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Investigation of Simplified Equation for Gas Transport

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*Electronically approved records are authenticated in the electronic document management system.

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RECORD OF REVISIONS

Revision	Date	Description
0	August 2010	Original
1	January 2011	Revision bars were included in the left margin to document all changes from Revision 0. This revision removes the 5% limitation on the allowable initial void fraction. Note that Sections 3.2, 4.3.1, 4.4.1.6.1, and 4.4.2.6.1 of Revision 0 were deleted; for ease of use, change bars were not included in the left margin of all subsequent section numbers.

PWR OWNERS GROUP
MEMBER PARTICIPATION* FOR PROJECT/TASK PA-SEE-0685 REV. 1

Utility Member	Plant Site(s)	Participant	
		Yes	No
AmerenUE	Callaway (W)	X	
American Electric Power	D. C. Cook 1&2 (W)	X	
Arizona Public Service	Palo Verde Unit 1, 2, & 3 (CE)	X	
Constellation Energy Group	Calvert Cliffs 1 & 2 (CE)	X	
Constellation Energy Group	Ginna (W)	X	
Dominion Connecticut	Millstone 2 (CE)	X	
Dominion Connecticut	Millstone 3 (W)	X	
Dominion Kewaunee	Kewaunee (W)	X	
Dominion VA	North Anna 1 & 2, Surry 1 & 2 (W)	X	
Duke Energy	Catawba 1 & 2, McGuire 1 & 2 (W), Oconee 1, 2, 3 (B&W)	X	
Entergy	Palisades (CE)	X	
Entergy Nuclear Northeast	Indian Point 2 & 3 (W)	X	
Entergy Operations South	Arkansas 2, Waterford 3 (CE), Arkansas 1 (B&W)	X	
Exelon Generation Co. LLC	Braidwood 1 & 2, Byron 1 & 2 (W), TMI 1 (B&W)	X	
FirstEnergy Nuclear Operating Co.	Beaver Valley 1 & 2 (W), Davis-Besse (B&W)	X	
Florida Power & Light Group	St. Lucie 1 & 2 (CE)	X	
Florida Power & Light Group	Turkey Point 3 & 4, Seabrook (W)	X	
Florida Power & Light Group	Pt. Beach 1 & 2 (W)	X	
Luminant Power	Comanche Peak 1 & 2 (W)	X	
Omaha Public Power District	Fort Calhoun (CE)	X	
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PSEG – Nuclear	Salem 1 & 2 (W)	X	
Southern California Edison	SONGS 2 & 3 (CE)	X	
South Carolina Electric & Gas	V. C. Summer (W)	X	
So. Texas Project Nuclear Operating	South Texas Project 1 & 2 (W)	X	
Southern Nuclear Operating Co.	Farley 1 & 2, Vogtle 1 & 2 (W)	X	
Tennessee Valley Authority	Sequoyah 1 & 2, Watts Bar (W)	X	
Wolf Creek Nuclear Operating Co.	Wolf Creek (W)	X	
Xcel Energy	Prairie Island 1 & 2	X	

* Project participants as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending this document to participants not listed above.

PWR OWNERS GROUP INTERNATIONAL MEMBER PARTICIPATION* FOR PROJECT/TASK PA-SEE-0685 REV. 1			
Utility Member	Plant Site(s)	Participant	
		Yes	No
British Energy	Sizewell B	X	
Electrabel (Belgian Utilities)	Doel 1, 2 & 4, Tihange 1 & 3	X	
Hokkaido	Tomari 1 & 2 (MHI)	X	
Japan Atomic Power Company	Tsuruga 2 (MHI)	X	
Kansai Electric Co., LTD	Mihama 1, 2 & 3, Ohi 1, 2, 3 & 4, Takahama 1, 2, 3 & 4 (W & MHI)	X	
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3 & 4 Yonggwang 1 & 2 (W)	X	
Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5 & 6 Ulchin 3, 4 , 5 & 6 (CE)	X	
Kyushu	Genkai 1, 2, 3 & 4, Sendai 1 & 2 (MHI)	X	
Nuklearna Electrarna KRSKO	Krsko (W)	X	
Nordostschweizerische Kraftwerke AG (NOK)	Beznau 1 & 2 (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Shikoku	Ikata 1, 2 & 3 (MHI)	X	
Spanish Utilities	Asco 1 & 2, Vandellos 2, Almaraz 1 & 2 (W)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	
Electricite de France	54 Units	X	

* This is a list of participants in this project as of the date the final deliverable was completed. On occasion, additional members will join a project. Please contact the PWR Owners Group Program Management Office to verify participation before sending documents to participants not listed above.

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1 INTRODUCTION

1.1 OVERVIEW OF DOCUMENT

A simplified approach has been proposed to model gas transport in pump suction piping. This approach utilizes the homogenous flow assumption with corrections for system static pressure variations and is referred to as the Simplified Equation. The key feature of the homogeneous flow assumption is equality of gas and liquid transport velocities. The Simplified Equation enables the determination of allowable gas volumes at high point locations in pump suction piping based on specified allowable air volume fraction criteria at the pump inlet, system flows and system pressures.

$$V_{allowable} = \alpha_{pump} \Delta t_{pump} Q_{pump} \left(\frac{P_{Pump}}{P_{High-Point}} \right)_{Post-Accident}$$ **(Simplified Equation, SE)**

α_{pump} = the allowable gas void fraction at the pump entrance.

Δt_{pump} = the time period over which the allowable gas void fraction enters the pump.

Q_{pump} = the pump flow rate.

P_{pump} = the absolute static pressure at the pump suction during post-accident operating conditions.

P_{high_point} = the absolute static pressure at the high point location during post-accident operating conditions.

PWROG Project Authorization PA-SEE-0685, Investigation of Simplified Equation for Gas Transport, included the following tasks:

1. Validate the Simplified Equation by comparison with the 2% and 5% initial gas volume fraction data collected at Purdue University. Data sets from the 4", 6", 8", and 12" tests will be used.

2. Determine limitations of the Simplified Equation in the light of the gaps identified in the gap analysis Project Authorization (PA-SEE-0530). An evaluation will be made to determine the extent to which engineering judgment can be used to close some of the gaps and define limitations. However, if available data does not support an engineering judgment, additional testing may be recommended.

3. Provide guidelines for usage of the Simplified Equation. This includes identifying appropriate limitations defined in Task 2. In addition, two example problems will be provided to demonstrate the application.

The following sections of this report will address each of these three tasks. Section 2 validates the Simplified Equation by comparison with the Purdue Test data. Section 3 identifies limitations on usage of the Simplified Equation. Section 4 provides guidelines for usage of the Simplified Equation along with two worked examples.

1.2 SUMMARY OF RESULTS

1.2.1 Validation of Simplified Equation

The results of the validation process can be summarized as follows:

- The gas volumetric flow ratio (β) is the relevant parameter to represent gas transport to the pump inlet as it represents the transfer of gas relative to the mixture rate of transfer.
- The definition of the gas volumetric flow ratio (β) exactly corresponds with the Simplified Equation proposed to relate an initial gas volume to the gas volume fraction at the pump inlet. This assures the validity of the Simplified Equation as long as appropriate time duration is used, as discussed below.
- The validation process indicated that the value of transport time (Δt) cannot be arbitrarily specified in the Simplified Equation. A correlation was developed to predict the transport time for use in the Simplified Equation.

1.2.2 Limitations on Usage of Simplified Equation

Four limitations on usage of the Simplified Equation were identified in Section 3 and are summarized in Section 3.6. In addition, an open item and recommendation for future work were identified as part of the process.

1.2.2.1 Open Item

The gas transport testing conducted at Purdue University forms the validation basis for the Simplified Equation. This program addressed the transport of gas through piping systems. As such, the flow dynamics at the inlet to pumps was not within the scope of this program. Therefore, additional limitations may be needed to deal with specific pump inlet concerns and these limitations should be identified as part of an additional PWROG project

1.2.2.2 Recommendation

Several limitations on the SE usage were documented in this report. Some of these limitations may be very restrictive depending on a particular utilities piping geometry. The basis for application of the Simplified Equation is the prevention of slug flow. Reference 1 demonstrates this occurs through the formation of a kinematic shock in a vertical down-comer and the subsequent transport of a bubbly flow mixture. If an off-take is present downstream of the vertical down-comer, it is necessary to consider the potential for the flow to stratify as it approaches the off-take. If it is determined that the gas flow will approach the tee in a dispersed flow regime, then it is conservative to assume that the gas volumetric flow rate through either tee branch is equal to the gas volumetric flow rate in the supply. However, stratification and slip of the gas flow could allow gas to collect and result in the subsequent transport of a slug of gas due to an air entraining vortex at the off-take. In this case, the Simplified Equation approach cannot be applied since it is not valid if the gas is allowed to collect and transport as a slug.

The Simplified Equation methodology is based on using the maximum flow. It is important to note that when an off-take is downstream of the gas accumulation location, the worst case may not be when the liquid flow is maximized. The worst case may be when the liquid flow is low enough to allow gas to stratify at an off-take. In this case the Simplified Equation methodology is not applicable.

It is recommended that additional work be done to define methods for establishing acceptance criteria when tees and off-takes are located downstream of the high point.

2 VALIDATION OF SIMPLIFIED EQUATION

2.1 INTRODUCTION

This section of the report validates the Simplified Equation. In order to accomplish this, it is first necessary to introduce relevant gas transport parameters. The validation consists of a comparison of predicted values of the transport parameters from the Simplified Equation with measured data from gas transport testing conducted at Purdue University.

2.2 GAS TRANSPORT PARAMETERS

This section defines relevant gas transport parameters which are used in the validation process.

2.2.1 Instantaneous Space Averaged Void Fractions

The fraction of the control volume or surface that is occupied by the gaseous phase at a given time is defined as:

$$\alpha = \frac{V_G}{V_G + V_L} = \frac{A_G}{A_G + A_L} \qquad \text{(Equation 1)}$$

2.2.2 Volumetric Flow Ratio

The volumetric flow ratio of gaseous fluid to the total mixture is given by:

$$\beta = \frac{Q_G}{Q_M} = \frac{Q_G}{Q_G + Q_L} \qquad \text{(Equation 2)}$$

2.2.3 Slip Ratio

In general, the gaseous and liquid phases are not transported at the same velocities. The slip ratio is defined as the ratio of the gaseous phase velocity to the liquid phase velocity:

$$S = \frac{U_G}{U_L} \qquad \text{(Equation 3)}$$

The slip ratio can be expressed in terms of the space averaged void fraction (α) and the volumetric flow ratio (β) as follows:

$$S = \frac{U_G}{U_L} = \frac{Q_G}{A_G}\frac{A_L}{Q_L} = \frac{A_L}{A_G}\frac{Q_G}{Q_L} = \frac{1-\alpha}{\alpha}\frac{\beta}{1-\beta} \qquad \text{(Equation 4)}$$

Equation 4 can be solved for the volumetric flow ratio (β) in terms of the space averaged void fraction (α) and slip ratio (S):

$$\beta = \frac{\alpha S}{1+\alpha(S-1)} \qquad \text{(Equation 5)}$$

Equation 4 can also be solved for the space averaged void fraction (α) in terms of the volumetric flow ratio (β) and slip ratio (S):

$$\alpha = \frac{\beta}{S+\beta(1-S)} \qquad \text{(Equation 6)}$$

2.3 APPLICATION OF TRANSPORT PARAMETERS TO PURDUE TESTS

2.3.1 Space Averaged Void Fraction

The void fraction meters used in the Purdue tests provided a direct measurement of the space averaged void fraction as a function of time at various locations throughout the test loop. The time averaged value of the space averaged void fraction over the transport duration (Δt) measured during the Purdue test can be calculated as follows:

$$\alpha_{AVG} = \overline{\alpha} = \frac{1}{\Delta t}\int_{t_S}^{t_F}(\alpha)dt \qquad \text{(Equation 7)}$$

Where the transport duration is defined as:

$$\Delta t = t_F - t_S \qquad \text{(Equation 8)}$$

The start time (t_S) and finish time (t_F) of the transport process were calculated from the void fraction measurements at each meter and therefore the transport duration is different for each meter in a given test.

2.3.2 Volumetric Flow Ratio

The magnetic flow meters used in the Purdue tests (M2 or GPM2 in Figures 13, 15, 17, and 19) provided a direct measurement of the mixture flow rate as a function of time in the test loop. The gaseous and liquid volumetric flows were not directly measured during the Purdue tests. However, an approximation of the overall average gaseous flow rate can be obtained from knowledge of the initial gas volume (V_G), initial gas pressure (P_I), instantaneous pressure at meter (P), and gas transport duration at the meter (Δt):

$$\overline{Q}_G = \frac{P_I}{P}\frac{V_G}{\Delta t} \qquad \text{(Equation 9)}$$

The time averaged mixture flow rate is calculated as:

$$\overline{Q}_M = \frac{1}{t_B - t_A}\int_{t_A}^{t_B}(Q_M)dt \qquad \text{(Equation 10)}$$

The time span (t_A, t_B) was chosen to determine the average steady state flow rate after the flow initiation transient was complete. This was done to simplify the calculation process and preclude anticipated scatter in results associated with using different values of Δt and Q_M for each meter location.

The average volumetric flow ratio is determined by substituting Equations 9 and Equation 10 into Equation 2:

$$\beta_{AVG} = \overline{\beta} = \frac{\overline{Q}_G}{\overline{Q}_M} = \frac{P_I}{P}\frac{V_G}{\overline{Q}_M \Delta t} \qquad \text{(Equation 11)}$$

2.3.3 Time Scale Ratio

A dimensionless time scale parameter (λ) was calculated for each meter location.

$$\lambda = \frac{\Delta t}{(\Delta t)_{HOMOGENEOUS}} \qquad \text{(Equation 12)}$$

This parameter is the ratio of the actual transport time interval to the ideal homogeneous transport time interval. Homogeneous flow theory assumes the gas and liquid can be treated as a mixture whereby there is no slip between the gas and liquid phases. The homogeneous transport time interval is equal to the volume of the top header divided by the average mixture flow rate and represents the transport time duration to clear the top header if the mixture was transported as a homogenous fluid.

$$(\Delta t)_{HOMOGENEOUS} = \frac{V_{TH}}{\overline{Q}_M} \quad \text{(Equation 13)}$$

It is noted that as the homogeneous mixture volume is transported through the loop the magnitude of the volume will change slightly as the static pressure changes. The volume of the mixture at any point in the loop is given by:

$$V = V_{TH}\left[\alpha_{INITIAL}\frac{P_I}{P} + (1-\alpha_{INITIAL})\right] \quad \text{(Equation 14)}$$

The quantity in brackets in Equation 14 will be very close to 1 since $\alpha_{INITIAL}$ is on the order of 0.05 for applications of the Simplified Equation. Therefore, a value of unity is used for simplicity.

2.3.4 Relation of Transport Parameters to Initial Void Fraction

In the following discussion $\alpha_{INITIAL-THVF}$ is the initial gas volume fraction in the top horizontal header at the start of the test. The parameter $\alpha_{INITIAL-THVF}$ is calculated as:

$$\alpha_{INITIAL-THVF} = \frac{V_{GAS}}{V_{TOP-HORIZONTAL}} \quad \text{(Equation 15)}$$

This can be related to β and λ by combining Equations 11, 12, and 13 to yield:

$$\beta = \frac{P_I}{P}\frac{\alpha_{INITIAL-THVF}}{\lambda} \quad \text{(Equation 16)}$$

It is observed that two factors determine whether $\beta > \alpha_{INITIAL-THVF}$ or $\beta < \alpha_{INITIAL-THVF}$; namely, the pressure ratio (P_I/P) and the time scale ratio ($1/\lambda=\Delta t_{HOMOGENEOUS}/\Delta t$). A pressure increase above the initial pressure ($P_I/P<1$) and a transport time greater than the ideal homogenous transport time ($1/\lambda=\Delta t_{HOMOGENEOUS}/\Delta t<1$); both drive β to become less than $\alpha_{INITIAL-THVF}$. An increase in the pressure ratio (P/P_I) means the gas pocket is being compressed and an increase in the time scale parameter (λ) means the gas pocket is being dispersed. Compression and dispersion both cause a reduction in β.

Therefore, the assumption that the initial void fraction can be scaled with pressure is valid only when the gas is transported at the homogeneous transport rate. It is also important to note that when the initial gas volume and flow conditions are such that a kinematic shock is formed, Reference 1 indicates that the relevant parameter is the initial gas volume as compared with the initial void fraction.

2.4 GAS TRANSPORT PROCESS

Reference 1 provides the technical basis for the gas transport process in pump suction piping. The gas is assumed to be initially trapped at a local high point in the piping system and is transported to the pump upon initiation of flow rate through the system. The essential features of the transport process as described in Reference 1 are as follows:

1. This combination of the pump suction demand in the down-comer and the supply flow from the water source causes the gas to be transported toward the down-turned downstream elbow which forms the boundary of the high point.

2. The gas continues to expand until the upstream volumetric flow rate equals the suction demand on the down-comer; that is, until the upstream volumetric flow rate equals the pump demand. In addition, the gas rapidly moves to the downstream elbow since the gas reacts more quickly to the driving head than the liquid as the gas has less inertia than the liquid.

3. As a consequence, the transport of gas into the downstream down-turned elbow results in pulling much of the accumulated gas into the top of the down-comer. For significant initial gas volumes, this gas transport results in a "waterfall" condition in the top of the down-comer, which is a vertically separated flow pattern. Specifically, water pours through, and next to the accumulated gas volume causing entrainment of the gas as the waterfall impinges on the accumulated water pool further down in the down-comer.

This transition from a vertically separated flow pattern to a bubbly flow pattern that is transferred toward the pump is the development of a kinematic shock at the top of the water column in the down-comer. An essential feature of this kinematic shock is that it involves the entrainment of the air by the "waterfall," as the water plunges into the top of the water column.

The formation of a kinematic shock is dependent on a sufficient volume of the vertical down-comer to accommodate the volume of gas being swept from the high point into the down-comer by the water flow.

