the cylindrical part of the containment consist of 31 vertical volumes. To make heat transfer between the PCCS and containment, heat structures are modeled between PCCHX outer surface and containment volume 300 and 400. The mass and energy (ME) release data due to LBLOCA with Max. SI are modeled as time-dependent volumes and time-dependent junctions, which are divided as steam discharge and liquid discharge. The time-dependent junctions are connected with the 100-03 volume.

Passive heat sinks (PHS) such as concrete wall, liner plate, embedment concrete, miscellaneous steels and so on are modeled as heat structures using design data.

2.2 Results and Discussions

- Loop Flow and Temperature

The PCCS loop flow rate is governed by natural circulation. As shown in Fig. 4, the tube temperature is increased after initiation of LBLOCA but temperature of PCCT still cold due to the large volume of PCCT water. This temperature difference induces density difference between the PCCT side and the PCCHX side. Due to this, single phase natural circulation flow is occurred in the PCCS loops. At 30,000 seconds (8.3 hours), the PCCS loop flow changed from the single phase natural circulation flow to two phase natural circulation flow. In the outlet pipe, flashing is occurred and the level starts to decreased. Hence the level difference between the PCCT side and the PCCHX side become larger. It induces that the loop flow rate is increased in the two phase natural circulation mode.

- Loop Temperature and Phase Change

After initiation of LBLOCA, temperature in the tubes starts to increase. In the single phase natural circulation mode, there is no phase change in the loop thus hot water from the tubes continuously moves into the PCCT and temperature in the bottom of the PCCT start to increase at 10,000 seconds which means that hot water moves into the PCCHX tubes. By the way, there is no boiling in the PCCHX tubes because saturation temperature in the PCCHX is higher than the provided water temperature due to hydrostatic pressure of the outlet pipe water level. The hot water goes up to the outlet pipe, and then the flashing is occurred in the outlet pipe due to decrease of the saturation temperature. Fig. 6 shows the summation of vapor generation rate in the PCCHX tubes and the outlet pipe. In this system, phase change from the liquid to vapor is occurred by only flashing in the outlet pipe not boiling in the PCCHX tubes. After 400,000 seconds (4.6 days), there is flow instability in the outlet pipe. This flow instability will not be discussed in detail in this paper but if there is no flow instability in the outlet pipe, flashing may be maintained without the boiling in the PCCHX tubes after 4.6 days. Once the water level is reduced near the bottom of the PCCT, boiling can be occurred in PCCHX tubes. But it will take more than 72 hours (3 days) thus this is not big concern because PCCS is designed to allow the supply of emergency cooling water into the PCCT after 3 days by operator action.

Therefore, flashing is very important phenomena in this system, which governs the phase change and the loss of inventory for PCCT water. The flow instability is not described in detail in this paper but the flashing can induce flow instability in the long riser pipe (outlet pipe), that is reported by many researchers [5, 6, 7, 8].

- Heat Transfer mode and Flow Pattern

Fig. 7 shows heat transfer modes and flow regimes in the top of tubes and outlet pipe. As mentioned above, single phase liquid convection heat transfer mode is maintained in the tubes before the flow instability. In the two phase natural circulation mode, slug flow regime due to the flashing is shown in the outlet pipe. After flashing is occurred in the outlet pipe, vapor terminal velocity is about 12 ~ 16 m/s.

- Heat Removal Performance and Containment Pressure

Fig. 9 represents discharged energy into the containment due to LBLOCA. This energy consist of the energy of discharged steam and liquid. The discharged steam plays a role in increasing the pressure of containment but the discharged liquid does not contribute all.

The total energy discharged into the containment is higher than the total heat removal of PCCS and PHS until 20 seconds thus the containment pressure is increased during this period. From 20 seconds to 200 seconds, the total heat removal of PCCS and PHS is higher than the LBLOCA energy thus the containment pressure is decreased during this period as shown in Fig. 10. Until 20 seconds, the PHS heat removal is increased but the heat removal performance of the PHS is decreased due to increase of the PHS temperature. From 200 seconds to 2,000 seconds, the discharged energy is higher than the total heat removal. Due to this, the containment pressure is re-increased at this period. After 3,000 seconds, the heat removal from the PCCS is higher than the PHS. After this time, the heat transfer from the containment is governed by the PCCS. As shown in Fig. 4, PCCT temperature is increased until 50,000 seconds. Due to this loss of subcooling, the heat transfer performance of the PCCS is decreased, and thus the containment is re-pressurized at this period.

GOTHIC code analysis is performed by FNC Tech. GOTHIC model used single node for containment and single node for PCCT and single node for PCCS tubes. Same ME data are used in this analysis. Fig. 10 shows that containment pressure results are similar with each other qualitatively. Detailed thermo-hydraulic variables will be compared with each other in future.

