Test Result for Simulation of a Loss of Residual Heat Removal System Accident during a Mid-Loop Operation in ATLAS facility

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1. Introduction

A residual heat removal system (RHRS) is necessary to remove the core decay heat to reduce the inventory in a pressurized water reactor (PWR) for maintenance or inspection of components through a pressurizer manway or an inspection hatch in a steam generator. During maintenance operations be performed, the water level in the primary system is below the top of hot leg and is usually maintained as center of hot leg, so called mid-loop operation (MLO). It is important to keep a continuous residual heat removal, since the steam generators can no longer perform as a heat removal system during MLO. There is no forced or natural circulation through the steam generators due to lowered water level in the primary system. Therefore, a loss of RHRS accident is one of great concern since the accident has reoccurred and a number of probabilistic risk assessment (PRA) studies have identified this accident as the highest-risk scenario in low-power operation [1]. An extensive review on a loss of RHRS accident can be found in reference [1].

During a MLO, it is important to maintain the water level within low enough to access the inspection hatches and high enough to uncover the inlet of the RHRS on the hot leg. If the water level in the primary system is below the lower limit of a 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 RHR during a MLO. According to the previous survey, this sequence has occurred in various forms more than 50 times over the past 25 years [1].

In this study, a loss of RHRS accident during a MLO of APR1400 (Advanced Power Reactor 1400 MWe) was experimentally investigated by utilizing the ATLAS (Advanced Thermal-hydraulic Test Loop for Accident Simulation) facility. The MLO-PRO-02 test was performed to expand the integral effect test database for a loss of RHRS accident during a MLO.

In the MLO-PRO-02 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 on the secondary side of the steam generator was empty, and the pressure was atmospheric pressure by opening the main steam safety valve (MSSV). The nozzle dams between the crossover legs and the SGs were not installed.

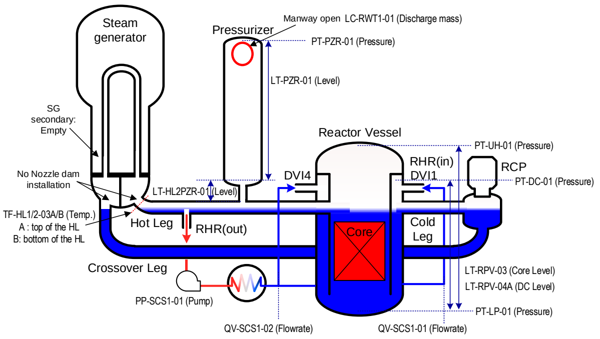

Fig. 1 Schematic of a loss of RHRS accident during MLO including instrumentation locations for the featured data in the MLO-PRO-02 test

2. Test Condition and Procedure

2.1 ATLAS Test Facility

ATLAS is a thermal-hydraulic integral effect test facility which has the same reactor coolant system (RCS) including 2 hot legs and 4 cold legs as APR1400. ATLAS is designed according to the scaling method suggested by Ishii and Kataoka [2]. The detailed description of ATLAS facility design and instrumentation can be found in the [3] and a scaling method of the ATLAS can be found in [4].

2.2 Mid-Loop Operation Test Condition

In the present MLO-PRO-02 test, it was assumed a MLO with the RHRS after opening of the pressurizer manway as shown in Fig. 1. The core power was applied by 91 kW as a core decay heat after the 65 hours of the reactor shutdown considering the time for drainage operation and opening of the pressurizer manway. During heat removal process in ATLAS, the suction supply of the RHRS was located at bottom of hot leg 1 and the pump of RHRS (PP-SCS1-01) sent the coolant through the heat exchanger to the direct vessel injection (DVI) 1 and 4 lines. The total flow rate of the RHRS was maintained to be about 1.4 kg/s (summation of the flow rate on DVI-1 (QV-SCS1-01) and -4 (QV-SCS1-02) as shown in Fig. 2). All of the test results in this paper were divided by an arbitrary value and plotted on the non-dimensional axis. The pressurizer (PZR) manway of APR1400 was simulated using three nozzles located at the top head of the PZR. The total flow area of these nozzles is 765.2 mm^2.

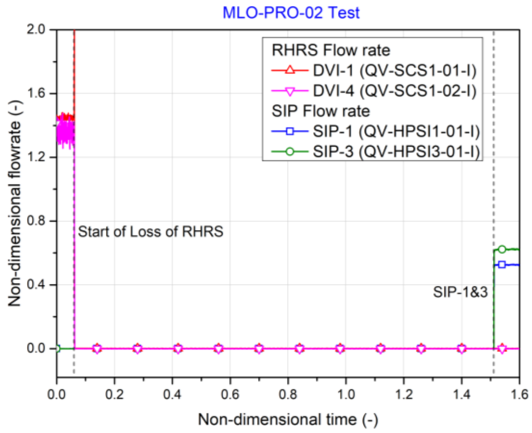

Fig. 2 Flow rates of the RHRS and the safety injection water from SIPs.

