Enclosure 1 to BWROG Letter

DESCRIPTION OF GI-193 TEST PROGRAM AT PURDUE UNIVERSITY

INTRODUCTION

The Purdue University Multi-Dimensional Integral Test Assembly (PUMA) was originally designed and scaled to produce integral test data relevant to the GE-designed, 2000-MWth Simplified Boiling Water Reactor. Three kinds of loss-of-coolant accidents (LOCAs) were conducted at PUMA in late 90's- Main Steam Line Break, Gravity-Driven Cooling System Line Break, and Bottom Drain Line Break. Currently, test data have been collected and stored in the NRC databank and are being used to assess the TRACE and MELCOR codes. The PUMA facility was subsequently modified to better represent the Economic Simplified Boiling Water Reactor and the various design changes made by GE to accommodate higher power.

In addition to the integral LOCAs tests, PUMA was also used to conduct a number of separate-effect tests to obtain data on the performance of the Passive Containment Cooling System (PCCS) and on the steam condensation in the Suppression Pool (SP). Data from the integral LOCAs tests and the separate-effects PCCS and SP tests provided a data base for assessing the TRACE code, as well as provide a measure of margin to core uncovery with respect to design-basis accidents.

This test program, related to Generic Issue (GI) 193, ECCS Suction Concerns, will use the PUMA facility to conduct additional separate-effects tests in the SP. In some BWRs, air and steam-air mixtures enter the SP during blowdown period through the downcomer. This may result in high void fractions where the strainers are located. The safety injection is withdrawn through the strainers in the SP by safety injection pumps. There is a concern, that if a sufficiently high amount of air is ingested by a safety injection pump, the pump may become inoperable. Thus, this study should help to understand if such a condition exists.

OVERVIEW

The primary objective of this study is to develop a physical understanding and to obtain experimental data for the void distribution and fluid dynamic characteristics exhibited in a BWR SP during blowdown from a postulated LOCA. Measurements of local void fraction and visual high speed movie recordings will be used to determine the break-up length of a downward jet containing steam and noncondensable gas. Measurements of the local void fraction give the rate at which the jet spreads, such that it is possible to estimate the void fraction and bubble size near the entrance of a strainer. The sensitivity of results to the noncondensable gas fraction is to be investigated.

OBJECTIVES

1. Modify the PUMA-E facility and SP configuration so that void distribution tests in the SP simulating blowdown period of LOCAs can be conducted.

2. Obtain a series of test data that covers a range of injection flow rates and noncondensible gas fraction for the blowdown conditions to determine local void fraction, bubble size and bubble velocity with a special focus on the locations where strainers for Emergency Core Cooling System (ECCS) suction are generally positioned.

3. Document results in data and/or evaluation reports, and provide the data in an electronic format suitable for future evaluation.

TECHNICAL APPROACH

The possible failure of the low pressure ECCS due to large amount of entrained gas into the ECCS suction piping of the BWR is addressed in the Generic Issue (GI) 193, BWR ECCS Suction Concerns. Furthermore, the air ingestion to the RHR (Residual Heat Removal) and containment spray pumps may degrade the pump performance. Therefore, it is important to understand the dynamics of the drywell (DW) to the SP venting phenomena during blowdown and the void distribution where the strainers are located. The void distribution, bubble size, and rate of jet spread are the key parameters in the analysis of the physical phenomena.

The void distribution in the SP during blowdown period of a design basis accident is affected by several important local phenomena. In the initial blowdown, the steam and superheated water are released into the DW. As a result, pressure in the DW and downcomers in the SP increase rapidly. At the early stage of the blowdown, mostly noncondensable gas is forced through downcomers into the SP. This is followed by the steam-air mixtures injection. In the later stage, mostly steam is vented. The water initially standing in the downcomers is accelerated into the SP and downcomers are voided. Then, a large air bubble is formed at the exit of a downcomer. The air injection from the DW results in the expansion of this bubble at the tip of the downcomer. After that, this large bubble may deform and smaller disintegrated bubbles spread and rise to the water surface.

During the air injection phase, some disintegrated bubbles may be entrained into the bottom of the pool due to the liquid circulating flow. When the steam/air mixtures come into the downcomers, condensation occurs at the exit of the downcomers. This induces chugging phenomena at the exit of the downcomers with the rapid condensation. Both the steady-state and transient tests using different test sections are proposed in this research in order to study the local phenomena in the SP.

In the steady-state tests, air will be injected into the downcomers and the flow rate will be controlled as a boundary condition.

For the transient tests, the blowdown period in the DW and subsequent injection of sequential flows of the air, steam-air mixtures and pure steam will be simulated by using the reactor pressure vessel (RPV), DW and SP of the PUMA-E facility. During this blowdown, the steam from the RPV will initially push the air into the SP. The steam concentration in the DW will increase rapidly due to the blowdown steam injection to the DW and venting of air and steam-air mixtures into the SP.

FACILITY MODIFICATIONS AND READINESS

1. The scaling approach of the MARK-I to PUMA-E is described in Appendix A.

2. The re-design for the test facility modification was completed and implemented.

3. The re-design of instrumentations was completed and implemented.

4. The samples of single and double sensor conductivity probes were fabricated and tested.

5. The current lab air supply line was extended and ready to be connected to the air injection line. Necessary equipment was obtained including a vortex flow meter, direct attached storage (DAS) computers, DAS boards and pneumatic valve actuator.

