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Investigation of thermal hydraulic behavior of SBLOCA tests in SMART-ITL facility

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ABSTRACT

An experimental investigation of the thermal hydraulic behavior of small break loss of coolant accident (SBLOCA) tests in an integral test loop (ITL) of a system-integrated modular advanced reactor (SMART) was performed, especially on the pressurizer safety valve (PSV) line and safety injection (SI) line breaks. Compared to typical phases of SBLOCAs in conventional and advanced active pressurized water reactors (PWRs), four sequential phases were identified: a blowdown to the upper downcomer (UDC) under saturation conditions, a pressure plateau under forced circulation, boil-off after the reactor coolant pump (RCP) trip, and core level restoration after the safety injection tank (SIT) injection or long-term cooling. The pressure plateau was deeply dependent under UDC saturation conditions and there were mass transfers among the reactor vessel (RV) regions during the pressure plateau. In the boil-off phase, a short reverse flow occurred from the lower dowoncomer (LDC) to the primary side of steam generator (SGP) owing to the occurrence of vaporization in the LDC region. The core level restoration is mainly dependent on the SIT injections. In the secondary system, the fluid conditions on the secondary side of steam generator (SGS) outlets were changed during the tests from superheat to saturation, from saturation to subcooling, and from subcooling to superheat. In the passive safety injection system (PSIS), there was a short reverse flow in the pressure balance lines (PBLs) of the core make-up tanks (CMTs) just after the break, and sufficient injection flowrates of the CMTs were achieved after the partial clearing/blocking of the PBL. In the case of a SIT actuation signal, duration times for the hydraulic equilibrium in pressure among the CMTs, SITs, and RV were needed.

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) launched a project to develop a small modular reactor (SMR) in 1997 and developed an integral type PWR with a rated thermal power of 330 MWt (electric power of 100 MWe), called SMART. For the overall philosophy of the SMART reactor development, KAERI (2010) article in Nuclear Engineering International can be given as reference. Current SMRs including SMART are relying only on the passive safety systems for reactor safety, e.g., NuScale (Reyes and Lorenzini, 2010), CAREM (Davis, 2013), IRIS (Carelli et al., 2004) etc.

The single reactor pressure vessel contains all primary components such as the reactor core, steam generators, reactor coolant pumps, and a pressurizer, as shown in Fig. 1. This integral arrangement of the reactor vessel assembly makes it possible to remove the large-sized pipe connections between major components in the primary system, thus essentially preventing the occurrence of large break loss of coolant accidents (LBLOCAs). The in-vessel pressurizer was designed to control the system pressure at a nearly constant level over the entire range of performance-related design basis events.

Another important design feature in the SMART is the introduction of simplified and improved safety systems. The SMART employs passive safety systems instead of active safety systems such as a passive residual heat removal system (PRHRS) and a PSIS to accomplish the inherent safety functions and mitigate the consequences of postulated accidents. The PRHRS prevents overheating and over-pressurization of the primary system in the case of emergency events by removing the core decay heat through only natural circulation. Engineered safety systems that are designed to function automatically on demand consist of a reactor shutdown system, a PSIS, a PRHRS, an automatic depressurization system (ADS), a shutdown cooling system (SCS), and a containment spray system. Additional safety systems include a reactor overpressure protection system and a severe-accident mitigation system. Under

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Nomenclature

ADS	Automatic Depressurization System
ATLAS	Advanced Test Loop for Accident Simulation
BS	Break Simulator
BMS	Break Flow Measuring System
CAREM	Central Argentina de Elementos Modulares
CD	Condenser
CL	Cold Leg
CMT	Core Make-up Tank
CMTAS	Core Make-up Tank Actuation Signal
CRDM	Control Rod Derive Mechanism
CS	Core Shroud
CSB	Core Support Barrel
DC	Downcomer
EA	Each
ECC	Emergency Core Cooling
ECT	Emergency Cooling Tank
FMHA	Flow Mixing Header Assembly
FW	Feedwater
FWP	Feedwater Pump
HL	Hot Leg
HPSI	High Pressure Safety Injection
HX	Heat Exchanger
ICI	In-Core Instrument
IRIS	International Reactor Innovative and Secure
ITL	Integral Test Loop
IV	Isolation Valve
KAERI	Korea Atomic Energy Research Institute
LBLOCA	Large Break Loss of Coolant Accident
LDC	Lower Downcomer
LPP	Low Pressurizer Pressure
LSC	Loop Seal Clearing
MSHP	Main Steam High Pressure
NuScale	NuScale Power, LLC
PBL	Pressure Balance Line
PRHRS	Passive Residual Heat Removal System
PRHRAS	Passive Residual Heat Removal Actuation Signal
PSIS	Passive Safety Injection System
PSV	Pressurizer Safety Valve
PWR	Pressurized Water Reactor
PZR	Pressurizer
RCP	Reactor Coolant Pump
RV	Reactor Vessel
RWT	Refueling Water Tank
SBLOCA	Small Break Loss of Coolant Accident
SCS	Shutdown Cooling System
SG	Steam Generator
SGP	Primary Side (or Shell-Side) of SG
SGS	Secondary Side (or Tube-Side) of SG
SI	Safety Injection
SIT	Safety Injection Tank
SITAS	Safety Injection Tank Actuation Signal
SL	Surge Line
SMART	System-integrated Modular Advanced ReacTor
SMR	Small Modular Reactor
UDC	Upper Downcomer
UGS	Upper Guide Structure

