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Sensitivity Analysis for PAFS Cooling during an SBLOCA under PECCS Operation using ATLAS Test Facility

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1. Introduction

A thermal hydraulic integral effect test facility, ATLAS (Advanced Thermal-hydraulic test Loop for Accident Simulation) [1], has been utilized for an international cooperation project, the OECD/NEA ATLAS. The key objective of the project is to address thermal-hydraulic safety issues and accident management issues relevant for light water reactors. In the second-phase of OECD/NEA ATLAS project, the B2.2 test was performed to investigate safety issue related to performance of passive safety systems during small break loss of coolant accident (SBLOCA) [2]. Passive emergency core cooling system (PECCS) was designed to mitigate core uncovery using automatic depressurization valves (ADVs) and safety injection tanks (SITs). The test results presented increase of cladding temperature after termination of safety injection from SITs because water from the in-containment refueling water storage tank (IRWST) could not be injected due to pressure of reactor coolant system (RCS). To resolve this challenge, the RCS needs a larger depressurization rate with an additional cooling measure, for example, an operation of passive auxiliary feedwater system (PAFS).

In this study, sensitivity analysis was conducted to simulate an additional cooling by PAFS during a cold leg SBLOCA with an operation of PECCS. Compared to the previous test, B2.2, effect of the depressurization of RCS by the operation of PAFS and the consequent core quenching will be investigated with MARS-KS code [3].

2. ATLAS Test Facility

2.1 ATLAS Configuration

ATLAS is a half-height and 1/288 volume scaled test facility following APR 1400 (Advanced Power Reactor 1400 MWe). ATLAS is being used to investigate the thermal-hydraulic behavior between the systems for a whole prototype plant or between subcomponents during anticipated transients and postulated accidents.

Fig. 1 shows a schematic diagram of ATLAS test facility. To simulate high-pressure and high-temperature accident scenarios, the RCS loop was designed to endure up to 18.7 MPa and 370℃. The fluid system of ATLAS consists of a primary system, a secondary system, a safety injection system, a break simulation system, a containment simulation system, and auxiliary systems. The primary system includes a reactor pressure vessel (RPV), two hot legs, four cold legs, a pressurizer (PZR), four reactor coolant pumps (RCPs), and two steam generators (SGs). The secondary system of ATLAS is simplified as a circulating loop-type. The steam generated at two steam generators is condensed in a direct condenser tank, and the condensed feedwater is re-circulated to the steam generators. In addition, ATLAS provides integral effect test data for the 2 hot legs and 4 cold legs for an RCS with a direct vessel injection (DVI) of emergency core cooling (ECC) using four SITs. The detailed design and a description of the ATLAS facility is presented in the literature [4].

2.2 Passive Safety Systems

As shown in Fig. 1, high pressure SITs (HPSIT-1 and 2) connected to the cold legs and DVI lines, were used to simulate PECCS injection. PECCS is activated when pressure of PZR decreases under set point after accident transient. However, safety injection from HPSIT is delayed because the pressure of RPV is maintained as high pressure compared to the hydraulic pressure difference between HPSIT and DVI line. Decay heat removes coolant inventory in core region, and cladding temperature starts to increase. When the cladding temperature exceeds the criteria for ADV opening, the ADV1 and 2 sequentially open. When safety injection is not enough to recover the inventory of the core, water of IRWST have to be injected. The primary system pressure needs to be depressurized under the pressure of containment for the safety injection from IRWST.

PAFS is a passive safety system to cool the RCS by utilization of heat exchanger inside a passive condensation cooling tank (PCCT) as presented in Fig 1. It can be used as an additional cooling system independent with PECCS.

