EXPERIMENTAL INVESTIGATION ON THERMAL-HYDRAULICS BEHAVIOR DURING A STATION BLACKOUT TRANSIENT IN A PRESSURIZED WATER REACTOR

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ABSTRACT

Considering the high-lighted safety concerns on the high risk multiple failures, a series of tests with a thermal-hydraulic integral effect test facility, ATLAS (Advanced Thermal-hydraulic Test Loop for Accident Simulation) was performed. In this study, the most conservative SBO transient and a more realistic SBO transient were simulated in the SBO-01R and the SBO-02 tests, respectively. The main objectives of these tests were not only to provide physical insight into the system response of the APR1400 during the SBO transients but also to produce an integral effect test data to validate a safety analysis code. In most nuclear power plants (NPPs), a turbine-driven auxiliary feedwater system was designed to remove the decay heat during the early period of an SBO transient. In the SBO-01R test, however, supply of turbine-driven auxiliary feedwater to steam generators was not considered from a conservative point of view. On the other hand, turbine-driven auxiliary feedwater was supplied to both steam generators in the SBO-02 test. From the present SBO-01R and SBO-02 experimental results, it could be confirmed that the supply of turbine-driven auxiliary feedwater plays a key role in maintaining the natural circulation flow during a SBO transient. An efficient heat removal through the supply of auxiliary feedwater to steam generators prevented the inventory discharge through opening of POSRV and the primary system became stable condition without any excursion of core wall temperature.

KEYWORDS
Station Blackout, Natural circulation, ATLAS

1. INTRODUCTION

After the Fukushima accident, design extension conditions (DECs) such as a station blackout (SBO) and a total loss of feed water (TLOFW) attracted wide international attention in that such high-risk multiple failure accidents should be revisited from the viewpoint of the reinforcement of the “defense in depth” concept. In particular, an SBO is one of the most important DECs because a total loss of heat sink can lead to a core melt-down scenario under high pressure without any proper operator action. Considering the high-lighted safety concerns on the high risk multiple failures, KAERI (Korea Atomic Energy Research Institute) has performed a series of thermal-hydraulic integral effect test on the SBO transients with ATLAS (Advanced Thermal-hydraulic Test Loop for Accident Simulation) [1].

In this study, the most conservative SBO transient and a more realistic SBO transient were simulated in the SBO-01R and the SBO-02 tests, respectively. The main objectives of these tests were not only to provide physical insight into the system response of a pressurized water reactor (PWR) during the SBO transients but also to produce an integral effect test data to validate a safety analysis code. In most nuclear power plants (NPPs), a turbine-driven auxiliary feedwater system was designed to remove the decay heat during the early period of an SBO transient. From a conservative point of view, however, it is necessary to investigate the thermal-hydraulic behaviors of the NPP when a turbine-driven auxiliary feedwater supply is not available during the initial period of an SBO transient. In the SBO-01R test, supply of turbine-driven auxiliary feedwater to steam generators was not considered from a conservative point of view. On the other hand, turbine-driven auxiliary feedwater was injected to both steam generators in the SBO-02 test. Description of the experimental results on the overall thermal-hydraulic behaviours during both SBO transients is given in this paper. Especially, the effect of turbine-driven auxiliary feedwater supply is highlighted.

2. DESCRIPTION OF ATLAS

After completion of an extensive series of commissioning tests in 2006, KAERI started the operation of the ATLAS, which is a thermal-hydraulic integral effect test facility for evolutionary pressurized water reactors [2]. The reference plant of the ATLAS is the APR1400 (Advanced Power Reactor 1400 MWe), which has a rated thermal power of 4000 MW and a loop arrangement of 2 hot legs and 4 cold legs for the reactor coolant system. The ATLAS can be used to investigate the multiple responses between the systems for a whole plant or between the subcomponents in a specific system during anticipated transients and postulated accidents. Besides, the ATLAS can be used to provide the unique test data for the 2(hot legs) x 4(cold legs) reactor coolant system with a DVI of emergency core cooling (ECC); this will significantly expand the currently available data bases for code validation.