<u>TEST MATRICES</u>

Currently, steady state and transient tests are planned. Peak spike injection tests are under consideration but a decision has not yet been made on them.

Steady-state tests

Table 1 provides the test matrix for the steady-state tests.

Table 1. Test Matrix for the Steady-State Tests

Test No.	Downcomer Size	Downcomer Condition	Flow Type	Air Mass Flow Rate (kg/s)	Velocity Ramp Rate (s)
A1	3 inch	Completely Filled with Water	DBA	0.081	1.0
A2					1.5
A3					2.0
A4			Category 4	0.045	2.0
A5			Category 2	TBD	TBD
A6		Partially Voided	DBA	0.081	1.0
A7					1.5
A8					2.0
A9			Category 4	0.045	2.0
A10			Category 2	TBD	TBD
A11		Completely Voided	DBA	0.081	2.0
A12			Category 4	0.045	2.0
A13	4 inch	Completely Filled with Water	DBA	0.138	1.0
A14					1.5
A15					2.0
A16			Category 4	0.077	2.0
A17			Category 2	TBD	TBD
A18		Partially Voided	DBA	0.138	1.0
A19					1.5
A20					2.0
A21			Category 4	0.077	2.0
A22			Category 2	TBD	TBD
A23		Completely Voided	DBA	0.138	2.0
A24			Category 4	0.077	2.0

"Flow types" (column 4) are based upon LOCA category definitions proposed in SECY-04-0060, "LOSS-OF-COOLANT ACCIDENT BREAK FREQUENCIES FOR THE OPTION III RISK-INFORMED REEVALUATION OF 10 CFR 50.46, APPENDIX K TO 10 CFR PART 50, AND GENERAL DESIGN CRITERIA (GDC) 35," dated April 13, 2004, whereby Category 2 is a medium break LOCA, Category 4 is a large break LOCA (smaller than the largest) and DBA refers to the design basis LOCA, i.e., a break corresponding to the largest primary system piping.

Transient tests

Table 2 shows the planned test matrix for the transient tests. It is noted that the medium blowdown flow condition is the scaled steady flow and the maximum blowdown flow condition is based on the full capacity of RPV steam flow in PUMA-E facility.

Table 2. Test Matrix for Transient Tests

Test No.	Downcomer size	Initial air concentration in DW (%)	Blowdown flow condition
T1	3-inch	100	Medium
T2	3-inch	100	Maximum
T3	3-inch	80	Medium
T4	3-inch	80	Maximum
T5	4-inch	100	Medium
T6	4-inch	100	Maximum
T7	4-inch	80	Medium
T8	4-inch	80	Maximum

Peak-Spike Injection Test

The staff is also considering adding a third series of tests to examine the initial burst of water and air that is driven into the suppression pool immediately following the LOCA.

If approved, the peak spike injection tests would likely be conducted after the completion of the steady-state tests and before the conduction of the transient tests. A two month period would be require for facility modifications to the air flow control, downcomer design, void fraction instrumentation system, experiments for 16 peak spike injection tests, data analysis and reporting.

Appendix B discusses the peak-spike injection test considerations that have taken place to date. Additional facility modifications, as discussed in the appendix, would be required in order to proceed with those tests.

Appendix A: Scaling Considerations

In order to study the venting phenomena of the BWR suppression pool during the blowdown using PUMA-E facility, proper scaling from the prototype to PUMA-E is required. In this study, the SP of the MARK I containment is considered as the prototype facility. Table 1 shows the comparison of the power, dimensions of the DW and Wetwell and the flow rate in a downcomer during blowdown period between the MARK I and PUMA-E facility.

Table 1 Comparison between MARK I and PUMA-E

Parameters	MARK I	PUMA-E
Power	3,300 MWth	600 kW (Maximum)
DW - Free Volume	 4,142	 12.68 m^3
Wetwell - Water Volume - Gas Space Volume - Water Level	 2,453.7 m^3 (34.08 m^3 per downcomer) 3114.8 m^3 3.76 m	 8.05 m^3 9.38 m^3 1.60 m
Vents - Orientation - Diameter of Downcomer - Submerged Depth - Number of Downcomers	 Vertical 0.6 m 1.32 m 72	 Horizontal 0.36 m 0.43 m 1
Maximum Flow Rate per Downcomer	44.7 kg/s of steam*	0.5 kg/s of steam** (during blowdown)

* based on data from NRC [3]   ** based on the RELAP5 calculation

To investigate the local phenomena in real time, the axial length scaling ratio (L_R) should be equal to the velocity ratio (u_R). The axial length, area, diameter, and mass flow rate are scaled by the following equations:

Time scale : $\tau_R = 1$

Axial velocity scale : $u_R = L_R$

Axial Length scale : $L_R = L_M / L_P$

Diameter scale : $D_R = D_M / D_P$

Area scale : $A_R = A_M / A_P = D_M^2 / D_P^2 = D_R^2$

Mass flow rate scale: $\dot{m}_R = \dfrac{\dot{m}_M}{\dot{m}_P} = \dfrac{\rho A_M u_M}{\rho A_P u_P} = \dfrac{A_M L_M}{A_P L_P} = A_R \cdot L_R$

where subscript M and P are the model (PUMA-E) and prototype (MARK-I), respectively. Here, we denote the ratio between the model and prototype by the subscript R.