In summary, the containment pressure behavior is governed by the discharged energy from the LBLOCA. The PCCS performance is continuously changed related the PHS performance and the condition of PCCT.

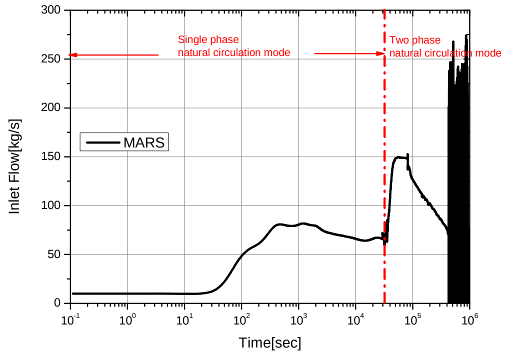

Fig. 3. Flow rate at the inlet pipe of one train.

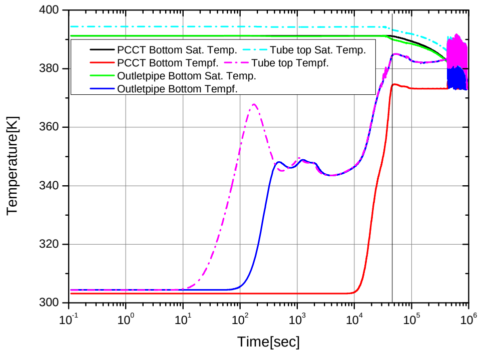

Fig. 4. PCCT temperature and PCCHX outlet temperature.

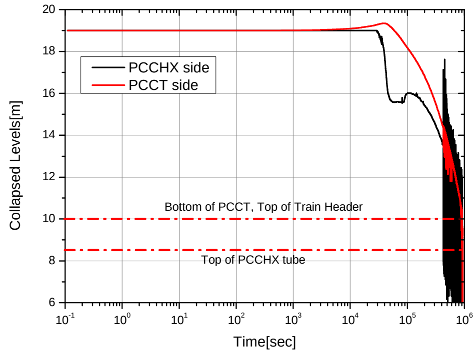

Fig. 5. Collapsed water level for PCCT side and PCCHX side.

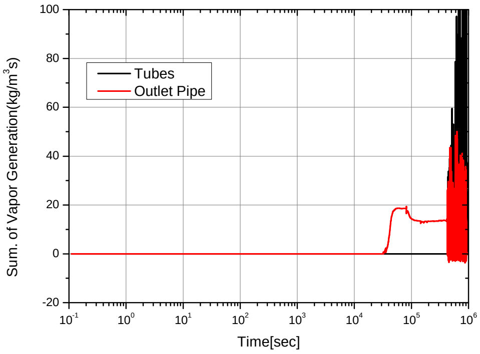

Fig. 6. Summation of vapor generation at outlet pipe and tube

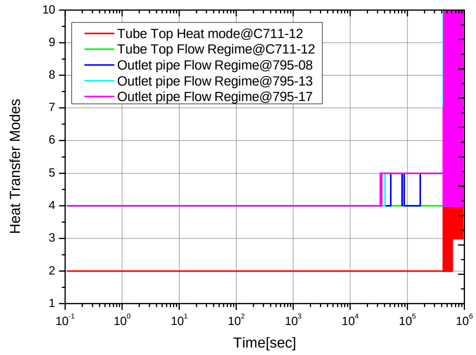

Fig. 7. Heat mode and flow regime for tube top and outlet pipe.

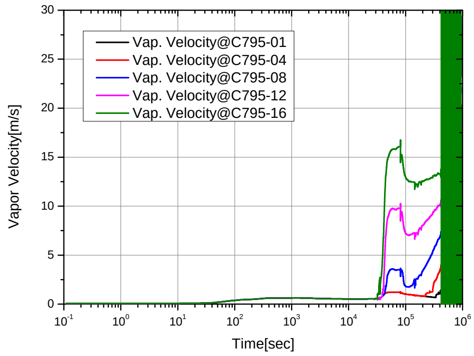

Fig. 8. Vapor velocity at the outlet pipe.

