ECC Bypass in the ATLAS Separate Effect Test for a Low Reflooding Rate

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1. Introduction

KAERI (Korea Atomic Energy Research Institute) has recently started the operation of the ATLAS (Advanced Thermal-Hydraulic Test Loop for Accident Simulation) [1], which is a thermal-hydraulic integral effect test facility for evolutionary pressurized water reactors. As the first phase of the ATLAS program, a series of large break loss of coolant accident (LBLOCA) reflood tests have been performed to resolve the safety issues related with thermal-hydraulic phenomena during the LBLOCA late reflood period in the APR1400 [2]. After completion of the integral LBLOCA reflood tests, separate effect test named as LB-CL-15 was performed to help validate the RELAP5 reflood models for a core quench phenomenon under a low flow rate ECC injection condition. A separate effect test data peculiar to the APR1400 could be obtained, which has the DVI injection, reverse heat transfer from steam generators and steam binding effect, etc. In this paper, among the typical thermal-hydraulic phenomena during the LBLOCA reflood period, the emergency core cooling (ECC) bypass is focused and a fraction of the direct ECC bypass in the LB-CL-15 test is evaluated.

2. Description of the ATLAS Facility

Realistic 3-dimensional view of the ATLAS is shown in Fig. 1. The ATLAS facility has the following characteristics: (a) 1/2-height and length, 1/288-volume, and a full-pressure simulation of APR1400, (b) maintaining a geometric similarity with the APR1400 including 4 DVI nozzles for an ECC water, integrated annular downcomer and a reactor coolant loop with a RPV, 2 hot legs, 2 steam generators, 4 intermediate legs and 4 cold legs, etc., (c) incorporation of specific design characteristics of OPR1000 such as cold leg injection and low-pressure SIPs (Safety Injection Pumps), (d) maximum 8% of a scaled nominal core power using the three-level scaling methodology of Ishii and Kataoka.

A total of 1,236 instrumentations are installed for the measurement of thermal hydraulics phenomena in the components. Most of the instrumentations are chosen from commercially available ones. However, an average BDFT (Bi-Directional Flow Tube, or BiFlow) and a break flow system are specially developed or designed for the measurements of the flow rates in the primary piping and in the containment system, respectively.

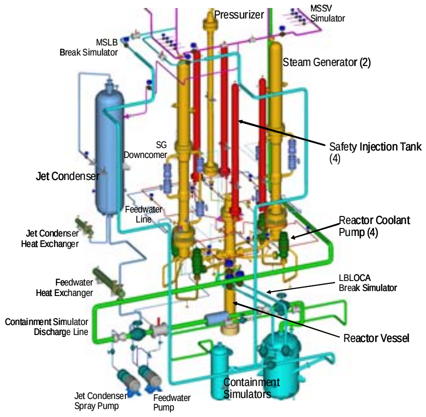

Fig. 1. 3-dimensional view of the ATLAS facility

3. Overview of the LB-CL-15 Test

In the LB-CL-15 test the ECC water was supplied through four SI lines to reduce the pressure at the pump discharge line. The opening degrees of the flow control valves were adjusted to give a pre-determined flow rate of 0.3 kg/s each. The ECC water temperature was about 58°C. The containment simulator pressure was fixed at around 0.10MPa and the initial outer wall temperature was determined to be 150°C when the effect of downcomer boiling is negligible. The initial heater surface temperature was set to be 300°C to prevent high temperature trip. The initial heater power was fixed to the scaled-down power which is corresponding to the downcomer wall temperature and it decayed down following the 102% of ANS-79 decay curve during the test. The actual core power was 388.5 kW in the beginning and there was a power jump to 466.6 kW instead of the pre-determined value of 490.5 kW due to the erroneous power control. Although the mismatch of the core power slows down the heating rate, it does not affect the thermal-hydraulic behavior significantly. The power distribution was uniform along a radial direction. The secondary pressure was set to be around 5.0MPa to consider the effects of a reverse heat transfer and steam binding.