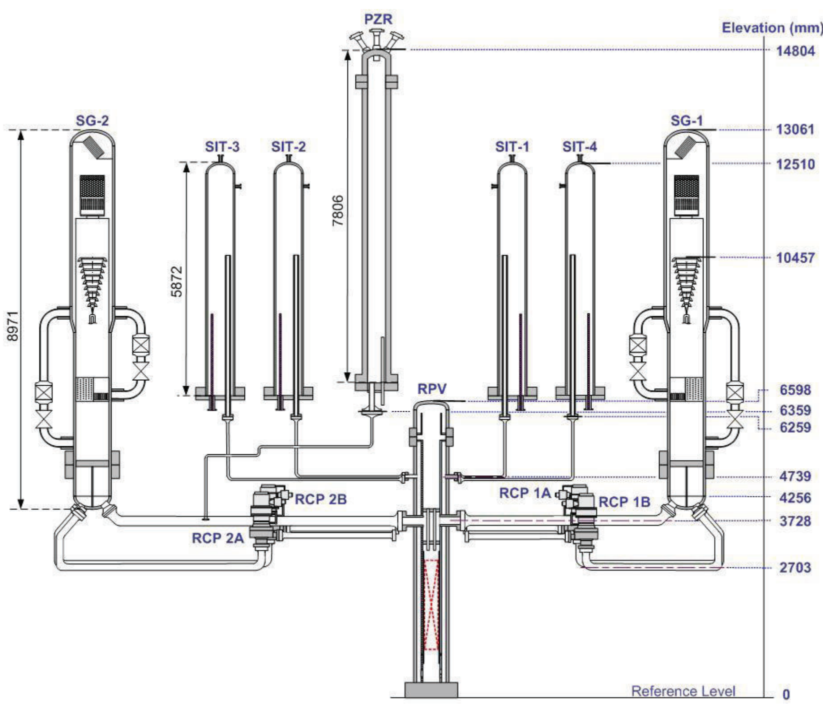


Figure 1. Schematic diagram of loop connection of ATLAS.

The ATLAS is designed according to the well-known scaling method suggested by Ishii and Kataoka [3] to simulate various test scenarios as realistically as possible. It is a half-height and 1/288-volume scaled test facility with respect to the APR1400. In order to allow for a simulation of high-pressure scenarios, the loop is designed to operate up to 18.7 MPa. The primary system includes a reactor pressure vessel (RPV), two hot legs, four cold legs, a pressurizer, four reactor coolant pumps (RCPs), and two steam generators (SGs). The total inventory is 1.6366 m^3, which was validated by the actual inventory measurement. The secondary system of the ATLAS is simplified to be 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. The safety injection system consists of four safety injection tanks (SITs), a high pressure safety injection pump (SIP) which can simulate a 400% of safety injection flow rate and long-term cooling, a charging pump for an auxiliary spray, and a shutdown cooling pump for a low pressure safety injection, a recirculation operation, and a shutdown cooling operation. A schematic diagram of a loop connection of ATLAS is shown in Fig. 1. In the ATLAS test facility, a total of about 1,600 instrumentations are installed for the measurement of thermal hydraulic phenomena in the components. A detailed ATLAS design features and instrumentations can be found in the literature [4].

3. EXPERIMENTAL CONDITIONS AND PROCEDURES

The SBO-01R test and the SBO-02 test were performed for simulating the most conservative SBO transient and the more realistic SBO transient, respectively. In the SBO-01R test, the turbine-driven auxiliary feedwater was not supplied. On the other hand, the turbine-driven auxiliary feedwater was supplied to both SGs in the SBO-02 test. A reactor trip, a turbine trip, a RCP trip, and main feedwater isolation were assumed to occur in concurrence with an SBO. In the present tests, seal failure of RCP was not considered and passive components such as a pilot-operated safety relief valve (POSRV) and a main steam safety valve (MSSV) were assumed to be available.

