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SCALING, EXPERIMENT, AND CODE ASSESSMENT ON AN INTEGRAL TESTING FACILITY

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Abstract

A series of integral tests simulating different types of Loss-Of-Coolant Accidents (LOCAs) for new Boiling Water Reactor (BWR) design were conducted on an integral test facility (Purdue University Multi-Dimensional Integral Test Assembly, PUMA) facility. The PUMA facility was built with a scaling methodology addressing both the conservation principles and constitutive laws. A systemic study about the safety evaluation of the advanced passively safe BWR design has been performed with the collaboration of experiments on the scaled-down test facility and RELAP5/Mod3.3 code simulation. Various types of LOCA tests were performed, such as Main Steam Line Break (MSLB), Bottom Drain Line Break (BDLB), Gravity-Driven Line Break (GDLB), and Feed Water Line Break (FWLB).

Introduction

Small scale experiment facilities have been widely used for research activities in the nuclear and chemical industries due to the space and budget limitation. Test facilities having the same geometric size as commercial applications are rare, especially for nuclear installations. To ensure the soundness and applicability of experimental results from small scale facilities, the scaling analysis and similarity evaluation need to been addressed. Due to the complexity and instability of two-phase flow, the scaling analysis for the BWR test facility is more complicated than that for single phase systems.

A three-level scaling approach (Ishii, 1998) has been developed and applied to the design and construction of PUMA facility (Ishii et al., 1996). The PUMA facility is a large BWR integral test facility designed to study the various thermal-hydraulic phenomena expected on the BWR design during the operational and accident transients. The PUMA facility contains most of the scaled engineered safety and safety grade systems, thus has the capability to simulate both the system-wide integral responses and local physical phenomena such as two phase flow, critical flow, pool mixing and stratification, direct contact condensation, and natural circulation. Various types of integral and separate effect tests have been performed on the PUMA facility and experimental data have been used as the reference for the licensing process and code benchmark. The PUMA facility has been upgraded several times to adapt the design change of prototype reactors. This paper focuses on the newest scaling and LOCA experiments accommodating the recent generic passively safe BWR design. The schematic of PUMA facility is shown in Figure 1.

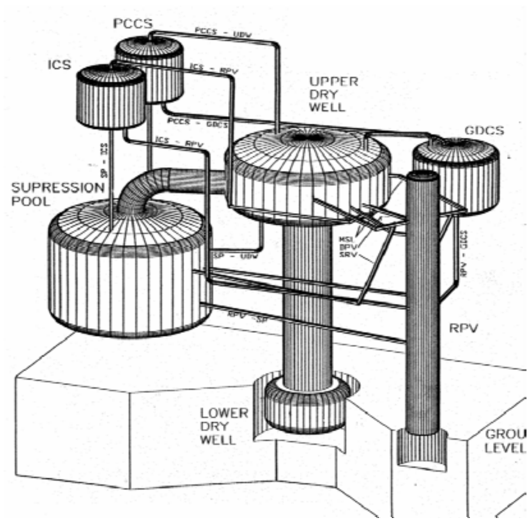


Figure 1 Schematic of PUMA Facility

1. Scaling analysis

1.1 Scientific scaling

The scaling analysis addressing the conservation principles has been called the top-down approach and the analysis addressing local phenomena and constitutive laws was called the bottom-up approach. Both of two approaches need to be considered in a comprehensive scaling analysis (Ishii, 1998). For the integral response scaling, every component is considered one dimensional. The single-phase and two-phase system conservation equations are solved analytically under dynamic conditions. The mass and energy control volume balance equations are non-dimensionalized to obtain the scaling criteria for the inter-component relations. These criteria scale the inter-component mass and energy flows as well as the mass and energy inventories in each component. After the overall scaling is determined from the integral and boundary flow scaling, the third level of scaling is considered.

1.2 Engineering scaling

Scaling distortions will exist in the test facility, especially for the third level scaling, due to the limitation of engineering construction and conflict of scaling requirements imposed by different physical phenomena. Compared to current prototypic passively safe BWR design, the PUMA facility has a scale of 1/4.5 in height, 1/580 in volume (Ishii, 2006). The major scaling ratios used in current PUMA facility are shown in Table 1. To simplify the construction, the containment is scaled as a separate tank in the PUMA facility called the Drywell (DW), and the pipe break is simulated with a pipeline between the vessel and the DW. Since the scaling distortions exist, the data extrapolation and interpretation should be done with proper adjustment and clarification (Ishii, 2008).