The axial and radial liquid velocity profiles inside the SP are scaled differently. As mentioned above, the axial liquid velocity (u_{fz}) is scaled by the length ratio (L_R). On the other hand, the radial liquid velocity (u_{fr}) profile is scaled by the diameter ratio (D_R), which can be explained as follows:

The liquid volumetric flow rate inside the SP (Q_f) is written as

$$Q_f = u_{fz} \cdot \frac{\pi}{4} D^2 \sim u_{fr} \cdot \pi D L$$

Thus, the radial liquid velocity is given by

$$u_{fr} \sim u_{fz} \cdot \frac{D}{L}$$

So the radial liquid velocity can be scaled by

$$\left(u_{fr}\right)_R \sim \left(u_{fz}\right)_R \cdot \frac{D_R}{L_R} \sim L_R \cdot \frac{D_R}{L_R} \sim D_R$$

<u>Steady-State Tests</u>

Scaling ratios between MARK I and PUMA-E for steady-state test are shown in Table 2.

Table 2 Scaling ratios between MARK I and PUMA-E for steady-state test

Parameter	MARK I	PUMA-E (Modified)	Scaling Ratios	PUMA-E (Modified)	Scaling Ratios
		3-inch Sch40 Downcomer		4-inch Sch40 Downcomer	
Wetwell Water Level (m)	3.76	1.05	1/3.58 (L_R)	1.05	1/3.58 (L_R)
Downcomer Submergence Depth (m)	1.32	0.37	1/3.58 (L_R)	0.37	1/3.58 (L_R)
Downcomer Diameter (m)	0.60	0.078	1/7.7 (D_R)	0.102	1/5.9 (D_R)
Cross-Sectional Area of Downcomer (m^2)	0.28	0.0048	1/59.3 (A_R)	0.0082	1/34.6 (A_R)
Air Mass Flow Rate at Downcomer (kg/s)	17.1*	0.081	1/212.4 $(\dot{m}_R)$	0.138	1/123.8 $(\dot{m}_R)$

* based on data from NRC

The required air mass flow rate (up to 0.081 kg/s) can be supplied steadily by the air compressor which has the maximum capacity of 0.6 kg/s discharge flow rate at 125 psig. Tests can be terminated within short period after obtaining the steady bubble formation.

<u>Transient Tests</u>

Table 3 shows the scaling ratios between MARK I and PUMA-E considering the facility modification for the transient tests. The steam mass flow rate of 0.21 kg/s for 3-inch downcomer and 0.36 kg/s for 4-inch downcomer can be supplied transiently by the RPV which has the maximum flow rate of 0.5 kg/s during blowdown period.

Table 3 Scaling ratios between MARK I and PUMA-E for transient test

Parameter	MARK I	PUMA-E (Modified)	Scaling Ratios	PUMA-E (Modified)	Scaling Ratios
		3-inch Sch40 Downcomer		4-inch Sch40 Downcomer	
Wetwell Water Level (m)	3.76	1.05	1/3.58 (L_R)	1.05	1/3.58 (L_R)
Downcomer Submergence Depth (m)	1.32	0.37	1/3.58 (L_R)	0.37	1/3.58 (L_R)
Downcomer Diameter (m)	0.60	0.078	1/7.7 (D_R)	0.102	1/5.9 (D_R)
Cross-Sectional Area of Downcomer (m^2)	0.28	0.0048	1/59.3 (A_R)	0.0082	1/34.60 (A_R)
Drywell Free Volume per Downcomer (m^3)	57.53	0.27	1/212.4 (V_R)	0.47	1/123.88 (V_R)
Steam Mass Flow Rate at Downcomer (kg/s)	44.7	0.21	1/212.4 $(\dot{m}_R)$	0.36	1/123.88 $(\dot{m}_R)$

Based on the maximum blowdown steam flow rate, RELAP5 calculates the SP downcomer inlet vapor velocity. As shown in Figure 1, the SP downcomer inlet vapor velocity between MARK I and PUMA-E is similar during blowdown period.

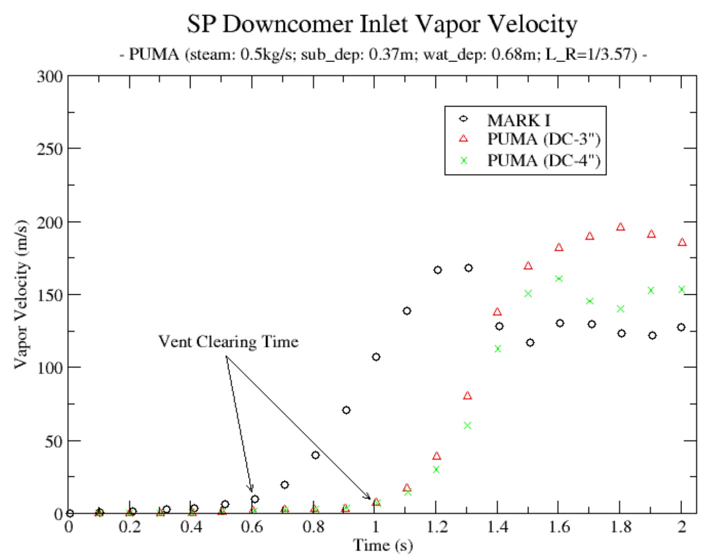

Figure 1 SP Downcomer Inlet Vapor Velocity

The key parameter to determine the entrainment of bubbles is the liquid velocity profile inside the SP. The dynamic phenomena in the SP of MARK I and modified PUMA-E are investigated preliminarily by using the Computation Fluid Dynamics (CFD) approach. The SP downcomer inlet vapor velocity shown in Figure 1 is used to be the boundary condition of CFD calculation.