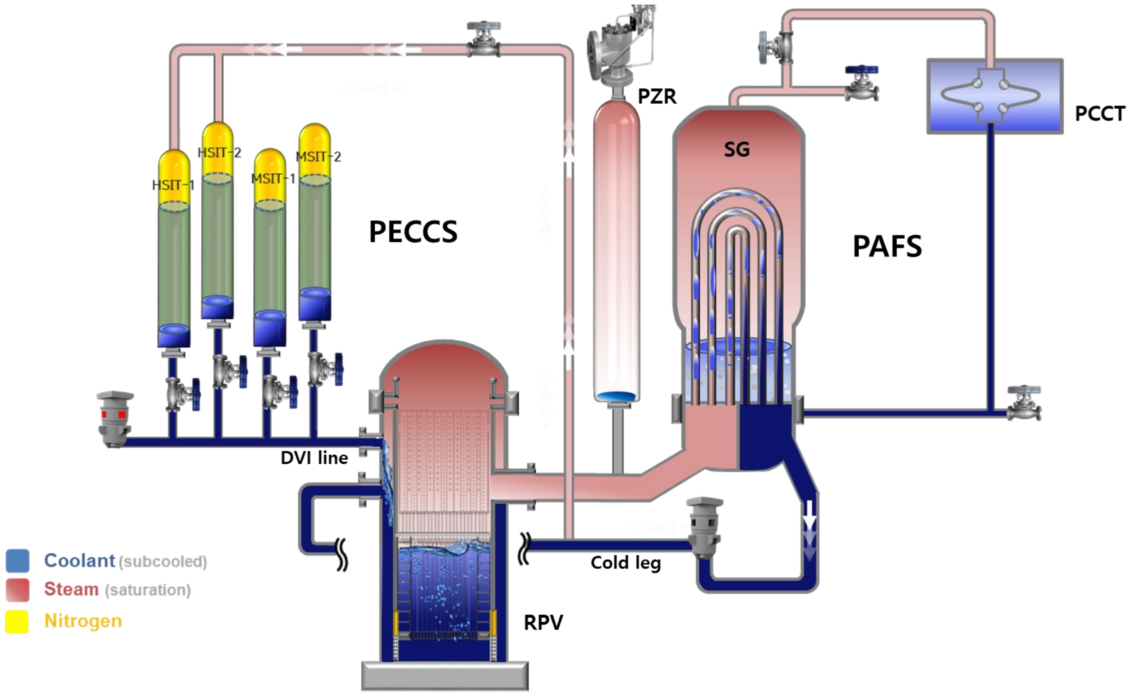

Fig. 1. Schematic drawing of the PAFS and PECCS operations in ATLAS.

3. Sensitivity Analysis for Additional PAFS Cooling

In this section, sensitivity analysis results are compared with test results of B2.2. Initiation of PAFS was simulated differently depending on the operation of PECCS or ADV which induces different calculation results in terms of additional cooling timing before or after increase of cladding temperature. All values in this paper will be discussed as normalized values.

3.1 B2.2 Test Results

B2.2 test simulated a cold leg SBLOCA transient with an operation of PECCS only. Start of SBLOCA in the B2.2 test was rearranged at 0 in this study as shown in Table I, because it was effective to compare test results with analysis results. Low pressurizer pressure (LPP) signal was initiated at t^*=0.041 after pressure of PZR reduced under set point (0.535). The reactor trip was activated and the secondary system was isolated when the feed water and the main steam isolation valves were closed after reactor trip. The HPSIT-1 and 2 were activated at 0.065 with opening of the PECCS line valves. Coolant injection was delayed due to small driving force of differential pressure between the HPSIT and the RPV down-comer. ADV1 and 2 opened after the cladding temperature increased up to criteria, 0.728 and 0.759, respectively.

In the B2.2 test, the coolant injection from the IRWST was not realized because pressure of RPV maintained too high to inject the coolant. In this study, it will be investigated about the earlier depressurization of RCS by additional cooling of PAFS can be advantageous for coolant injection from IRWST.