3.1. Test conditions

The present test conditions were determined by a pre-test calculation with a best-estimate thermal-hydraulic safety analysis code, MARS-KS (Multi-dimensional Analysis of Reactor Safety-KS). First, a transient calculation was performed for an SBO scenario of the APR1400 to obtain the referenced initial and boundary conditions. The initial and boundary conditions for the present tests were obtained by applying the scaling ratios of ATLAS to the MARS calculation results for the APR1400 [5]. Table I compares the steady-state conditions between the APR1400 and ATLAS for the present tests. The actual initial conditions of the SBO-01R and the SBO-02 tests were also summarized in Table I. The decay heat was simulated to be 1.2 times that of the ANS-73 decay curve from a conservative point of view. The initial heater power was controlled to be maintained at about 1.627 MW, which was equal to the sum of the scaled-down core power (1.565 MW) and the heat loss rate of the primary system (about 60 kW). The heater power was then controlled to follow the specified decay curve after 12.07 seconds from the reactor trip. In the present tests, the uniform radial power distribution was applied. The same core power was applied to both tests.

3.2. Test procedures

When the whole system reached a specified initial condition for the test, as shown in Table I, the steady-state conditions of the primary and the secondary systems were maintained for more than 30 minutes. After storing the data during this steady-state period for 310 seconds, the SBO transient was initiated by inducing a trip signal of the reactor core and turbine. When the reactor was tripped, both the RCP and the turbine were stopped. Coincidently with the reactor trip, main feedwater pumps stopped and a main feedwater isolation signal (MFIS) was generated to close the main feedwater isolation valves (MFIVs). The main steam isolation valves (MSIVs) were also closed at the initiation of the transient. In the SBO-02 test, the turbine-driven auxiliary feedwater was supplied to both SGs depending on the secondary level of SG. The turbine-driven auxiliary feedwater was designed to be supplied at a wide-range level of 25% and be terminated at a wide-range level of 40%. The supply of the turbine-driven auxiliary feedwater was simulated by a metering pump with constant flow rate in the SBO-02 test. Table II summarizes the sequence of the events observed in the present SBO-01R and SBO-02 tests.

Table I. Calculated and actual initial conditions for the SBO-01R and SBO-02 tests

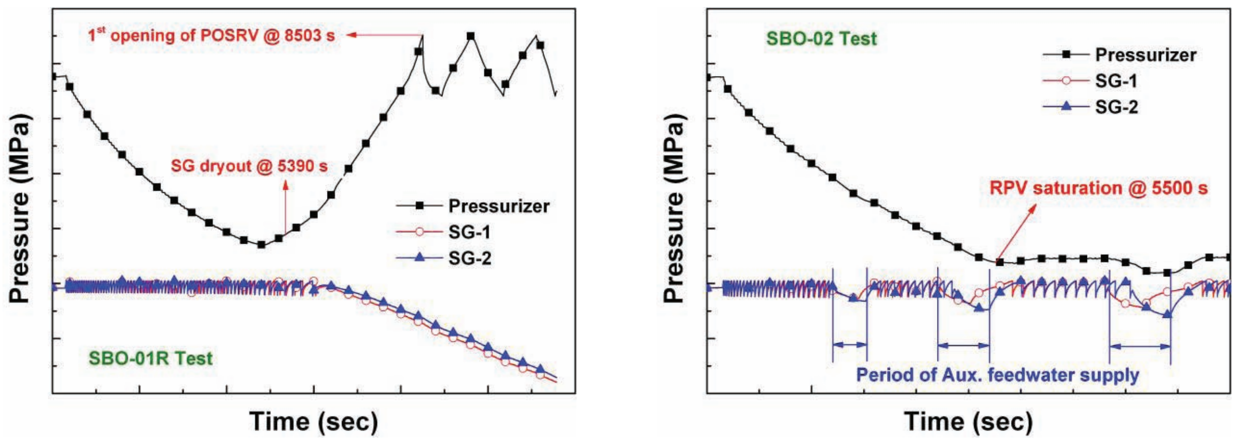
Design parameters	APR1400	Design Values	Test	
			SBO-01R	SBO-02
Normal power (MWt)	3983	1.56	1.627	1.627
Pressurizer pressure (MPa)	15.5	15.5	15.5	15.5
Core inlet/outlet temperature (^{o}C)	291.3/324.2	290.7/324.2	290.5/326.1	290.1/325.8
SG feed water flow rate (kg/s)	1152.4	0.444	(SG-1/SG-2) 0.454 / 0.432	(SG-1/SG-2) 0.409 / 0.421
SG steam pressure (MPa)	6.9	7.83	(SG-1/SG-2) 7.83 / 7.83	(SG-1/SG-2) 7.84 / 7.84
SG secondary side level (m)	10.0	5.0	(SG-1/SG-2) 4.98 / 4.99	(SG-1/SG-2) 5.06 / 5.00
Cold leg flow (kg/s)	5540.1	2.0	1.92	1.93