Table 1 Scaling ratios of current PUMA Facility

Symbol	Scaling Parameter	Scaling Ratio
P_R	Pressure	1
a_R	Area	1/128.8
l_R	Length	1/4.5
V_R	Volume	1/579.8
u_R	Velocity	1/2.12
q_R	Power	1/273
t_R	Time	1/2.12
m_R	Mass Flow	1/273

2. Experiment

2.1 LOCA transient

Postulated LOCAs are mitigated in this natural circulating, passively safe BWR due to the design concept of the passive emergency cooling systems. The Reactor Pressure Vessel (RPV) is flooded with cold water from Gravity Driven Cooling System (GDCS) pools by gravity after it is depressurized through the Automatic Depressurization System (ADS). Safety Relief Valves (SRVs) are connected to the Suppression Pool (SP) and Depressurization Valves (DPVs) are connected to the containment. Those valves are activated in a preset sequence after a low water level in the vessel is confirmed. Steam discharged from vessel is condensed in the SP and in the Passive Containment Cooling system (PCCS) to ensure the containment pressure remain below the design limit. The Isolation Condenser System (ICS) takes steam from the RPV and drains the condensed water back to the RPV directly. Condensate from the PCCS returns to GDCS pools then to the RPV.

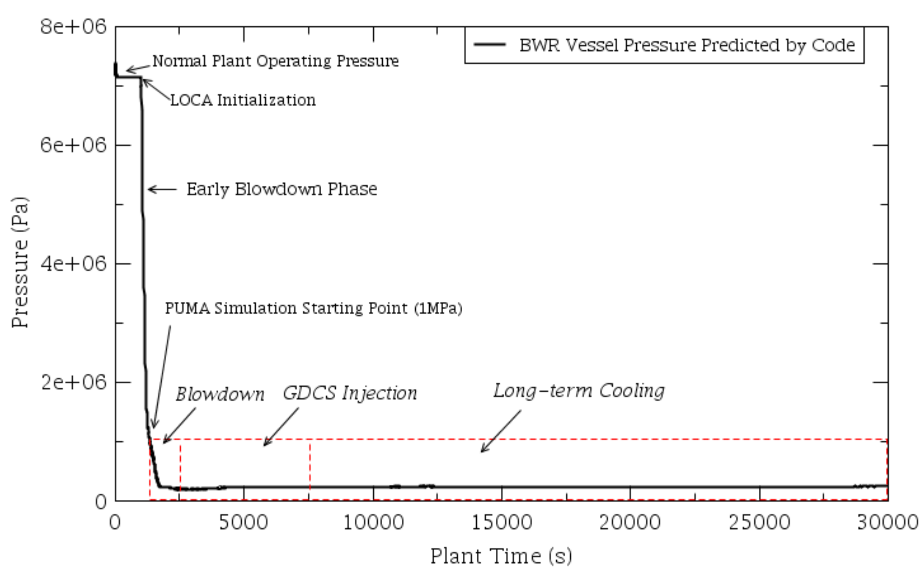


Figure 2 LOCA transient indicated by reactor vessel pressure trend

Integral tests and analysis programs can be carried out to evaluate the thermal-hydraulic performance of the passive safety systems in the event of LOCAs. Since The PUMA facility contains all of major engineering safety system, LOCA scenario can be reproduced in the PUMA facility, with scaled physical quantities. The typical system pressure trends in a LOCA are presented in Figure 2 with the pressure in the vessel. Generally, the sequence of events during a LOCA can be classified into three phases: blowdown phase, GDCS injection phase and long-term cooling phase. Since the PUMA facility is designed to be operated at low pressure (below 1 MPa), the PUMA facility only simulates the transient after the vessel pressure drops down to 1 MPa (150 psi). The early high-pressure blowdown of LOCA transient is simulated with prototypic-geometry model by code. The initial conditions for the integral test are extracted from the prototypic system condition predicted by code simulation.

2.2 Test design

The LOCA experiments were performed at the PUMA facility. The whole operation procedure for an integral test can be classified into the following stages: Pre-test preparation, System initialization, Test conduction, System restoration, and Data certification. Depending on the size and location of pipe break, four types of tests were chosen to represent the different LOCAs: Main Steam Line Break test, Bottom Drain Line Break test, Gravity-Driven Line Break test and Feed Water Line Break test. The BDLB test simulates the Small Break LOCA (SB LOCA). The break is assumed as a double-ended pipe break at bottom drain line. The MSLB test is initiated by assuming that a double-ended pipe break takes place at one of the steam lines. The MSLB seriously challenges the containment safety due to the large amount of steam discharged to the DW. The GDLB test is an SB LOCA assumed that one of GDCS injection lines undergoes a double-ended pipe break. The FWLB test belongs to LB LOCA category. The feed water lines are designed to supply water to the reactor vessel. The features of different LOCAs are shown in Table 2.

