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Test result for evaluation of the cooling capability of steam generators during a loss of residual heat removal system at mid-loop operation in ATLAS facility

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1. Introduction

A residual heat removal system (RHRS) is used to remove the core decay heat at lower coolant temperature condition. Continuous cooling of the reactor core by using the RHRS is required to maintain the low temperatures required for maintenance or inspection of components. During a maintenance operation such as refueling, the water level in the primary system is required to keep middle of hot legs, called a middle loop operation (MLO). RHRS is the only heat sink in the reactor coolant system (RCS) when the water level in the primary system is lowered to middle of hot legs. Steam generators can no longer play a role of a heat sink, since there is no forced or natural circulation through the steam generator.

RHRS has a high probability of losing its function due to the requirement of low water level condition during an MLO. It is required to maintain the water level within low enough to access the inspection hatches and high enough to uncover the inlet of the RHRS on hot legs. If the water level in the primary system becomes below the lower limit of an MLO, an air ingression into RHRS caused by vortexing at the junction of the RHRS inlet and hot leg can lead to irreversible pump damage. Consequently, the irreversible RHRS pump damage may cause an event of loss of RHRS during an MLO. According to the previous survey, this sequence has occurred in various forms more than 50 times over the past 25 years [1].

Considering the importance of a loss of RHRS scenario from a safety issue perspective, a loss of RHRS pump during an MLO with asymmetric secondary system inventory was selected as the B4.2-PRE2-01 test by utilizing ATLAS (Advanced Thermal-hydraulic Test Loop for Accident Simulation) facility [2]. The B4.2-PRE2-01 test was performed to expand the integral effect test database for a loss of RHRS during an MLO and this test is in the extension of MLO-PRO-02 [3] and B4.2-01 test.

The main objective of B4.2-PRE2-01 test was not only to investigate thermal-hydraulic transient in the RCS during the loss of RHRS pump but also to evaluate the effectiveness of reflux condensation. In this paper, the overall T-H behavior during the loss of RHRS is presented with the B4.2-PRE2-01 test, and the cooling capability of steam generators with asymmetric water inventory in the secondary system is highlighted by comparing with the previous ATLAS MLO test series.

2. ATLAS MLO Test Condition

ATLAS is a T-H integral effect test facility for a pressurized water reactor (PWR) which can simulate the overall T-H behavior of major systems and components during transient and accident conditions at prototypic pressure and temperature conditions. ATLAS is designed according to the three-level scaling method suggested by Ishii and Kataoka [4]. The detailed description of ATLAS facility design and instrumentation can be found in the reference [2] and a scaling method of the ATLAS can be found in reference [5].

ATLAS is equipped one RHRS loop which has a suction inlet of RHRS at hot leg number 1 (HL-1), and the pump of RHRS (PP-SCS1-01) sends the coolant through the heat exchanger to the direct vessel injection (DVI) 1 and 4 lines. In general, one RHRS loop has sufficient cooling capacity to remove the decay heat rate, and enables the RCS to be completely depressurized and cold shutdown conditions to be reached [6].

2.1 ATLAS MLO test series

Key features of selected ATLAS MLO tests are summarized in Table I. In this study, the core power is selected by 91 kW, which is corresponding to a core decay heat after the 65 hours of the reactor shutdown considering the time for drainage operation and opening of a pressurizer manway.

All of the selected tests were performed under MLO conditions, the pressurizer manway open in the primary system, and atmospheric pressure condition in the secondary system. The characteristic differences among the tests are whether the bypass valve on the reactor pressure vessel (RPV) is opened or closed, and the availability of the inventory in the steam generator secondary side. ATLAS simulates the flow rate of the annulus flow path between the HL and the downcomer and between the upper head of RPV and the downcomer of the prototype plant according to the ATLAS scaling ratio using valves of two pipe lines, respectively [7]. In addition, the safety injection condition is not identical, but this does not affect the accident evolution during the loss of RHRS.

Table I: Summary of key features on boundary condition for ATLAS MLO test series

		MLO-PRO-02	B4.2-PRE2-01	B4.2-01
Core power		91 kW		
RCS water level		Middle of Hot legs		
Opening	Primary	Pressurizer manway		
	Secondary	Opening of MSSV	Opening of ADV-1/2	
PRV bypass (HLDC / UHDC)		Open	Close	Open
Secondary inventory	SG1	empty	empty	empty
	SG2	empty	5.0 m	5.0 m
Safety Injection		SIP startup at cladding temp. > 300°C	SIP startup at cladding temp. > 400°C	SIT startup at cladding temp. > 300°C SIP startup at cladding temp. > 400°C

All the test data displayed in this manuscript, such as time, temperature, collapsed water level, flow rate, discharged water mass, are normalized by arbitrary values for the confidential problem of test data.