Table II. Actual sequence of events of the SBO-01R and SBO-02 tests

Event	Time (sec)		Remarks (Set-point)
	SBO-01R	SBO-02	
SBO start	303	303	
Decay power start	315	315	Core power @ 8%
MSSV first opening	316	316	SG secondary pressure @ 8.1 MPa
Turbine-driven Auxiliary Feedwater Supply	Not actuated	2313 / 2383	SG secondary level = 2.67m/3.9m (on/off)
SG dryout	5390	Not occurred	
PZR full	6450	7750	
POSRV first opening	8503	Not occurred	PZR pressure @ 17.03 MPa (close @ 14.82 MPa)
PCT occurrence	11573	Not occurred	

4. EXPERIMENTAL RESULTS

With the start of SBO transient, the reactor, all four RCPs, turbine, MFIV, and MSIV were tripped simultaneously. The failure of the main feedwater supply and MSIV closure led to an increase of the secondary system pressure until the set point of the opening of a MSSV. Fig. 2 shows the variation of the system pressures in the SBO-01R and the SBO-02 tests. Due to a periodic discharge of the secondary inventory through MSSV the secondary side of SGs became dried out in the SBO-01R test. On the other hand, the supply of turbine-driven auxiliary feedwater prevented the dry-out in the secondary side of SGs in the SBO-02 test. While the turbine-driven auxiliary feedwater was supplied to SGs, the secondary system pressure decreased continuously and the MSSV was not opened as shown in Fig. 2. Since the turbine-driven auxiliary feedwater system was designed to operate depending on the secondary level of SGs, the supply of turbine-driven auxiliary feedwater was terminated when the secondary level was recovered to a wide-range of 40%. The secondary system pressure increased and then the MSSV was opened again.

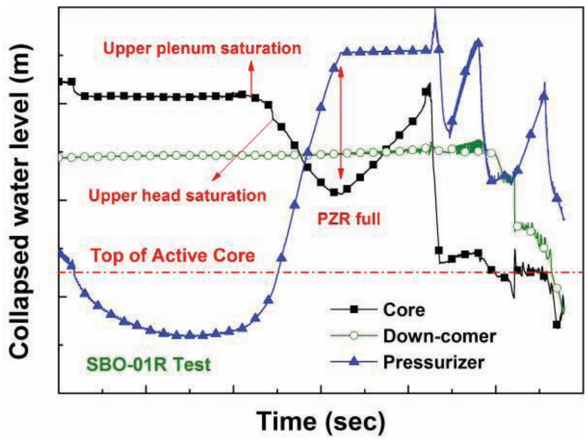


(a) SBO-01R Test (b) SBO-02 Test

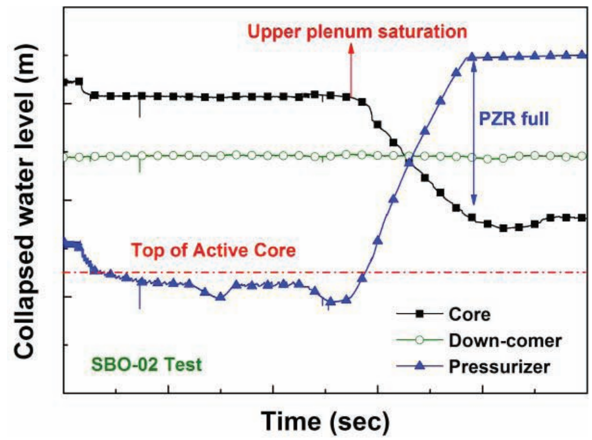
Figure 2. Variation of the system pressures.