Reference 1 developed an analytical model for predicting the initial length of the kinematic shock (y_1), the average gas entrainment rate (Q_G), and the time duration of the transport process (Δt). This model was based on a jet entrainment mechanism, and the coefficients come from a jet impinging an open pool of water. Equation 17 provides an implicit expression for y1 as a function of the initial gas volume (V_{GAS}) adjusted for static pressure at the high point during post-accident operation, liquid flow rate (Q_0), liquid velocity (U_0) and piping area (A). Equation 18 provides a relation between the average gas flow rate ($q_{GAS,AVG}$) and the waterfall flow rate (Q_{WATER}) as a function of y_1 and the pipe diameter. Equation 18 was obtained by integration over the total length of the waterfall, and therefore, accounts for the fact that the length varies from y_1 to zero as the gas volume is depleted by entrainment. Equation 19 simply indicates that the transport time is the initial gas volume divided by the average volumetric entrainment rate over the transport process.

$$y_1 = \frac{1}{A}\left\{V_{GAS} + \frac{Q_0}{g}\left[\sqrt{2gy_1} - U_0 \ln\left(U_0 + \sqrt{2gy_1}\right) + U_0 \ln\left(U_0\right)\right]\right\} \quad \text{(Equation 17)}$$

$$\frac{Q_{GAS,AVG}}{Q_{WATER}} = 0.029\left(\frac{y_1}{D}\right)^{0.68} = \frac{\alpha_{AVG}}{1-\alpha_{AVG}}$$ (Equation 18)

$$\Delta t = \frac{V_{GAS}}{Q_{GAS,AVG}}$$ (Equation 19)

Equation 17 can be re-written in the following form which is convenient for solution.

$$y_1 = \frac{1}{A}\left\{V_{GAS} + \frac{Q_0 U_0}{g}\left[\frac{\sqrt{2gy_1}}{U_0} - \ln\left(1 + \frac{\sqrt{2gy_1}}{U_0}\right)\right]\right\}$$ (Equation 20)

2.5 RELATION OF SIMPLIFIED EQUATION TO TRANSPORT PARAMETERS

The Simplified Equation is a method for determining the allowable gas volume as a function of the allowable void fraction at the pump inlet and the allowable transport time:

$$V_{allowable} = \alpha_{pump}\Delta t_{pump} Q_{pump}\left(\frac{P_{pump}}{P_{high\_point}}\right)$$ (SE)

Equation 11, which defines the gas volumetric flux ratio (β) in terms of measured parameters, can be arranged as follows:

$$V_G = \bar{\beta}\left(\bar{Q}_M\right)(\Delta t)\frac{P}{P_I}$$ (Equation 21)

Equation 21 has the same form as the Simplified Equation. There are two fundamental differences between the equations:

1. The Simplified Equation is based on the space averaged void fraction (α) and Equation 21 is based on the gas volumetric flow ratio (β).

2. The Simplified Equation is based on Δt_{PUMP} (time criteria for pump, Reference 3) and Equation 21 is based on the actual transport time duration, Δt.

A comparison of the two equations indicates that if the Simplified Equation is expressed in terms of the average volumetric flow ratio instead of the space averaged void fraction, it is satisfied by definition. In fact, the average gas volumetric flow ratio has historically been the parameter measured during pump tests involving two phase flow (e.g., Reference 7). This is also the approach taken by Reference 1, as reflected by Equation 18. Therefore, it is appropriate to interpret the void fraction in the Simplified Equation as the gas volumetric flow ratio (β).

The intent of the Simplified Equation is to use the inlet void fractions and time durations from the Reference 3 pump criteria as input parameters. The Reference 3 criteria are reformulated as Tables 2 and 3 of this report. Note that this criterion may change in the future and it is up to the user to verify the correct criteria is used. Section 2.3 and item 2, above, point out the fact that care must be exercised in choosing the time duration used in the Simplified Equation. If arbitrarily large time duration is used as an input to the Simplified Equation the resulting allowable gas volume will be correspondingly large and will not ensure that the actual average gas volumetric flow ratio is within the Reference 3 limits. In order to avoid this problem it is proposed that Equations 17-19 be used to constrain the transport time duration. This will be discussed in Sections 2.6 and 3.

2.6 EVALUATION OF TRANSPORT PARAMETERS

Figures 1 through 4 show the location of the space averaged gas volume fraction meters in the vertical down-comers for the 4", 6", 8", and 12" test loops at Purdue University. Figures 12 through 19 show detailed Process & Instrumentation Diagrams and isometrics for these loops. Table 1 defines key instrumentation terminology associated with Figures 12 through 19. This section will evaluate measurements of the transport parameters at these void fraction meter locations in the Purdue University tests.

Table 1 : Instrumentation Referred to in Figure 12 through Figure 19

Instrument Type Identifier	Measurement Type
P	Gage pressure transducer
M/GPM	Magnetic flow meter
DP	Differential pressure transducer
TC	Thermocouple
PW	Parallel wire conductance void fraction probe
RW/RIMP	Ring type impedance void fraction meter
A/AIMP	Arch type impedance void fraction meter
DAIMP	Double arch type impedance void fraction meter

2.6.1 Volumetric Flow Ratio

The average gas volumetric flow ratio for the Purdue Tests was calculated using Equation 11. Equation 18 is the Reference 1 method for calculating the gas volumetric flow rate. Equation 18 indicates the ratio of $Q_{GAS,AVG}$ to Q_{WATER} is equal to the ratio of α_{AVG} to $(1-\alpha_{AVG})$. Two points are noted. First, this reflects the historical practice of associating void fraction with gas volumetric flow ratio. Second, Equation 18 is valid only in the local vicinity of the plunging liquid jet. This latter point requires explanation. Figures 7 and 8 of Reference 1 are repeated as Figures 5 and 6 of this report. The volumetric flow rate in the waterfall of Figure 5 and the jet of Figure 6 is equal to the pump volumetric flow rate. Therefore, Equation 18 is valid around a control volume enclosing the submersed liquid jet of Figure 6. A water flow rate equal to Q_{PUMP} and a gas flow rate equal to Q_{GAS} enter the top of the control volume and exit the bottom of the control volume. However, as shown in Figure 5 and discussed in Reference 1, the total flow rate leaving the bottom of the vertical down-comer is the pump volumetric flow rate (Q_{PUMP}). This total flow rate consists of Q_{GAS} and Q_{WATER}; that is, $Q_{WATER}=Q_{PUMP} - Q_{GAS}$ at the down-comer exit. However, Equation 18 is based on the jet volumetric flow rate which is also equal to Q_{PUMP}. The difference between the water flow rate within the jet (Q_{PUMP}) and that leaving the down-comer exit ($Q_{PUMP} - Q_{GAS}$) is the rate at which the gas is being entrained as the kinematic shock is being depleted and filled with water. Therefore, Equation 18 is reformulated as follows:

$$\frac{Q_{GAS,AVG}}{Q_{PUMP}} = \frac{Q_{GAS,AVG}}{Q_{MIXTURE}} = \beta_{AVG} = 0.029\left(\frac{y_1}{D}\right)^{0.68} \quad \text{(Equation 22)}$$

a, c

2.6.2 Transport Time

a, c

2.7 CONCLUSIONS FROM VALIDATION PROCESS

The results of the validation process can be summarized as follows:

- The gas volumetric flow ratio (β) is the relevant parameter to represent gas transport to the pump inlet as it represents the transfer of gas relative to the mixture transfer rate.

- The definition of gas volumetric flow ratio (β) is equivalent with the Simplified Equation proposed to relate an initial gas volume to the gas volume fraction at the pump inlet. This assures the validity of the Simplified Equation as long as appropriate time durations are used, as discussed below.

- The validation process indicated that the value of transport time (Δt) cannot be arbitrarily specified in the Simplified Equation. In order to ensure the transport time used in the Simplified Equation is conservative, the following process should be used.

1. Calculate $V_{GAS} = V_{ALLOWABLE}$ using the Simplified Equation with α and Δt_{PUMP} obtained from the Reference 3 pump criteria. The Reference 3 criteria are reformulated as Tables 2 and 3 of this report. Note that this criterion may change in the future and it is up to the user to verify the correct criteria is used.

2. Verify that the Reference 3 value of Δt_{PUMP} is not larger than the transport time dictated by the gas volume and flow conditions. This is done as follows.

   a. Calculate the maximum depth of the kinematic shock (y_1) using Equation 17 or Equation 20 with V_{GAS} calculated by the Simplified Equation.

   b. Calculate the transport time ($\Delta t_{TRANSPORT}$) using Equation 23 based on y_1 and V_{GAS}.

   c. If $\Delta t_{TRANSPORT} < \Delta t_{PUMP}$ then multiply the gas volume allowed by the Simplified Equation by the ratio ($\Delta t_{TRANSPORT} / \Delta t_{PUMP}$) to yield the allowable volume.

3 LIMITATIONS ON USAGE OF THE SIMPLIFIED EQUATION

This section identifies limitations on usage of the Simplified Equation to ensure it results in a conservatively low value of allowable gas volume at the high point location,

3.1 PUMP ENTRANCE LIMITATIONS

The gas transport testing conducted at Purdue University forms the validation basis for the Simplified Equation. This program addressed the transport of gas through piping systems. As such, the flow dynamics at the inlet to pumps was not within the scope of this program. Therefore, additional limitations may be needed to deal with specific pump inlet concerns and these limitations should be identified as part of a future PWROG project.

3.2 FLOW RATES

The system flow rates must be limited to the range over which the Simplified Equation was validated.

The system flow rates must be limited to those used in the Purdue University Test Program. The Purdue University tests used a maximum Froude number of 2.5 for pipe diameters of 4 inch, 6 inch, and 8 inch. A maximum Froude number of 1 was used for the 12 inch test. However, Section 2.5 of this report demonstrates that the use of β (as opposed to α) ensures the validity of the Simplified Equation as long as an appropriate time duration is used (Section 3.4). Therefore, a high flow limit of Froude No. = 2.5 will be used for all pipe sizes.

Limitation 1: $N_{FR} \leq 2.5$; this can also be expressed as the following limitation between flow rate (gal/min) and inside pipe diameter (inch): $Q \leq 10\ D^{2.5}$

3.3 TRANSPORT TIME DURATION LIMITS

References 2 and 3 provide pump acceptance criteria in terms of allowable maximum void fractions for maximum allowable time intervals. The intent is to use the time intervals from Reference 2 or 3 as input to the Simplified Equation.

The validation process indicated that the value of transport time (Δt) cannot be arbitrarily specified in the Simplified Equation. In order to ensure the transport time used in the Simplified Equation is conservative, the following process should be used.

Limitation 2: Verify that the Reference 3 value of Δt_{PUMP} is not larger than the transport time dictated by the gas volume and flow conditions. Calculate $V_{GAS} = V_{ALLOWABLE}$ using the Simplified Equation with α and Δt_{PUMP} obtained from the Reference 3 pump criteria. Calculate the transport time duration as follows.

a. Calculate the maximum depth of the kinematic shock (y_1) using Equation 17 or 20 with V_{GAS} calculated by the Simplified Equation.

b. Calculate the transport time ($\Delta t_{TRANSPORT}$) using Equation 23 based on y_1 and V_{GAS}.

c. If $\Delta t_{TRANSPORT} < \Delta t_{PUMP}$ then multiply the gas volume allowed by the Simplified Equation by the ratio ($\Delta t_{TRANSPORT} / \Delta t_{PUMP}$) to yield the allowable volume.

3.4 LAYOUT LIMITATIONS

Task 2 of the project authorization for the Simplified Equation indicated that limitations on use of the Simplified Equation should be established in the light of the gaps identified in the gap analysis Project Authorization (PA-SEE-0530). The Phenomenon Identification and Ranking Table (PIRT) project (Reference 4) defined a bounding analysis as an analysis which considers all high ranked phenomena, but does not require analytical models for each phenomenon.

Instead, the analysis would provide a basis for evaluating some important phenomena in a bounding manner. The most simplistic bounding approach is the homogeneous flow assumption which forms the basis for the Simplified Equation. However, implementing such an approach requires applying appropriate limitations which conservatively bound high ranked phenomena that are not directly modeled.

3.4.1 Vertical Down-comer Length Requirement to Ensure Dispersed Flow

There are several limitations or criteria to consider when implementing such a modeling approach. The first criterion is that the flow be dispersed. The main argument to demonstrate this relies heavily on testing observations which show that at the exit of a vertical kinematic shock, the flow must be dispersed. Reference 1 demonstrates that the kinematic shock will be contained with the vertical down-comer if the following criterion is met:

Limitation 3: The volume of a vertical down-comer located between the high point and the pump must exceed the gas volume by a factor of 4:

$$\frac{V_{DOWNCOMER}}{V_{GAS}} \rangle 4$$

3.4.2 Prevention of Slug Flow Formation

A second criterion for implementing a homogenous flow model is that the flow must not form a slug flow downstream of the dispersed flow region. Under these conditions, the homogeneous flow prediction would not be valid. A re-accumulation of gas may not necessarily lead to slug formation, such as would occur as gas accumulates upstream of a kinematic shock. However, a re-accumulation and subsequent instability may form slug flow leading to a large gas flux downstream. In essence, a low upstream gas flux, over a sufficient time period, could lead to a greater downstream gas flux over a shorter time period.

The PIRT determined that the phenomena that could lead to re-accumulation and subsequent slug formation in any portion of the system as well as the entrance to a pump include "Formation of Kinematic Shock in Horizontal Pipe," "Flow stratification in horizontal pipes," and "Pump entrance phenomena."

3.4.2.1 Kinematic Shock Formation in Horizontal Pipe

Testing at Purdue University has indicated that with sufficient gas volume and under certain flow conditions that a kinematic shock can form in the lower horizontal header. This is potentially an issue only if the horizontal pipe is at the inlet to a pump. There is a knowledge gap in this area which will be addressed as part on pump entrance phenomenon.

3.4.2.2 Flow Stratification

For sufficiently long horizontal pipes, where the required length is a function of flow Froude Number, the gas flow could stratify above the liquid flow rate. This phenomenon was not studied as part of the testing performed at Purdue University (References 5, 6, and 7). In addition, adequate guidance was not found in the open literature on this subject. Therefore, criteria for formation of stratified flow are not presented in this document. Flow stratification is only an issue where it could lead to subsequent formation of slug flow, such as tee branches and off-takes. These conditions are discussed in Section 3.4.3.

3.4.2.3 Pump Entrance Phenomenon

The gas transport testing conducted at Purdue University forms the validation basis for the Simplified Equation. This program addressed the transport of gas through piping systems. As such, the flow dynamics at the inlet to pumps was not within the scope of this program. Therefore, any additional limitations that are needed to deal with specific pump inlet concerns will have to be identified as part of a future PWROG project. This will listed as an open item (Sections 1.2.2.1 and 3.1) to this report.

3.4.3 Treatment of Off-Takes

In some instances, an off-take may exist in the suction piping between the high point location and the pump inlet. Adequate knowledge does not currently exist to determine the fraction of gas volumetric flow rate transported through different sections of the off-take. In general, the gas volumetric flow distribution would be dependent on the two phase flow regime, the relative flow split at the off-take, and the physical orientation of the off-take.

As documented in Reference 1, the basis for application of the Simplified Equation is the prevention of slug flow through the formation of a kinematic shock and the subsequent transport of a bubbly flow mixture. Therefore, if an off-take is present, it is necessary to first consider the potential for the flow to stratify as it approaches the off-take. If it is suspected that the flow will stratify, the potential for gas build-up and subsequent transport of a slug of gas due to an air entraining vortex exists. In this case, the Simplified Equation approach cannot be applied. In order to apply the Simplified Equation to an off-take, it is necessary to demonstrate that bubbly flow exits at the off-take. In this case, it can conservatively be assumed that all of the gas is transported through a single branch of the off-take. The gas volumetric flow ratio is then obtained by direct application of Equation 2, using the pump flow rate as the mixture flow rate. Criteria for demonstrating that bubbly flow exists at the tee are beyond the scope of the current document.

As gas is transported from the system high points to a horizontal header it may stratify at the top of the pipe. The entrainment forces needed to entrain air from the top of the pipe into an off-take are then dependent on the depth of the water at that location. As the gas is transported into and as the air volume builds up in the horizontal header, a critical depth is reached, at which point the entrainment forces overcome the buoyancy forces holding the air at the top of the pipe. A hydraulic jump condition would then occur resulting in an air entraining vortex and the off-take piping would see a large void fraction (Refer to Figure 11). The Simplified Equation is not applicable in this situation.

In order for this phenomenon to occur, the flow regime has to be stratified (this requires a horizontal header) and the off-take has to be oriented such that it does not reach the top of the horizontal pipe. The latter condition will occur as the result of the following off-take geometries:

- A branch off-take from the header where the branch is not horizontal; for example, if the branch is rotated downward by some angle, say 30°, 45°, 90°, etc.
- A branch off-take from the header where the diameter of the branch connection is smaller than the diameter of the header.

Each of the above physical orientations could allow the gas flow to stratify and form an open channel flow configuration which would be susceptible to large gas entrainment rates (slugs of gas) due to the formation of gas entraining vortices at the off-take. The Simplified Equation is not applicable in these conditions because the Simplified Equation assumes a steady transport of the gas and does not apply when the gas is allowed to accumulate and subsequently transport in a slug.

Limitation 4: If the gas flow is stratified, as it approaches an off-take, then it is necessary to protect against slug flow resulting from a sudden in-surge of gas due to an air entraining vortex. The Simplified Equation cannot be applied under these conditions since the flow distribution model used to establish the transport time is not applicable in this situation.

3.5 SYSTEM PRESSURE CHANGES UPON ACCIDENT INITIATION

The Simplified Equation contains a pressure ratio which represents the ratio of the pressure at the pump inlet (P_{PUMP}) to the high point pressure ($P_{HIGH\ POINT}$) during post-accident operation. This ratio accounts for the fact that there may be a significant pressure change between the locations where the gas is initially located and the pump inlet. Since the intent of the Simplified Equation is to develop criteria for allowable gas volumes, it is noted that an additional adjustment is necessary to determine the gas volume at the time of the gas intrusion surveillance test. In some cases, the system pressure changes due to different suction sources during surveillance testing (normal operation) and postulated operating scenarios. Any such variation must be taken into account when the allowable gas volume is determined. This adjustment is done by multiplying the Simplified Equation allowable gas volume by the ratio of the high point pressure during post-accident conditions to the high point pressure during surveillance testing.

3.6 SUMMARY OF LIMITATIONS

Limitation 1:$N_{FR} \leq 2.5$; this can also be expressed as the following limitation between flow rate (gal/min) and inside pipe diameter (inch): $Q \leq 10\ D^{2.5}$.

Limitation 2: Verify that the Reference 3 value of Δt_{PUMP} is not larger than the transport time dictated by the gas volume and flow conditions. The Reference 3 criteria are reformulated as Tables 2 and 3 of this report. Note that these criteria may change in the future and it is up to the user to verify the correct criteria is used. Calculate $V_{GAS} = V_{ALLOWABLE}$ using the Simplified Equation with α and Δt_{PUMP} obtained from the Reference 3 pump criteria. Calculate the transport time duration as follows.

a. Calculate the maximum depth of the kinematic shock (y_1) using Equation 17 or Equation 20 with V_{GAS} calculated by the Simplified Equation.

b. Calculate the transport time ($\Delta t_{TRANSPORT}$) using Equation 23 based on y_1 and V_{GAS}.

c. If $\Delta t_{TRANSPORT} < \Delta t_{PUMP}$, then multiply the gas volume allowed by the Simplified Equation by the ratio ($\Delta t_{TRANSPORT} / \Delta t_{PUMP}$) to yield the allowable volume.