2.2 Mid-loop operation for B4.2-PRE2-01

In the B4.2-PRE2-01 test, an initial steady-state condition was an MLO with the one available loop of RHRS after opening of the pressurizer manway as shown in Fig. 1. In order to simulate the cooling process using RHRS during an MLO, heat-up phase was implemented to realize the heating state of ATLAS before cooling. Figure 2 presents the steady-state MLO condition of the B4.2-PRE2-01 test before the loss of RHRS (normalized time = 0.625) showing temperature, water level of RCS, and flowrate of RHRS outlet. The fluid temperatures of RCS remain constant during the MLO, which shows that the RHRS performs well as a heat sink. In addition, the water level of RCS was maintained at the middle of HL (orange dash horizontal line). In the B4.2-PRE2-01 test, the initial flowrate of RHRS was sufficient to cool down the core and the loss of the RHRS pump was successfully simulated at 0.625 normalized time.

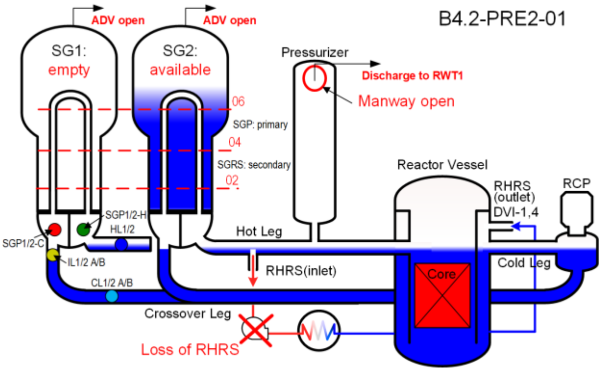

Fig. 1. Schematic drawing for the loss of RHRS accident during MLO as B4.2-PRE2-01 test including instrumentation locations in ATLAS facility

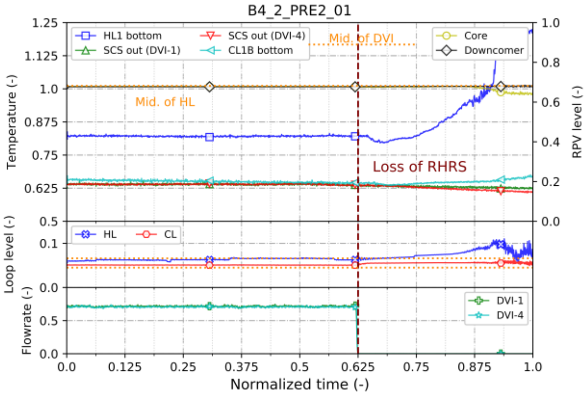

Fig. 2. Steady-state MLO condition of the B4.2-PRE2-01 test

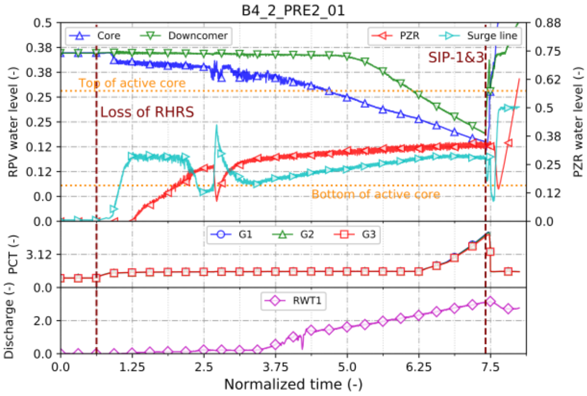

Fig. 3. Major T-H behavior of the loss of RHRS in the B4.2-PRE2-01 test

3. Experimental results and discussion

3.1 Loss of RHRS

In the present test, a loss of RHRS was initiated by the shutdown of the RHRS pump simulating an irreversible pump damage. Figure 3 shows overall T-H behavior of RCS during the loss of RHRS. As the loss of RHRS occurred, boiling started in the core and the steam generated in the core was discharged through the pressurizer manway. The coolant can be entrained by the steam to the inlet of surge line and filled in the pressurizer (collapsed water level in the pressurizer displayed in the Fig. 3. with skyblue line for the surge line, and red line for the pressurizer). The mass of discharged flow was depicted with purple line on the bottom column, and shows two different behaviors. During the early stages (normalized time < 3.6), the mass of discharged flow was small, since the condensation of the steam in the pressurizer halted. After all of the pressurizer fluid reached the saturation temperature, the steam generated in the core was effectively discharged through the pressurizer manway. And then increasing rate of the collapsed water level in

