Experimental Results of OECD-ATLAS A3.1 Test

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1. Introduction

As a part of an OECD-ATLAS project [1], A3.1 test was performed using a thermal-hydraulic integral effect test facility, ATLAS on November 17, 2015. The target scenario for A3.1 test is a total loss of feedwater (TLOFW) with additional failures in order to simulate one of the typical beyond design basis accident combined with a multiple failure. After the Fukushima accident, design extension conditions (DECs) such as a station black-out (SBO) and a TLOFW attracted a wide international attention in a sense that such high-risk multiple failure accidents should be revisited from a viewpoint of the reinforcement of the “defense in depth” concept. In particular, a TLOFW event has been considered as one of the typical beyond design basis accident (bDBA) in a safety analysis of the pressurized water reactors. In the current safety analysis methodology, the additional failure of the safety components is not taken into account. From a conservative point of view, however, failure of the active safety components needs to be considered in the safety analysis. During a TLOFW accident the most effective safety-related active components are the safety injection pumps (SIPs) and the pilot-operated safety relief valves (POSRVs) which are used in a feed and bleed operation. In addition, the starting time of the feed and bleed operation also plays an important role in whether the excursion of the peak cladding temperature (PCT) occurs or not. The objective of the A3.1 test is to investigate the cooling performance of the reactor coolant system (RCS) by a feed and bleed operation under the condition of TLOFW with additional failures such as the partial failure of the POSRVs and the SIPs. This paper presents a brief description of the experimental results of the A3.1 test

2. Test Conditions and Procedures

A3.1 test consists of two temporal phases: Phase (I) for steam generator (SG) dry-out similar to the SBO event and Phase (II) for feed and bleed operation as an accident mitigation action. The test is started with termination of supply of main feedwater into the SGs. It is assumed that 2 out of 4 SIPs and half of the POSRVs are unavailable to simulate additional failures during entire test period. However, passive components such as the safety injection tanks (SITs) and the main steam safety valves (MSSVs) are assumed to be fully available. Note that the supply of auxiliary feedwater is unavailable under the TLOFW event. Feed and bleed operation starts with maintaining the POSRVs open by operator action for an accident management.

2.1 Test Conditions

The initial conditions of A3.1 test are also summarized in Table I. The measured values present averaged values calculated during a steady-state period from -10 to 300 seconds.

Table I: Initial Conditions for A3.1 Test

Design Parameters	Target	Measured	Stand. Dev.
Core Power (MWt)	1.56	1.644	5E-4
PZR press. (MPa)	15.5	15.5	2E-3
Core inlet temp. (^{o}C)	290.7	290.1	0.17
Core outlet temp. (^{o}C)	324.2	326.2	0.1
Thermal power (MWt)	0.78	0.752/ 0.749	-
Steam flow rate (kg/s)	0.444	0.40 / 0.43	0.001 / 0.001
FW flow rate (kg/s)	0.444	0.43 / 0.42	0.001 / 0.001
Feedwater temp. (^{o}C)	232.2	233.6 / 232.9	0.11 / 0.13
Steam press. (MPa)	7.83	7.83 / 7.83	0.002 / 0.002
Steam temp. (^{o}C)	293.5	292.7 / 292.2	0.09 / 0.06
SG level (m)	5.0	4.99 / 5.00	0.008 / 0.008
Cold leg flow (kg/s)	2.0	2.01*	0.01*