Limitation 3: The volume of a vertical down-comer located between the high point and the pump must exceed the gas volume by a factor of 4:

$$\frac{V_{DOWNCOMER}}{V_{GAS}} \rangle 4$$

Limitation 4: If the gas flow is stratified as it approaches an off-take, then it is necessary to protect against slug flow resulting from a sudden in-surge of gas due to an air entraining vortex. The Simplified Equation cannot be applied under these conditions since the flow distribution model used to establish the transport time is not applicable in this situation.

4 GUIDELINES FOR APPLICATION OF SIMPLIFIED EQUATION

4.1 BACKGROUND

The Simplified Equation provides a method for the user to calculate maximum allowable gas volumes at high point locations in pump suction piping systems such that the gas transport rate to the pump will be within allowable gas volume fraction limits. The intent of this report is to provide guidelines for use of the Simplified Equation and worked examples to illustrate the application principles. The Simplified Equation is a conservative method of specifying allowable gas volumes at high point locations if it is applied in the manner described in Section 4.2 of this report and the limitations defined in Section 4.3 of this report are met.

4.2 METHOD DISCUSSION

A methodology is described for calculating the allowable initial gas volume at a piping system high point based on allowable pump inlet void fractions. Determining allowable volumes in the suction side of these systems includes the following steps:

- Determine the allowable pump inlet void fraction.
- Determine possible gas accumulation locations.
- Define the suction path from the suction source to the pump for all modes of operation.
- Define the Simplified Equation hydraulic input parameters.
    - Define the system flow rates.
    - Define static pressure at accumulation location during surveillance test.
    - Define minimum static pressures at pump suction and accumulation locations during required operating scenarios.
- Verify limitations on use of the Simplified Equation are met. This requires the identification of certain layout parameters.
    - Define volume of gas accumulation location.
    - Define volume of vertical down-comer downstream of accumulation location.
    - Identify if there are any off-takes between the high point location and pump inlet.
- Perform gas transport analysis using Simplified Equation.

Each of these steps will be discussed in detail in this section and will be illustrated by worked example problems in Section 4.4.

4.2.1 Determine Allowable Pump Inlet Gas Volume Fraction

Reference 3 transmitted the industry criteria for allowable average non-condensable gas volume fractions at pump inlets. The results are reformulated as Table 2 and Table 3. Note that these criteria may change in the future and it is up to the user to verify the correct criteria is used. It is also noted that criteria are provided for steady state and transient operation. The transient criteria are used in conjunction with the Simplified Equation.

Table 2 : Allowable Average Non-Condensable Gas Void Fractions (to preclude pump mechanical damage)

		$\%\frac{Q}{Q_{BEP}}$	BWR Typical Pumps	PWR Typical Pumps		
				Single Stage (WDF)	Multi-Stage Stiff Shaft (CA)	Multi-Stage Flexible Shaft (RLIJ, JHF)
A	Steady State Operation	40%-120%	2%	2%	2%	2%
B	Steady State Operation	< 40% or > 120%	1%	1%	1%	1%
C	Transient Operation	70%-120%	10% for ≤ 5 sec	5% for ≤ 20 sec	20% for ≤ 20 sec	10% for ≤ 5 sec
D	Transient Operation	< 70% or > 120%	5% for ≤ 5 sec	5% for ≤ 20 sec	5% for ≤ 20 sec	5% for ≤ 5 sec

Table 3 : Allowable Average Non-Condensable Gas Void Fractions (to preclude significant reduction in discharge head)

	$\%\frac{Q}{Q_{BEP}}$	BWR Typical Pumps	PWR Typical Pumps		
			Single Stage	Multi-Stage Stiff Shaft	Multi-Stage Flexible Shaft
Steady State Operation	40%-120%	2%	2%	2%	2%
Steady State Operation	< 40% or > 120%	1%	1%	1%	1%

It is noted that determination of the correct criteria to apply requires knowledge of the following information:

- pump type,
- pump best efficient point (BEP) flow rate, and
- pump operating flow rate for scenario under consideration.

It is noted that in most cases, the allowable gas volume fraction at the pump inlet is decreased if the pump flow rate is less than 70% of the BEP flow rate or greater than 120% of the BEP flow rate.

4.2.2 Identify Gas Accumulation Locations

The identification of gas accumulation locations are discussed in detail in Reference 6. The following list provides some examples of gas accumulation locations in the piping system:

- Vent valve locations (criteria required for venting).
- Check valve locations.
- Valves that are not "full port."
- Loop seals.
- Orifice plates.
- Points identified as local high points as result of laser scanning or other detection methods.

4.2.3 Define Suction Paths

In order to define the minimum pump pressure during required operations, it is necessary to define all of the suction sources and paths which apply to the pump under consideration. The following are examples of suction paths that may be applicable:

High Pressure Safety Injection (HPSI) Pump

- Safety injection with suction from the refueling water storage tank (RWST).
- Post-accident long term core cooling recirculation with suction from the containment sump.

Low Pressure Safety Injection (LPSI) or RHR Pump

- Safety injection with suction from the RWST.
- Normal cooldown with suction from reactor coolant system (RCS) hot legs.
- Post-accident long term core cooling recirculation with suction from the sump.

Charging Pump

- Safety injection with suction from the refueling water storage tank (RWST).
- Recirculation with suction from the residual heat removal (RHR) pumps (cross-tie to RHR).

Intermediate Head SI Pump

- Safety Injection with suction from the refueling water storage tank (RWST).
- Recirculation with suction from the residual heat removal (RHR) pumps (cross-tie to RHR).

Containment Spray Pump

- Spray with suction from the RWST.
- Post-accident long term core cooling recirculation spray with suction from the sump.

Any possible gas accumulation locations in any of the above listed suction paths should be evaluated to determine the allowable gas accumulation volume based on the defined allowable pump inlet gas volume fraction.

4.2.4 Define Simplified Equation Hydraulic Input Parameters

4.2.4.1 System Flow Rates

The allowable void volume calculation using the Simplified Equation is based on the maximum system flow rate. The use of the maximum system flow rates in both the common suction piping and the single train piping is conservative because it results in lower transport time and higher entrained peak gas volume fraction. Following are some guidelines for use in determining the maximum system flow rate for various sections of piping:

- To determine the maximum flow rate in a section of pipe common to multiple systems (supply header), the sum of the maximum flow-rates for each of the downstream systems is used.
- To determine the maximum flow rate in piping sections supplying two pumps, both pumps are considered to be running.
- The flow rate in a single train downstream of any common piping can be assumed to be the single train operation maximum flow rate.

Selection of maximum flow rates will be illustrated in the worked examples.

4.2.4.2 Minimum Pump Suction Pressures

The Simplified Equation uses the minimum possible pump suction pressure during postulated operating scenarios as an input. The minimum pump suction pressure defines the most conservative allowable volume. The minimum pump suction pressures can be based on the net positive suction head calculations with adjustments made as necessary to correct for conditions which would apply during gas transport. This will be illustrated in the worked examples.

4.2.4.3 Minimum High Point Pressures

The Simplified Equation uses the minimum high point pressure during postulated operating scenarios as an input. This value is used to determine the maximum gas volume which would exist at the high point during post-accident operation. It is necessary to know this value to predict the length of the kinematic shock and verify the adequacy of the vertical down-comer volume and the transport time. This will be illustrated in the worked examples.

4.2.4.4 Static Pressure at Gas Accumulation Location during Surveillance Test

In most cases, the surveillance test to detect gas accumulation is performed during normal operation when the ECCS or CS system is under pressure dictated by the maximum RWST elevation. It is necessary to correct the allowable gas volume from the gas transport analysis for the static pressure which exists at the high point while the pump is operating to the corresponding static pressure during the time of the void measurement when the system is not operating. The maximum suction source elevation along with the gas accumulation site elevation defines the static elevation head at the gas accumulation location at the time of the void measurement and provides the most conservative allowable volume. Therefore, the suction source water elevation during both the gas accumulation surveillance test and the postulated gas transport operating scenario must be identified.

In the case of the charging pumps in a Westinghouse plant design, the pump suction is aligned to the volume control tank (VCT) during surveillance testing. Therefore, the high point pressure must be based on the normal operating line-up, and knowledge of the VCT level and pressure is required.

4.2.5 Verify limitations on use of the Simplified Equation are met

In order to verify the limitations on use of the Simplified Equation are met, it is necessary to identify some plant layout information. The necessary information will be discussed in this section. The limitations on use of the Simplified Equation are discussed in Section 4.3.

4.2.5.1 Define volume of gas accumulation location

The total pipe volume of the gas accumulation location under consideration must be known.

4.2.5.2 Define volume of vertical down-comer downstream of accumulation location

Use of the Simplified Equation assumes there is a vertical down-comer downstream of the high point location with a volume which is adequate to contain the kinematic shock. Therefore, the volume of the largest vertical down-comer downstream of the high point in the pump suction piping must be identified. This limitation is discussed in Section 4.3.3.

4.2.5.3 Identify any off-take between high point location and pump inlet

The Simplified Equation requires special treatment for application to flow through off-takes. This is discussed in Section 4.3.3. Therefore, the user must identify if there are any flow splitting off-takes between the high point location and the pump inlet.

4.2.6 Gas Transport Analysis

The Simplified Equation provides a method for the user to calculate maximum allowable gas volumes at high point locations in pump suction piping systems such that the gas transport rate to the pump will be within allowable gas volume fraction limits. Application of the Simplified Equation requires knowledge of the allowable gas volume fraction criteria at the pump inlet, system flows and system pressures.

$$V_{allowable} = \alpha_{pump} \Delta t_{pump} Q_{pump} \left(\frac{P_{pump}}{P_{high\_point}} \right)_{Post-Accident} \qquad \textbf{(Simplified Equation)}$$

The Simplified Equation is a conservative method of specifying allowable gas volumes at high point locations if the limitations defined in Section 4.3 are met.

4.3 LIMITATIONS ON USAGE OF THE SIMPLIFIED EQUATION

The following limitations on the usage of the Simplified Equation ensure the resultant allowable gas volume calculations are conservative.

4.3.1 Flow Rates

Limitation 1: The system flow rate must be limited to those corresponding to the maximum Froude Number tested at Purdue University: $N_{FR} \leq 2.5$. This limit on Froude number will be met if the flow rate meets the following criteria:

$$Q \leq 10\ D^{2.5}$$

Where Q is the flow rate (gpm) and D is the pipe inside diameter (inches).

4.3.2 Transport Time Duration Limits

References 2 and 3 provide pump acceptance criteria in terms of allowable maximum void fractions for maximum allowable time intervals. The intent is to use the time intervals from References 2 or 3 as input to the Simplified Equation. The validation process indicated that the value of transport time (Δt) cannot be arbitrarily specified in the Simplified Equation. In order to ensure the transport time used in the Simplified Equation is conservative, the following process should be used.

Limitation 2: Verify that the Reference 3 value of Δt_{PUMP} is not larger than the transport time dictated by the gas volume and flow conditions. The Reference 3 criteria are reformulated as Tables 2 and 3 of this report. Note that these criteria may change in the future and it is up to the user to verify the correct criteria is used. Calculate $V_{GAS} = V_{ALLOWABLE}$ using the Simplified Equation with α and Δt_{PUMP} obtained from the Reference 3 pump criteria. Calculate the transport time duration as follows.

a. Calculate the maximum depth of the kinematic shock (y_1) using Equation 17 or 20 with V_{GAS} calculated by the Simplified Equation.

b. Calculate the transport time ($\Delta t_{TRANSPORT}$) using Equation 23 based on y_1 and V_{GAS}.

c. If $\Delta t_{TRANSPORT} < \Delta t_{PUMP}$ then multiply the gas volume allowed by the Simplified Equation by the ratio ($\Delta t_{TRANSPORT} / \Delta t_{PUMP}$) to yield the allowable volume.

4.3.3 Layout Limitations

The following layout limitations must be met to ensure that the allowable gas volumes calculated by the Simplified Equation are conservatively low.

4.3.3.1 Vertical Down-comer Volume

Limitation 3: Application of the Simplified Equation is based on the assumption that there is a vertical down-comer downstream of the high point location which is large enough to contain the kinematic shock region. The dynamics of the kinematic shock formation dictate that the available down-comer volume must be at least 4 times as great as the allowable gas volume. That is the length of a vertical down-comer located between the high point and the pump must exceed the gas volume by a factor of 4:

$$\frac{V_{DOWN-COMER}}{V_{ALLOWABLE}} \rangle\ 4$$

If this limitation is not met by the gas volume calculated by the Simplified Equation, then the allowable gas volume ($V_{ALLOWABLE}$) must be restricted to ¼ of the vertical down-comer volume.

4.3.3.2 Treatment of Off-Takes

In some instances, an off-take may exist in the suction piping between the high point location and the pump inlet. Adequate knowledge does not currently exist to determine the fraction of gas volumetric flow rate transported through different sections of the off-take. In general, the gas volumetric flow distribution would be dependent on the two phase flow regime, the relative flow split at the off-take, and the physical orientation of the off-take.

As documented in Reference 1, the basis for application of the Simplified Equation is the prevention of slug flow through the formation of a kinematic shock and the subsequent transport of a bubbly flow mixture. Therefore, if an off-take is present, it is necessary to first consider the potential for the flow to stratify as it approaches the off-take. If it is suspected that the flow will stratify, the potential for gas build-up and subsequent transport of a slug of gas due to an air entraining vortex exists. In this case, the Simplified Equation approach cannot be applied. In order to apply the Simplified Equation to an off-take, it is necessary to demonstrate that bubbly flow exits at the off-take. In this case, it can conservatively be assumed that all of the gas is transported through a single branch of the off-take. The gas volumetric flow ratio is then obtained by direct application of Equation 2 using the pump flow rate as the mixture flow rate. Criteria for demonstrating that bubbly flow exists at the tee are beyond the scope of the current document.

As gas is transported from the system high points to a horizontal header it may stratify at the top of the pipe. The entrainment forces needed to entrain air from the top of the pipe into an off-take are then dependent on the depth of the water at that location. As the gas is transported into, and as the air volume builds up in the horizontal header, a critical depth is reached, at which point the entrainment forces overcome the buoyancy forces holding the air at the top of the pipe. A hydraulic jump condition would then occur resulting in an air entraining vortex and the off-take piping would see a large void fraction (Refer to Figure 11). The Simplified Equation is not applicable in this situation.

In order for this phenomenon to occur, the flow regime has to be stratified (this requires a horizontal header) and the off-take has to be oriented such that it does not reach the top of the horizontal pipe. The latter condition will occur as the result of the following off-take geometries:

- A branch off-take from the header where the branch is not horizontal; for example, if the branch is rotated downward by some angle, say 30°, 45°, 90°, etc.
- A branch off-take from the header where the diameter of the branch connection is smaller than the diameter of the header.

Each of the above physical orientations could allow the gas flow to stratify and form an open channel flow configuration which would be susceptible to large gas entrainment rates (slugs of gas) due to the formation of gas entraining vortices at the off-take. The Simplified Equation is not applicable in these conditions because the Simplified Equation assumes a steady transport of the gas and does not apply when the gas is allowed to accumulate and subsequently transport in a slug.

Limitation 4: If the gas flow is stratified as it approaches an off-take, then it is necessary to protect against slug flow resulting from a sudden in-surge of gas due to an air entraining vortex. The Simplified Equation cannot be applied under these conditions since the flow distribution model used to establish the transport time is not applicable in this situation.

A worked example will illustrate how to apply this adjustment.

4.4 EXAMPLE APPLICATIONS OF SIMPLIFIED EQUATION

A few worked examples of application of the Simplified Equation are provided to illustrate the concepts. The examples have been chosen to illustrate key methods and limitations of the Simplified Equation.

4.4.1 Example Problem 1

The intent of this example problem is to illustrate the overall methodology and to demonstrate pressure correction and treatment of tees. The layout for this problem is illustrated in Figure 20. Figure 20 shows a high point location downstream of the containment sump check valve. The high point location is outside of containment and could be monitored using ultrasonic transducers (UT). During normal operation when the surveillance would be performed, the high point location would be under static head from the RWST. During required post-accident operation the RWST flow path would be isolated and the containment sump path would be in service. Therefore, the high point pressure would be based on RWST head during normal operation and the pump pressure would be based on operation with sump in service.

The sump flow rate goes through the high point location and then travels down two vertical down-comers before splitting at a tee to the HPSI and CS pumps. The example will illustrate some of the issues related to the treatment of tee branches.

It is assumed that inputs required for the calculation are obtained from appropriate sources for the plant. For example, typical references for this particular problem could be:

- Plant process & instrumentation diagrams (P&IDs) and plant layout isometric drawings yield the following information:
    - High point location.
    - Piping elevations.
    - Pipe diameters and schedules.
- Calculation of available NPSH from containment sump yields the following information:
    - Pump flow rates.
    - Sump minimum water level during post-accident operation.
    - $NPSH_A$ to pumps.
    - Overpressure in containment applicable in $NPSH_A$ calc.
    - Hydraulic friction and form loss from high point to pump inlet.
- Calculation of RWST level set-points yields the following information:

- RWST level during normal plant operation.

- Two-phase flow hand book
  - Appropriate flow regime maps for horizontal and vertical flow conditions approaching tee branches.
- Pump manuals
  - Pump best efficiency operating point.

4.4.1.1 Determine the allowable pump inlet void fraction

The data for the two pumps is shown in Table 4.

Table 4 : Example Problem 1 Pump Information

Example Pump Information		
Pump	**HPSI**	**CS**
Type	Multi-stage Stiff Shaft CA	Single-stage WDF
BEP Flow	900 gpm	4300 gpm
Maximum Flow Rate during Post-Accident Recirculation Mode of Operation	1400 gpm	5200 gpm
Q/Q_{BEP}	1.56	1.21

Since the value of Q/QBEP > 1.20 for both pumps, Table 2 indicates that the allowable gas volume fraction at the pump inlet is 5% for 20 seconds.

4.4.1.2 Determine possible gas accumulation locations

The gas accumulation location dealt with in this example is the location outside containment downstream of the check valve. The check valve acts to collect any gas which migrates to the high point.

4.4.1.3 Define the suction path from the suction source to the pump for all modes of operation

The following operating modes are applicable to the HPSI and CS pumps.

High Pressure Safety Injection (HPSI) Pump

- Safety injection with suction from the refueling water storage tank (RWST).
- Post-accident long term core cooling recirculation with suction from the containment sump.