Table I: Sequence of Events in Test and Sensitivity Calculations

Event	Description	Normalized time (t^*)		
		B2.2 test results	PAFS operation at PECCS injection	PAFS operation at ADV open
Test start	2-inch cold leg SBLOCA	0	0	0
Low pressurizer pressure (LPP) signal	$P_{PZR} \leq 0.535$	0.041	0.096	0.096
HPSIT-1 and -2 open	$P_{PZR} \leq 0.5$	0.065	0.102	0.103
ADV1 open	$T_{max\_clad} \geq 0.728$	0.641	-	0.624
ADV2 open	$T_{max\_clad} \geq 0.759$	0.655	-	0.680
Termination of test		0.876	1.000	1.000

3.2 Sensitivity Analysis Results

Sensitivity analysis was performed using MARS-KS 1.4 code. In the B2.2 test, safety injection from the IRWST was not realized due to the late depressurization of RPV. In order to investigate the sensitivity effect of additional cooling by PAFS, PAFS operation was simulated differently depending on timing before or after increase of cladding temperature. As shown in the Table I, 'PAFS operation at PECCS injection,' means 'before increase of cladding temperature' and 'PAFS operation at ADV open' indicates 'after increase of cladding temperature.'

PZR pressure and the maximum cladding temperature trends along to PAFS operation are presented in Figs. 2 and 3, respectively. When the PAFS operation was initiated at 'PECCS injection,' the PZR pressure decreased continuously as shown in Fig. 2. Cooling performance of PAFS was enough to cool the reactor core as shown in Fig. 3. When PAFS was operated at 'ADV open,' of course, the PZR pressure did not decrease before cladding temperature increased. After ADV1 open, the maximum cladding temperature did not decrease in B2.2 test as shown in Fig. 3. However, the cladding temperature in code calculation result started to decrease immediately by an operation of PAFS. And it could be observed that ADV2 open was delayed in the code calculation result due to the heat removal through PAFS. Even though the depressurization by combination of PAFS and ADV1 was not enough to prevent core uncovery, the heated core was quenched after ADV2 open and IRWST injection.

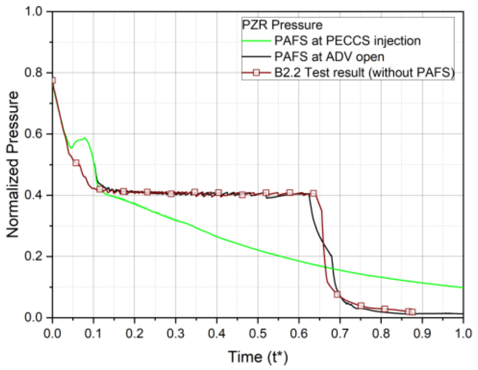

Fig. 2. Sensitivity Analysis Results for Additional PAFS Cooling Based on B2.2 Test Results (Normalized Pressure).

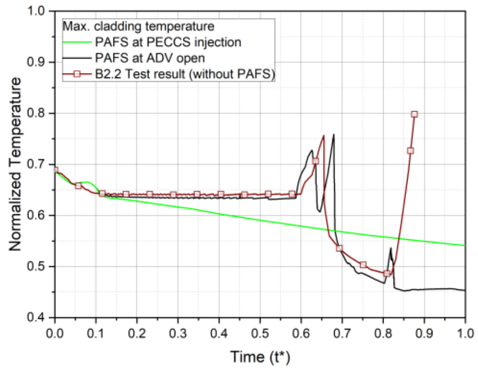

Fig. 3. Sensitivity Analysis Results for Additional PAFS Cooling Based on B2.2 Test Results (Normalized Temperature).

3. Conclusions

Sensitivity analysis with MARS-KS was conducted to evaluate an additional cooling performance of PAFS during an SBLOCA scenario with an operation of PECCS. The B2.2 test in the second-phase of OECD/NEA ATLAS project was selected as a reference test result. It was found that the heated core can be cooled by PAFS operation and coolant injection from IRWST due to depressurization of RCS. As a result, earlier depressurization by PAFS operation is expected to contribute to effective cooling the RCS.

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