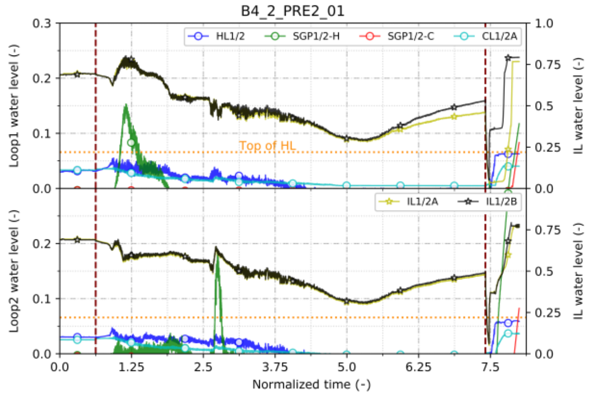

Fig. 4. Collapsed water level of the RCS piping including lower plenum of the SGs

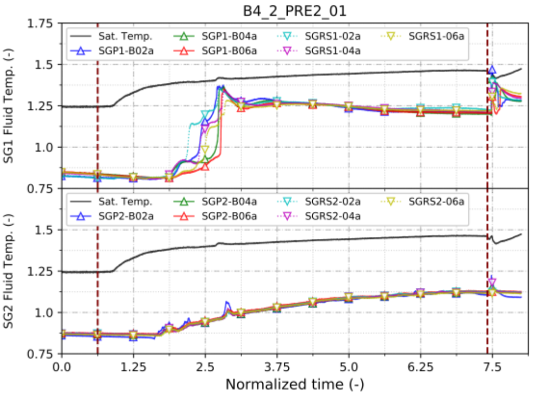

Fig. 5. Fluid temperature of the U-tube riser and the secondary side riser in the SGs

the pressurizer started to decrease. Decrease of the collapsed water level in the core (showing blue line for the core, green line for the downcomer) caused the excursion behavior of the maximum heater rod surface temperature presented as peak cladding temperature (PCT). Since the water level in the core decreased by the discharge of the steam through the pressurizer manway, the top part of the core was uncovered and the heater rod surface temperature started to increase from around 6.25 normalized time. The maximum heater rod surface temperature reached 400 ºC and then the safety injection water was supplied from the safety injection pumps (SIPs) through DVI-1 and 3.

3.2 Coolant distribution during MLO

In the B4.2-PRE2-01 test, the asymmetric water inventory condition for the steam generator secondary side was simulated to evaluate the effectiveness of reflux condensation. Figure 4 shows the collapsed water levels in the RCS piping and lower plenum of the steam generators (see the Fig. 1 for the measured location). The water levels in the lower plenum of the SGs and intermediate legs (ILs) indicate not only condensate produced by a reflux condensation from U-tubes and a wall condensation at lower plenums, but also the amount of coolant entrained by the steam from HLs. In addition, the behavior of the water level in ILs shows a pressure build-up between HL to CL. Since this pressure build-up can be considered to be the effect of closing the RPV bypass valve between HL to downcomer (DC), this phenomenon did not appear in other tests. As the primary system pressure increased due to liquid holdup in the pressurizer, the pressure difference between HL to DC built up, which induced to further supply IL coolant through the DC to the core.