Containment Spray Pump

- Spray with suction from the RWST.
- Post-accident long term core cooling recirculation spray with suction from the sump.

This particular example will only treat the suction flow path from the containment sump since that is where the accumulation location is. However, in general, all of these flow paths would be reviewed for possible accumulation locations.

4.4.1.4 Define the Simplified Equation hydraulic input parameters

4.4.1.4.1 Define the system flow rates

In this particular example, each train has a separate connection to the sump. In addition, the LPSI pump is isolated on the switchover signal. Therefore, only one HPSI pump and one CS pump are operating. The maximum HPSI pump flow rate is 1400 gpm and the maximum CS pump flow rate is 5200 gpm. The total header flow rate is 6600 gpm.

4.4.1.4.2 Define static pressure at accumulation location during surveillance test

During normal operation, when the gas accumulation surveillance test is performed, the RWST head will dictate the static backpressure on the accumulation location. It is conservative to use the maximum high-point pressure in the Simplified Equation. Therefore, the maximum RWST level of 125 feet elevation will be used. The elevation of the accumulation location is 80 feet. The minimum RWST temperature is 40°F. The fluid density at this temperature is 62.4 lbm/ft^3. Therefore, the maximum high point static pressure during surveillance conditions is:

$$P_{HIGH-POINT} = P_{ATM} + \frac{\rho}{144}\frac{g}{g_c}\left(Z_{RWST} - Z_{HIGH-POINT}\right)$$

$$P_{HIGH-POINT} = 14.7\ psia + \frac{62.4\,\frac{lb_m}{ft^3}}{144\,\frac{in^2}{ft^2}}\left(\frac{32.2\,\frac{ft}{\sec^2}}{32.2\,\frac{lb_m - ft}{lb_f - \sec^2}}\right)\left(125\ ft - 80\ ft\right) = 34.2\ psia$$

4.4.1.4.3 Define minimum pump suction pressures during required operating scenario

The NPSH$_A$ calculation for the sump recirculation mode of operation indicates the minimum NPSH$_A$ to the HPSI pump at 1400 gpm is 29.2 feet and the minimum NPSHA to the CS pump at 5200 gpm is 25.9 feet. The fluid density used in this NPSH$_A$ calculation was 57.3 lb$_m$/ft^3. Since we are interested in a minimum pressure at the pump inlet, it will be conservatively assumed that the vapor pressure considered in the NPSH calculation was atmospheric pressure. Therefore, the minimum pump suction pressure during post-accident operating conditions is:

$$P_{PUMP} = P_{VAPOR} + \frac{\rho}{144}\frac{g}{g_c} NPSH_A$$

$$P_{HPSI} = 14.7\ psia + \frac{57.3\,\frac{lb_m}{ft^3}}{144\,\frac{in^2}{ft^2}} \left(\frac{32.2\,\frac{ft}{\sec^2}}{32.2\,\frac{lb_m - ft}{lb_f - \sec^2}} \right) (29.2\ ft) = 26.3\ psia$$

$$P_{CS} = 14.7\ psia + \frac{57.3\,\frac{lb_m}{ft^3}}{144\,\frac{in^2}{ft^2}} \left(\frac{32.2\,\frac{ft}{\sec^2}}{32.2\,\frac{lb_m - ft}{lb_f - \sec^2}} \right) (25.9\ ft) = 25.0\ psia$$

4.4.1.4.4 Define high point pressures during required operating scenario

The elevation of the high point location is 80 feet. The elevation of the pump suction is 46 feet. The hydraulic friction and form loss from the high point to the HPSI pump inlet is 10 ft. Therefore, the high point pressure during post-accident operating conditions is:

$$P_{HIGH-POINT} = P_{Pump} + \frac{\rho}{144}\frac{g}{g_c}\left(Z_{PUMP} - Z_{HIGH-POINT} + \Delta h_{LOSS}\right)$$

$$P_{HIGH-POINT} = 26.3\ psia + \frac{57.3\,\frac{lb_m}{ft^3}}{144\,\frac{in^2}{ft^2}} \left(\frac{32.2\,\frac{ft}{\sec^2}}{32.2\,\frac{lb_m - ft}{lb_f - \sec^2}} \right) (46\ ft - 80\ ft + 10\ ft) = 16.8\ psia$$

4.4.1.5 Verify limitations on use of the Simplified Equation are met

This requires the identification of certain layout parameters.

4.4.1.5.1 Define volume of gas accumulation location

The distance from the sump check valve outlet to the centerline of the down-comer is 15 feet. The pipe inside diameter is 23.25 inch. Therefore, the volume of the high point location is:

$$V_{HIGH-POINT} = \frac{\pi}{4}\left(\frac{D}{12}\right)^2 L$$

$$V_{HIGH-POINT} = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 (15\ ft) = 44.22\ ft^3$$

4.4.1.5.2 Define volume of vertical down-comer downstream of accumulation location

The elevation of the high point location is 80 feet. The elevation of the RWST check valve is 65 feet. The elevation of the pump suction is 46 feet. Therefore, the volumes of the vertical down-comers are:

$$V_{DOWN-COMER-1} = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 (80\ ft - 65\ ft) = 44.22\ ft^3$$

$$V_{DOWN-COMER-2} = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 (65\ ft - 46\ ft) = 56.02\ ft^3$$

4.4.1.5.3 Identify if there are any off-takes between the high point location and pump inlet

There is a tee branch where the RWST supply header ties into the sump supply header and a tee branch where the sump flow splits to the HPSI and CS pumps.

4.4.1.6 Evaluate Limitations on Simplified Equation

4.4.1.6.1 Flow Rates

1. The system flow rate must be limited to those corresponding to the maximum Froude Number tested at Purdue University: $N_{FR} \leq 2.5$. This limit on Froude number will be met if the flow rate meets the following criteria:

   $Q \leq 10\ D^{2.5} = 10\ (23.25)^{2.5} = 26{,}065$ gpm.

   We are well within this limit.

4.4.1.6.2 Layout Limitations

Application of the Simplified Equation is based on the assumption that there is a vertical down-comer downstream of the high point location which is large enough to contain the kinematic shock region. The dynamics of the kinematic shock formation dictate that the available down-comer volume must be at least 4 times as great as the allowable gas volume. The allowable gas volume ($V_{ALLOWABLE}$) must be restricted to ¼ of the maximum vertical down-comer volume. The maximum vertical down-comer volume was determined to be 56.02 ft^3 in Section 4.4.1.5.2.

Therefore, this limitation requires that $V_{ALLOWABLE} \leq 0.25\ (56.02\ ft^3) = 14\ ft^3$. This criterion is not limiting.

4.4.1.6.3 Treatment of Off-Takes

There are two tees in the system. Tees have to be evaluated in a very thorough manner since the potential for gas accumulation and subsequent pull-through of a slug of gas exists as explained in Section 3.4.3.

The first tee is the RWST supply connection to the sump supply and is located in a horizontal plane. Because of the horizontal path, the potential exists for the gas flow to stratify as it approaches the tee. By use of an appropriate flow regime map for horizontal flow, it is determined that the gas flow will not be stratified for this particular set of flow conditions since the superficial liquid velocity approaches that required for dispersed bubbly flow. In addition, the flow path to the pumps is by means of the "thru" leg of the tee, which promotes gas transport through the tee. There is no flow through the "branch" leg of the tee, and the distance from the branch leg to the RWST check valve is sufficiently small so as to not allow a large volume of gas to collect. This fact, coupled with the fact that both the "thru" leg and "branch" leg are both full port legs in the horizontal plane, minimizes the risk of gas build-up leading to pull-through of a large slug of gas. This means that gas build up will not occur at the tee inlet and the potential for large slugs of gas to be pulled into the tee branch due to an air entraining vortex is eliminated. Therefore, it is appropriate to assume the gas is dispersed throughout the flow field and conservative to assume that the gas volumetric flow rate in the tee branch is less than or equal to the gas volumetric flow rate in the supply header.

The second tee is the sump supply to the individual pumps and is located in a vertical plane. By use of an appropriate flow regime map for vertical two-phase flow, it is verified that the flow regime is bubbly flow as it approaches the tee. This means that gas build up will not occur at the tee inlet and the potential for large slugs of gas to be pulled into the tee branch due to an air entraining vortex is eliminated. Therefore, it is appropriate to assume the gas is dispersed throughout the flow field and conservative to assume that the gas volumetric flow rate in the tee branch is less than or equal to the gas volumetric flow rate in the supply header.

The limiting gas volume will be calculated for each pump and the lower value will be used as the acceptance criteria.

4.4.1.7 Gas Transport Evaluation

The Simplified Equation will now be applied to the HPSI and CS pumps, using the input values in Table 5.

Table 5 : Simplified Equation Input Parameters

Simplified Equation Input Parameters		
PARAMETER	**HPSI Pump**	**CS Pump**
α_{PUMP}	.05	.05
Δt_{PUMP}	20 sec	20 sec
Q_{PUMP}	1400 gal/min	5200 gal/min
$P_{HIGH\text{-}POINT}$	16.7 psia	16.7 psia
P_{PUMP}	26.3 psia	25.0 psia

The resultant gas volume allowed by the Simplified Equation is:

$$V_{allowable} = \alpha_{pump} \Delta t_{pump} Q_{pump} \left(\frac{P_{PUMP}}{P_{HIGH\_POINT}} \right)$$

$$V_{allowable-HPSI} = 0.05(20\ \sec)\left(1400 \frac{gal}{\min} \frac{ft^3}{7.48\ gal} \frac{\min}{60\ \sec}\right)\left(\frac{26.3\ psia}{16.8\ psia}\right) = 4.91\ ft^3$$

$$V_{allowable-CS} = 0.05(20\ \sec)\left(5200 \frac{gal}{\min} \frac{ft^3}{7.48\ gal} \frac{\min}{60\ \sec}\right)\left(\frac{25.0\ psia}{16.7\ psia}\right) = 17.35 ft^3$$

4.4.1.8 Transport Time Duration Limits

The transport time used in the Simplified Equation must not exceed the transport time limit. Therefore, the user should compare the appropriate pump criterion transport time limit ($\Delta t_{PUMP\ CRITERIA}$) from Table 2 with the transport time limit, and the minimum value should be used. The pump transport time limit from Table 2 is 20 seconds as determined in Section 4.4.1.1. The transport time limit is calculated as follows.

a. Calculate $V_{GAS} = V_{ALLOWABLE}$ using the Simplified Equation with α and Δt_{PUMP} obtained from the Reference 3 pump criteria. This was done in Section 4.4.1.7.

b. Calculate the maximum depth of the kinematic shock (y_1) using Equation 20 with V_{GAS} calculated by the Simplified Equation.

$$A = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 = 2.948\ ft^2$$

$$Q_0 = 6600\frac{gal}{\min}\left(\frac{ft^3}{7.48\ gal}\right)\left(\frac{\min}{60\ \sec}\right) = 14.706\frac{ft^3}{\sec}$$

$$U_0 = \frac{14.706\ \frac{ft^3}{\sec}}{2.948\ ft^2} = 4.988\frac{ft}{\sec}$$

$$y_1 = \frac{1}{A}\left\{V_{GAS} + \frac{Q_0 U_0}{g}\left[\frac{\sqrt{2gy_1}}{U_0} - \ln\left(1 + \frac{\sqrt{2gy_1}}{U_0}\right)\right]\right\}$$

This equation is easily solved using successive approximations. The initial guess is set as:

$$y_{1-0} = \frac{V_{GAS}}{A} = \frac{4.91\ ft^3}{2.948\ ft^2} = 1.665\ ft$$

The next iteration is:

$$\frac{Q_0 U_0}{g} = \frac{\left(14.706\ \frac{ft^3}{\sec}\right)\left(4.988\ \frac{ft}{\sec}\right)}{32.2\ \frac{ft}{\sec^2}} = 2.278\ ft^3$$

$$\frac{\sqrt{2gy_1}}{U_0} = \frac{\sqrt{2\left(32.2\ \frac{ft}{\sec^2}\right)(1.666\ ft)}}{4.988\ \frac{ft}{\sec}} = 2.077$$

$$y_1 = \frac{1}{A}\left\{V_{GAS} + \frac{Q_0 U_0}{g}\left[\frac{\sqrt{2gy_1}}{U_0} - \ln\left(1 + \frac{\sqrt{2gy_1}}{U_0}\right)\right]\right\}$$

$$y_{1-1,HPSI} = \frac{1}{2.948\ ft^2}\left\{4.91\ ft^3 + \left(2.278\ ft^3\right)\left[2.077 - \ln(1 + 2.077)\right]\right\} = 2.402\ ft$$

The remaining iterations are shown in Table 6.

Table 6 : Example Problem -Solution of Equation 20

Solution of Equation 20 Example Problem 1		
y_1 Guess	$\frac{\sqrt{2gy_1}}{U_0}$	y_1 Equation 20
1.6654	2.0762	2.4013
2.4013	2.4932	2.6253
2.6253	2.6068	2.6883
2.6883	2.6380	2.7058
2.7058	2.6465	2.7105
2.7105	2.6488	2.7118
2.7118	2.6495	2.7122

c. Calculate the transport time ($\Delta t_{TRANSPORT}$) using Equation 23 based on y_1 and V_{GAS}.

a, c

d. If $\Delta t_{TRANSPORT} < \Delta t_{PUMP}$, then multiply the gas volume allowed by the Simplified Equation by the ratio ($\Delta t_{TRANSPORT} / \Delta t_{PUMP}$) to yield the allowable volume.

Since $\Delta t_{TRANSPORT}$ =18.3 sec and Δt_{PUMP} = 20 sec, we must use the lower value of 18.3 sec. the revised gas volume is:

$$V_{allowable} = \left(4.91\ ft^3\right)\left(\frac{18.3\ \text{sec}}{20\ \text{sec}}\right) = 4.49\ ft^3$$

4.4.1.9 Adjustment of Allowable Gas Volume for Surveillance Conditions

The allowable gas volume must be adjusted to account for the difference in pressure at the high point during surveillance testing and post-accident operation.

$$V_{\text{Allowable,Surveillance}} = V_{Allowable} \frac{P_{HIGH-POINT,POST-ACCIDENT}}{P_{HIGH-POINT,SURVEILLANCE}}$$

$$V_{\text{Allowable,Surveillance}} = \left(4.49\ ft^3\right)\frac{16.7\ psia}{34.2\ psia} = 2.19\ ft^3$$

Therefore, the gas volume at the high point is limited to 2.19 ft^3 during surveillance testing which corresponds to a gas volume fraction of:

$$\alpha_{HIGH-POINT} = \frac{V_{ALLOWABLE}}{V_{HIGH-POINT}} = \frac{2.19\ ft^3}{44.22\ ft^3} = 0.05$$

4.4.1.10 Comparison of Volume Allowed by Simplified Equation with Limitations

A comparison of the Simplified Equation allowable gas volume with the various limitations on gas volume is shown in Table 7.

Table 7 : Comparison of Gas Volume Allowed by Simplified Equation with Limitations

Item	Criterion	Allowable Gas Volume (ft^3)	
1	Gas Volume $\leq$ 0.25 Down-comer Volume	14.0	
2	Simplified Equation Calculation	4.91	
3	Transport Time Limit	4.49	
4	Minimum of Items 1-3		4.49
5	Correction for Static Pressure during Surveillance Test	2.19	
6	Minimum of Items 5-6		2.19

4.4.1.11 Comments on Example 1

The following comments are made on the example problem:

- The difference between the pump operating pressure and the surveillance pressure has a large impact on the allowable gas volume in this example. The compression ratio of surveillance test to post-accident operating pressure is 34.2 : 16.7 ≈ 2 : 1.
- The transport time limit was more restrictive than the pump criterion limit for both pumps. This resulted in a slight restriction of the allowable gas volume.
- As documented in Reference 1, the basis for application of the Simplified Equation is the prevention of slug flow through the formation of a kinematic shock and the subsequent transport of a bubbly flow mixture. Therefore, if a tee is present, it is necessary to first considering the potential for the flow to stratify as it approaches the tee. If it is suspected that the flow will stratify, the potential for gas build-up and subsequent transport of a slug of gas due to an air entraining vortex exists. In this case, the Simplified Equation approach cannot be applied. If it is determined that the gas flow will approach the tee in a dispersed flow regime, then it is conservative to assume that the gas volumetric flow rate through either tee branch is equal to the gas volumetric flow rate in the supply. The effects of this assumption on gas volumetric flow ratio for example problem 1 are illustrated below.
    - o Gas volumetric flow rate in supply header to vertical tee.

$$Q_{GAs} = \frac{V_{GAS}}{\Delta t_{TRANPSORT}} = \frac{\left(4.49\ ft^3\right)\frac{16.7\ psia}{26.3\ psia}}{18.3\ \text{sec}} = 0.156\frac{ft^3}{\text{sec}}$$

- o Gas volumetric flow ratio at tee inlet.

$$\beta_{TEE-INLET} = \frac{Q_{GAS}}{Q_{TOTAL}} = \frac{0.156\ ft^3/\text{sec}}{14.7\ ft^3/\text{sec}} = 0.011$$

- o Gas volumetric flow ratio at CS pump inlet.

$$\beta_{CS} = \frac{Q_{GAS}}{Q_{CS}} = \frac{0.156\frac{ft^3}{\text{sec}}\left(\frac{26.3\ psia}{25.0\ psia}\right)}{11.59\ ft^3/\text{sec}} = 0.014$$

- o Gas volumetric flow ratio at HPSI pump inlet.

$$\beta_{HPSI} = \frac{Q_{GAS}}{Q_{HPSI}} = \frac{0.156\ ft^3/\text{sec}}{3.12\ ft^3/\text{sec}} = 0.050$$

Therefore, it is noted that the approach used ensures the gas volumetric flow ratio at the limiting pump is restricted to the limiting pump criterion.

- It is important to note that this example illustrates that, in the presence of off-takes, the worst case may not be when the liquid flow is maximized. The worst case would be when the liquid flow is low enough such that flow could stratify in a tee or off-take. In that case, the methodology is not applicable. Therefore, if system operation would allow flow rates lower than those considered in this example, the applicability of the allowable gas volumes at these lower flow rates would have to be considered.

4.4.2 Example Problem 2

The intent of this example problem is to illustrate the overall methodology and demonstrate treatment of horizontal headers with off-takes. The layout for this problem is illustrated in Figure 21. The Figure shows a high point location downstream of the RWST check valve. The high point location is outside of containment and could be monitored using ultrasonic transducers (UT).