* Average value of two loops

2.2 Test Procedures

When the whole system reached the specified initial condition, the TLOFW transient was initiated by terminating the supply of main feedwater into both SGs. As the SG water level decreased to the set-point of low SG level, the reactor trip signal occurred and turbine was also tripped coincident with the reactor scram. After the turbine trip, the SG pressure increased and the MSSVs started to actuate to prevent the SG over-pressurization. The main steam isolation valves (MSIVs) were not closed at the initiation of the transient. The MSIVs were automatically closed when the SG pressure decreased below 5.9 MPa. During a TLOFW transient, the primary system inventory was discharged through a POSRV. The POSRV was designed to be opened at 17.03 MPa and closed at 14.82 MPa depending on the pressurizer pressure. As-fore mentioned, the nozzle was replaced with one of 50% capacity to simulate the partial failure of the POSRVs in the test. Because a TLOFW is a kind of long transient compared to the conventional DBAs, heat loss through a pressurizer needs to be compensated in the test. Heat loss was compensated by actuating the pressurizer proportional heater until the first opening of the POSRV. After termination of main feedwater supply, the 2nd system inventory was discharged through an MSSVs as the SG pressure increased after the turbine trip. The MSSV was designed to be opened at 8.1 MPa and closed at 7.7 MPa of the 2nd pressure. As the auxiliary feedwater was unavailable during a TLOFW, the SGs dried out and the RCS were heated up. Afterwards the primary system pressure increased and the POSRV were opened to prevent over-pressurization. According to the emergency operating guidelines (EOG) for the APR1400 [2], the operator should perform the feed and bleed operation immediately after the first opening of the PORSV. However, to simulate a more severe test condition, delayed feed and bleed operation was assumed in the present test. The bleed operation by maintaining the POSRV open as an operator action started with delay time of 637 seconds in the ATLAS time after the first opening of the POSRV. This delay time is equivalent to 900 seconds in the prototypic APR1400. Due to the primary inventory loss through the POSRV, the primary pressure decreased to the set-point of the SIP actuation (12.47 MPa), and emergency core cooling water was supplied into the RCS through the DVI lines number 1 and 3. After the SIP injection, the cooling circuit for the primary system was established from the DVI to the POSRV as shown in Fig. 1. There are 4 SITs in the ATLAS facility and all of them were actuated as the primary system pressure decreased below the pressure of 4.0 MPa in the present test.

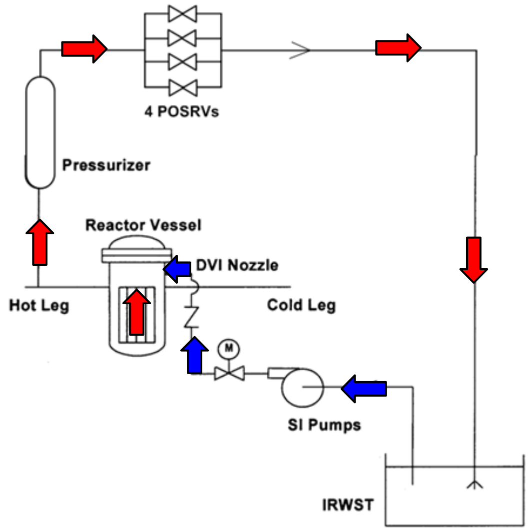

Fig. 1. Concept of feed and bleed operation in APR1400

3. Experimental Results

Table II summarizes the sequence of the major events observed in the present test.

Table II: Sequence of Events in A3.1 Test

No.	Event	Remarks
1	TLOFW	Start
2	Reactor/TBN/RCP trip	SG WR < 38%
3	Reactor scram	
4	SG dry-out (SG-1/SG-2)	
5	1st POSRVs open	$P_{PZR} > 17.03$ MPa
6	Start of bleed	No.5 + 637 sec.
7	SIP injection signal SIP injection start	$P_{PZR} < 12.46$ MPa SIP-1 & 3
8	MSIV-1/2 close	$P_{SG} < 5.9$ MPa
9	SIT injection start	$P_{RCS} < 4.0$ MPa
10	SCS condition	$T_{Core\_Exit} < 450$ K, $P_{RCS} < 3.1$ MPa

Note that the exact value in all resulting figures cannot be shown according to the agreement of the OECD/NEA project. The experimental results can be released in three years after the each OECD/NEA project is ended.