Table 2 Comparison of four types of LOCAs

Category	Type	Break location	Elevation (m)	Break flow
Small Break	BDLB	Bottom Drain Line	0.0	Liquid
Small Break	GDLB	Gravity Drain Line	2.373	Liquid/Steam
Large Break	FWLB	Feed Water Line	3.999	Steam/Liquid
Large Break	MSLB	Main Steam Line	5.095	Steam

2.3 Test results

In this section, we will discuss the performance of the passive safety system related to safety criteria by examining the experiment results. The most important safety criteria are the peak containment pressure and minimum RPV water level. RPV water level is affected by the performance of the ECCS and containment pressure is mainly determined by the performance of the PCCS.

The DW pressures for different LOCA tests are illustrated in Figure 3. In four types of LOCA tests, the peak DW pressures are within the design limit. During the blowdown phase, DW pressure increases and equalizes to the pressure of the RPV. After GDCS injection starts, DW pressure decreases due to the condensation and termination of steam generation in the vessel. In this period, the DW pressure is lower than that of the WW so vacuum breakers are opened to allow gases flow back into the DW from the WW. The DW pressure increases slightly during the GDCS injection phase and continues to climb to its peak in the long-term cooling phase. The peak pressure value time corresponds to the time when noncondensable gases are cleared from the DW. In the long-term cooling phase, the pressure trends start decreasing, this demonstrates that the safety systems were able to remove the decay heat and keeping DW from overpressure. It should be mentioned, since there is some distortion existing in the DW volume scaling (< 5%), the peak pressure data could be a little higher when extrapolated to the prototype, but it would be still well below the design limit.

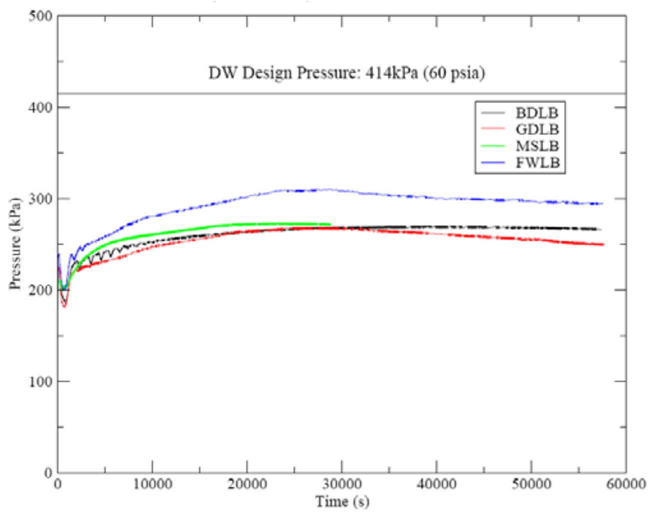


Figure 3 Containment Pressures in LOCA Tests

Figure 4 shows the RPV coolant levels in the blowdown phase for the four different tests. The minimum coolant level in the vessel during LOCA is an important safety criterion in the reactor design. In the current experiment, all tests show a minimum downcomer collapsed level below the Top of Active Fuel (TAF, ~1.62 m) except the MSLB case. This may bring a concern for core safety. Since the two-phase mixture level is higher the collapsed level, even the collapsed water levels is below the TAF, the minimum two-phase levels are still higher than the TAF for all cases. This was confirmed by the differential pressure and void fraction measurement. The minimum RPV water level is determined by the relative speed of break discharging flow and RPV depressurization. The RPV needs to be depressurized to allow the GDCS water injection. On the other hand, if coolant loss is too fast then the core may become uncover even before the GDCS injection could happen. This should be taken into account in the design of ADS. Except the design basis LOCA tests, some beyond design basis LOCA tests with additional partial failure of safety system were also performed. More extensive and detailed data analysis can be found in the technical report (Ishii, 2008) and thesis work (Yang, 2010).