It is assumed that inputs required for the calculation are obtained from appropriate sources for the plant. For example, typical references for this particular problem could be:

- Plant process & instrumentation diagrams (P&IDs) and plant layout isometric drawings yield the following information:
  - o High point location.
  - o Piping elevations.
  - o Pipe diameters and schedules.
- Calculation of available NPSH from RWST yields the following information:

  - Pump flow rates.
  - RWST minimum water level during post-accident operation.
  - $NPSH_A$ to pumps.
  - Overpressure applicable in $NPSH_A$ calc.
  - Hydraulic friction and form loss from high point to pump inlet.
- Calculation of RWST level set-points yields the following information:
  - RWST level during normal plant operation.
- Two-phase flow hand book
  - Appropriate flow regime maps for horizontal and vertical flow conditions approaching off-takes.
- Pump manuals
  - Pump best efficiency operating point.

4.4.2.1 Determine the allowable pump inlet void fraction

The data for the three pumps is shown in Table 8.

Table 8 : Example 2 Pump Information

Example 2 Pump Information			
Pump	**HPSI**	**LPSI**	**CS**
Type	Multi-stage Stiff Shaft CA	Single Stage WDF	Single-stage WDF
BEP Flow	900 gpm	4300 gpm	4300 gpm
Maximum Flow Rate during Post-Accident Recirculation Mode of Operation	1400 gpm	5500 gpm	5200 gpm
Q/Q_{BEP}	1.56	1.28	1.21

Since the value of Q/Q_{BEP} > 1.20 for all pumps, Table 2 indicates that the allowable gas volume fraction at the pump inlet is 5% for 20 seconds.

4.4.2.2 Determine possible gas accumulation locations

The gas accumulation location dealt with in this example is the location outside containment downstream of the check valve. The check valve acts to collect any gas which migrates to the high point.

4.4.2.3 Define the suction path from the suction source to the pump for all modes of operation

The following operating modes are applicable to the HPSI, LPSI and CS pumps.

High Pressure Safety Injection (HPSI) Pump

- Safety injection with suction from the refueling water storage tank (RWST).
- Post-accident long term core cooling recirculation with suction from the containment sump.

Low Pressure Safety Injection (LPSI) or RHR Pump

- Safety injection with suction from the RWST.
- Normal cooldown with suction from reactor coolant system (RCS) hot legs.
- Post-accident long term core cooling recirculation with suction from the sump.

Containment Spray Pump

- Spray with suction from the RWST.
- Post-accident long term core cooling recirculation spray with suction from the sump.

This particular example will only treat the suction flow path from the RWST during the safety injection mode since that is where the accumulation location is. However, in general, all of these flow paths would be reviewed for possible accumulation locations.

4.4.2.4 Define the Simplified Equation hydraulic input parameters

4.4.2.4.1 Define the system flow rates

In this particular example, each train has a separate connection to the RWST. The maximum HPSI pump flow rate is 1400 gpm, the maximum LPSI pump flow rate is 5500 gpm, and the maximum CS pump flow rate is 5200 gpm. The total header flow rate is 12,100 gpm.

4.4.2.4.2 Define static pressure at high point location during surveillance test

During normal operation when the gas accumulation surveillance test is performed the RWST head will dictate the static backpressure on the accumulation location. It is conservative to use the maximum high-point pressure in the Simplified Equation. Therefore, the maximum RWST level of 125 feet elevation will be used. The elevation of the accumulation location is 95 feet. The minimum RWST temperature is 40°F. The fluid density at this temperature is 62.4 lb_m/ft^3. Therefore, the maximum high point static pressure during surveillance conditions is:

$$P_{HIGH-POINT} = P_{ATM} + \frac{\rho}{144}\frac{g}{g_c}\left(Z_{RWST} - Z_{HIGH-POINT}\right)$$

$$P_{HIGH-POINT} = 14.7\ psia + \frac{62.4 \frac{lb_m}{ft^3}}{144 \frac{in^2}{ft^2}} \left(\frac{32.2 \frac{ft}{\sec^2}}{32.2 \frac{lb_m - ft}{lb_f - \sec^2}} \right) (125\ ft - 95\ ft) = 27.7\ psia$$

4.4.2.4.3 Define minimum pump suction pressures during required operating scenario

The $NPSH_A$ calculation for the injection mode of operation indicates the minimum $NPSH_A$ to the HPSI pump at 1400 gpm is 43.8 feet, the minimum $NPSH_A$ to the LPSI pump at 5500 gpm is 41.3 feet, and the minimum $NPSH_A$ to the CS pump at 5200 gpm is 42.2 feet. The fluid density used in this $NPSH_A$ calculation was 61.7 lb_m/ft^3 and the associated vapor pressure is 1.7 psia. Therefore, the minimum pump suction pressure during post-accident operating conditions is:

$$P_{PUMP} = P_{VAPOR} + \frac{\rho}{144} \frac{g}{g_c} NPSH_A$$

$$P_{HPSI} = 1.7\ psia + \frac{61.7 \frac{lb_m}{ft^3}}{144 \frac{in^2}{ft^2}} \left(\frac{32.2 \frac{ft}{\sec^2}}{32.2 \frac{lb_m - ft}{lb_f - \sec^2}} \right) (43.8\ ft) = 20.5\ psia$$

$$P_{LPSI} = 1.7\ psia + \frac{61.7 \frac{lb_m}{ft^3}}{144 \frac{in^2}{ft^2}} \left(\frac{32.2 \frac{ft}{\sec^2}}{32.2 \frac{lb_m - ft}{lb_f - \sec^2}} \right) (41.3\ ft) = 19.4\ psia$$

$$P_{CS} = 1.7\ psia + \frac{61.7 \frac{lb_m}{ft^3}}{144 \frac{in^2}{ft^2}} \left(\frac{32.2 \frac{ft}{\sec^2}}{32.2 \frac{lb_m - ft}{lb_f - \sec^2}} \right) (42.2\ ft) = 19.8\ psia$$

However, the $NPSH_A$ calculations were based on an RWST water elevation of 106 feet. It is expected that the gas transport process will occur at the initiation of the injection mode when the RWST water level is at the technical specification minimum required level of 121 feet. Therefore, the pressure equivalent of 121 ft – 106 ft = 15 feet can be added to each of the minimum static pressures. This is equivalent to:

$$\Delta P_{RWST-LEVEL} = \frac{61.7 \frac{lb_m}{ft^3}}{144 \frac{in^2}{ft^2}} \left(\frac{32.2 \frac{ft}{\sec^2}}{32.2 \frac{lb_m - ft}{lb_f - \sec^2}} \right) (15\ ft) = 6.4\ psi$$

The revised values are:

P_{HPSI} = 20.5 psia + 6.4 psi = 26.9 psia

P_{LPSI} = 19.4 psia + 6.4 psi = 25.8 psia

P_{CS} = 19.8 psia + 6.4 psi = 26.2 psia

4.4.2.4.4 Define high point pressures during required operating scenario

The elevation of the high point location is 95 feet. The elevation of the pump suction is 46 feet. The hydraulic friction and form loss from the high point to the HPSI pump inlet is 15 ft. Therefore, the high point pressure during post-accident operating conditions is:

$$P_{HIGH-POINT} = P_{Pump} + \frac{\rho}{144}\frac{g}{g_c}\left(Z_{PUMP} - Z_{HIGH-POINT} + \Delta h_{LOSS}\right)$$

$$P_{HIGH-POINT} = 26.9\ psia + \frac{61.7\ \frac{lb_m}{ft^3}}{144\ \frac{in^2}{ft^2}}\left(\frac{32.2\ \frac{ft}{\sec^2}}{32.2\ \frac{lb_m - ft}{lb_f - \sec^2}}\right)\left(46\ ft - 95\ ft + 15\ ft\right) = 12.3\ psia$$

4.4.2.5 Verify limitations on use of the Simplified Equation are met.

This requires the identification of certain layout parameters.

4.4.2.5.1 Define volume of gas accumulation location

The distance from the check valve outlet to the centerline of the down-comer is 15 feet. The pipe inside diameter is 23.25 inch. Therefore, the volume of the high point location is:

$$V_{HIGH-POINT} = \frac{\pi}{4}\left(\frac{D}{12}\right)^2 L$$

$$V_{HIGH-POINT} = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\ \frac{in}{ft}}\right)^2 (15\ ft) = 44.22\ ft^3$$

4.4.2.5.2 Define volume of vertical down-comer downstream of accumulation location

The elevation of the high point location is 95 feet. The elevation of the horizontal header is 65 feet. The elevation of the pump suction is 46 feet. Therefore, the volumes of the vertical down-comers are:

$$V_{DOWN-COMER-1} = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 (95\ ft - 65\ ft) = 88.45\ ft^3$$

$$V_{DOWN-COMER-2} = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 (65\ ft - 46\ ft) = 56.02\ ft^3$$

4.4.2.5.3 Identify if there are any off-takes between the high point location and pump inlet

There is a tee branch where the RWST splits to the LPSI and horizontal header which supply the HPSI and CS pumps. There is also a horizontal header which supplies the HPSI and CS pumps.

4.4.2.6 Evaluate Limitations on Simplified Equation

4.4.2.6.1 Flow Rates

1. The system flow rate must be limited to those corresponding to the maximum Froude Number tested at Purdue University: $N_{FR} \leq 2.5$. This limit on Froude number will be met if the flow rate meets the following criteria:

   $Q \leq 10\ D^{2.5} = 10\ (23.25)^{2.5} = 26{,}065$ gpm.

   We are well within this limit.

4.4.2.6.2 Layout Limitations

Application of the Simplified Equation is based on the assumption that there is a vertical down-comer downstream of the high point location which is large enough to contain the kinematic shock region. The dynamics of the kinematic shock formation dictate that the available down-comer volume must be at least 4 times as great as the allowable gas volume. The allowable gas volume ($V_{ALLOWABLE}$) must be restricted to ¼ of the maximum vertical down-comer volume. The maximum vertical down-comer volume was determined to be 88.45 ft^3 in Section 4.4.2.5.2.

Therefore, this limitation requires that $V_{ALLOWABLE} \leq 0.25\ (88.45\ ft^3) = 28\ ft^3$. This criterion is not limiting.

4.4.2.6.3 Treatment of Off-Takes

There is a tee in the system. Tees have to be evaluated in a very thorough manner since the potential for gas accumulation and subsequent pull-through of a slug of gas exists as explained in Section 3.4.3.

The tee is the RWST supply connection to the pump supply header and is located in a vertical plane. By use of an appropriate flow regime map for vertical two-phase flow, it is verified that the flow regime is bubbly flow as it approaches the tee. This means that gas build up will not occur at the tee inlet and the potential for large slugs of gas to be pulled into the tee branch due to an air entraining vortex is eliminated. Therefore, it is appropriate to assume the gas is dispersed throughout the flow field and conservative to assume that the gas volumetric flow rate in the tee branch to the LPSI pump is less than or equal to the gas volumetric flow rate in the RWST supply header.

A horizontal header supplies the HPSI pump and CS pump. These will be evaluated in the following paragraphs.

The HPSI pump is supplied by a 10-inch connection which branches horizontally from the 24 inch supply header. The insider diameter of this pipe is 10.25 inches. This leaves a gap of (23.25 inches – 10.25 inches)/2 = 6.5 inches above the connection where stratified gas in the horizontal header can accumulate. If the gas stratifies and the depth of gas reaches a critical depth an air entraining vortex can occur which may result in a large slug of gas being transported to the HPSI pump. Therefore, the first step is to determine the flow regime in the supply line to the off-take. The flow rate in this line is the HPSI flow and CS flow and is 6600 gpm. By use of an appropriate flow regime map for horizontal flow, it is determined that the flow regime is not stratified and the potential to establish open channel flow and entrain gas by means of an air entraining vortex is eliminated. Therefore, it is conservative to assume the gas volumetric flow in the HPSI off-take is less than or equal to the gas volumetric flow rate in the RWST supply line.

The CS pump is supplied by means of a 90° elbow turned vertically downward at the end of the horizontal header. The flow rate in this line is the CS pump flow rate. The potential exists for the flow to stratify in the horizontal header. Since the total gas volume supplied to this header is less than or equal to the gas volume at the high point location, and the flow rate is less than the flow rate at the high point location, it is concluded that the gas volumetric flow rate down the down-comer will be less than the gas volumetric flow rate in the supply header. It is conservative to apply the gas volumetric flow rate in the RWST supply header to this flow path.

4.4.2.7 Gas Transport Evaluation

The Simplified Equation will now be applied to the LPSI and CS pumps, using the input values in Table 9.

Table 9 : Simplified Equation Input Parameters

PARAMETER	HPSI	LPSI	CS
α_{PUMP}	.05	.05	.05
Δt_{PUMP}	20 sec	20 sec	20 sec
Q_{PUMP}	1400 gal/min	5500 gal/min	5200 gal/min
$P_{HIGH\text{-}POINT}$	12.3 psia	12.3 psia	12.3 psia
P_{PUMP}	26.9 psia	25.8 psia	26.2 psia

The resultant gas volume allowed by the Simplified Equation is:

$$V_{allowable} = \alpha_{pump} \Delta t_{pump} Q_{pump} \left(\frac{P_{pump}}{P_{high\_point}} \right)$$

$$V_{allowable-HPSIS} = 0.05(20\ \text{sec})\left(1400 \frac{gal}{\min} \frac{ft^3}{7.48\ gal} \frac{\min}{60\ \text{sec}}\right)\left(\frac{26.9\ psia}{12.3\ psia}\right) = 6.82\ ft^3$$

$$V_{allowable-LPSI} = 0.05(20\ \text{sec})\left(5500 \frac{gal}{\min} \frac{ft^3}{7.48\ gal} \frac{\min}{60\ \text{sec}}\right)\left(\frac{25.8\ psia}{12.3\ psia}\right) = 25.71\ ft^3$$

$$V_{allowable-CS} = 0.05(20\ \text{sec})\left(5200 \frac{gal}{\min} \frac{ft^3}{7.48\ gal} \frac{\min}{60\ \text{sec}}\right)\left(\frac{26.2\ psia}{12.3\ psia}\right) = 24.68\ ft^3$$

Therefore, the limiting allowable gas volume based on the Simplified Equation is 6.82 ft^3.

4.4.2.8 Transport Time Duration Limits

The transport time used in the Simplified Equation must not exceed the transport time limit. Therefore, the use should compare the appropriate pump criterion transport time limit ($\Delta t_{PUMP\ CRITERIA}$) from Table 2 with the transport time limit, and the minimum value should be used. The pump transport time limit from Table 2 is 20 seconds as determined in Section 4.4.2.1. The transport time limit is calculated as follows.

a. Calculate $V_{GAS} = V_{ALLOWABLE}$ using the Simplified Equation with α and Δt_{PUMP} obtained from the Reference 3 pump criteria. This was done in Section 4.4.2.7.

b. Calculate the maximum depth of the kinematic shock (y_1) using Equation 20 with V_{GAS} calculated by the Simplified Equation.

$$A = \frac{3.1416}{4}\left(\frac{23.25\ in}{12\frac{in}{ft}}\right)^2 = 2.948\ ft^2$$

$$Q_0 = 12100 \frac{gal}{\min}\left(\frac{ft^3}{7.48\ gal}\right)\left(\frac{\min}{60\ \text{sec}}\right) = 26.96 \frac{ft^3}{\text{sec}}$$

$$U_0 = \frac{26.96 \frac{ft^3}{\text{sec}}}{2.948\ ft^2} = 9.145 \frac{ft}{\text{sec}}$$

$$y_1 = \frac{1}{A}\left\{V_{GAS} + \frac{Q_0 U_0}{g}\left[\frac{\sqrt{2gy_1}}{U_0} - \ln\left(1 + \frac{\sqrt{2gy_1}}{U_0}\right)\right]\right\}$$

This equation is easily solved using successive approximations. The initial guess is set as:

$$y_{1-0} = \frac{V_{GAS}}{A} = \frac{6.82\ ft^3}{2.948\ ft^2} = 2.313\ ft$$

The next iteration is:

$$\frac{Q_0 U_0}{g} = \frac{\left(26.96\ \frac{ft^3}{\sec}\right)\left(9.145\ \frac{ft}{\sec}\right)}{32.2\ \frac{ft}{\sec^2}} = 7.657\ ft^3$$

$$\frac{\sqrt{2gy_1}}{U_0} = \frac{\sqrt{2\left(32.2\ \frac{ft}{\sec^2}\right)(2.313\ ft)}}{9.145\ \frac{ft}{\sec}} = 1.335$$

$$y_1 = \frac{1}{A}\left\{V_{GAS} + \frac{Q_0 U_0}{g}\left[\frac{\sqrt{2gy_1}}{U_0} - \ln\left(1 + \frac{\sqrt{2gy_1}}{U_0}\right)\right]\right\}$$

$$y_{1-1,HPSI} = \frac{1}{2.948\ ft^2}\left\{6.82\ ft^3 + \left(7.657\ ft^3\right)\left[1.335 - \ln(1 + 1.335)\right]\right\} = 3.578\ ft$$

The remaining iterations are shown in Table 10.

Table 10 : Example Problem -Solution of Equation 20

Solution of Equation 20 Example Problem 2		
y_1 Guess	$\frac{\sqrt{2gy_1}}{U_0}$	y_1 Equation 20
2.3132	1.3347	3.5774
3.5774	1.6599	4.0832
4.0832	1.7733	4.2694
4.2694	1.8133	4.3360
4.3360	1.8274	4.3597
4.3597	1.8324	4.3680
4.3680	1.8341	4.3710
4.3710	1.8347	4.3720
4.3720	1.8349	4.3724
4.3724	1.8350	4.3725

c. Calculate the transport time ($\Delta t_{TRANSPORT}$) using Equation 23 based on y_1 and V_{GAS}.

a, c

d. If $\Delta t_{TRANSPORT} < \Delta t_{PUMP}$, then multiply the gas volume allowed by the Simplified Equation by the ratio ($\Delta t_{TRANSPORT} / \Delta t_{PUMP}$) to yield the allowable volume.

Since $\Delta t_{TRANSPORT}$ =10.0 sec and Δt_{PUMP} = 20 sec, we must use the lower value of 10.0 sec. The revised gas volume is:

$$V_{allowable} = \left(6.82\ ft^3\right)\left(\frac{10\ \text{sec}}{20\ \text{sec}}\right) = 3.41\ ft^3$$

4.4.2.9 Adjustment of Allowable Gas Volume for Surveillance Conditions

The allowable gas volume must be adjusted to account for the difference in pressure at the high point during surveillance testing and post-accident operation.

$$V_{\text{Allowable,Surveillance}} = V_{Allowable} \frac{P_{HIGH-POINT,POST-ACCIDENT}}{P_{HIGH-POINT,SURVEILLANCE}}$$

$$V_{\text{Allowable,Surveillance}} = \left(3.41\ ft^3\right)\frac{12.3 psia}{27.7\ psia} = 1.51\ ft^3$$

Therefore, the gas volume at the high point is limited to 1.51 ft^3 during surveillance testing which corresponds to a gas volume fraction of:

$$\alpha_{HIGH-POINT} = \frac{V_{ALLOWABLE}}{V_{HIGH-POINT}} = \frac{1.51\ ft^3}{44.22\ ft^3} = 0.034$$

4.4.2.10 Comparison of Volume Allowed by Simplified Equation with Limitations

A comparison of the Simplified Equation allowable gas volume with the various limitations on gas volume is shown in Table 11.