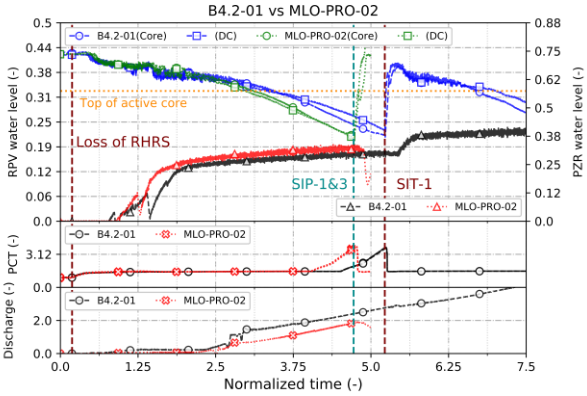

Fig. 6. Comparison between B4.2-01 and MLO-PRO-02

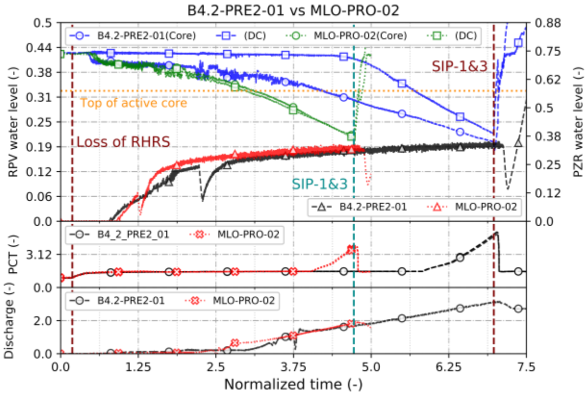

Fig. 7. Comparison between B4.2-PRE2-01 and MLO-PRO-02

Figure 5 presents the fluid temperature in the U-tube and the riser in the SGs (LOCi-B0Ya tag means that "SGP" indicates thermocouple (TC) in U-tube, "SGRS" means TC in SG secondary side, "i": 1 for SG1/ 2 for SG2, "B": group of U-tube in ATLAS SG located closest to the TF-SGRSi-0Ya, "0Y" shows elevation of TCs presented in Fig. 1., and "a" means hot side of SG).

During the loss of RHRS, the fluid temperature cross U-tube to SG riser shows asymmetric behavior which is related to the existence of secondary system inventory. In case of SG-1 filled with air, the fluid temperature in the U-tube (triangle up symbol) increased after the temperature in the riser (triangle down symbol) increased. The fluid temperature rise in the U-tube through the reverse heat transfer is due to the thermal stratification of the secondary side heated by the structure of the SG lower plenum. Steam generated from the core did not flow into the U-tube filled with air at the beginning of the MLO and condensed on the wall of the SG lower plenum. Mostly, steam transferred to the SG lower plenum served to heat the structure of the SG lower plenum. In contrast, in case of SG-2 filled with water in the secondary side, the heat transfer from the steam generated from the core gradually increased the fluid temperature of primary and secondary side. Therefore, the wall condensation would be last longer in the lower plenum of SG-2 than SG-1.

It is difficult to quantify the amount of condensate during a loss of RHRS with ATLAS. In addition, the heat loss of ATLAS is much bigger than a nuclear power plant due to the limitation of the scaled experimental facility. In the B4.2-PRE2-01 test, the wall condensation was dominant comparing to a reflux condensation expected in a nuclear power plant. Therefore, in the later section, the effect of the condensation in ATLAS will be discussed with a comparison among ATLAS MLO test series.

3.3 Cooling capability of steam generator during a loss of RHRS

The main factor determining the cooling capability during a loss of RHRS is the amount of coolant that can be delivered to the core. During a loss of RHRS, condensate is the only way to replenish the coolant if the safety injection is unavailable. Figure 6 presents comparison between B4.2-01 and MLO-PRO-02 highlighting the effect of the condensation during the loss of RHRS. Although the set-point for safety injections, such as safety injection tank (SIT) and safety injection pump (SIP) is identical, the initiation time for safety injections is different. Since condensation works for the B4.2-01 test with sufficient inventory of the secondary side, the rate of RPV water level decrease changes during the late period after normalized time is larger than 3.0 (see blue and green lines in Fig. 6).

Figure 7 shows comparison between B4.2-PRE2-01 and MLO-PRO-02 spotlighting the role of the secondary side inventory in the SG-2 and the effect of the closing of the RPV bypass valve. As explained in 3.2 section, the pressure build-up between HL to CL by closing of RPV bypass valve can push the coolant from ILs to the DC. Therefore, cooling period in the B4.2-PRE2-01 test can last longer than that in the MLO-PRO-02 test after the loss of RHRS.

4. Conclusions

In this study, a loss of RHRS accident during an MLO was experimentally investigated by utilizing the ATLAS facility. Overall T-H transient in the RCS during the loss of RHRS is presented with the B4.2-PRE2-01 test. And cooling capability of steam generator with the asymmetric water inventory in the secondary side is discussed by comparing with ATLAS MLO test series.

In the present B4.2-PRE2-01 test, the water level in the primary system was set to the middle of hot leg while RHRS operated and the pressurizer manway was simulated to be opened. The water in the secondary side of SG-1 was empty and that of SG-2 was set to be 5.0 m. The secondary system pressure was atmospheric pressure by opening the ADV-1/2. As the loss of RHRS occurred, boiling started in the core and the steam generated in the core was discharged through the pressurizer manway. The water level in the RPV decreased due to the discharge through pressurizer manway and finally the top part of the core was uncovered. Therefore, the maximum heater rod surface temperature reached the set-point of the initiation of the safety injection.

In this study, coolant distribution was discussed with the collapsed water level in RCS piping and lower plenum of SGs, and the fluid temperature cross U-tube to the riser region. From a qualitative point of view, the existence of condensate is explained during the loss of RHRS. Furthermore, the comparison among ATLAS MLO test series showed the cooling capability of the secondary side inventory and the effect of the closing of the RPV bypass valve.

The ATLAS MLO test data can be used to evaluate the prediction capability of existing safety analysis codes for a mid-loop operation condition.

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