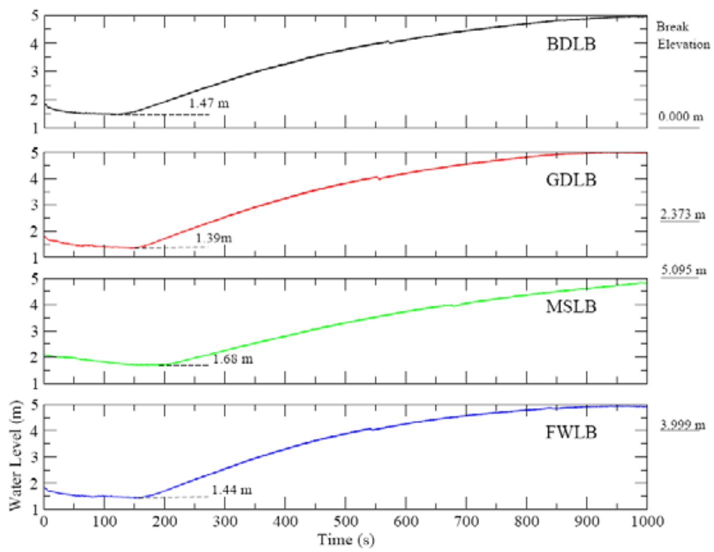


Figure 4 Vessel Minimum Water Levels in LOCA Tests

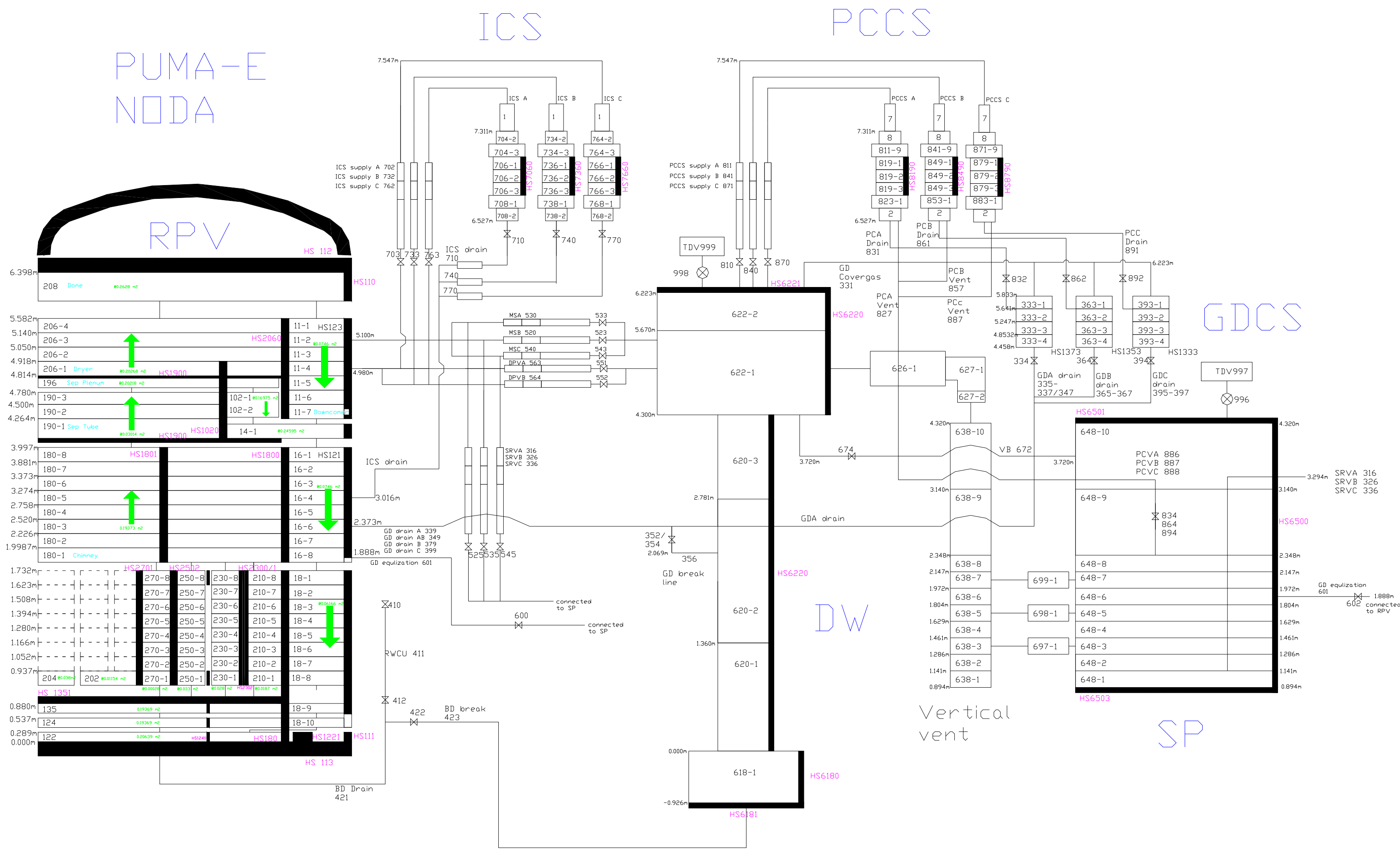
3. Code simulation

3.1 Code mode

When the experimental data from the small scale test facility are applied to the prototype, it is needed to consider the degree of similarity and the quantification of distortions due to the scaling. The applicability of small scale integral test data to the LOCA analysis has been addressed (Saha, et al., 2009). Although the scaling methodology of PUMA facility supposed to inherently support the applicability of integral test to the power plant LOCA analysis, the necessity to verify the scalability of LOCA integral tests still exists. To help to achieve this goal, two RELAP5/Mod 3.3 models were developed based on the geometry information and operational parameters of the prototypic reactor and PUMA facility, respectively. The code simulation results are compared with the experiment data to evaluate the scalability and applicability of integral tests, and examine the code capability (Ransom, 1998).

The methodologies to develop two code models are similar: the reactor system is separated into several distinct components, such as the RPV, DW, WW, GDCS, ICS, PCCS and ADS. For simplification some multiple loops are lumped. The nodalization diagram of PUMA code models are shown in Figure 5. The RPV has the most complicated geometry therefore it is important to preserve the flow area and height in the code model. The upper DW is connected to the RPV by the ADS lines so the steam can be discharged from the RPV to the DW. The top of upper DW is connected to the GDCS gas space through the cover gas line. The upper DW is also connected to the WW through the main vent line. The horizontal venting holes on the vent are modelled as three valves between the vent and the WW. Models of the PCCS and the ICS are quite similar. Each unit is composed of supply line, condenser, liquid drain line and gas vent line. PCCS supply lines are connected to the upper DW, while drain lines are connected to the GDCS pools and vent lines are connected to the SP.

Figure 5 Nodalization of PUMA code model



3.2 Comparison of code and experiment

This section focused on BDLB and MSLB tests since they are two representative LOCAs in terms of break size, location and flow type. BDLB is a small, liquid, low elevation break and a MSLB is a large, steam, high elevation break. The three important data channels are presented here: the vessel water level, indicating the core safety and being related to the system mass and energy balance; the emergency cooling (GDCS) flow, representing the scaling