Using the inlet velocity boundary condition from RELAP5 and the axial/radial liquid velocity scaling approach, the liquid velocity profiles in the SP are calculated. Figures 2 and 3 show MARK I and scaled up PUMA-E liquid velocity profiles in the axial and radial direction from the exit of downcomer at vent clearing time, respectively.

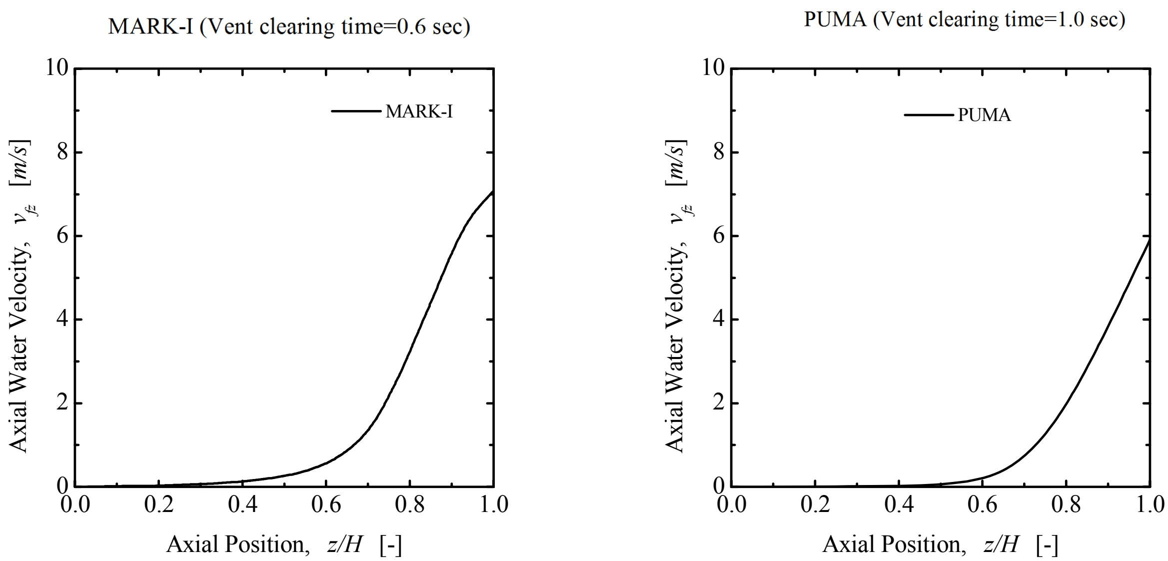

Figure 2 Axial Liquid Velocity Profiles of MARK I and PUMA-E (Scaled Up)

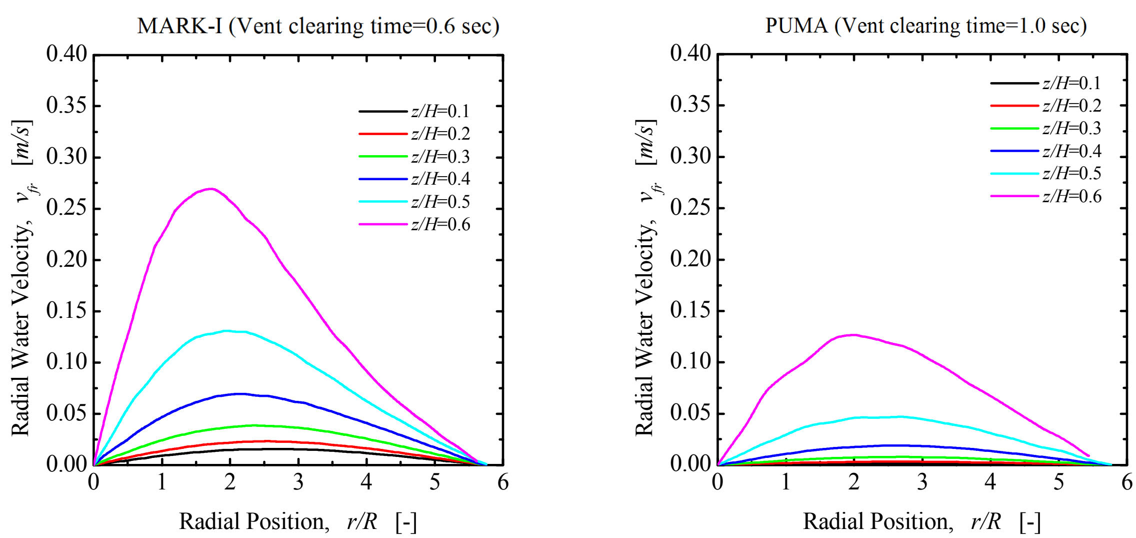

Figure 3 Radial Liquid Velocity Profiles of MARK I and PUMA-E (Scaled Up)

As shown in Figures 2 and 3, the liquid velocity profiles in the SP are similar between the MARK I and PUMA-E at vent clearing time.