Table 11 : Comparison of Gas Volume Allowed by Simplified Equation with Limitations

Item	Criterion	Allowable Gas Volume (ft^3)	
1	Gas Volume $\leq$ 0.25 Down-comer Volume	28.0	
2	Simplified Equation Calculation	6.82	
3	Transport Time Limit	3.41	
4	Minimum of Items 1-3		3.41
5	Correction for Static Pressure during Surveillance Test	1.51	
6	Minimum of Items 5-6		1.51

4.4.2.11 Comments on Example 2

The following notes are made on the example problem:

- This example illustrated the care that must be exercised when there are either tee branches or a horizontal header with off-takes between the high point location and the pump inlet. As documented in Reference 1, the basis for application of the Simplified Equation is the prevention of slug flow through the formation of a kinematic shock and the subsequent transport of a bubbly flow mixture. Therefore, if a tee or off-take is present, it is necessary to first, consider the potential for the flow to stratify, as it approaches the tee. If it is suspected that the flow will stratify, the potential for gas build-up and subsequent transport of a slug of gas due to an air entraining vortex exists. In this case, the Simplified Equation approach cannot be applied. If it is determined that the gas flow will approach the tee in a dispersed flow regime, then it is conservative to assume that the gas volumetric flow rate, through either tee branch, is equal to the gas volumetric flow rate in the supply. The effects of this assumption on gas volumetric flow ratio for example problem 2 are illustrated below.
    - Gas volumetric flow rate in supply header to vertical tee.

$$Q_{GAs} = \frac{V_{GAS}}{\Delta t_{TRANPSORT}} = \frac{\left(3.41\ ft^3\right)\frac{12.3\ psia}{26.9\ psia}}{10.0\ \sec} = 0.156\frac{ft^3}{\sec}$$

- Gas volumetric flow ratio at tee inlet.

$$\beta_{TEE-INLET} = \frac{Q_{GAS}}{Q_{TOTAL}} = \frac{0.156\ ft^3/\sec}{26.96\ ft^3/\sec} = 0.006$$

- Gas volumetric flow ratio at LPSI pump inlet.

$$\beta_{CS} = \frac{Q_{GAS}}{Q_{CS}} = \frac{0.156\frac{ft^3}{\sec}\left(\frac{26.9\ psia}{25.8\ psia}\right)}{12.25\ ft^3/\sec} = 0.013$$

- Gas volumetric flow ratio at HPSI off-take inlet.

- $$\beta_{TEE-INLET} = \frac{Q_{GAS}}{Q_{TOTAL}} = \frac{0.156\ ft^3/\sec}{14.706\ ft^3/\sec} = 0.011$$

- Gas volumetric flow ratio at CS pump inlet.

- $$\beta_{CS} = \frac{Q_{GAS}}{Q_{CS}} = \frac{0.156\frac{ft^3}{\sec}\left(\frac{26.9\ psia}{25.8\ psia}\right)}{11.59\ ft^3/\sec} = 0.014$$

- Gas volumetric flow ratio at HPSI pump inlet.

$$\beta_{HPSI} = \frac{Q_{GAS}}{Q_{HPSI}} = \frac{0.156\ ft^3/\sec}{3.12\ ft^3/\sec} = 0.050$$

Therefore, it is noted that the approach used ensures the gas volumetric flow ratio at the limiting pump is restricted to the limiting pump criterion.

- It is important to note that this example illustrates that the worst case may not be when the liquid flow is maximized. The worst case would be when the liquid flow is low enough such that flow could stratify in a tee or off-take. In that case, the methodology is not applicable. Therefore, if system operation would allow flow rates lower than those considered in this example, the applicability of the allowable gas volumes at these lower flow rates would have to be considered.

5 REFERENCES

1. PWROG Letter OG-10-16, "Transmittal of Fauske & Associates Report, FAI/09-130, 'Technical Basis for Gas Transport to the Pump Suction,' (PA-SEE-0533 Revision 1)," January 11, 2010.
2. NRC Division of Safety Systems, "Revision 2 to NRC Staff Criteria for Gas Movement in Suction Lines and Pump Response to Gas," Accession Number ML090900136, March 2009.
3. NEI APC Letter, "Industry Guidance - Evaluation of Unexpected Voids or Gas Identified in Plant ECCS and Other Systems," June 18, 2009.
4. Westinghouse Electric Company LLC, "Phenomena Identification and Ranking Table (PIRT) to Evaluate Void Fraction / Flow Regime at ECCS, RHR and CS Pump Suctions," WCAP-17167-NP, Rev. 0, December 2009.
5. Westinghouse Electric Company LLC., "Air-Water Transport in large Diameter Piping Systems: Evaluation and Analysis of Large Diameter Testing Performed at Purdue University (DRAFT)," WCAP-17271-P, Volumes 1 - 3, Draft Revision 0-A, July, 2010, (Revision 0 to be issued August, 2010).
6. NEI-09-10, "Guidelines for Effective Prevention and Management of System Gas Accumulation," October 30, 2009.
7. "Emergency Core Cooling Pump Performance with Partially Voided Suction Conditions," Smyth et.al., NUREG/SP-0152, Vol. 6, Proceedings of the Ninth NRC/ASME Symposium on Valves, Pumps, and Inservice Testing.

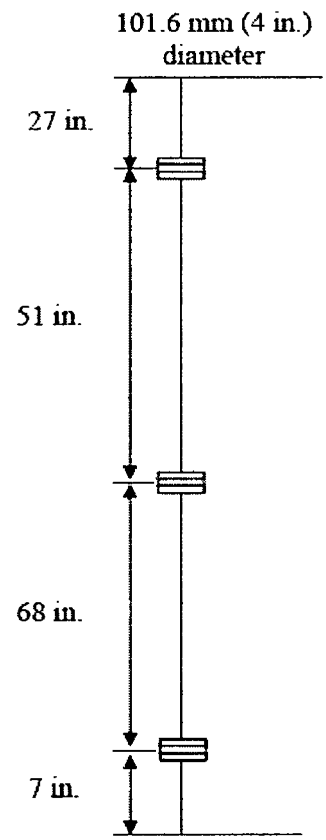

Figure 1 : Purdue University 4-inch Vertical Down-comer Void Meter Locations

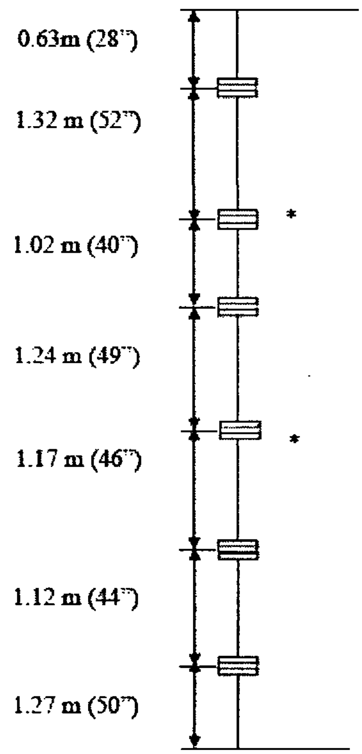

Figure 2 : Purdue University 6-inch Vertical Down-comer Void Meter Locations

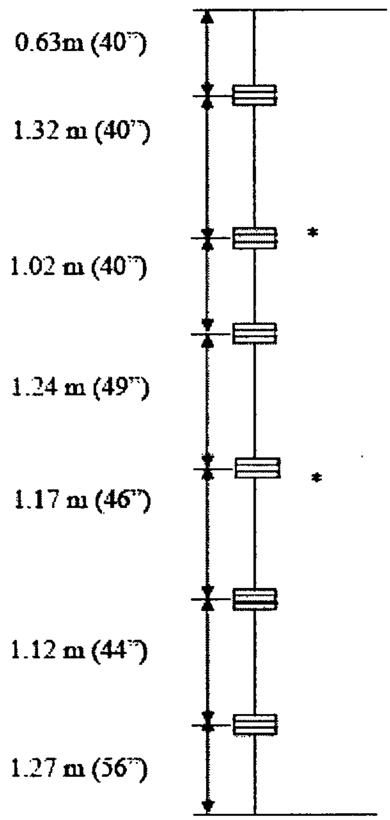

Figure 3 : Purdue University 8-inch Vertical Down-comer Void Meter Locations

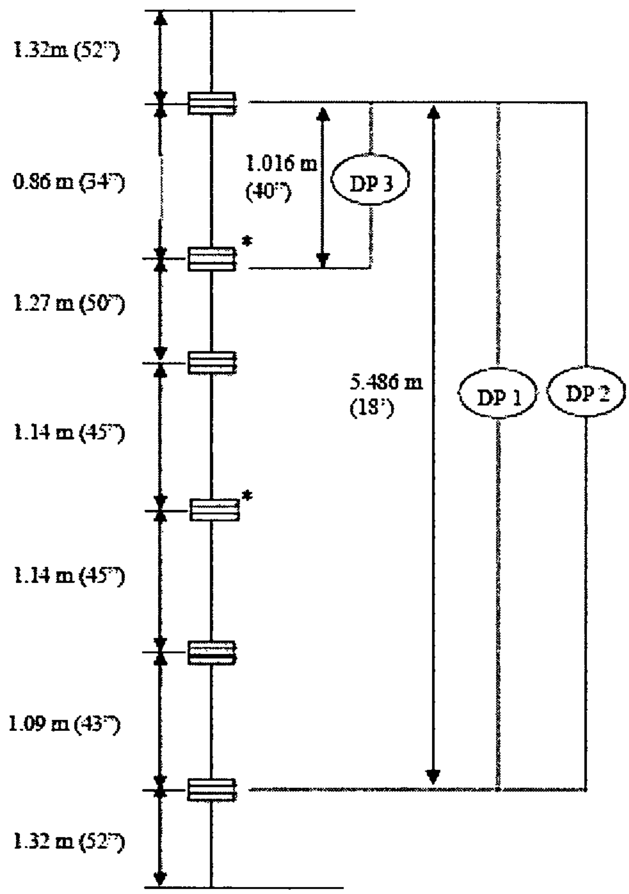

Figure 4 : Purdue University 12-inch Vertical Down-comer Void Meter Locations

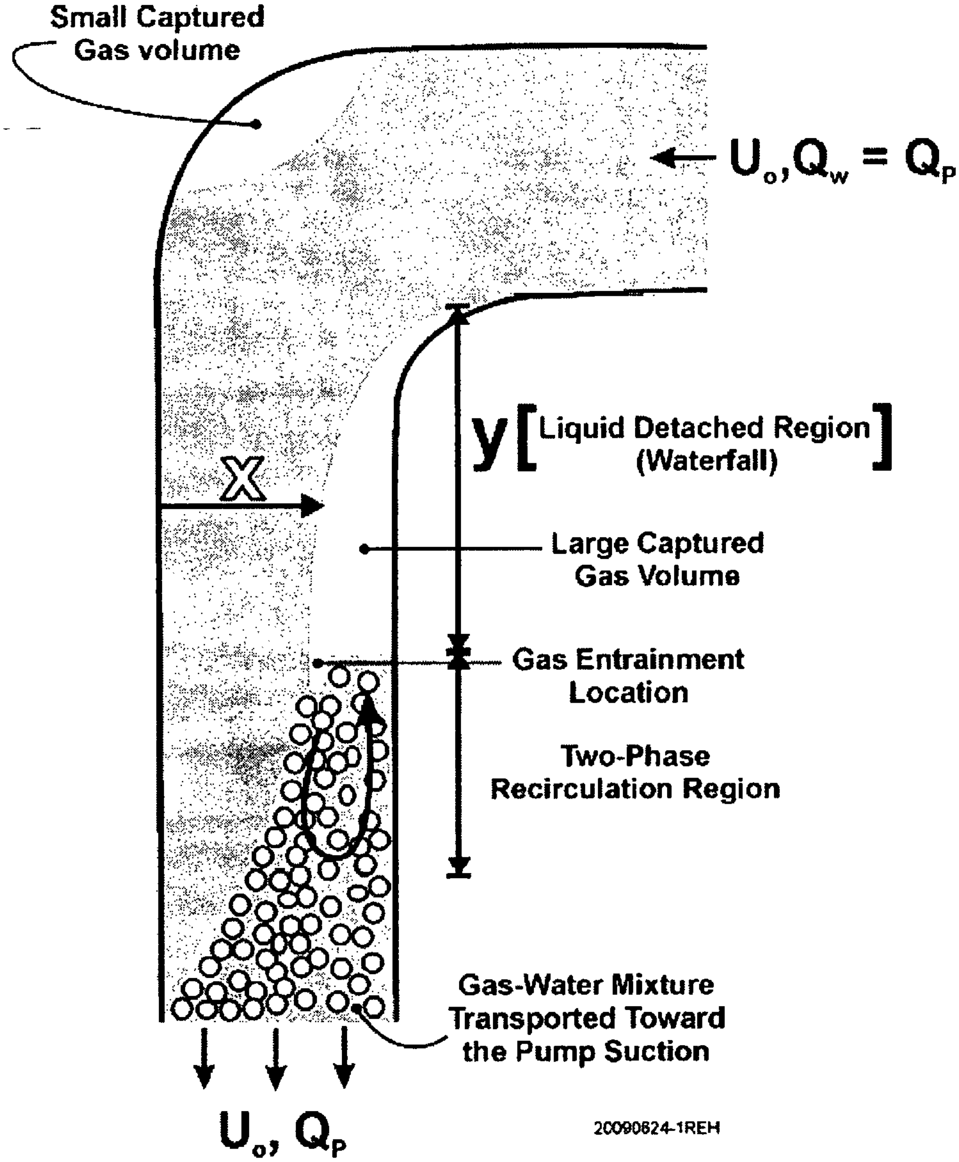

Figure 5 : Waterfall and Gas Entrainment by the High Velocity Jet Entering the Water

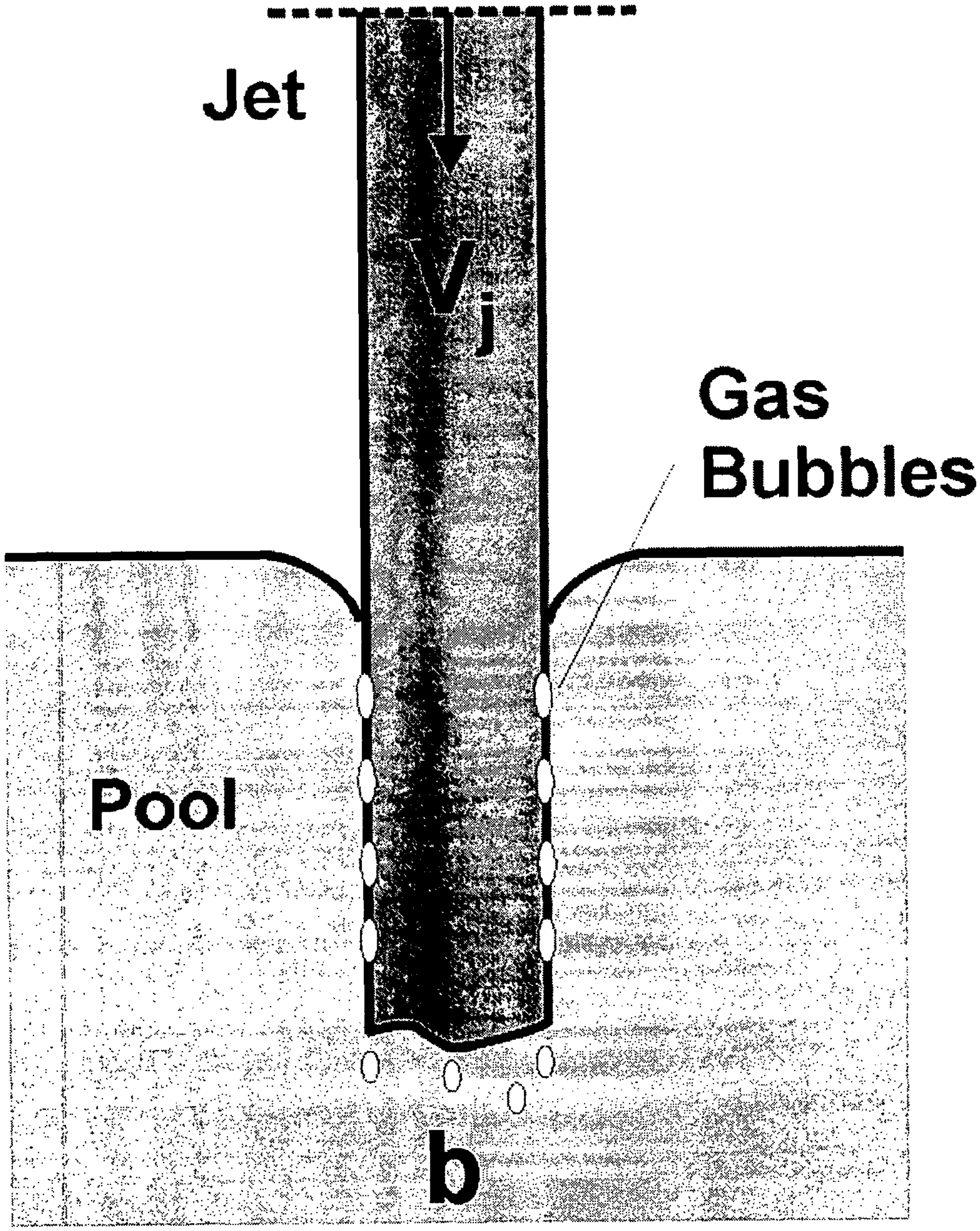

Figure 6 : Entrainment Mechanism for Plunging Liquid Jets

a, c

Figure 7 : Comparison of Gas Volumetric Flow Ratio Calculated by FAI/09-130 with Purdue Tests

a, c

Figure 8 : Comparison of Transport Time Calculated by FAI/09-130 with Purdue Tests