Fig. 2 shows the pressure behaviors of the primary and secondary systems in the test. After the turbine trip, the 2nd pressure showed an oscillating behavior according to the opening and closing of the MSSV until the secondary system became dried out. After the SGs dry-out, the 2nd system pressures decreased slightly due to small leakage in the main steam lines as well as the heat loss to the atmosphere and the MSIVs were closed by the low SG pressure signal. The primary system pressure started to increase due to degradation of the heat removal capacity of the steam generators. The primary system pressure reached the opening set-point of POSRV and the POSRV was opened. The feed and bleed operation started with a delay time of 637 seconds after the first POSRV open. Afterwards the primary system pressure drastically decreased as the primary coolant inventory was discharged through the POSRV and the SIPs were actuated by the low pressurizer pressure signal (12.47 MPa). The primary pressure continuously decreased until the end of test and the SITs were injected into the RCS below the pressure of 4.0 MPa.

Fig. 3 and Fig. 4 present the transient behavior of collapsed water level in the primary system including the pressurizer and the reactor pressure vessel, and in the secondary side of the steam generators, respectively. After the steam generator dry-out, heat-up of the primary system led to an increase of the pressurizer water level. After the feed and bleed operation was actuated, the pressurizer water level showed a step-wise increment due to a swelling effect but it decreased rapidly due to an inventory loss through the POSRV. However, the pressurizer water level was recovered again by the compensation of inventory through the SIP injection. Continuous discharge of the coolant in the primary system through the POSRV by the feed and bleed operation decreased the collapsed water level in the core and the downcomer. After the SIP injection, however, the core level was recovered and the minimum core level was slightly higher than the top end of heated region of active core.

Fig. 5 shows the behavior of the fluid temperature in the RPV during the entire transient. The core outlet temperature dropped right after the reactor trip. Both core inlet and outlet temperature increased after the SG became dried out and decreased after the feed and bleed operation. The core inlet temperature sharply decreased after the SIP injection whereas the core outlet temperature decreased slowly compared with the core inlet temperature. It is also found that the core outlet temperature became sub-cooled after the SIP injection.

The behavior of the heater rod temperature was similar to the behavior of the core outlet temperature as shown in Fig. 6. As the collapsed water level in the core was maintained above the top of the active core, the excursion of the heater surface temperature was not observed, that is, no core heat-up occurred during the entire test period.

3. Conclusions

OECD-ATLAS A3.1 test was performed to simulate a TLOFW with additional failures such as partial failure of the SIPs and POSRVs. This test was performed with two temporal phases with an aim of investigating the effect of feed and bleed operation as an accident mitigation measure. Major findings of the A3.1 test are summarized as follows:

- Following the termination of the feedwater supply, the SGs became dried out due to the cyclic opening and closing of the MSSVs. However, the coolant discharge from the secondary side of steam generators through MSSVs resulted in removing the decay heat and establishing the natural circulation in the primary system.
- A large coolant inventory loss of the primary system through the POSRV during a feed and bleed operation resulted in a reduction of the core collapsed level but the minimum core level was still above the top of the active core. As a result, the excursion of the maximum PCT was not observed.
- Delayed feed and bleed operation for the primary system was still effective to cool down the RCS without the excursion of the PCT under the present test condition of a TLOFW with reduced capability of the SIP and the POSRV.

Acknowledgements

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REFERENCES

[1] C.-H. Song et al., ATLAS Program for Advanced Thermal-Hydraulic Safety Research, Accepted to *NED Special Issue* (IW-NRTHS, Mumbai, India, Jan. 13-15, 2014), 2015.

[2] APR1400 Emergency Operating Guidelines, Revision 0.0, KEPCO Engineering & Construction Co., Inc., 2013.

