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Evaluation on Long-term Cooling of CANDU after Sump Blockage using MARS-KS

Seon Oh YU[a*] , Yong Jin CHO[a] and Sung Joong KIM[b]
[a] *Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon, 305-338, Korea*
[b] *Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul, 133-791, Korea*
[*]*Corresponding author: k378yso@kins.re.kr*

1. Introduction

It has often been addressed that the safe operation of nuclear power plants is assured by maintaining the basic safety functions such as reactivity control, cooling fuels, and confinement. Among these, the cooling fuels is the major one related to the thermal integrity of fuel channels of pressurized heavy water reactor (PHWR) over the occurrence of a loss of coolant accident (LOCA). In such event, the fuel channels are likely to be impaired due to the insufficient cooling caused by the reduction of the coolant flow rate into the primary heat transport (PHT) system from the recirculation sump, at which substantial amount of debris are entrained. There was a real incident that part of the fibrous insulation debris stripped by steam jet was transported to the pool and clogged the intake strainers of the drywell spray system, which revealed a weakness in the defense-in-depth concept which under other circumstances could have led to the ECCS failing to provide coolant to the core [1]. Since the above Barsebäck-2 incident in 1992, lots of the international activities have been carried out to identify essential parameters and physical phenomena and to promote consensus on the technical issues, important for safety and possible paths for their resolution [2-5].

In nuclear power plant under operation, if an unplanned reactor trip or a power reduction occurs, operators are required to maintain the reactor in a stable state according to emergency operating procedure (EOP) and to take diagnosis and appropriate mitigation actions if necessary. Subject to the EOP of Wolsong unit 1 (the first Korean PHWR NPP) under LOCA, intact or broken loops are diagnosed using the available plant information such as pressure and temperature of outlet headers. For the intact loop, effective long-term cooling is envisioned through the operation of shutdown cooling system as implemented in the EOP. However, for the broken loop, viable cooling is maintained only by low pressure emergency coolant injection (LP ECI) through the flow path from the recirculation sump. This is likely to cause the flow area through the mesh screen equipped in the sump to be reduced and eventually the flow rate in the broken loop diminishes. If the comprehensive understandings of the major parameters which can detect reasonably the blockage of the recirculation sump and of their operational ranges are achievable through in-depth studies and practices, the sustainable long-term cooling of the broken loop can be maintained more stable during the recirculation phase, with mitigating the possible adverse consequences.

Therefore, the purpose of this study is to investigate closely the effects of the reduced flow area caused by substantial amount of debris on the adequacy of long-term cooling in the broken loop under the postulated LOCA using a computer program for system analysis.

2. Description of Modelling

In this study, the evaluation of the adequacy of the long-term cooling was performed for a LOCA scenario, a transient initiated by 35% break of an inlet header, where all the safety systems were assumed to be available. So, the PHT system consists of 2 loops with an intact loop and a broken loop.

MARS-KS (Multi-dimensional Analysis of Reactor Safety-KINS Standard) computer program developed for the realistic multi-dimensional thermal-hydraulic system analysis [6] was used for this study. Although this code has usually been used to analyze light water reactor transients, it has been also employed for heavy water reactors with the adoption of the PHWR-oriented models, reflecting the characteristics such as the fuel channel model (CANCHAN), components models (Wolsong pump model, header-feeder model, etc.), to mention a few [7,8]. To evaluate thermal-hydraulic behaviors of the plant system with the code, the standard input deck used for the audit calculation for LOCA event [9] was used to analyze system transients and subsequential long-term cooling with slight modifications. The following shows the brief explanation.

Figure 1 shows the nodalization diagram of the typical PHWR power plant. Total 380 fuel channels were modelled by 4 multi-averaged channels (100, 200, 300, and 400) in accordance with the power and the location of each fuel channel. One of the averaged channels in the broken loop (400) was divided into 7 fuel channel groups (025~085) to perform a detailed analysis for core flow. Each loop includes fuel channels, inlet/outlet headers, inlet/outlet feeders, steam generators, and coolant pumps. The loop isolation valve is located at the pressurizer to isolate the loops under the condition of emergency operation.

