BWR DRYWELL BEHAVIOR UNDER STEAM BLOWDOWN*

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Abstract

Historically, thermal hydraulics analyses on Large Break Loss of Coolant Accidents (LOCA) have been focused on the transients within the reactor or steam generator. Few have studied the effects of steam blowdown on the containment building. This paper discusses some theoretical issues as well as presenting numerical and experimental results of the blowdown tests performed at the Purdue University Multi-dimensional Integrated Test Assembly (PUMA).
1 INTRODUCTION

In the event of a major Loss of Coolant Accident (LOCA) such as a guillotine break on a Main Steam Line, high-pressure steam is injected into the containment atmosphere. Cooling the superheated steam is critical in ensuring that containment pressure remains below design limits. Historically, active containment cooling systems such as fans and sprays were designed to enhance cooling and condensation rates. However, new passively safe engineered safety systems such as those for General Electric Simplified Boiling Water Reactor (SBWR) rely exclusively on natural circulation to provide core and containment cooling.

The SBWR Emergency Core Cooling System (ECCS) is made up of a high pressure Integral Cooling System (ICS), and a low pressure Gravity Driven Condensate System (GDCS). Long term containment cooling is provided by the Passive Containment Cooling Systems (PCCS). The ICS and PCCS consist of a system of condensers that draw steam from the Reactor Pressure Vessel (RPV) or containment and return the condensate to the RPV and GDCS respectively (Figure 1).

Ultimately, reactor decay heat is transferred to the atmosphere via PCCS and ICS secondary pool evaporation.

PCCS operation depends on natural convection to move discharged steam through a set of condensers and vent non-condensables to the Suppression Pool (SP). It is suggested that the stratification of steam and non-condensables negatively affect the PCCS heat removal capability. Therefore, it is important for design and safety analysis engineers to understand the thermal hydraulic phenomena and associated mechanisms of the steam-air mixture inside the containment subsequent to reactor blowdown.

In addition to performing the experiments, a RELAP5 model of PUMA was also created. The numerical results were used to set PUMA initial conditions as well as comparing with the final results. Even though the RELAP5 model of the Upper Drywell (UDW) is rudimentary (one large node to represent the entire UDW); the code adequately predicts both the reactor and containment pressure and temperature. However, as expected, the code results do not provide insights on the UDW’s three-dimensional thermal hydraulics phenomena.

![Figure 1: SWBR Layout](image-url)
On the other hand, it is found experimentally that steady state UDW atmosphere is stably stratified. Furthermore, wall condensation in the upper Drywell ceases once the reactor core is flooded by GDCS injection. Finally, SBWR's long term containment cooling is done exclusively by the PCCS.

2 EXPERIMENTAL FACILITY

The Purdue University Multi-Dimensional Integral Test Assembly, PUMA, was designed to study both integral and separate effects of various reactor accident scenarios. It was scaled to preserve system wide phenomena and interactions between the safety related systems as well as local thermal hydraulic phenomena.

To study long term, low-pressure performance and interactions of SBWR safety systems, PUMA was designed to simulate reactor accidents after the RPV is depressurized to less than 1.03 MPa (150 psia). This allows PUMA experiments to be executed at prototypical pressure and ensures that the most important thermal hydraulic phenomena within the reactor as well as those in the containment and other systems at the PUMA facility are similar to those of the prototype.

2.1 SCALING OF PUMA

The scaling of PUMA facility is based on the both top-down (system level), and bottom up (local flow structure) principles. The top-down approach preserves the integral response functions, control volume and boundary flows. The bottom up approach preserves local phenomena such as flashing, choking, condensation, mixing and thermal stratification. The integral system scaling requires that the single and two-phase flows regimes and structures of the scaled system be consistent with the prototype. To satisfy this requirement, the ratios of the dimensionless numbers between the prototype and scaled system must be as close to unity as possible. The control volume and boundary flows scaling criteria determine the mass and energy inventory of the scaled system.

![Figure 2: PUMA Layout](image-url)
From these sets of scaling requirements, the pressure, time, height, power, volume and other geometric scaling factors are determined as follows (PUMA/Prototype) [5]:

- Pressure: 1/1
- Volume: 1/400
- Height: 1/4
- Power: 1/200
- Time: 2/1
- Area: 1/100

2.2 INSTRUMENTATION

PUMA is extensively instrumented. Besides temperature and pressure measurements, this facility is also capable of measuring single and two phase flows. Vortex flow meters are used to measure low volumetric flow rates; gas sampling system measures non-condensable concentration etc. For the purpose of this paper however, only the instrumentation of the Drywell is discussed.