4. Evaluation of ECC Bypass

The APR1400 adopts a new safety feature of a direct vessel injection (DVI) system that supplies the emergency core cooling (ECC) water directly into the reactor vessel downcomer. The ECC water is supplied through four independent trains of the safety injection system. During an LBLOCA, since the DVI nozzles are located above the cold legs, the ECC water has more chance to discharge directly to the broken cold leg compared with the cold leg injection (CLI). It is generally known that there are two ECC bypass mechanisms of a sweep-out and a direct ECC bypass. Sweep-out is caused by the steam injected from the intact cold legs, which interacts with the coolant in the downcomer and induces the coolant to be discharged to the broken cold leg. From the UPTF test results [3], it could be found that a direct ECC bypass is the major bypass mechanism of the DVI system. ECC bypass has been identified as playing an important role in a depletion of the coolant inventory in the reflood phase of a LBLOCA.

In the LB-CL-15 test, a fraction of the direct ECC bypass is evaluated from the measuring the break flow rate data, which consists of a steam and water mixture. Direct ECC bypass fraction is defined as follows.

$$R_{ECC,bypass} = \frac{W_{LC}}{W_{ECC}} \qquad (1)$$

In the above equation, W_{LC} is the water component of a break flow rate and W_{ECC} is the injected ECC water flow rate. Because the downcomer water level is sufficiently lower than that of the centerline of the cold leg (3.391 m from RPV bottom), as shown in Fig. 2, the effect of an entrainment from the water in the downcomer for the direct ECC bypass can be excluded. As for the onset of an entrainment which induces sweep-out phenomena, a simple calculation was performed using Cho's correlation [4]. Critical void height (h_b) below which a sweep-out is started by the steam injected from the intact cold legs can be calculated from the following correlation.

$$Fr_g \left[\frac{\rho_g}{\Delta\rho}\right]^{0.5} = 0.548\left[\frac{h_b}{D_{CL}}\right]^{1.597} \qquad (2)$$

Considering the steam flow rate from the intact cold legs and the system parameters such as the pressure and temperature, the critical void height is calculated to be 0.106 m during LB-CL-15. The calculated critical void height is significantly lower than the distance from the centerline of the intact cold legs to the top of the water in the downcomer as shown in Fig. 2, which confirms that the sweep-out phenomena does not occur in the present test.

Fig. 3 shows the fraction of a direct ECC bypass during LB-CL-15. The ECC bypass fraction increases steadily during the initial 100 seconds period and it maintain its value at around 0.5 until it varies following the trend of the system pressure. The break flow rates of the steam and water vary according to the system pressure. As the steam flow rates increase the direct ECC bypass fraction increases, which shows a general agreement with the findings of previous studies and understandings.

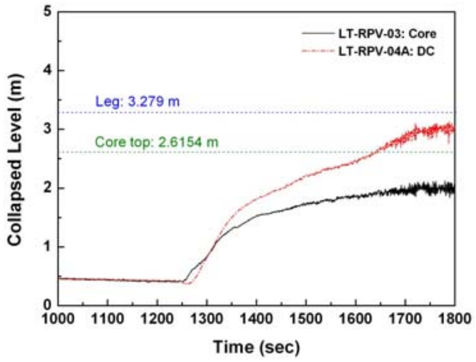

Fig. 2. Collapsed water level variations in the LB-CL-15 test

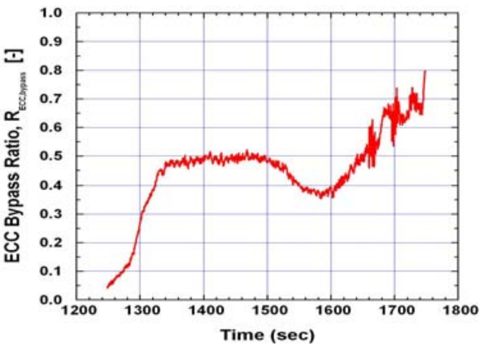

Fig. 3. Direct ECC bypass fraction in the LB-CL-15 test

3. Conclusions

Direct ECC bypass fraction is evaluated in the LB-CL-15 test. A critical void height, below which a sweep-out is started by the steam flow from the intact cold legs, was calculated to be 0.106 m which is significantly lower than the distance from the centerline of the intact cold legs to the top of the water in the downcomer. It was confirmed from the measured and calculated data that the sweep-out phenomena did not occur in the present test. The ECC bypass fraction increases steadily during the initial 100 seconds period and it maintain its value at around 0.5 until it varies following the trend of the system pressure.

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