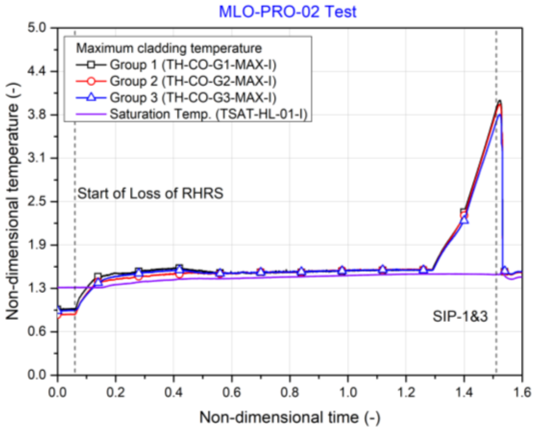

Fig. 3 Variation of the peak cladding temperatures

3. Test Results

A loss of RHRS accident in the MLO-PRO-02 test was initiated by the shutdown of the RHRS pump (PP-SCS1-01) simulating irreversible pump damage caused by air ingression. The core power was maintained about 91 kW during the whole test period. As a loss of RHRS occurred, boiling started in the core and the primary system pressure increased continuously until the SIPs were operated. Figure 3 shows a variation of the peak cladding temperature during the loss of RHRS accident. The water in the primary system was a heat up in the reactor pressurized vessel (RPV). Consequently, it was reached the saturation temperature and bulk boiling ensued in the early phase ($t < 0.7$). Figure 4 shows an integrated discharge mass through the PZR manway. Steam generated in the core can be condensed in the PZR during the early phase ($t < 0.7$). In addition, the steam dragged the water in the hot leg to the PZR through surge line as shown in Fig. 5. The collapsed water level in the surge line was fluctuated during the early phase and there was complicated two-phase flow. This may increase the steam condensation during the early phase. Most of generated steam was discharged through the PZR manway during later phase ($t > 0.7$) and the water level in the PZR hold up started.

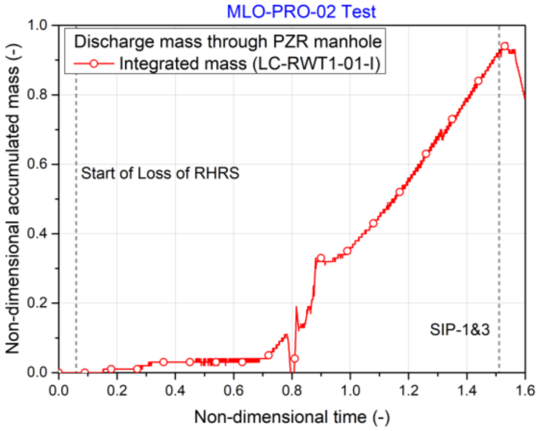

Fig. 4 Discharge mass through the PZR manway

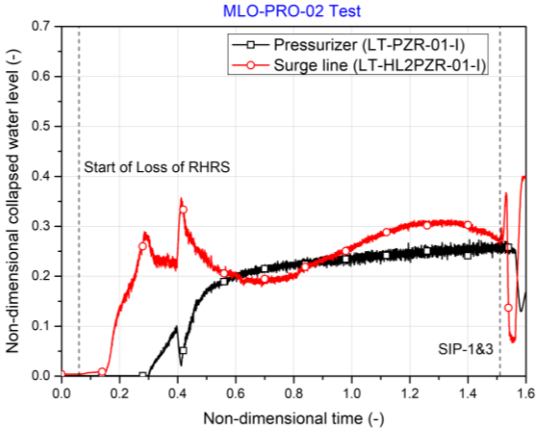

Fig. 5 Variation of the collapsed water level in PZR and surge line

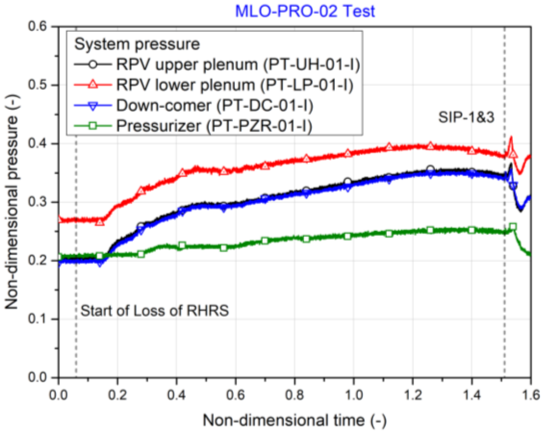

Fig. 6 Variation of the system pressure

The water hold up in the PZR led to increase the system pressures. Figure 6 shows a variation of the system pressures. The pressures started to increase gradually as the water level increase in the surge line. The pressure difference between RPV upper plenum and PZR played a role as the driving force to steam flow through the water hold up in PZR.