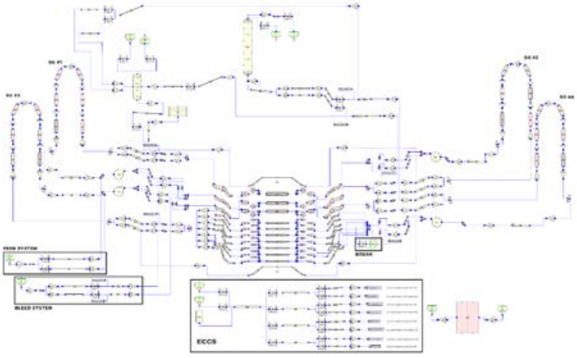


Fig. 1. Nodalization of Wolsong unit 1 for MARS-KS simulation.

The steam generators consisting of the major components such as steam drum, separator, U-tubes, downcomer were modelled to be operated by the level control logic and the assumptive manual actions for avoiding undesired flooding by continuous auxiliary feedwater supply. The main steam safety valves were also modelled for simulating the crash cooling down of the system by opening at 30 seconds after the occurrence of LOCA signal as designed.

Three stages of ECCS actuated by operating pressure are envisioned as high pressure (HP), medium pressure (MP), and low pressure (LP) ECI. The HP and MP/LP ECIs were modelled using an accumulator component and time dependent volume components, respectively.

3. Results and Discussion

A steady state calculation was performed first given the 103% reactor power and all major parameters were found to reach the steady values. Table 1 shows a comparison of the calculation results and final safety analysis report (FSAR) values of Wolsong unit 1. It is observed that major parametric values computed by the code are in good agreement with FSAR values.

Table 1. Values of major parameters in the steady state condition

Parameter, [unit]	FSAR	MARS-KS
Reactor inlet header pressure, [MPa]	11.2	11.26
Reactor inlet header temperature, [K]	540	538.50
Reactor outlet header pressure, [MPa]	10.0	10.01
Reactor outlet header temperature, [K]	584	583.72
Channel flow rate, [kg/s]	2,062	2,100.85
Averaged power for each channel, [MW]	527.88	527.88
Total feedwater flow rate, [kg/s]	1,061	1,062.88
SG drum pressure, [MPa]	4.7	4.77
SG drum temperature, [K]	533	534.14
Steam flow rate, [kg/s]	1,076	1,060.16

LOCA transient was initiated with the postulated 35% inlet header break, which was simulated by quick opening of the break valve connecting the inlet header of channel 400 and the containment under atmospheric pressure modelled by the time dependent control volume component. The Henry-Fauske discharge model was used to simulate the break flow and the break size was obtained by adjusting the cross section area of the inlet header. Because of the code limitation that the reactivity model of the point kinetics is unavailable for simulating instantaneous power pulse due to the coolant loss from the fuel channels, causing the reactor trip by the regional overpower signal, the transient reactor power [9] after occurrence of LOCA was incorporated in the input. As shown in Table 2, the major equipment since the transient started were properly operated subject to the designed control logic.

Table 2 Sequence of significant events for PHWR LOCA

Time, [s]	Major Sequences	Control logic
0.00	35% inlet header break	break valve opens
	Reactor trip	LOCA + 0.0 sec
9.05	LOCA signal occurrence	Max[min(OH), min(IH)] ≤ 5.25MPa
	Loop isolation	LOCA signal + 0.0 sec
14.06	Turbine governor trip	LOCA signal + 5.0 sec
	PHT pump trip	
29.64	HP ECI signal (open)	Max[min(OH), min(IH)] ≤ 3.62MPa
39.05	SG crash cooldown (MSSV open)	LOCA signal + 30.0 sec
119.64	MP ECI signal (open)	HP ECI start + 90 sec
194.06	AFWP operation	LOCA signal + 185 sec
313.96	HP ECI signal (close)	accumulator inventory ≤ 5.47m^3
638.32	MP ECI signal (close)	MP ECI stop (amount of MP ECI > 200 m^3)
	LP ECI signal (open)	

The blockage of the recirculation sump was modelled by reducing the flow area of the LP ECI valve, resulting in the decrease of the coolant flow rate and was assumed to be initiated with the LP ECI signal for the conservative calculation. Figure 2 shows the decrease of LP ECI flow rate with the reduced flow area of the recirculation sump, indicating that the coolant inventory necessary for cooling the PHT system is getting decreased, which implies that the present modelling was achieved reasonably.