The Drywell temperatures are measured by K-type thermocouples (TC) with estimated errors of ±1°C. The TC locations are designed to best obtain three-dimensional temperature distribution and stratification pattern of the steam-air mixture (Figure 3). There are also coupled groups of wall and steam temperature measurements for condensation calculations. The upper DW gas concentration is determined by periodic sampling throughout the duration of the tests. Additionally, in future experiments, Thermocouple Cross-Correlation velocity meters will measure natural convection velocity.

2.3 EXPERIMENTAL SCOPES

Steam blowdown is simulated by opening a break valve in one of the main steam lines to discharge steam to the containment (Figure 1). Once the reactor coolant level decreases to approximately 1 meter above top-of-active-fuel, (about 150 seconds after the opening of the break valve), the Automatic Depressurization System (ADS) activates and sequentially opens the Safety Relief Valves (SRV’s) and Depressurization Valves (DPV’s) to discharge steam into containment and rapidly reduce RPV pressure. Once RPV pressure is lower than that of the GDCS, gravity drains cool water (=20°C) from the GDCS into the RPV. The sequence of ADS events can be followed from Figure 4.

Initially, the discharged steam inside the containment is vented to both the SP, through a series of horizontal vents, and to the PCCS. Long term cooling of the containment, however, is handled solely by the PCCS. The PCCS is situated above the containment (external to the DW) and draw steam from the top of the DW dome. Since the containment is initially filled with inert gas, mostly nitrogen, the initial high-pressure steam entrains most of the inert gas and carries it to the SP [5].

For the SBWR design, once ADS is activated, all of the decay heat is ejected to the containment and ultimately expelled to the atmosphere through the PCCS condensers. Since the heat removal capacity of the PCCS is much greater than the reactor decay heat, it is expected that steady state containment temperature and pressure would be either decreasing or constant.

3 NUMERICAL MODELS

To set PUMA initial test conditions, RELAP5 results were used. Since both the experiment and RELAP5 have the same starting point, the experimental results can then be used to assess RELAP5 thermal hydraulic models and their predictive capabilities. However, it should be noted that since RELAP5 is a one-dimensional code, it could not give multi-dimensional information.
such as natural convection and stratification effects in the upper Drywell. To study the migration and stratification pattern of the steam-air jet mixture in the upper Drywell, a 2-D (R-Z) turbulent steam jet is modeled using a commercial Computational Fluid Dynamics (CFD) package, PHOENICS (by CHAM). However, the result of that study is outside of the scope of this paper and is reserved for another report.

3.1 RELAP5 MODEL OF THE DRYWELL

In RELAP5, three sections, the upper Drywell, (UDW), middle Drywell (MDW) and a lower wet-well section represent the PUMA containment. The UDW is modeled as two volumes; a thin top layer represents the connection between UDW and GDCS. A much larger volume represents the entire upper Drywell with the PCCS steam inlets connected to this node [8]. Therefore, strictly speaking, the Upper Drywell is modeled as one volume and the mixing is assumed to be complete.

The difficulty of modeling the upper Drywell with multiple volumes is apparent. Since prior to the PUMA experiments, the Drywell mixing pattern is unknown; therefore, if more than one node is used to represent the UDW, it is practically impossible to estimate the interactions between them. Consequently, to simplify matters and reduce calculation time, complete mixing in UDW is assumed. In the final analysis, this is a necessary assumption since multi-dimensional information within a vessel is not easily computable with RELAP5.

4 RESULTS

The results presented here are from several different PUMA blowdown experiments. The experimental results are consistent and repeatable. The RELAP5 results also agree well with PUMA experiments.

4.1 RELAP5 VS. EXPERIMENT

Globally, RELAP5 results match PUMA experimental results very closely. Figure 5 shows remarkable agreement in RPV pressure. RELAP5 encounters more difficulty in predicting Drywell pressure (Figure 6). Experimentally, RPV and DW pressures from different tests agree extremely well with each other during the blowdown phase and slightly diverge to different asymptotic levels. The cause for this divergence was found to be a clogged PCCS condensate return line. In any case, agreements in both trends and levels between RELAP5 outputs and experiments are quite acceptable.

RELAP5 is not as capable in predicting the containment temperature as it is in predicting pressure. Though the trend was generally correct, RELAP5 over-predicts the temperature rise subsequent to the GDCS injection by as much as 5°C (Figure 7).