Figure 7 shows the variation of the collapsed water levels in the core and down-comer, respectively. Since there was no heat removal source, no RHRS and no inventory on a steam generator of secondary, the coolant temperature in the core increased and consequently boiling occurred. Therefore the collapsed water level in the core started to decrease. During the early phase ($t < 0.7$), the collapsed water level in the RPV decreased slowly due to stagnation and condensation of the steam in the PZR.

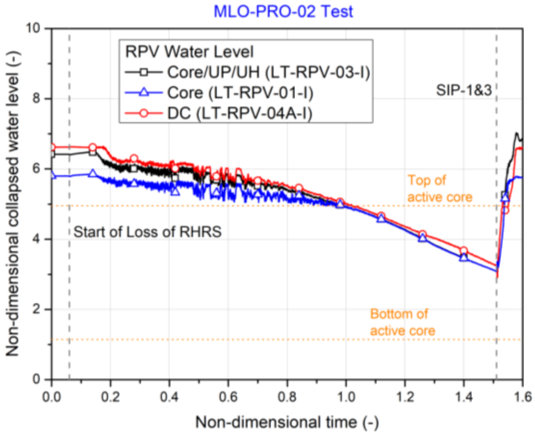

Fig. 7 Variation of the collapsed water level in the RPV

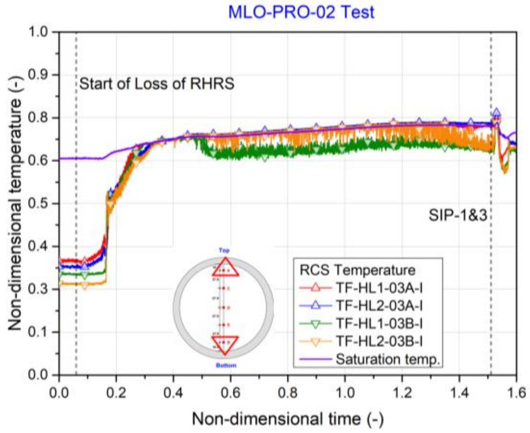

Fig. 8 Variation of the temperature on the hot leg

However, after the steam was effectively discharged through the PZR manway and the water hold up in the PZR was retained, the collapsed water level in the RPV decreased rapidly and the top part of the core was uncovered. Consequently, the peak cladding temperature reached to the set point (TH-CO-G1/2/3-MAX > 300°C) of actuation of safety injection pump (SIP). After the supply of the safety injection water from SIPs, the core was successfully quenched.

Figure 8 shows variation of the fluid temperatures in the hot leg according to different axial elevations (top: A and bottom: B). After boiling started, the temperatures of fluid in the hot legs rapidly increased and reached the saturated temperatures. After a period of time ($t > 0.5$), the temperatures at the bottom of the hot leg 1 (HL1) decreased and remained below the saturation temperature. In ATLAS, the pressurizer is connected on the hot leg 2 (HL2). In the MLO-PRO-02 test, the steam generated in the core made a loop to the opening of the PZR manway as short as possible. In this sense, it can be assumed that the steam flow stagnated in the HL1 and the reflux condensation occurred through heat exchange between the steam and the steam generator structure, although the water of the secondary side was empty.

4. Conclusions

In this study, a loss of RHRS accident during a MLO of APR1400 was experimentally investigated by utilizing the ATLAS facility. In the MLO-PRO-02 test, the water level in the primary system was set to the middle of hot leg while RHRS operated and the PZR manway was simulated to be opened. The water on the secondary side of the steam generator was empty, and the pressure was atmospheric pressure by opening the MSSV. The nozzle dams between the crossover legs and the SGs were not installed. The core power was maintained as a constant value of 91 kW during the whole test period.

In the present test, the steam generated in the core was discharged through the PZR man-way. During the early phase, the steam was condensed in the PZR and stagnated. The water level in the surge line was fluctuated and the collapsed water level in the RPV decreased slowly. During later time ($t > 0.7$), the steam generated in the core was effectively discharged through the PZR manway. The water hold up in the PZR maintained and the collapsed water level in the RPV decreased rapidly and the top of the core was uncovered.

The present MLO-PRO-02 test data can be used to evaluate the prediction capability of existing safety analysis codes for a mid-loop operation condition. Furthermore, detailed experimental data can be used to validate the code performance and identify a deficiency for a simulation of a mid-loop operation.

ACKNOWLEDGMENTS

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