The primary system pressures decreased to below 10 MPa which was attributed to the heat loss through the pressurizer and the efficient heat removal via inventory discharge through MSSV. In the SBO-01R test, after the dry-out in the secondary side of SGs, the primary system pressure started to increase and reached the opening set point of POSRV at 8503 seconds. A total 3 POSRV openings occurred as shown in Fig. 2. Due to a periodic supply of the turbine-driven auxiliary feedwater, the heat removal through SGs were maintained in the SBO-02 test and then the primary system pressure showed stable values comparable to the secondary system pressures. After the dry-out in the secondary side of SGs in the SBO-01R test, the opening of MSSV stopped and the secondary system pressures started to decrease. This abnormal pressure behavior was attributed to some leakage through MSSV.

After the secondary sides of SGs were empty, the level of pressurizer started to increase rapidly which resulted from the reduction of heat removal through SGs in the SBO-01R test. When the upper plenum of RPV reached to the saturation condition, the level of core started to decrease as shown in Fig. 3. The RPV took over the pressurizer function after the upper plenum of the RPV became saturated. This means that after the RPV starts to function like a pressurizer, the pressurizer loses its pressure control function and starts to behave like a buffer tank to be compressed. Due to the combined effects of the reduction of heat removal through the steam generators and the saturated condition in the upper plenum of the RPV, the pressurizer level increased until the pressurizer became full. In the SBO-01R test, the level of pressurizer increased up to the full level and then decreased due to a loss of inventory through the POSRV. With the continuous inventory loss through the POSRV, the upper part of the core was uncovered, and finally, the core heat-up started and the excursion of the core wall temperature was observed as shown in Fig. 4. PCT stands for a peak cladding temperature in Fig. 4. Contrary to the SBO-01R test, the core level maintained at upper region from the top of active core in the SBO-02 test.

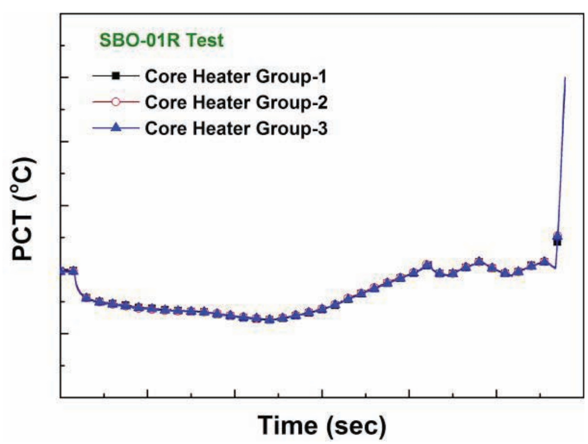


(a) SBO-01R Test

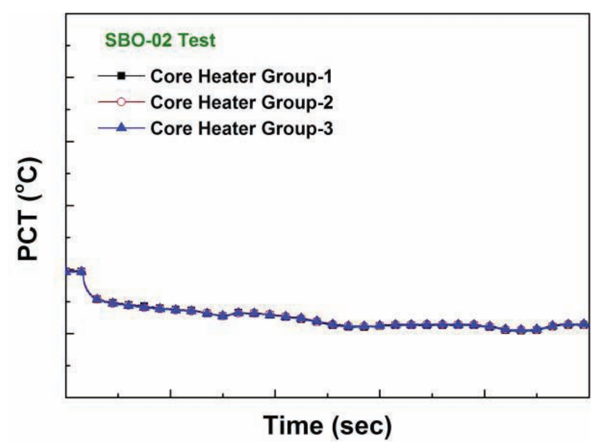


(b) SBO-02 Test

Figure 3. Variation of the collapsed water levels.