It is noted that the current DW free volume of PUMA-E (12.68 m^3, shown in Table 1) is much larger than the scaled DW free volume (0.27 m^3 or 0.47 m^3, shown in Table 3) since the current DW free volume of PUMA-E was originally scaled down from the SBWR. Thus, the scaling of the DW free volume cannot be considered in the transient test. However, the downcomer inlet vapor velocity is scaled and the parametric studies for the different initial DW air concentrations are investigated. Table 4 shows the preliminary proposed test matrix for the transient tests. The transient test will be conducted under two steam blowdown flow conditions: Medium and Maximum flow condition. Medium flow condition will simulate the scaled steam flow by opening certain part of DPV and MSL lines while the maximum flow condition will utilize full capacity of RPV steam flow by opening all DPV and MSL lines. Inside the DW, jet deflector plates were installed at the exit of MSL and DPV lines to prevent direct steam injection from RPV to the SP as shown in Figure 4.

Table 4 Preliminary Proposed Test Matrix for Transient Tests

Test No.	Downcomer size	Initial air concentration in DW (%)	Blowdown flow condition
T1	3-inch Sch40	100	Medium
T2	3-inch Sch40	100	Maximum
T3	3-inch Sch40	80	Medium
T4	3-inch Sch40	80	Maximum
T5	4-inch Sch40	100	Medium
T6	4-inch Sch40	100	Maximum
T7	4-inch Sch40	80	Medium
T8	4-inch Sch40	80	Maximum

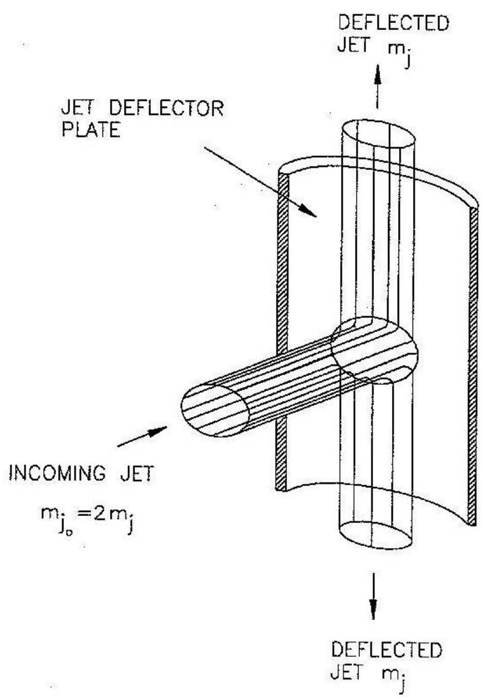

Figure 4 Jet Deflector Plate in the DW of the PUMA-E Facility

Appendix B: Peak Injection Test Considerations

Note: These tests have not yet+ been approved and the decision to proceed with them may be impacted by a number of factors including the results of the other tests.

To better understand the requirements of peak spike injection tests, Purdue performed 1-D RELAP5 calculation to investigate the inlet boundary condition at the downcomers of the MARK I during blowdown phase of the large break LOCA (the recirculation line break). The gas velocity at downcomers of MARK I and scaled-down air velocity at downcomer in PUMA (3-inch downcomer) are shown in Figure 1.

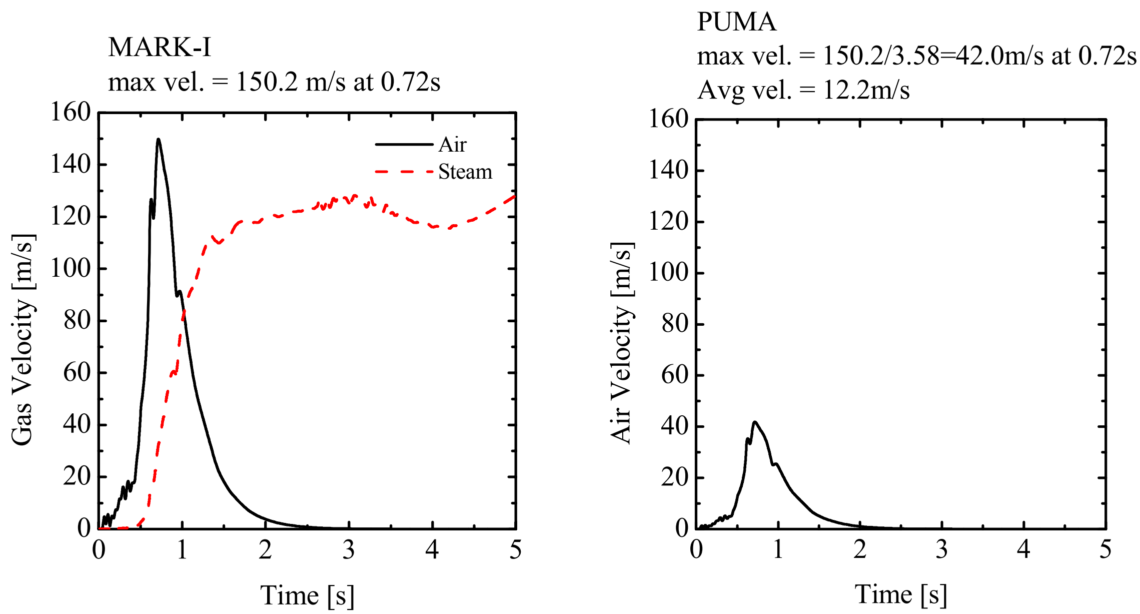

Figure 1 RELAP5 Results of Gas Velocities at Downcomer during Blowdown in MARK I and Scaled-Down Air Velocity in PUMA

The simulation result indicate that the spike of inlet air velocity occurs during 2.5 seconds of air blowdown period. The peak of this spike is 150.2 m/s in the MARK I and it corresponds to the scaled-down velocity of 42 m/s in the PUMA. This scaled-down velocity is 2.8 times of the inlet boundary velocity (15 m/s) specified in the test matrix for the steady-state tests. The steady-state maximum velocity of 15 m/s is the average gas velocity during the air blowdown period. The spike of inlet air velocity can significantly affect the void distribution in the suppression pool during early phase of blowdown as the demonstrated by the early GE tests.