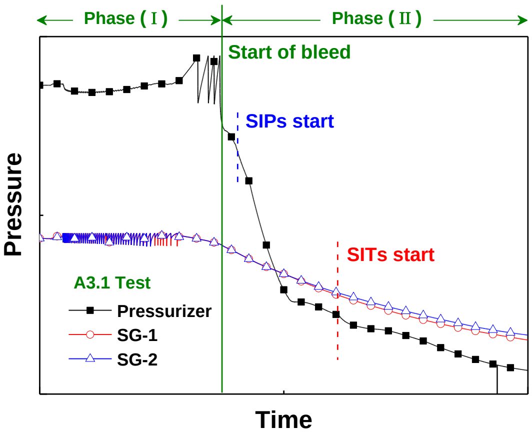

Fig. 2. Pressurizer and SG pressure

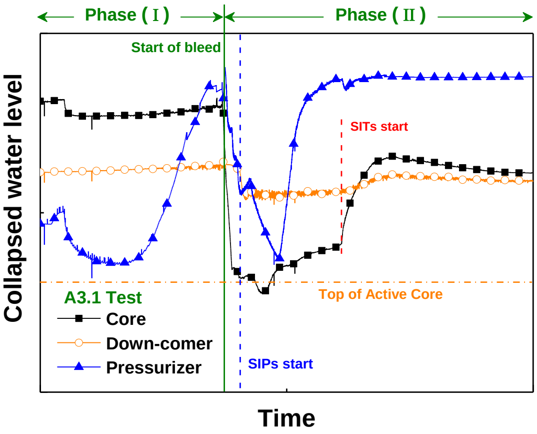

Fig. 3. Collapsed water level in the primary system

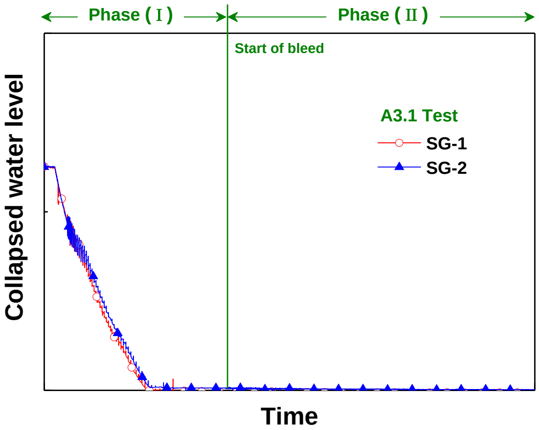

Fig. 4. Collapsed water level in the SGs

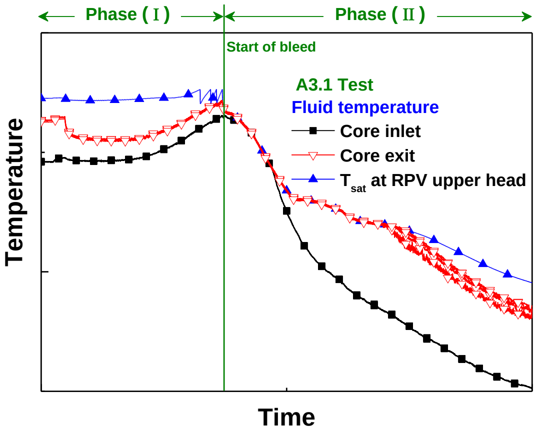

Fig. 5. shows the behavior of the fluid temperature

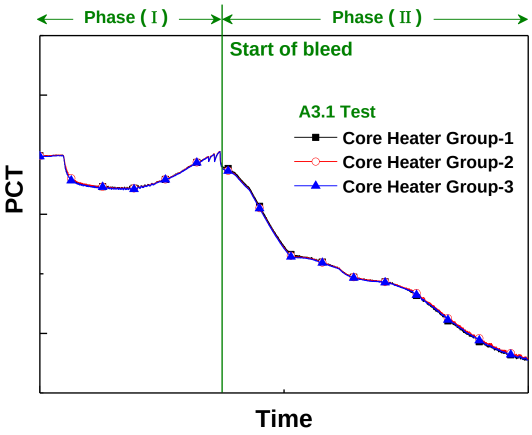

Fig. 6. Heater rod temperature