of flow driven by natural force (hydrostatic head); the break flow at blow down, showing the scaling of flow driven by the pressure difference. The correct scaling of these three parameters is important for the overall scaling validation of the whole system. The scaled plant data in the following graphs are based on plant code model calculation results, scaled by corresponding scaling ratios as listed in Table 1. The transient time is synchronized between code and experiment.

For LB LOCA (MSLB), the comparison of vessel water level is shown in Figure 6. The water level in the plant model has been scaled down using the length scaling ratio given in Equation (1):

$$l_R = 1/4.5 \tag{1}$$

since certain area scaling has been chosen for the core cross section, the level indicates the mass inventory as well. After scaling ratio applied, the integral test data, facility model result, plant model result match with each other, this validates the pressure and mass flow scaling since the vessel inventory are related to pressure difference of vessel and other components, and consequently, inter-component mass flow.

Figure 7 shows a comparison of the emergency core cooling flow from the GDCS. The flow in the plant has been scaled down using the mass flow scaling ratio given in Equation (2):

$$\dot{m}_R = 1/273 \tag{2}$$

The scaled mass flow in the plant model agree with the facility data. This confirms the scaling design of mass flow driven by gravity. In the scaling analysis, the flow in the GDCS injection lines is single-phase liquid driven by the hydrostatic head. Consider a quasi-steady state condition in which pressure is already equalized, the momentum equation gives:

$$\rho \tfrac{du}{dt} l + \tfrac{\rho u^2}{2}\left(\tfrac{fl}{d} + K\right) = \rho g H \tag{3}$$

where l, H and d are the line length, driving head and hydraulic diameter, respectively, f and K stand for the major and minor flow loss. Equation (3) shows that the liquid hydrostatic head controls the GDCS flow against the liquid inertia, friction. The flow is determined by the balance between friction and gravity. Therefore, the velocity scale ratio is given by

$$\mathrm{u_R} = \left(\frac{\mathrm{H}}{\mathrm{f}l/\mathrm{d} + \mathrm{K}}\right)_{\mathrm{R}}^{1/2} \tag{4}$$

Furthermore, the mass inventory scaling requires that

$$\dot{m}_R = u_R a_R \tag{5}$$

where a_R is the line flow area ratio. The scaling of the flow area and friction may go beyond the basic geometrical scale to guarantee that the mass flow is scaled to preserve the mass inventory. In practice, flow restriction orifices were used to obtain proper friction scaling for a given line size.