It is considered very important to address the impact of this very rapid liquid slug ejection and subsequent gas carry under to the bottom of the suppression pool and bubble disintegration. The air ingress phenomena can be divided into three phases. These are the initial peak spike gas injection, quasi steady injection period and steam-gas mixture injection period with significant chugging phenomena.

For this reason, the downcomer inlet gas velocity during the initial blowdown of large break, mid size large break, medium break and small break LOCAs are considered to determine the peak spike injection test conditions. Figures 2 to 5 show the scaled-down gas velocity during the initial blowdown of different sizes of LOCAs as mentioned above.

For the peak spike injection tests, the experiment would simulate various size LOCAs which affect the gas injection peak and duration of the initial gas injection. The larger the break is, the higher the gas flow peak is and the shorter the duration is, because this spike is produced by the air in the lower drywell that is pushed by the steam to come out initially.

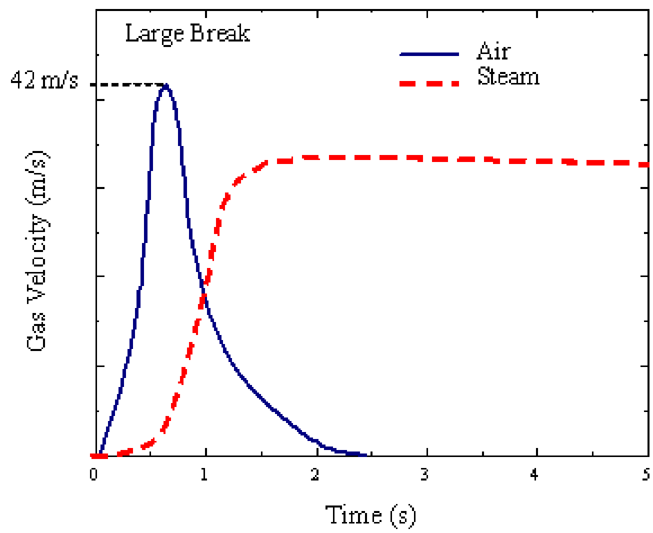

Figure 2 Scaled-Down Gas Velocity during Initial Blowdown of LOCA (Large Break)

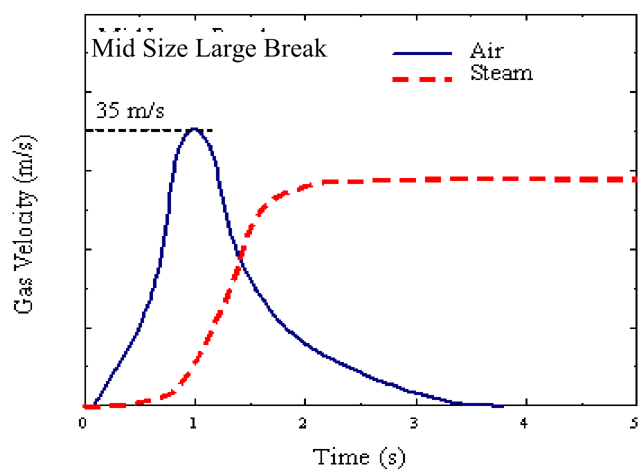

Figure 3 Scaled-Down Gas Velocity during Initial Blowdown of LOCA (Mid Size Large Break)

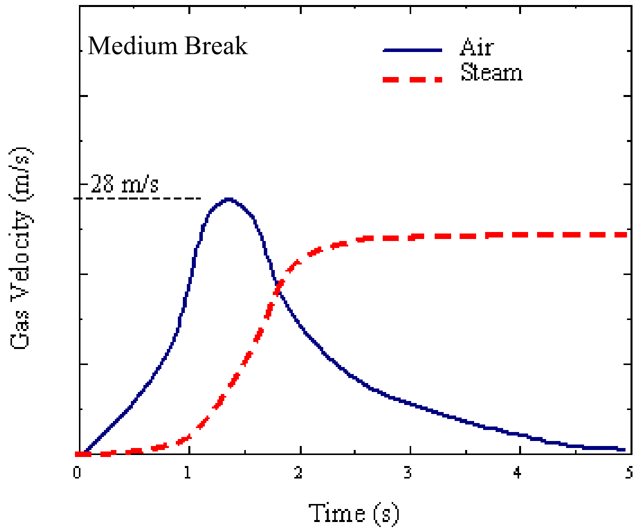

Figure 4 Scaled-Down Gas Velocity during Initial Blowdown of LOCA (Medium Break)