(a) SBO-01R Test

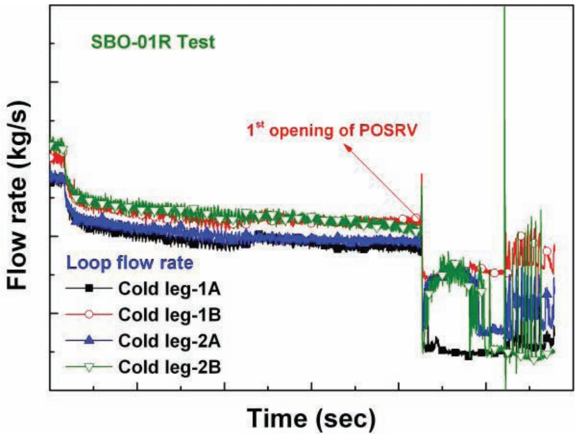


(b) SBO-02 Test

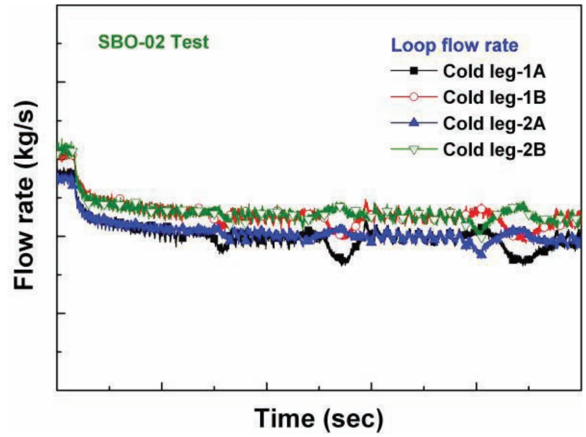
Figure 4. Variation of the core wall temperatures.

Natural circulation flow was established after the RCP trip and a single-phase natural circulation flow was maintained until the SGs became dried out. Voiding at the top of the U-tube interrupted the single-phase natural circulation flow and then the two-phase natural circulation flow continued until the upper plenum of the core became empty. The primary loop flows maintained during the whole test period in the SBO-02 test as shown in Fig. 5. On the other hand, the natural circulation flow became degraded after the opening of POSRV in the SBO-01R test.
Fig. 6 shows the collapsed water levels in the U-tubes of SGs in both tests. The water levels in the U-tubes of SGs maintained full conditions until the first opening of the POSRV in the SBO-01R test. After

the second opening of the POSRV the U-tubes of SGs became empty which means complete termination of the natural circulation flow in the SBO-01R test. On the other hand, the water levels in the U-tubes of SGs maintained full conditions during the whole test period of SBO-02 test.

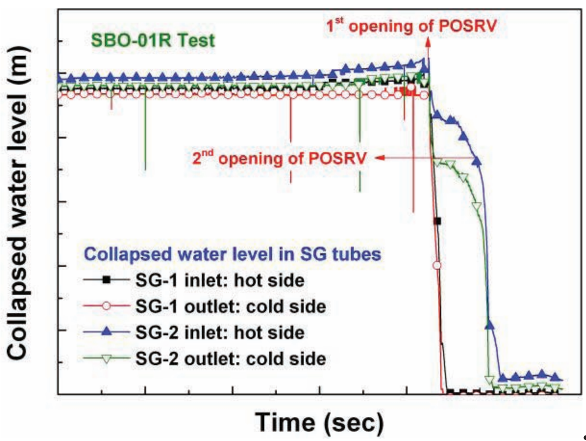


(a) SBO-01R Test

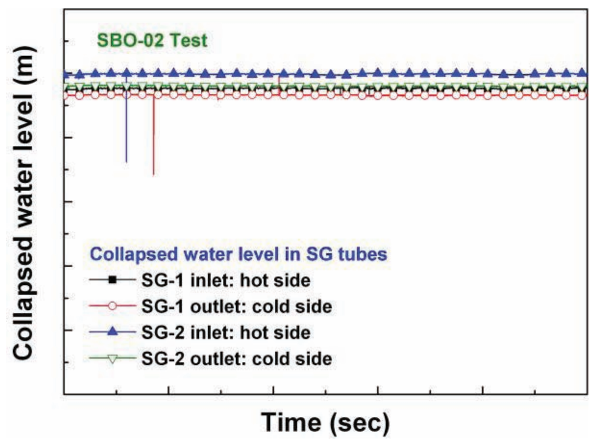


(b) SBO-02 Test

Figure 5. Variation of the primary loop flows.