Finally, since it is difficult to match the initial conditions for each blowdown tests, it is reasonable to expect that the initial values of the transients may be different. Except for explainable mechanical failures, the final asymptotic states in the RPV, DW and PCCS are expected to converge within reasonable limits of accuracy.

4.2 CONDENSATION

Prior to these PUMA blowdown experiments, it was not clear how important a role condensation plays in these passively safe designs. In this analysis, two UDW condensation modes are considered: homogeneous and laminar wall condensation. It is found that neither mode of condensation contributes significantly to long-term containment cooling.
4.2.1 Homogeneous Condensation

Homogeneous condensation is possible when steam is isothermally compressed to a pressure slightly above saturation pressure [1]. This mode of condensation is often observed in smooth expansion joints where the slight increase in pressure causes droplets to form. However, Figure 8 shows that in the PUMA Drywell, homogeneous condensation is never possible because the steam atmosphere is always slightly superheated.

4.2.2 Wall Condensation

Experiments show that wall condensation is possible only during the initial blowdown phase. Following GDCS injection, the upper Drywell atmosphere was cooled below that of the DW walls (Figure 10). Therefore DW wall condensation effectively stopped subsequent to GDCS injection. The film condensation was laminar with \( Re < 30 \) [4], and film thickness of \( \delta_{UDW} \leq 3.3 \text{ mm} \) in the upper DW and \( \delta_{MDW} \leq 4.5 \text{ mm} \) in the mid-section. The total computed wall condensation rate was less than 20 grn/s. With the duration of wall condensation of about 250 seconds, compared to the total RPV and GDCS inventory, the condensate return in the containment is negligible.

4.3 LONG TERM CONTAINMENT COOLING

The bulk of long term containment cooling is done by the Passive Containment Cooling System. During the initial phase of ADS blowdown, almost all of the discharged steam is pushed to the SP through the horizontal vents and condensed by Direct Contact Condensation. Also during the early stages of RPV depressurization, Ishii et. al. suggested that due to high momentum flux carried by the discharged steam jet, most of the non-condensables \( \approx 99.99\% \), would be carried to the SP gas space [5]. From Figure 11, it is clear that for the first 250 seconds after the blowdown, the complete mixing hypothesis is correct.

The remaining non-condensables are trapped in the PCCS condenser tubes and eventually are vented to the SP via vent lines. Since the design PCCS heat removal capacity is greater than the reactor decay heat, it is expected that at some point, DW pressure would fall below that of the SP. A series of vacuum break check valves were installed to equalize DW and SP pressures. During these vacuum-break pressure equalization events, some non-condensables may be released to the DW. However, eventually they would be carried to the PCCS condensers and then vented to SP. The DW-PCCS-SP non-condensable venting phenomenon is currently being studied aggressively by many investigators. The DW-PCCS-SP venting and vacuum break events can be seen as corresponding periodic step changes in the DW and SP pressure differences (Figure 12).

5 CONCLUSIONS

The blowdown tests show that the PUMA facility is well designed and operated. The data is consistent and repeatable. Comparing RELAP5 results with experiments, the degree of agreement is remarkable. RELAP5 is adequate in predicting bulk RPV and Drywell temperatures and pressures.

Figure 11 shows significant DW temperature stratification. With the rate of temperature change of 1.15°C/m, the stratification is considered to be stable [6]. For these tests, the natural convection velocity probes were not installed; thus no direct measurement of natural convection flow inside the DW is available. However, based on the analysis of gas space and wall temperature distribution, natural convection flow in the upper Drywell is believed to be very small. Wolf L. and Mun K. [10] reported
that for the scaled AP600 facility, the measured natural convection velocity was as low as 0.10 m/s.

Experimental data show that wall condensation occurred very briefly during the initial blowdown phase. Subsequent to GDCS injection however, DW wall temperatures were about 1°C higher than that of the bulk steam temperature. Thus, GDCS injection effectively stopped the wall condensation process. Additionally, because the discharged steam inside the containment was always slightly superheated throughout the blowdown tests, homogeneous condensation was not possible.

Finally, long term containment cooling by the PCCS is not significantly affected by the temperature stratification. Non-condensables were effectively vented and trapped in the gas space of the SP and did not affect long-term operation of the PCCS. In all cases, the PCCS was able to remove all decay heat to the atmosphere, with steady state containment temperature and pressure were either constant or decreasing.

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Figure 8: PUMA DW & P-T Saturation Curve

Figure 9: PUMA DW Wall & Steam Temperature

Figure 10: PUMA DW Wall & Steam Temperature

Figure 11: DW Temperature Distribution

Figure 12: DW-SP Pressure Differences