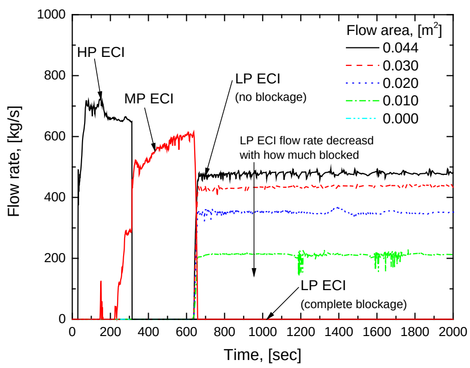
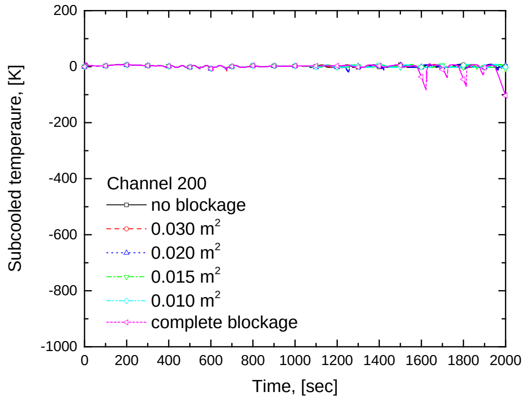


Fig. 2. Variations of ECCS flow rate with the recirculation sump blockage.

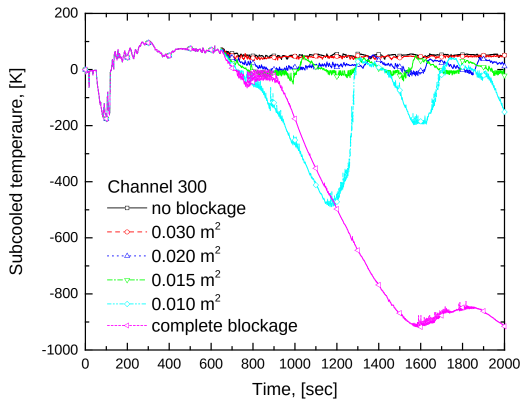
The sensitivity evaluation was performed to assess whether the thermal integrity of the fuel channel could be challenged by varying the area of the LP ECI valve, which simulated the flow area reduced by debris inflow into the recirculation sump. Figure 3(a) shows the subcooled temperature of the fuel channel in the mid-plane of channel 200 in the intact loop. If the flow area was reduced to 0.02 m^2 (45.5% of nominal flow area) since the LOCA occurred, slight temperature increase of approximately 35 K was observed at 1,250 seconds. Since then, however, no virtual temperature rise was estimated. In the severer case, if the flow area was completely blocked, meaning the LP ECI flow rate of 0.0 kg/sec, irregular fluctuation of temperature started to be observed since 1,500 seconds. In this period of sporadic fluctuation, maximum temperature rise of approximately 80 K was observed at 1,600 seconds, at which incipience of boiling was evaluated to occur unless external intervention was employed. In the practical operation, according to the operator's actions guided by the EOP, the state of cooling and depressurization of the intact loop can be effectively maintained by the shutdown cooling system. Thus it is expected that the proper long-term cooling can be achieved in the intact loop regardless of the degree of the blockage of the recirculation sump.

For the broken loop, Fig. 3(b) shows a different tendency of the subcooling temperature of the fuel channel in the mid-plane of the channel 300. If the flow area was reduced to 0.03 m^2 (68.3% of nominal flow area), neither dramatic temperature rise nor irregular temperature fluctuation were observed. Likewise, no incipience of boiling was observed. Unlike the temperature behavior in the intact loop, however, if flow area was reduced to 0.02 m^2, boiling was evaluated to occur in the fuel channel, which was the similar event observed in the intact loop. In addition, beginning of the irregular temperature fluctuation was estimated much earlier as the reduction of the flow area was larger. If more debris induced a dramatic blockage of flow area less than or equal to 0.01 m^2 (22.8% of the nominal flow area), insufficient LP ECI flow rate caused the significant temperature rise in the fuel channel followed by the termination of the MP ECI. Subsequently, virtually large amplitude of temperature fluctuation occurred, which may cause deficiency of subcooling margin. Thus incipience of boiling influencing undesirable effect on the thermal integrity of the fuel channel may be expected.