Symbols

A	Upper Region or Vapor Region in TF or Location of PBL Saturation
B	Lower Region or Liquid Region in TF or Location of Partial PBL Clearing/Blocking Start
C	Location of CMT Top Saturation
ID	Inner Diameter (mm)
IV	Isolation Valve
LT	Level Transmitter (m)
PT	Pressure Transmitter (MPa)
TF	Fluid Temperature (°C)

any circumstances, the reactor can be shut down by inserting control rods or injecting borated water.

In the SMART design, the primary water inventory is quite large and distributed in various regions of the RV, e.g., the flow skirt, core, upper guide structure (UGS), surge line (SL), pressurizer (PZR), gap region between the core shroud (CS) and core support barrel (CSB), gap region between the UGS and CSB, shell (or primary) side of the steam generator (SG), and flow mixing header assembly (FMHA), as shown in Fig. 2. In the SBLOCA scenarios, inventory distributions in the RV are important because major components were integrated into one RV. In this paper, three regions were defined to investigate the inventory distributions in the RV, as shown in the figure, i.e., RV-Inner, RV-Outer1, and RV-Outer2 regions.

The SMART integral test loop (SMART-ITL) facility was designed to simulate the integral thermal-hydraulic behavior of the SMART design. The SMART-ITL facility has been designed following the well-known three-level scaling methodology (Ishii and Kataoka, 1983), which consists of integral scaling, boundary flow scaling, and local phenomena scaling similar to those of ATLAS integral test facility (Kim et al., 2008). In the SMART-ITL design, its height is preserved to the full scale for the preservation of natural circulation, and its area and volume are scaled down to 1/49 compared with the prototype plant, the SMART plant. The maximum core power is 2.0 MW, which is about 30% of the scaled full power, generated by indirectly heated electrical heaters. The design pressure and temperature of the SMART-ITL facility can simulate the maximum operating conditions, i.e., 18.0 MPa and 370 °C, respectively. The major thermal hydraulic design data for SMART and SMART-ITL are summarized in Table 1, along with the scaling ratios.

Until the end of 2013, SMART-ITL consisted of a primary system, four SGs, a secondary heat removal system, four trains of a PRHRS, two trains of a SCS, several break simulators (BS), a break flow measuring system (BMS), and auxiliary systems (Park et al., 2013). After then that, two stages of an ADS and four trains of a PSIS were additionally installed corresponding to the upgrade of the current SMART design. Typical safety systems simulated in SMART-ITL are summarized in Table 2, and their schematic diagrams are depicted in Fig. 3.

As shown in Fig. 3, each train of the PRHRS consists of one emergency cooling tank (ECT), one ECT heat exchanger (HX), an isolation valve (IV2), and connected lines to the secondary side of each SG. In SMART, a total of four SGs were equipped in the RV and thus there are four trains in the PRHRS. For the PSIS, each train of the PSIS consists of one CMT, one SIT, and pressure balance lines (PBLs), which connect between the RV's upper down comer (UDC) and the top and/of the CMT or SIT. Through the PBLs, the RV pressure is transferred to the top of each tank. Normally, the CMT and SIT are full of emergency core cooling (ECC) water, and the PBL for the CMT is also full of water, but that for the SIT is partially filled with water. As can be seen in Fig. 3, the PBL for the CMT is normally opened between the RV and CMT, but that for the SIT, normally closed by an isolation valve, e.g., IV4 in the figure, and this is reason why it is partially filled with water in the PBL for the SIT. Thus, the CMT is under normal pressure of the RV, but the SIT is maintained a lower pressure, e.g., 2 MPa. The SI injection line of the CMT and SIT