Another type of flow scaling is reflected in Figure 8. The break flow is determined by the pressure difference between the vessel and containment, and the choked area since the break flow is critical at initial blowdown when the pressure in the vessel is much higher than the containment. The mass flow ratio is still following the Equation (2). Consider

$$(a_{ch}u_{ch})_R = \dot{m}_R \tag{6}$$

where a_{ch}, and u_{ch} are the area and velocity scaling ratios in the choked point. For critical flow, the ratio of velocity at the throat is given by $(u_{ch})_R = 1$ since the prototypic pressure condition is simulated ($P_R = 1$), so the scaling ratio for choked flow area will be

$$a_{ch}=1/273 \tag{7}$$

This is different from the geometrical area scaling ratio (1/128.8), as well. In the facility design, special nozzles with certain throat diameter were used to satisfy the choked flow area. Generally the nozzle throat area are smaller than the flow area in pipelines, since the flow loss caused by this abrupt area change usually dominate the total loop flow loss, the mass flow scaling can be satisfied even when the flow is unchoked. The more detailed analysis can be found in the facility scaling report (Ishii, 1994). As a result, Figure 8 shows that the scaled plant data has agreement with the facility data, considering the pressure cut-off point at 1 MPa (150 psi).

Figure 9, Figure 10 and Figure 11 show the corresponding results for the SB LOCA (BDLB) case. The analysis is omitted since it is similar with the MSLB case. From the comparison of experiment and code simulation based on the two types of LOCA tests, we observed an agreement between the experiment and code simulation, also correctly scaled physical phenomena based on the scaling criteria. Considering the scaling distortion, experiment and code uncertainty, this overall agreement confirms the facility scaling design and code capability on the LOCA for this type of BWR.

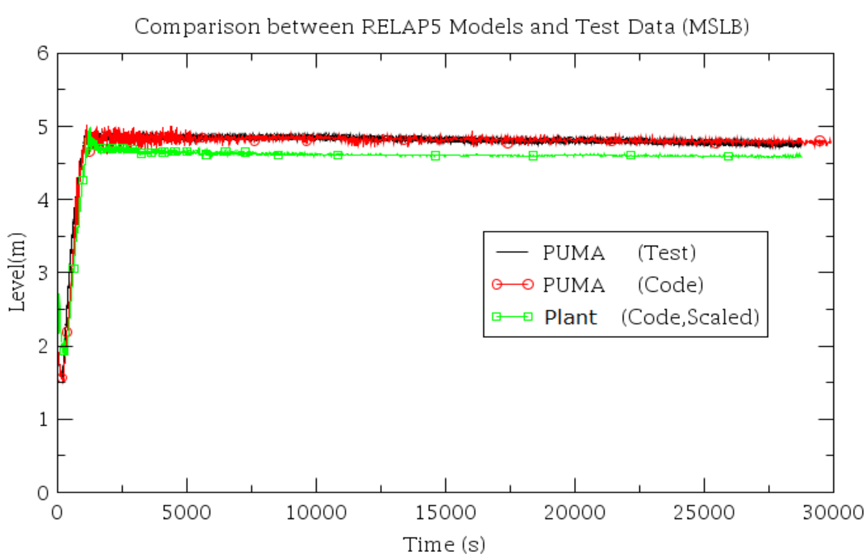


Figure 6 Comparison of vessel inventory (LB LOCA)