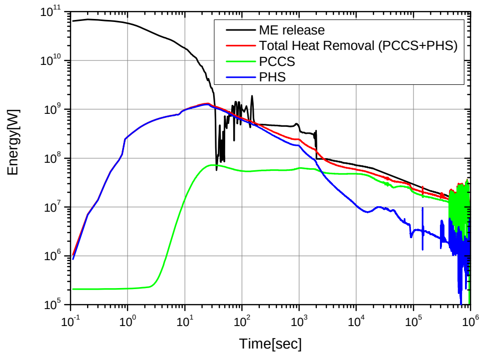

Fig. 9. LBLOCA ME and heat removal rate by PHS and PCCS

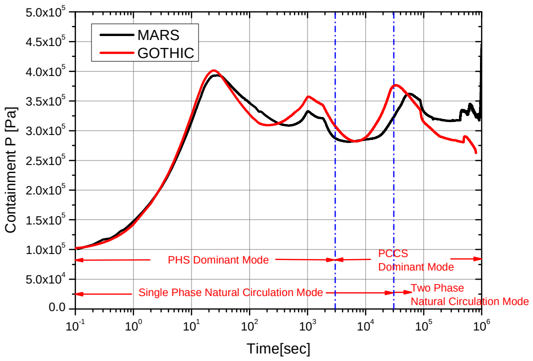

Fig. 10. Containment pressure.

Table I: Sensitivity Analysis Matrix and major boundary conditions

Description of Sensitivity Analysis Matrix		Mass and Energy Release (Reference Reactor Power, MW)	PCCT modeling	PCCS modeling
PCCT model sensitivity	Base Case	1,400	2 train	4 train
	Case A	1,400	4 train	
Reference reactor power sensitivity	Base Case	1,400	2 train	
	Case B-1	1,350		
	Case B-2	1,300		
	Case B-3	1,250		
	Case B-4	1,200		
Reference reactor power sensitivity with PCCT model sensitivity	Case C-1	1,350	4 train	
	Case C-2	1,300		
	Case C-3	1,250		
	Case C-4	1,200		

3. Sensitivity Analysis Results

In this section sensitivity analysis results using various design options are discussed. Models and major boundary conditions are described and the heat transfer performance of PCCS is discussed comparing with the results of the bases model.

3.1 Models and Conditions

Nodalization in the sensitivity analysis is same with bases model.

One of sensitivity analysis has been performed to determine the effect of heat transfer performance on the PCCS dependent upon the number of the PCCT tanks. As shown in Table. I, Case B increases number of PCCT tanks from 2 to 4. In this case, each PCCS loop connected with each PCCT.

The other of sensitivity analysis has been performed to find optimal reactor power for iPOWER considering heat removal performance of the PCCS. In real, mass and energy release data from LBLOCA in each reactor power should be analyzed separately but detailed configuration of reactor coolant system in iPOWER is not determined yet. So, mass and energy release data are assumed that the discharged energy linearly decreased versus reactor power ratio from reference reactor power (1,400MW).

3.2 Results and Discussions

As shown in Fig. 11, the re-pressurization of containment in Case A is delayed about 50,000 seconds (13.8 hours) compared with the bases case. This is because total amount of the PCCT volume in Case A is 2 times larger than the bases case. But, re-pressurization of containment due to a loss of subcooling in the PCCT water is still occurred.

These phenomena are very challenge in the design viewpoint. Containment pressure is re-build up during a long period about 1 day. In according to functional recovery guideline of conventional PWR, operator should need continue effort establish the containment pressure and temperature control after accidents. In PCCS design, however, they just watch the status of the containment pressure and temperature during a long period. Therefore, another component may be necessary for the closure of the accident such as non-safety class backup spray system.

Fig. 13 and 14 shows the sensitivity analysis results based on various reactor power. As we expected, reduced mass and energy release data brings decreased containment pressure linearly.

NUREG-0800 provided the requirement of containment pressure in the long term period. In the NUREG-08000, the containment pressure should be reduced less than 50% of the peak calculated pressure for the design bases loss-of-coolant accident within 25 hours after the postulated accident [9]. Not only bases case and but also various design options cases cannot meet this requirement. So, innovative ideas to enhance the heat transfer performance of PCCS should be necessary in the future. Fin-type of tube and inclined tube can enhance the heat removal performance of PCCS.

MARS code under-estimated the condensation heat transfer in the validation calculation for the separate effect test such as COPAIN test. Thus prediction capability of MARS and GOTHIC code should be thoroughly validated using the prototype PCCS experiments which will be performed by KAERI.

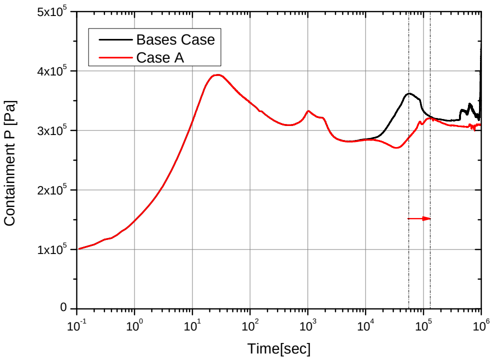

Fig. 11. Containment pressure for PCCT 4 train effect

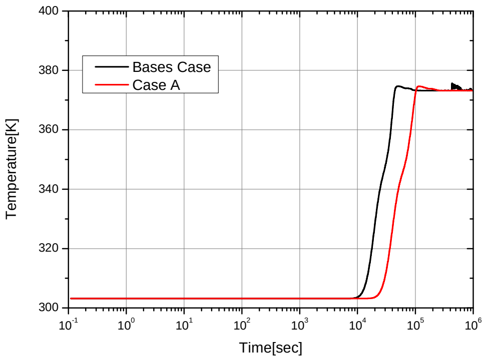

Fig. 12. PCCT bottom liquid temperature.