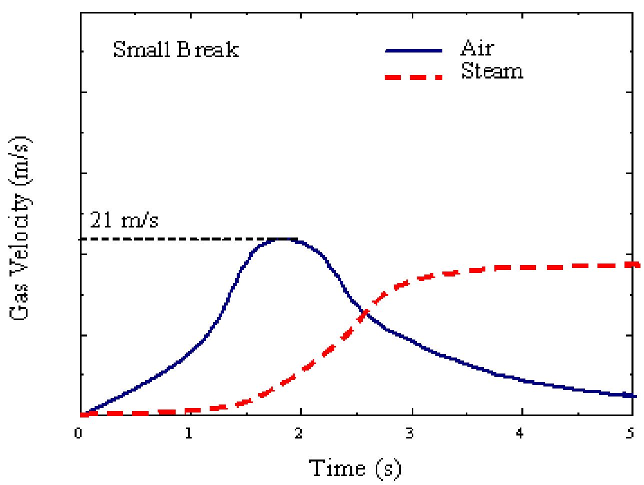

Figure 5 Scaled-Down Prototypic Gas Velocity during Initial Blowdown of LOCA (Small Break)

<u>Additional Tasks Necessary in order to conduct Peak-Spike Injection Tests</u>

The followings additional modifications would be needed in order to conduct the peak spike injection tests:

- √ Installation of another parallel branch of air injection system to achieve peak spike injection condition
- √ Installation of additional motorized valve actuator
- √ Installation of additional vortex flow meter
- √ Installation of additional pressure gauge
- √ Installation of additional manual valve
- √ Installation of additional measurement levels of supporting cage
- √ Installation of additional conductivity probes.
- √ Installation of additional Data Acquisition System (DAS) boards

After modification of the test apparatus, re-calibration of instrumentations and shakedown testing would be necessary.

Draft Test Matrix

Based on the RELAP5 results the test matrix for the peak spike injection tests are provided in Table 1. The test conditions, shown in Table 1 would be conducted with 3-inch downcomer pipe.

Table 1 Test Matrix for Peak-Spike Injection Tests

Test No.	Peak Velocity (m/s)	Ramp time (s)	Steady-State Velocity (m/s)
S1	42	0.7	12.2
S2	42	0.7	8.0
S3	42	0.7	4.0
S4	42	0.7	0.0
S5	35	1.0	12.2
S6	35	1.0	8.0
S7	35	1.0	4.0
S8	35	1.0	0.0
S9	28	1.5	12.2
S10	28	1.5	8.0
S11	28	1.5	4.0
S12	28	1.5	0.0
S13	21	2.0	12.2
S14	21	2.0	8.0
S15	21	2.0	4.0
S16	21	2.0	0.0

Figure 6 provides an estimate of the timing and magnitude of the peak and steady state air velocity for tests S1 through S4.

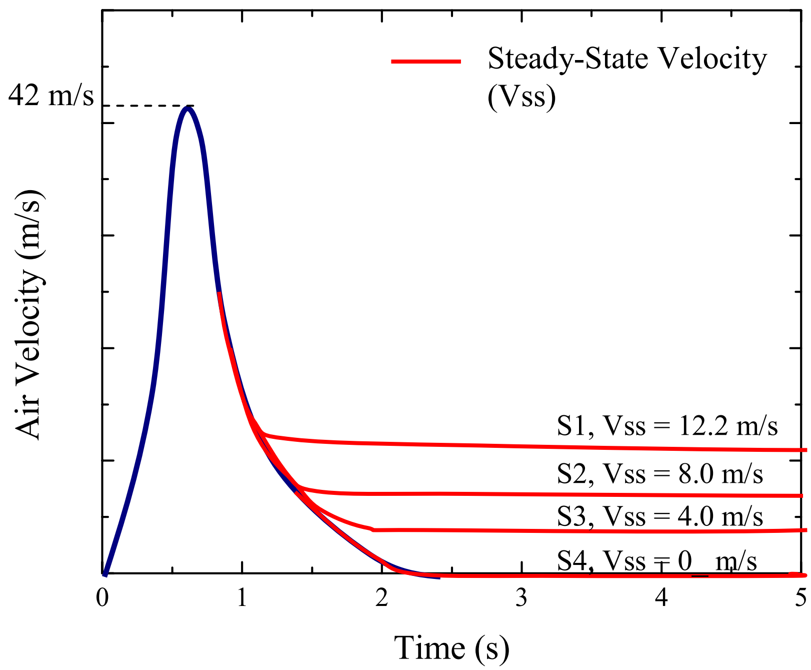

Figure 6 Inlet Boundary Condition in Test No. S1, S2, S3 and S4

<u>Additional Details of Proposed Facility Modifications for Peak-Spike Injection Test</u>

The new air supply line and flow measurement are designed to serve the peak spike injection tests. The existing air supply line will be partially modified by replacing a 2-inch main pipeline with 4-inch pipeline. A new 4-inch vortex flow meter will be installed to measure the higher inlet air velocities and two automatic control valves will be installed to control the ramp rate of flow. Figure 7 shows the proposed air supply line for the peak spike injection tests.