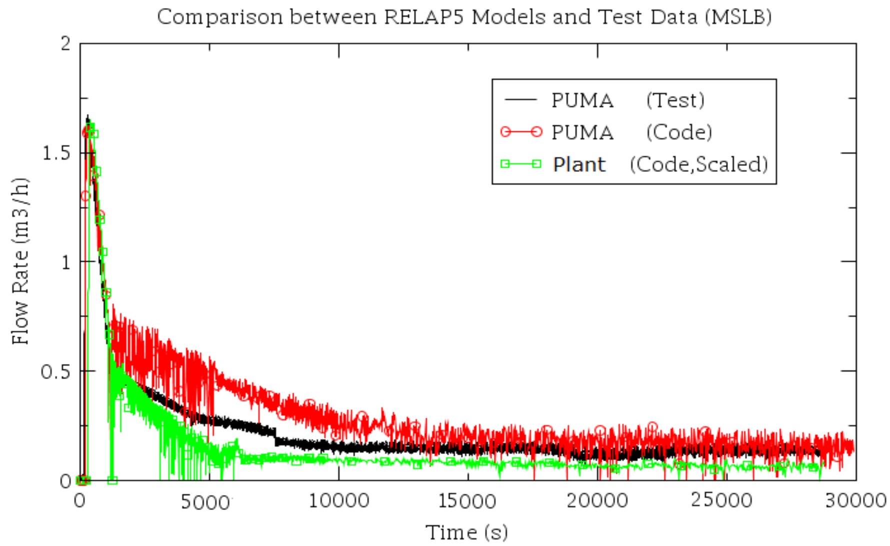


Figure 7 Comparison of GDCS injection flow (LB LOCA)

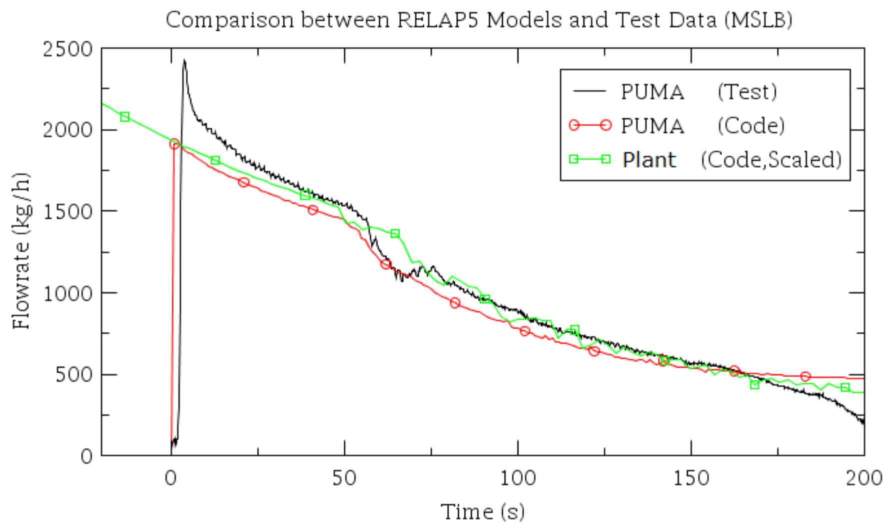


Figure 8 Comparison of steam break flow (LB LOCA)

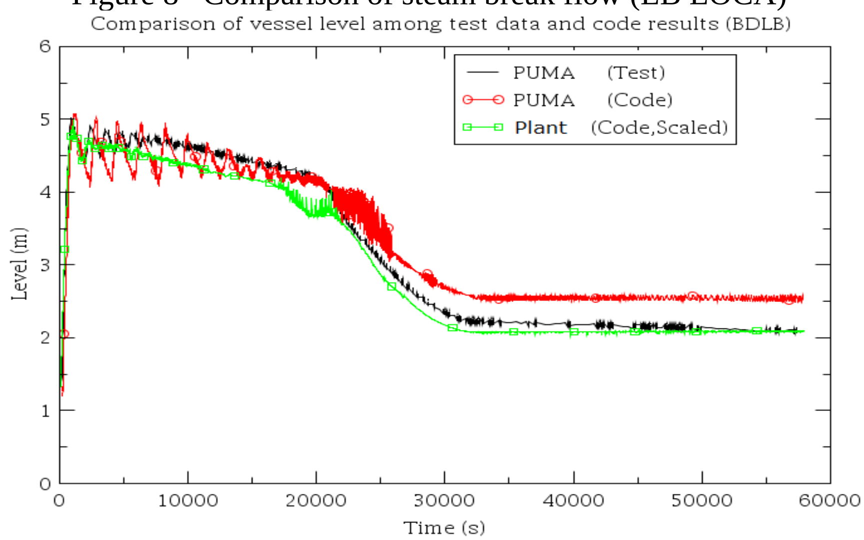


Figure 9 Comparison of vessel inventory (SB LOCA)