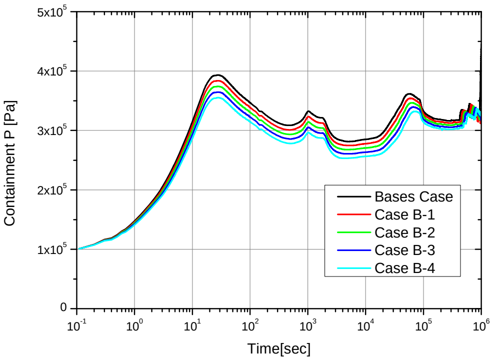

Fig. 13. Containment pressure for PCCT 2 train under various reactor power

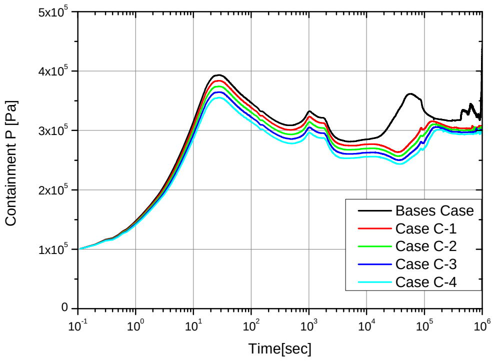

Fig. 14. Containment pressure for PCCT 2 train under various reactor power

3. Conclusions

Prediction of performance of the conceptual PCCS is conducted using MARS-KS code version 1.14. Key thermo-hydraulic phenomena are identified in this paper.

- Flashing phenomena dominate in the phase change and the loss of inventory in PCCT.
- Due to this, natural circulation flow is changed from single phase natural circulation mode to two phase natural circulation mode.
- Containment pressure is re-pressurized by the loss of subcooling in the PCCT water.
- Containment status can be divided as distinguishable periods related with the PCCS status.

Design considerations are also identified to enhance the performance of PCCS against postulated accidents.

- It needs idea that can improve the performance of the PCC heat transfer innovatively.
- Fin-type tubes and inclined tube type of PCCS design are considered.

Through this paper, selection of test matrix for the prototype of PCCS test and further code validation plans can be prepared.

Acknowledgement

This work was supported by the Nuclear Research & Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry and Energy (No. 20161510400120)

Special thanks to Dr. H. J. Chu, Dr. S. S Jeon and Dr. S. J. Hong from FNC Tech. They provided the GOTHIC analysis results.

REFERENCES

[1] IAEA, Natural Ciculation in Water Cooled Nuclear Power Plants, IAEA-TECDOC-1474, Vienna, 2005.

[2] General Electric, The ESBWR Plant Gerneral Description, April, 2007.

[3] Denis Kolchinsky, AES-2006-New Design with VVER Reactor and INPRO Methodology, Presentation Materials, INPRO Forum, Nov.19-22, 2013, Vienna.

[4] Han-Gon Kim, Sun-Heo, The Conceptual Design of Innovative Safe PWR, Transactions of the Korean Nuclear Society Autumn Meeting, Oct.27-28, 2016, Gyeongju.

[5] M. Furuya et al, Flashing-induced Density Wave Oscillations in a Natural Circulation BWR-Mechanism of Instability and Stability Map, Nuclear Engineering and Design, Vol. 235, pp. 1557-1569, 2005.

[6] I. S. Kyung, S. Y. Lee, Experimental Observations on Flow Characteristics in an Open Two-phase Natural

Circulation Loop, Nuclear Engineering and Design, Vol. 159, pp.163-176, 1994.

[7] S. P. Lakshmanan, M. Pandey, Numerical Investigation of Startup Instabilities in Parallel-Channel Natural Circulation Boling Systems, Science and Technology of Nuclear Installations, Vol. 2010, Article ID 574195, 2010.

[8] H. Atajafari et al, Validation of RELAP5/MOD3.2 Code for Flashing-Induced Instabilities in a Single Channel, World Journal of Nuclear Science and Technology, Vol. 5, pp. 6-17, 2015.

[9] U.S. NRC, Standard Review Plan, NUREG-0800, Revision 3, Mar., 2007.