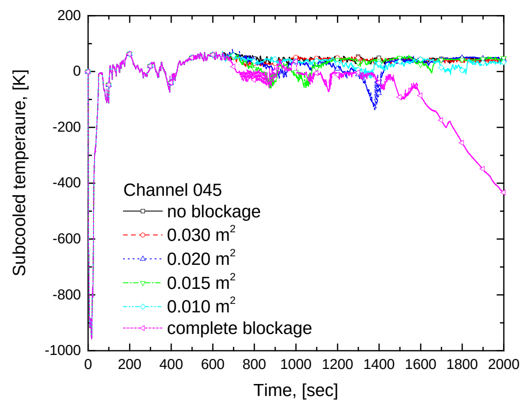
Figure 3(c) shows the subcooling temperature of the fuel channel in the mid-plane of the channel 045 (one of 7 fuel channel groups of channel 400) with respect to the blockage of the recirculation sump. If flow area was reduced to 0.03 m^2, no temperature fluctuation or dramatic rise were observed, which was similar to the results in the channel 300. If more blockage occurred and the resulting flow area was reduced to 0.02 m^2, however, some temperature fluctuation was observed to occur in the range of 900 to 1,500 seconds, in which maximum temperature rise of approximately 120 K was estimated at about 1,400 seconds. In addition, no substantial temperature fluctuation was observed since 1,500 seconds. If the blockage of the flow area continued and the resulting flow area was reduced more than half the nominal flow area, however, temperature started to disturb and increases irregularly. For the complete blockage, relatively frequent temperature fluctuations were observed and eventually it started to increase rapidly since 1,300 seconds. It should be noted that the calculation continued until 2,000 seconds. Thus if no additional actions of the operators were taken to mitigate the event, the temperature of the fuel channel may reach to failure condition of the fuel rod.



(a) channel 200 of intact loop



(b) channel 300 of broken loop



(c) channel 045 of broken loop

Fig. 3. Effects of the reduced flow area of the recirculation sump on subcooled temperature in the recirculation phase.

Through the results addressed so far, as shown in Figure 4, it can be deduced that long-term cooling of fuel channel was feasible in the broken loop only if the reduced flow area was more than about 70% (corresponding to flow rate of 90%), which facilitated sufficient LP ECI. If the reduced flow area became below more, however, incipience of boiling was expected, which impaired the thermal integrity of fuel channel. In addition, if the flow area of the recirculation sump dramatically was reduced to below about 25% (corresponding to flow rate of 45%), excursion and frequent fluctuation of temperature of fuel channel can be unavoidable and the impairment of the fuel channels be anticipated. Also, there can be the severe vibrant measurement of differential pressure between upstream and downstream of the mesh screen in the sump due to the much reduced flow area, causing the drastic fluctuation of LP ECI flow rate during event progress.

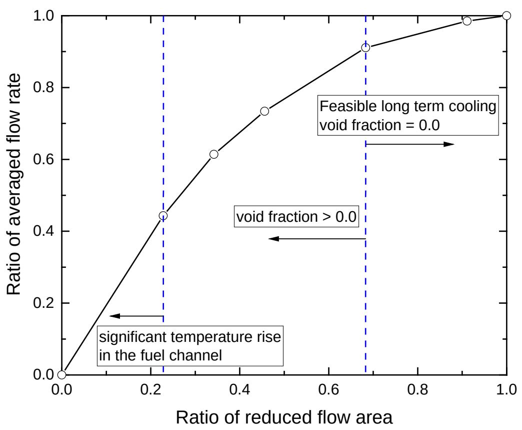


Fig. 4. Effect of the reduced flow area of the recirculation sump on long-term cooling.

Based on the above results, therefore, through the detailed analysis on the reasonable operating ranges of the major system parameters facilitating the sufficient and stable cooling in the broken loop, it can be seen that how much blocked by measuring the pressure drop and LP ECI flow rate, and then appropriate corrective measures prohibiting the violation of the operating preset ranges can be taken prior to entering more severe states.

4. Conclusions

In this work, the adequacy of long-term cooling during the recirculation phase of LOCA was evaluated under the postulated condition of the reduced flow path of the recirculation sump due to the inflow of substantial amount of debris released by the break flow with high energy. For the intact loop, although the incipience of boiling in the fuel channel was evaluated to occur, the effective long-term cooling can be achieved through the shutdown cooling system as guided in the EOP. For the broken loop, however, if the reduced flow area becomes below about 70% of the nominal flow area, incipience of boiling was expected. Additionally, if the flow area of the recirculation sump dramatically was reduced to below about 25%, the impairment of the fuel channels was anticipated with the frequent fluctuation and sharp increase of fuel channel temperature.

It is expected that sustainable long-term cooling of the broken loop can be maintained more stable by taking the appropriate corrective actions reflecting the results of the present work and the further detailed analysis on the major system parameters facilitating the sufficient cooling in the broken loop as part of the effort of preventing and mitigating the possible adverse consequences.

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