a, c

Figure 9 : [ ]a, c

a, c

Figure 10 : [ ]a, c

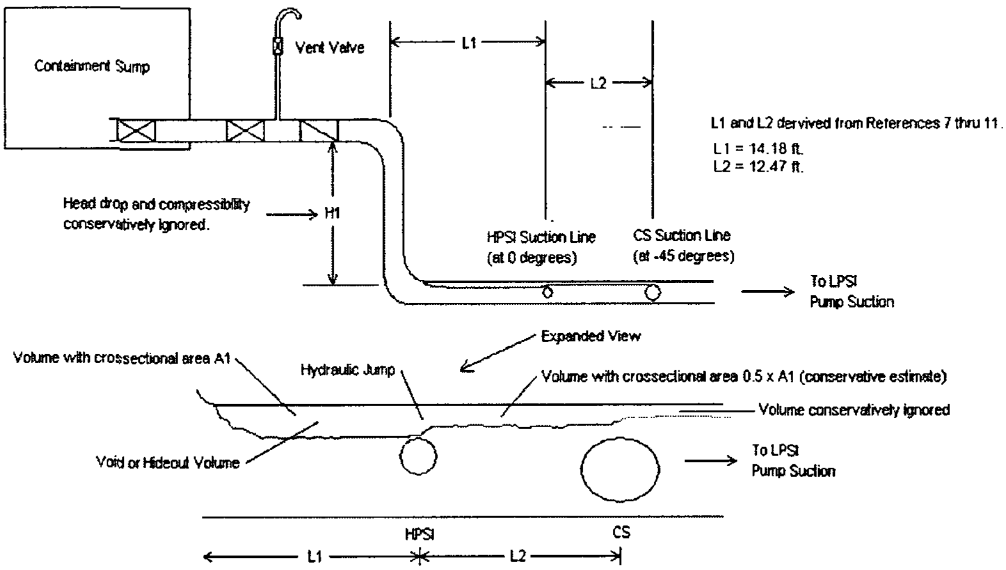

Figure 11: Horizontal Supply Header Example

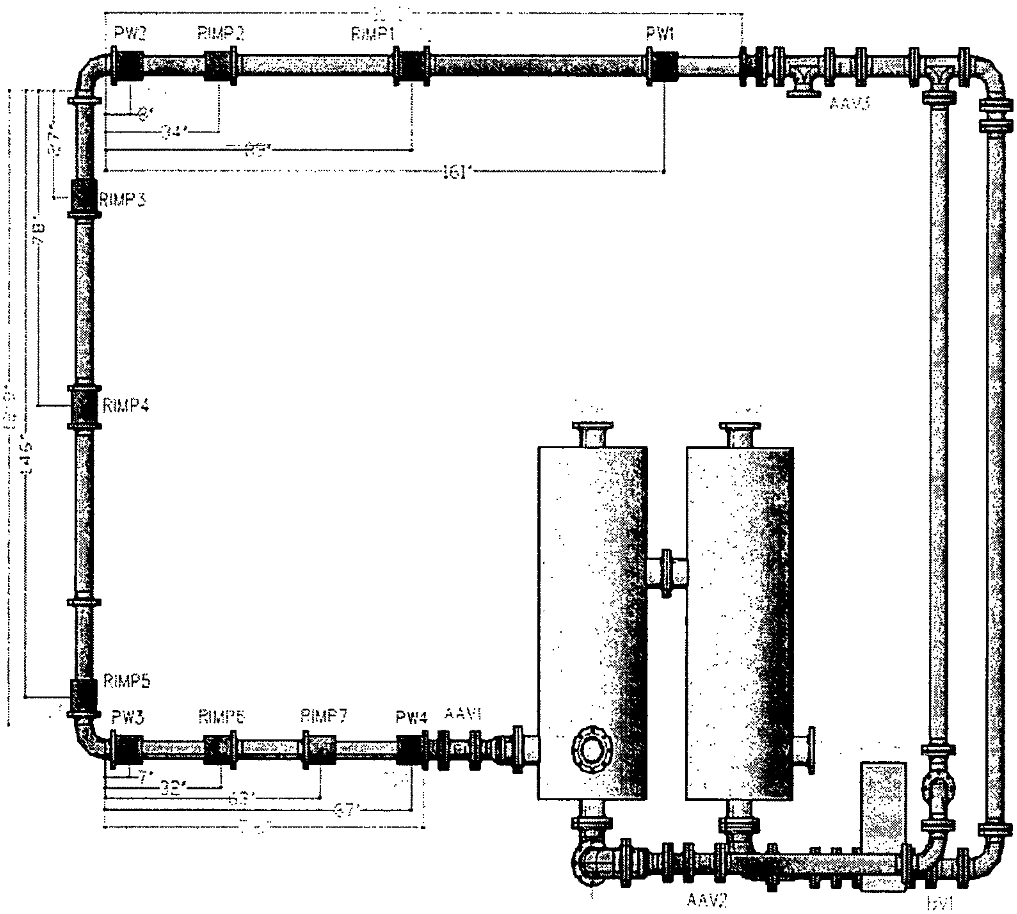

Figure 12: Piping Layout for 4 inch Test Facility

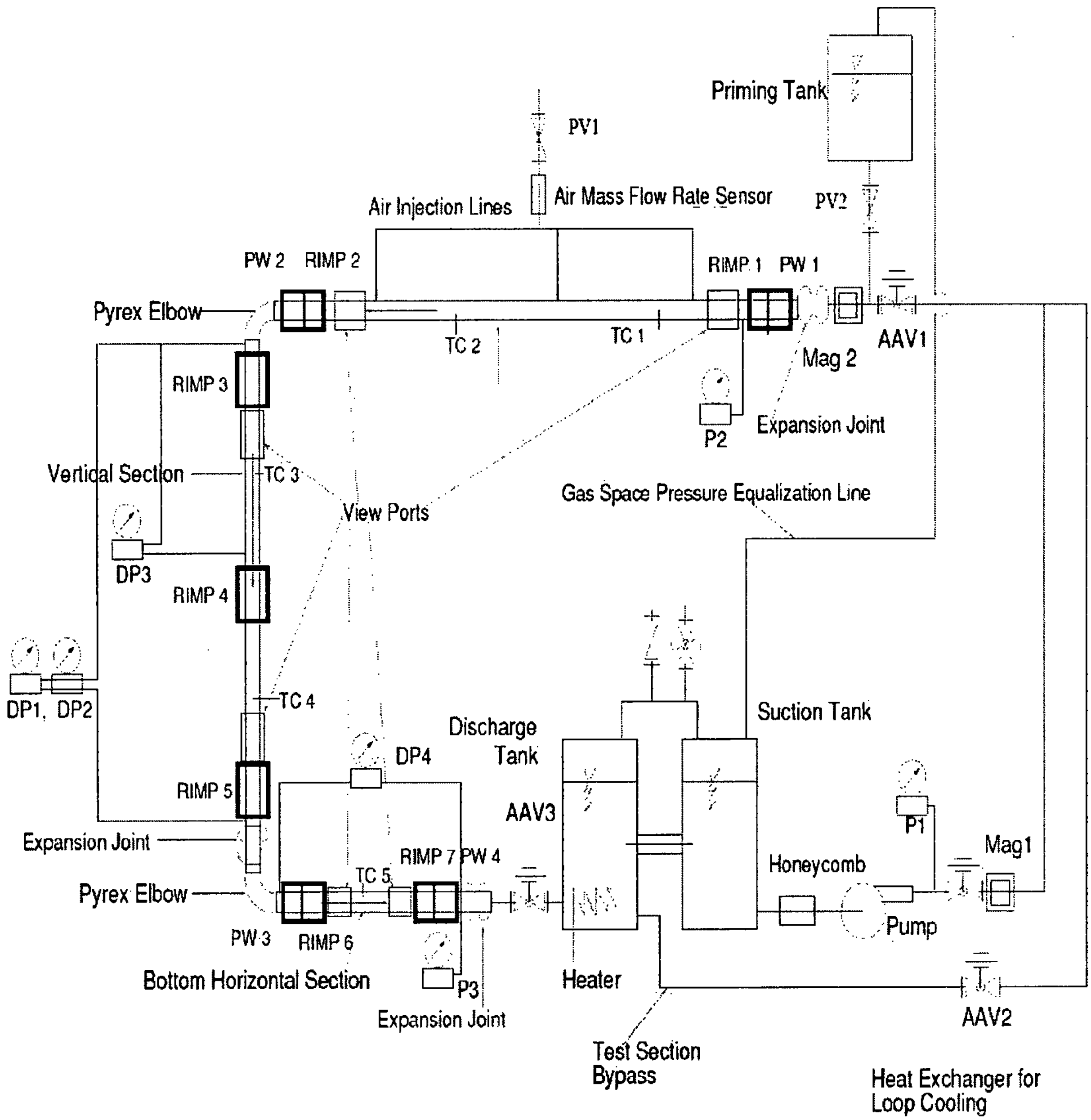

Figure 13: Piping and Instrumentation Layout for 4 inch Test Facility

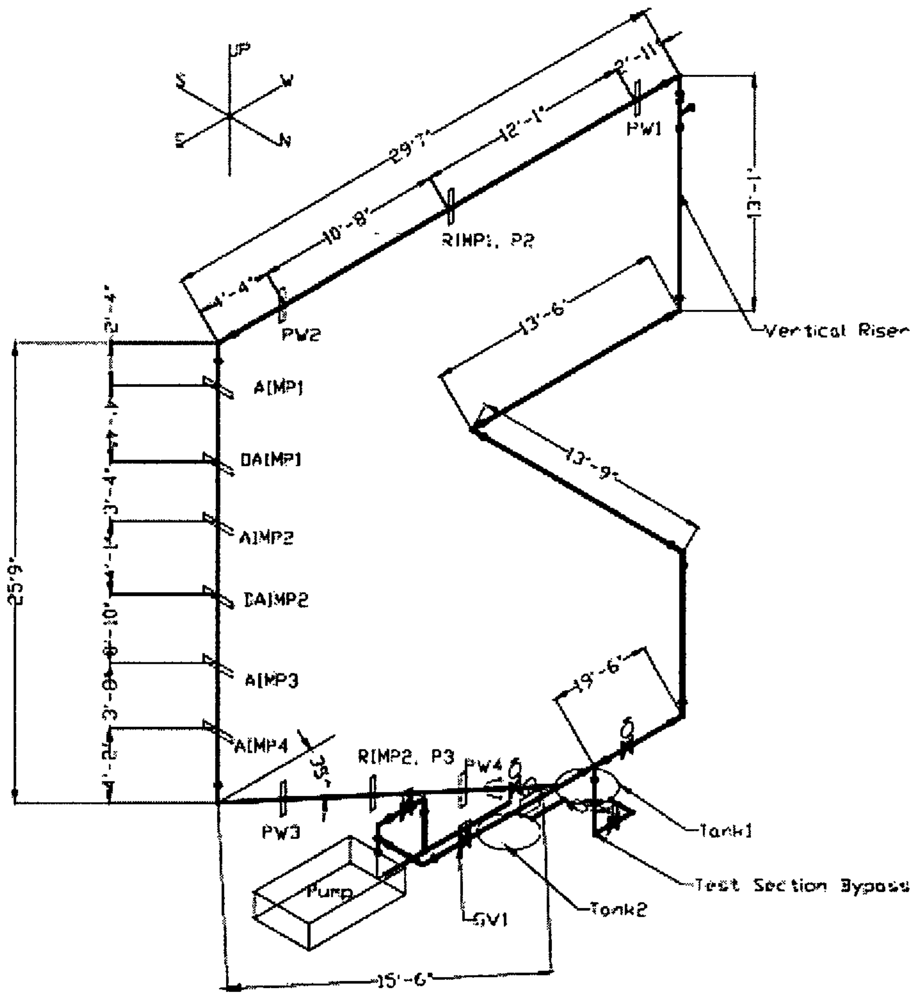

Figure 14: Isometric Diagram of 6 inch Test Facility

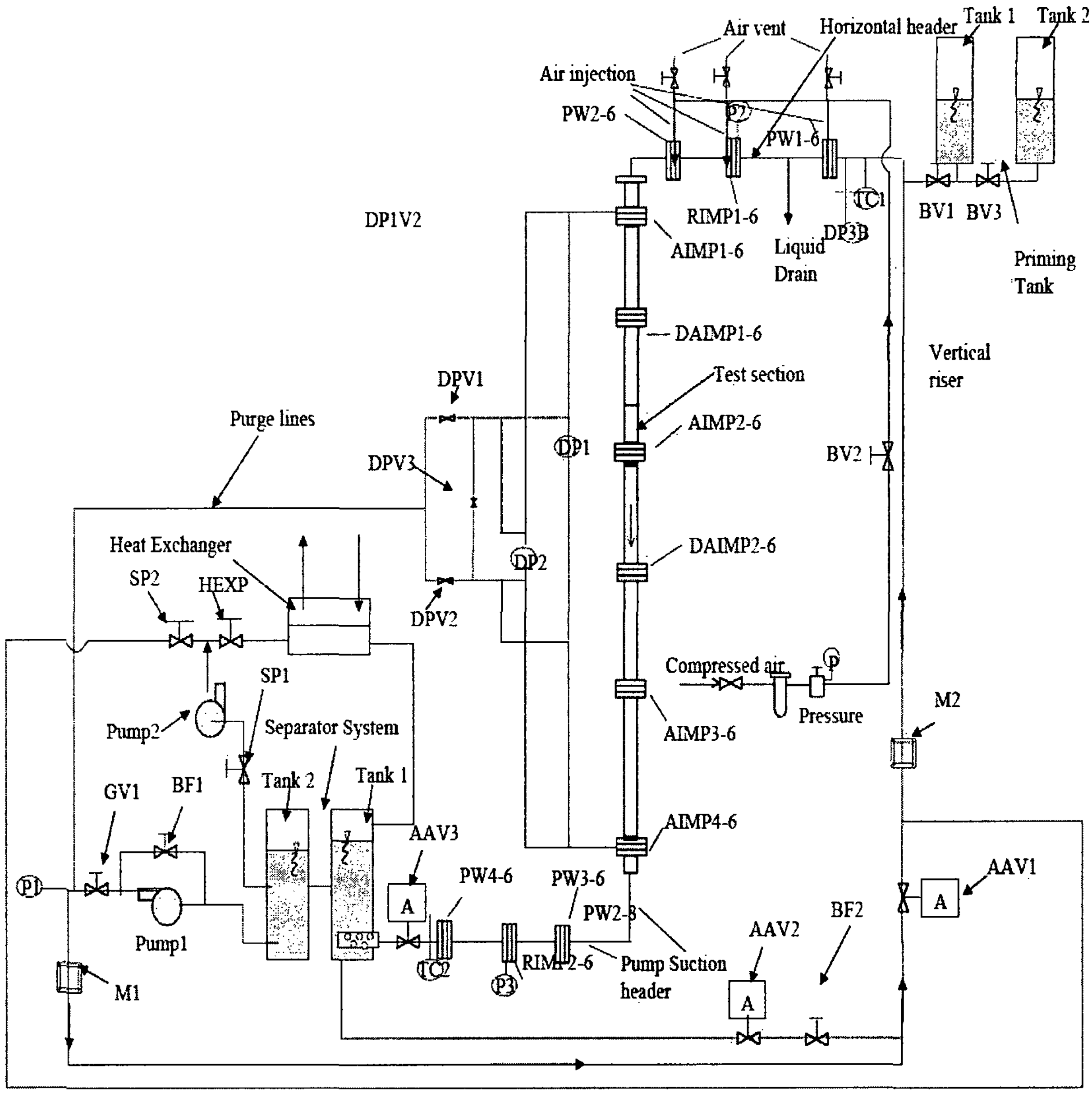

Figure 15: Piping and Instrumentation Layout for 6 inch Test Facility