(a) SBO-01R Test



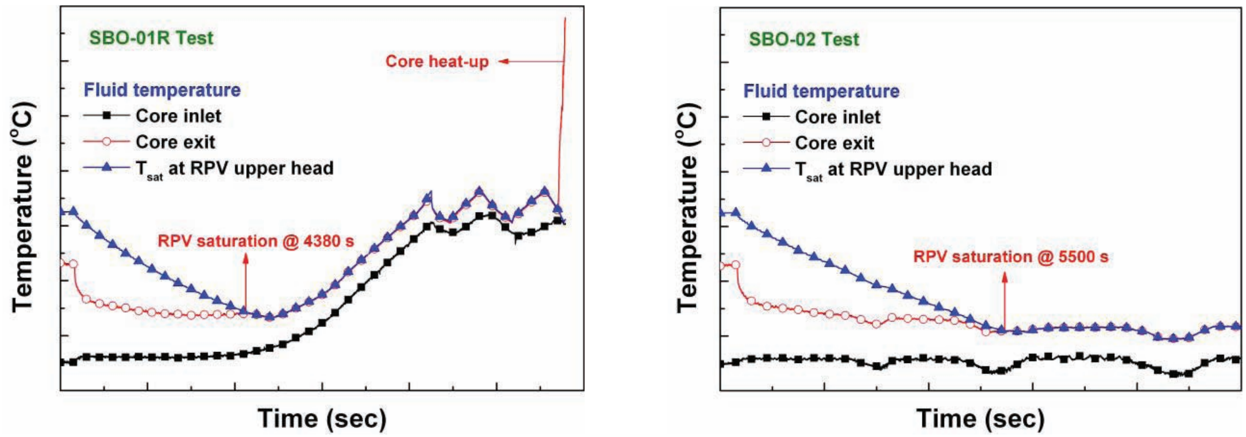
(b) SBO-02 Test

Figure 6. Variation of the collapsed water levels in the U-tubes of SGs.

Fig. 7 shows the variation of fluid temperatures at the inlet and outlet of the core in both tests. Due to the efficient heat removal through the supply of the turbine-driven auxiliary feedwater, the fluid temperatures maintained stable values in the SBO-02 test. In the SBO-01R test, however, a loss of heat removal through SGs resulted in the continuous increase of the fluid temperatures and the core started to heat-up and the peak cladding temperature (PCT) was observed as shown in Fig. 4.

From the present SBO-01R and SBO-02 experimental results, it could be confirmed that the supply of the turbine-driven auxiliary feedwater plays a key role in maintaining the natural circulation flow during an

SBO transient. An efficient heat removal through the supply of the auxiliary feedwater contributed to the stabilization of the primary system pressure without the inventory discharge through opening of POSRV.



(a) SBO-01R Test

(b) SBO-02 Test

Figure 7. Variation of the fluid temperatures at the inlet and outlet of the core.

5. CONCLUSIONS

In this study, the most conservative SBO transient and a more realistic SBO transient were simulated with ATLAS named as SBO-01R and SBO-02, respectively. The main objectives of these tests were not only to provide physical insight into the system response of a PWR during an SBO transient but also to produce an integral effect test data to validate a safety analysis code. A turbine-driven auxiliary feedwater system was designed to remove the decay heat during the early period of an SBO transient. In the SBO-01R test, however, the supply of the turbine-driven auxiliary feedwater to SGs was not considered from a conservative point of view. On the other hand, the turbine-driven auxiliary feedwater was supplied to both SGs in the SBO-02 test. From the present SBO-01R and SBO-02 experimental results, it could be confirmed that the supply of the turbine-driven auxiliary feedwater plays a key role in maintaining the natural circulation flow during an SBO transient. An efficient heat removal through the supply of the auxiliary feedwater contributed to the stabilization of the primary system pressure without the inventory discharge through opening of POSRV. This integral effect test data will be used to evaluate the prediction capability of existing safety analysis codes. Furthermore, this data can be utilized to identify any code deficiency for an SBO simulation, especially focused on the effect of turbine-driven auxiliary feedwater supply.

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