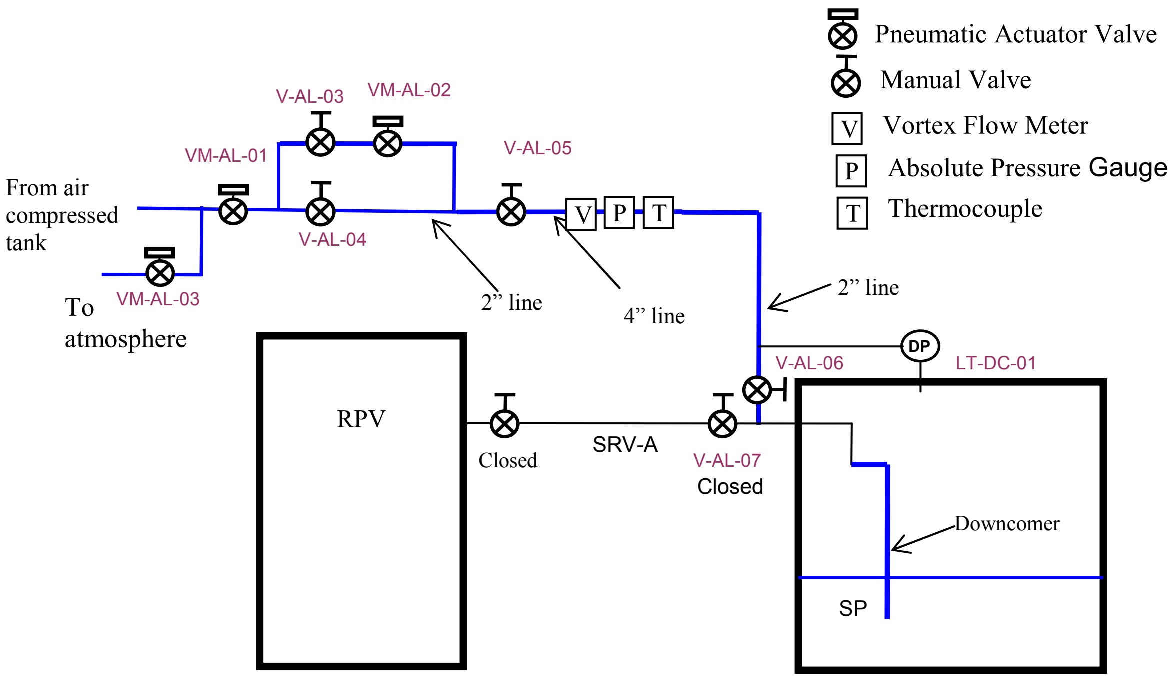

Figure 7 Proposed Air Supply Line for the Peak-Spike Injection Tests

Additional Measurement Levels of Conductivity Probes

Due to the possibility that the initial air bubbles penetrate deeper into the bottom of the suppression pool in the peak spike injection tests, three additional levels of conductivity probes will be installed below the current lowest level. Thus the information on the void distribution at the locations near the bottom of the suppression pool can be obtained. Figure 8 shows the configuration of three additional levels (line G, H and I) of conductivity probes for the peak spike injection tests.

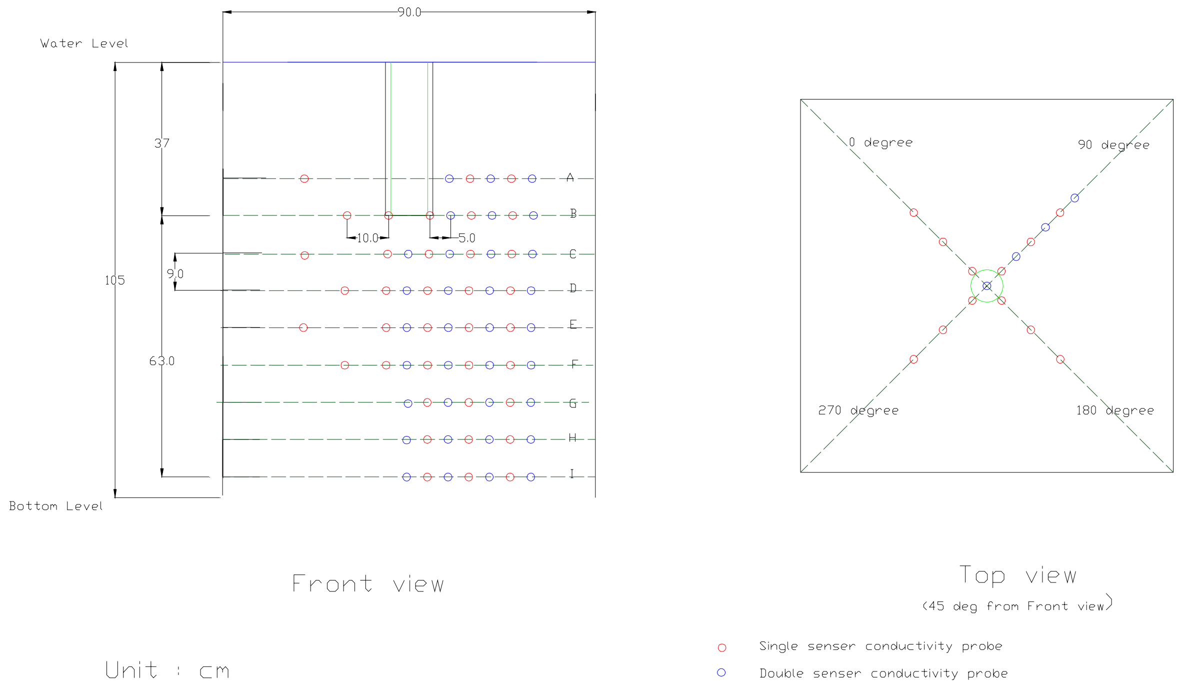

Figure 8 Configuration of Three Additional Levels (Line G, H and I) of Conductivity Probes for the Peak-Spike Injection Tests