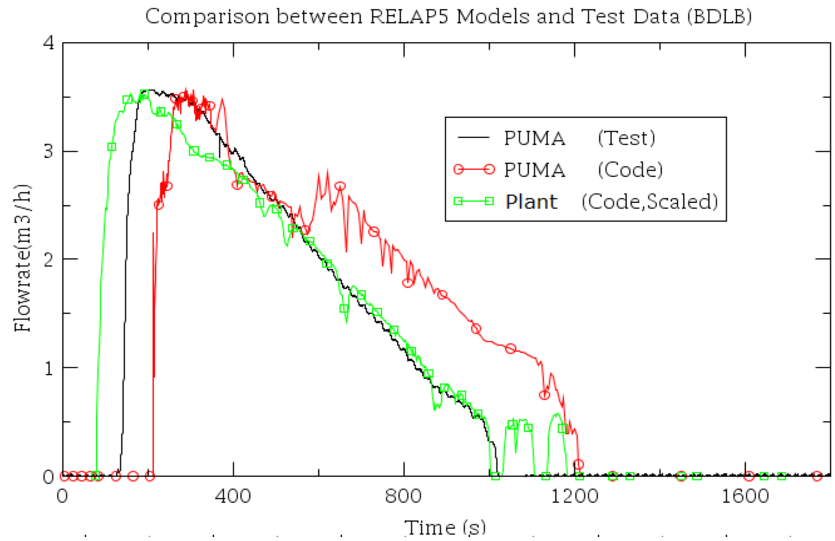


Figure 10 Comparison of GDCS injection flow (SB LOCA)

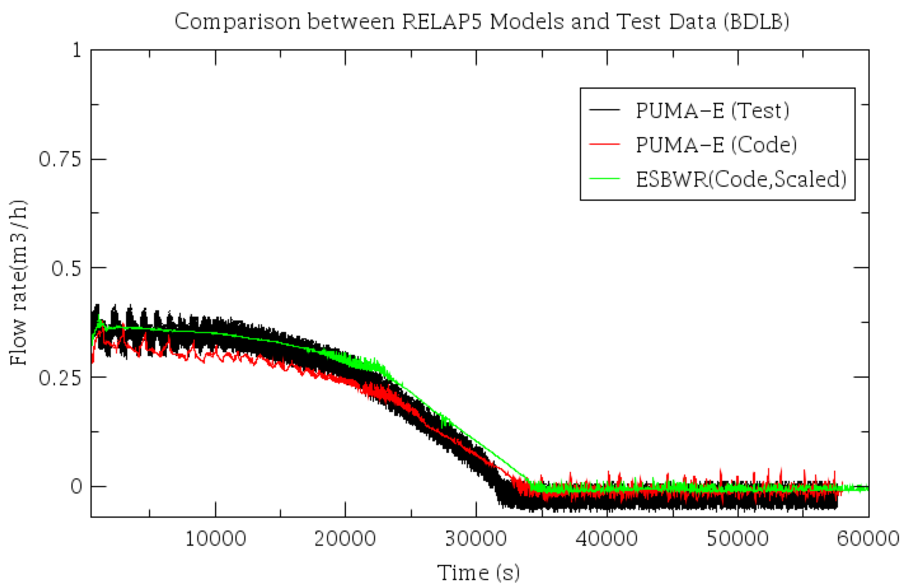


Figure 11 Comparison of liquid break flow (SB LOCA)

4. Conclusion

A series of LOCA integral tests have been performed on an integral test facility to address the system behaviors for the natural circulating, passively safe BWR. Experiment results demonstrate that the passive safety systems function normally when responding to the postulated LOCAs. Majority of the important phenomena happened in the plant have been reproduced by the integral tests. The specific flow area and flow loss scaling requirement has been applied in the flow driven by the pressure difference (choked or unchoked) and the flow driven by the hydrostatic head and both of them yield the same mass scaling.

RELAP5/MOD3.3 has been used to model the test facility and prototype power plant for LOCA tests. Generally the code models gave a good prediction of the system thermal-hydraulic behaviors. The plant code model results had an overall agreement with facility model and test data for global phenomena with some distortions. This integral test facility supplied a good demonstration of scientific and engineering scaling design for a complicated two–phase system. Overall the integral test and facility code scalability has been confirmed by a triad of data sets consisting of plant model, facility model, and facility integral test. Based on the current study, further investigation can be done to help to establish the Code Scaling, Applicability, and Uncertainty (CSAU) evaluation methodology.

Acknowledgement

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