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An experimental investigation of loop seal clearings in SBLOCA tests

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ABSTRACT

An investigation of the loop seal clearing (LSC) in a small-break loss-of-coolant accident (SBLOCA) for direct vessel injection (DVI) line and cold leg (CL) breaks was performed. The behavior of an LSC appears to be closely related to the break location and break size. In the tests of SBLOCAs, a loop seal or cross-over leg (COL) in the broken loop was cleared first, and the number of loop seals cleared was dependent on the break size. The larger the break size was, the more the loop seals or COLs that were cleared. The location of the LSCs appeared to have a consistent behavior under each scenario. In the SBLOCA tests, the downcomer water level just before an LSC was a very important parameter to the peak cladding temperature (PCT). The initiation of an LSC might not be related to the existing flooding condition, but to the magnitude of the pressure difference between the reactor upper head and downcomer, which is sufficient to push the upflow leg of a COL. The sustaining of an LSC without refilling was evaluated using the test data and existing flooding conditions.

1. Introduction

ATLAS, the acronym for advanced thermal-hydraulic test loop for accident simulation, is a thermal-hydraulic integral effect test facility for evolutionary pressurized water reactors (PWRs) of an advanced power reactor of 1400 MWe (APR1400) and an optimized power reactor of 1000 MWe (OPR1000). The reference plant of ATLAS is the APR1400, which is an advanced power reactor developed by Korean industry and 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 (RCS), as shown in Fig. 1. ATLAS also incorporates some specific design features of the Korean standard nuclear power plant, the OPR1000, such as a cold-leg injection mode for high and low pressure safety injections. ATLAS can be used to investigate the multiple responses between systems for a whole plant or between the subcomponents in a specific system during anticipated transients and postulated accidents.

ATLAS was designed according to the well-known scaling method suggested by Ishii and Kataoka (1983) to simulate various test scenarios as realistically as possible (for more detailed information, refer to Kim et al. (2008)). It is a half-height, 1/288-volume scaled test facility with respect to the APR1400. The main motive for adopting the reduced-height design is to allow for an integrated annular downcomer where the multidimensional phenomena can be important under certain accident conditions with DVI operation. According to the scaling law, the reduced height scaling has time-reducing results in the model. For a one-half-height facility, the time for the scaled model is $\sqrt{2}$ times faster than the prototypical time. The friction factors in the scaled model are maintained the same as those of the prototype. The hydraulic diameter of the scaled model is maintained the same as that of the prototype to preserve the prototypical conditions for the heat transfer coefficient.

During a certain class of SBLOCA in a PWR like an advanced power reactor of 1400 MWe (APR1400), the steam volume in the reactor vessel upper plenum and/or upper head may continue expanding until steam blows liquid out of the U-shaped pump suction cold leg, called a COL or loop seal (LS), opening a path for the steam to be relieved from the break. In the cold leg injection (CLI) design, some portion of this steam might be condensed in the CL in contact with the emergency core coolant (ECC) before being relieved from the break. The steam volume expansion in the reactor vessel upper plenum and/or upper head would involve concurrent, manometric liquid level depressions in the loop seal downflow leg and in the reactor core. A schematic illustration for a loop seal clearing phenomenon in a conventional PWR can be seen in Kukita et al. (1990).

In general, a typical sequence of events (SOEs) of SBLOCAs in PWRs consists of five phases: a blowdown, natural circulation or pressure plateau, loop seal clearance, boil-off, and core recovery (Cho et al., 2011). The duration of each phase depends on the break size and performance of the ECC system. Among the five phases, the loop seal clearing in SBLOCAs is an important phenomenon that governs the whole thermal-hydraulic behavior of the primary system. This paper presents an interpretative description, especially on the LSC behavior, of the test results obtained at the ATLAS facility.