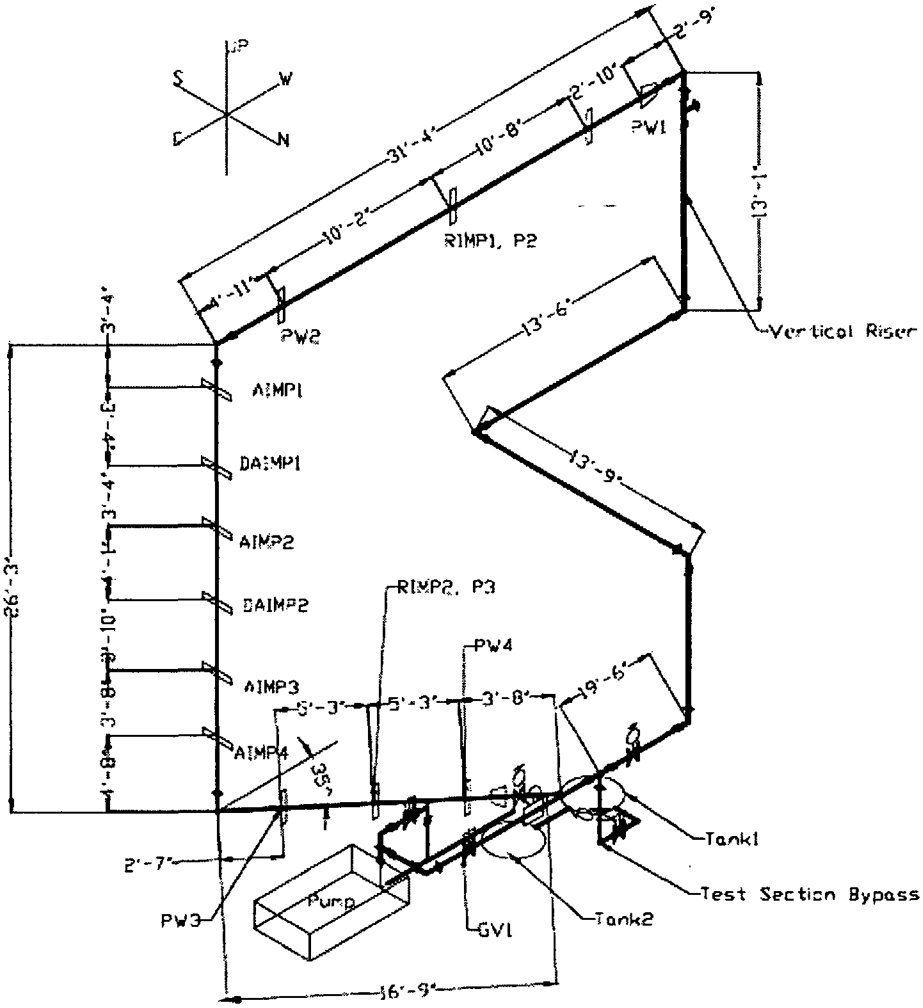

Figure 16: Isometric Diagram of 8 inch Test Facility

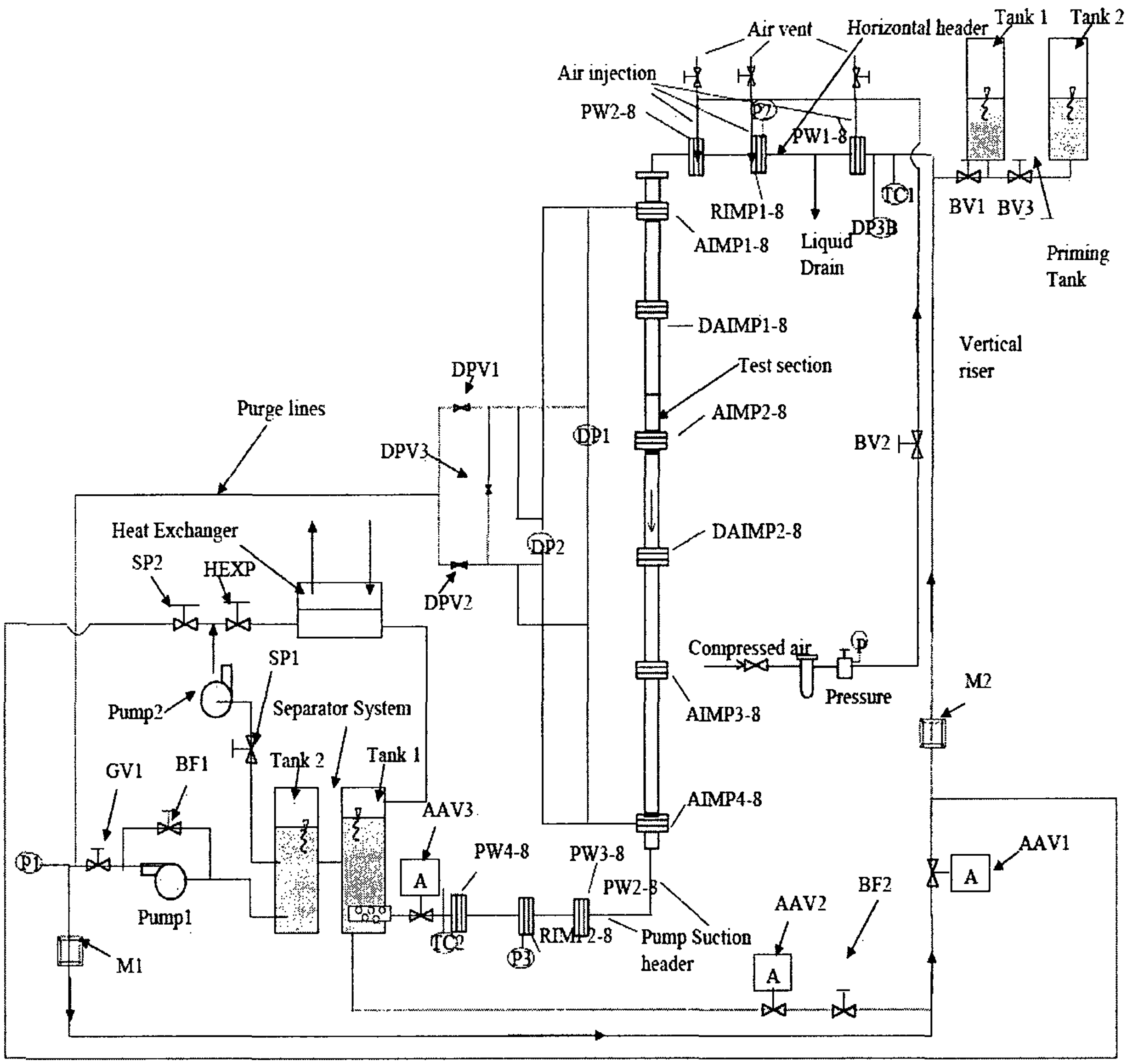

Figure 17: Piping and Instrumentation Layout for 8 inch Test Facility

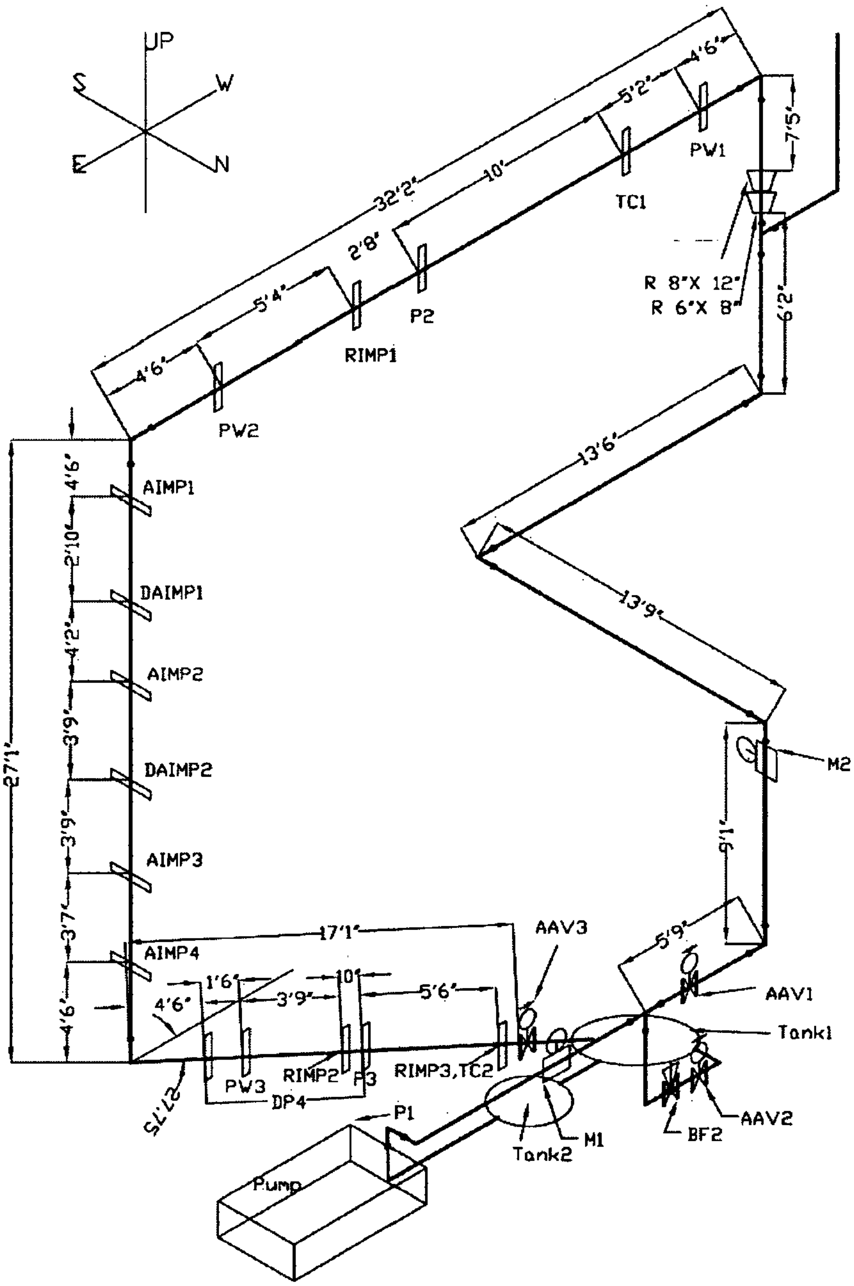

Figure 18: Isometric Diagram of 12 inch Test Facility

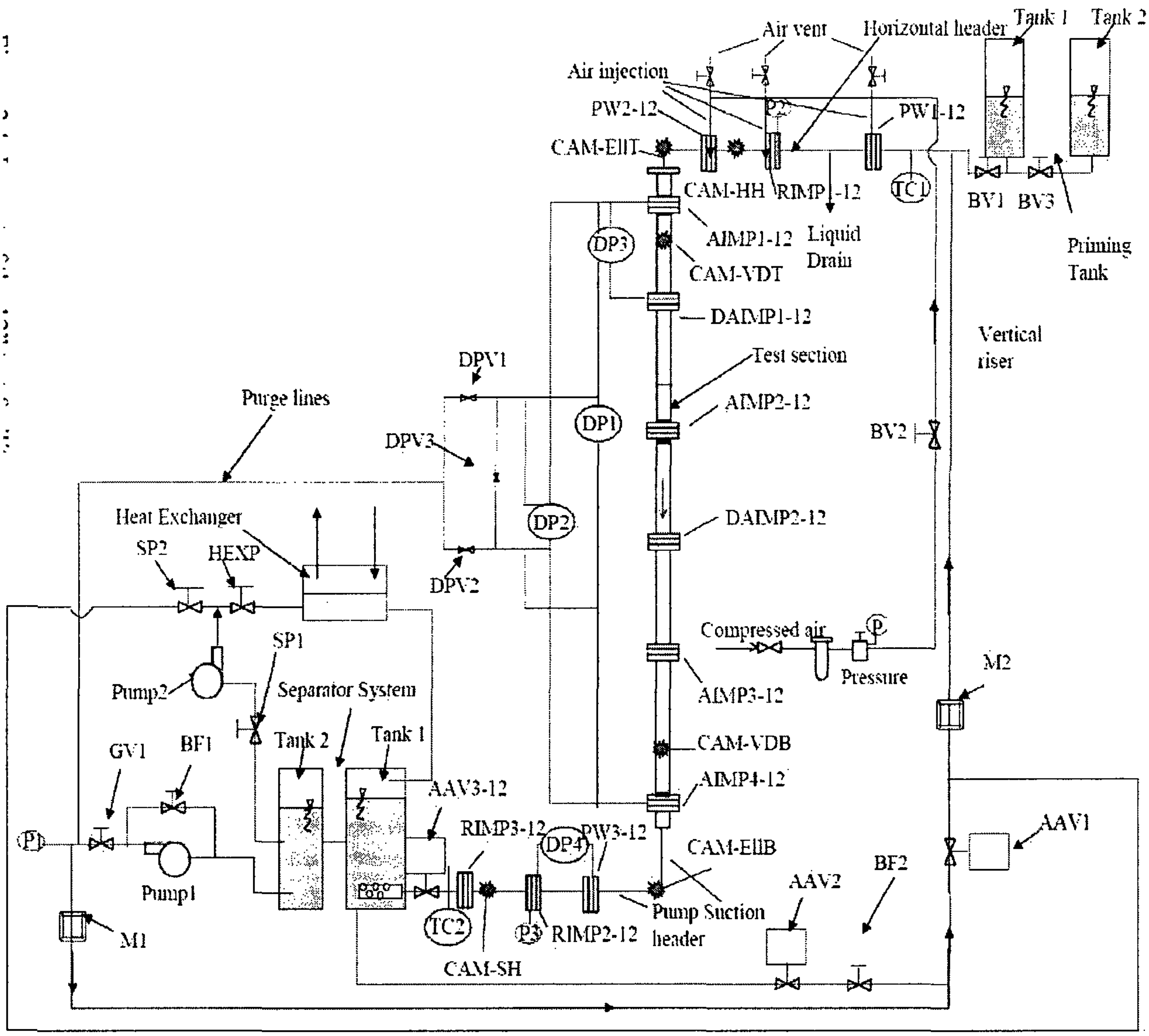

Figure 19: Piping and Instrumentation Layout for 12 inch Test Facility

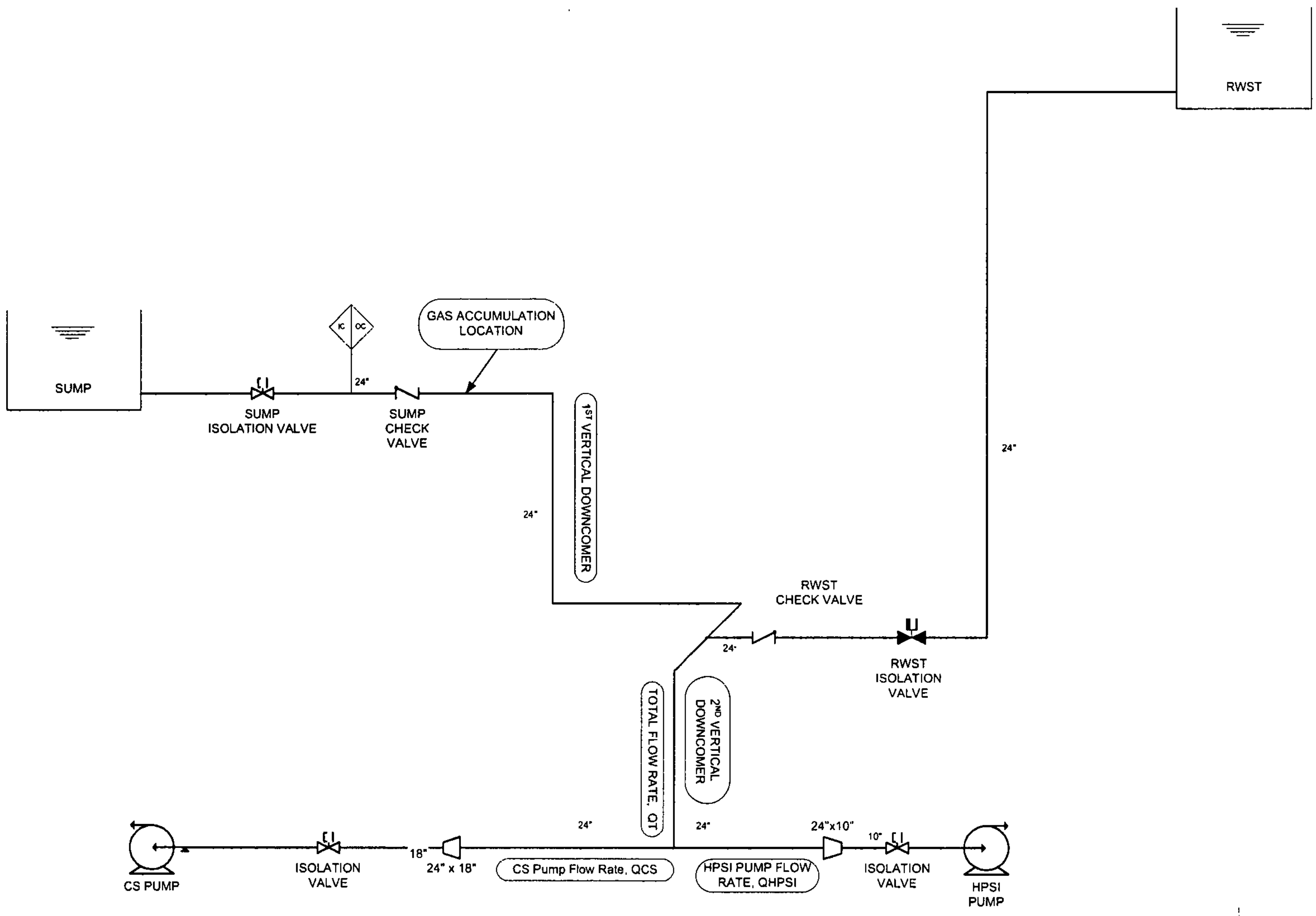

Figure 20: Example Problem 1

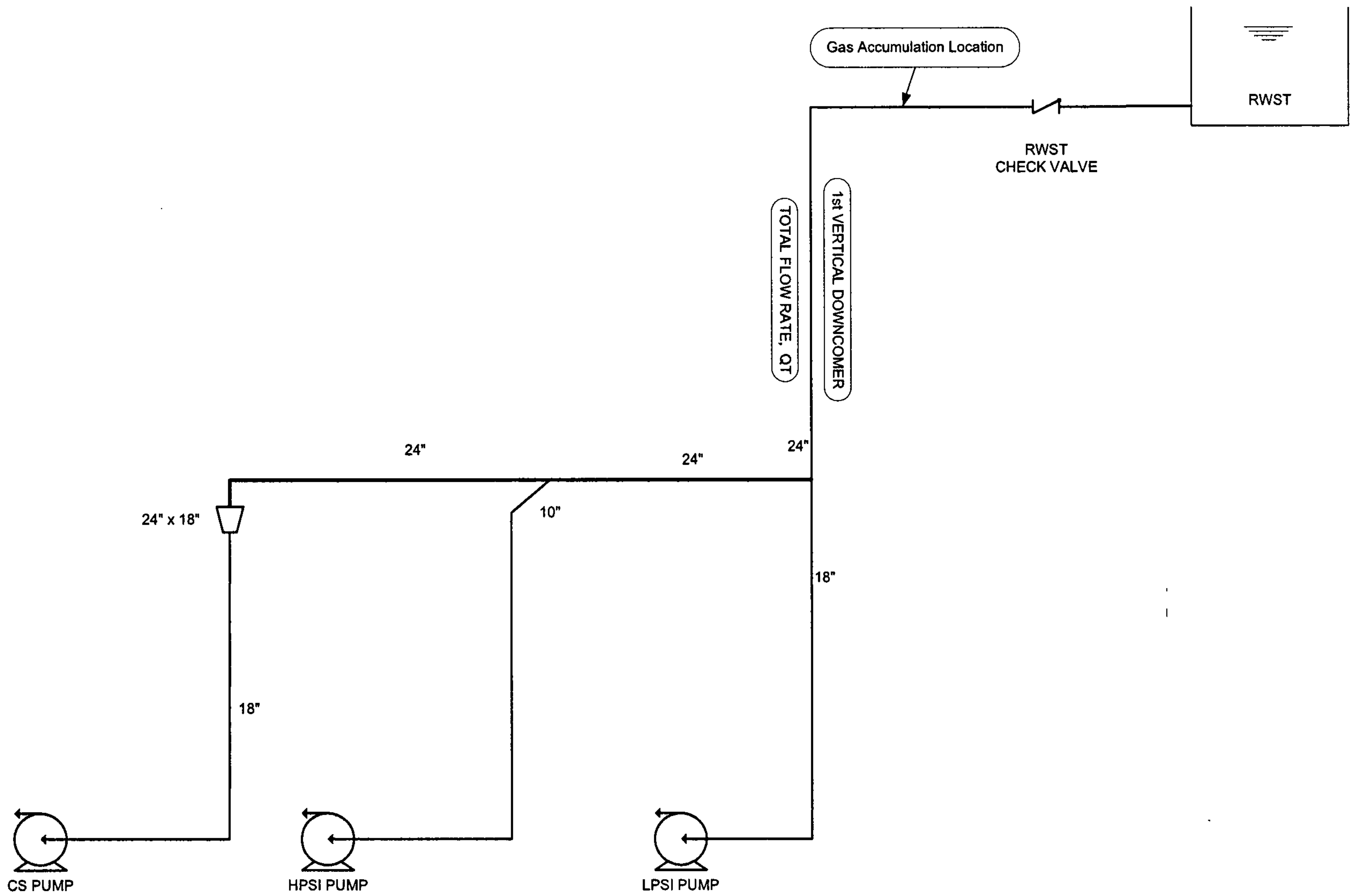

Figure 21: Example Problem 2