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Nomenclature

ANS	american nuclear society
APR1400	advanced power reactor with 1400 MWe
ATLAS	advanced thermal-hydraulic test loop for accident simulation
CCFL	counter-current flow limit
CL	cold leg
CLI	cold leg injection
COL	cross-over leg
CPT	counter-part test
DC	downcomer
DCUH	between downcomer and upper head
DP	differential pressure or DP transmitter
DVI	direct vessel injection
ECC	emergency core cooling
HL	hot leg
ID	identification
IET	integral effect test
IL	intermediate leg
KAERI	Korea Atomic Energy Research Institute
LPP	low pressurizer pressure trip
LS	loop seal
LSC	loop seal clearing
LSR	loop seal refilling
LSTF	large-scale test facility
MARS	multi-dimensional analysis of reactor safety
M/P	ratio of the model to prototype
MSIS	main steam isolation signal
MSSV	main steam safety valve
OPR1000	optimized power reactor with 1000 MWe
PCT	peak cladding temperature
PT	pressure transmitter
PWR	pressurized water reactor
PZR	pressurizer
RCP	reactor coolant pump
RCS	reactor coolant system
ROSA	rig of safety assessment
SBLOCA	small break loss of coolant accident
SG	steam generator
SIP	safety injection pump
SIT	safety injection tank
SOE	sequence of event
UH	upper head

Symbols

C	constant for flooding condition, e.g., 0.7–1.0
C_w	wall friction factor, e.g., 0.008
D	diameter (m)
DP	pressure difference (kPa)
g	gravitational acceleration, e.g., 9.80 m/s^2
DH	height difference (m)
h_{FG}	latent heat of vaporization (kJ/kg)
Dh_{in}	core inlet subcooling (kJ/kg)
j	mass flux (m/s)
m	constant for mass transfer between two-phases
$\dot{m}$	mass generation rate (kg/s)
N_B	bond number, defined as Eq. (4)
Ku	Kutateladze number, defined as Eqs. (3) or (6)
Q	core decay power (kW)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Superscript

$*$	dimensionless mass flux

Subscripts

G	gas or steam
L	liquid or water

2. Description of test facility related to the loop seal clearance

For an understanding of the loop seal clearing phenomena, the arrangements of loop seal, downcomer, and core in a relatively vertical elevation are important, and govern the characteristics of the loop seal clearing or refilling. Fig. 2 shows the overall arrangements of the COL or LS, downcomer, core, and safety injection nozzles of the ATLAS facility (hereinafter, the U-shaped pump suction cold leg is called COL in this paper). The center line of the horizontal pipe of COL is above 1.344 m from the bottom of the active core, whose total height is 1.905 m. The ATLAS facility also simulates the core bypass of the reference plant by two bypasses, e.g., downcomer vs. upper head (DC–UH) and downcomer vs. hot leg (DC–HL) bypasses, as shown in Fig. 2. All the flow control valves on each bypass lines allow bypass flowrates of about 0.5% and 1.4% of the total core flowrate, respectively, during single-phase steady-state operation. There are two types of safety injection nozzles in ATLAS, e.g., DVI and CLI. The location of the DVI nozzle is above 1.501 m from the centerline of the CL (or hot leg) on the reactor vessel, and that of the CLI nozzle is on the top of the CL downstream of the reactor coolant pump discharge. In a real plant, the DVI nozzles are for an APR1400, and the CLI nozzles, for an OPR1000. Planar arrangements for the main loop pipings and safety injection nozzles are shown in Fig. 3.

The design of the primary pipings for the ATLAS facility was based on a scaling analysis preserving the local phenomena, e.g., two-phase flow patterns, flooding conditions, and volume ratio. For the design of horizontal piping diameters, e.g., CL, hot leg (HL), and horizontal section of the COL, the preservations of Froude number (Taitel and Dukler, 1976) and flooding condition (Ohnuki et al., 1988) were adopted between the reference and model designs. For the design of vertical piping diameters, e.g., COL downflow and upflow pipings, a flooding condition using Wallis correlation (Wallis, 1969) was adopted. For the design of all horizontal piping lengths, a global scale for volume, e.g., 1/288, was applied to preserve the volume ratio between the APR1400 and ATLAS. In addition, for the design of all vertical piping lengths, a global scale for height (or length), e.g., 1/2, was applied. The diameters of the primary pipings for APR1400 and ATLAS are summarized in Table 1.

3. Test conditions and procedure

All the SBLOCAs for DVI line and CL breaks were performed according to the following test procedure. Basically, the test conditions for the SBLOCA tests were determined by a pre-test calculation with a best-estimate thermal hydraulic code. First, a transient calculation was performed for the DVI line or CL break of the reference plant, APR1400, to obtain the reference initial and boundary conditions. A best-estimate safety analysis methodology, which is now commonly accepted in the nuclear community, was applied to the transient calculation of the APR1400. The