# TECHNICAL BASIS FOR THE SIMPLIFIED EQUATION

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# Presentation Outline

- What are the issues on the suction side?
- What are the individual features affecting the gas response?
- What is needed to prevent a "gas slug" from being transmitted to the pump suction?
- How are the criteria implemented?
- Conclusions.

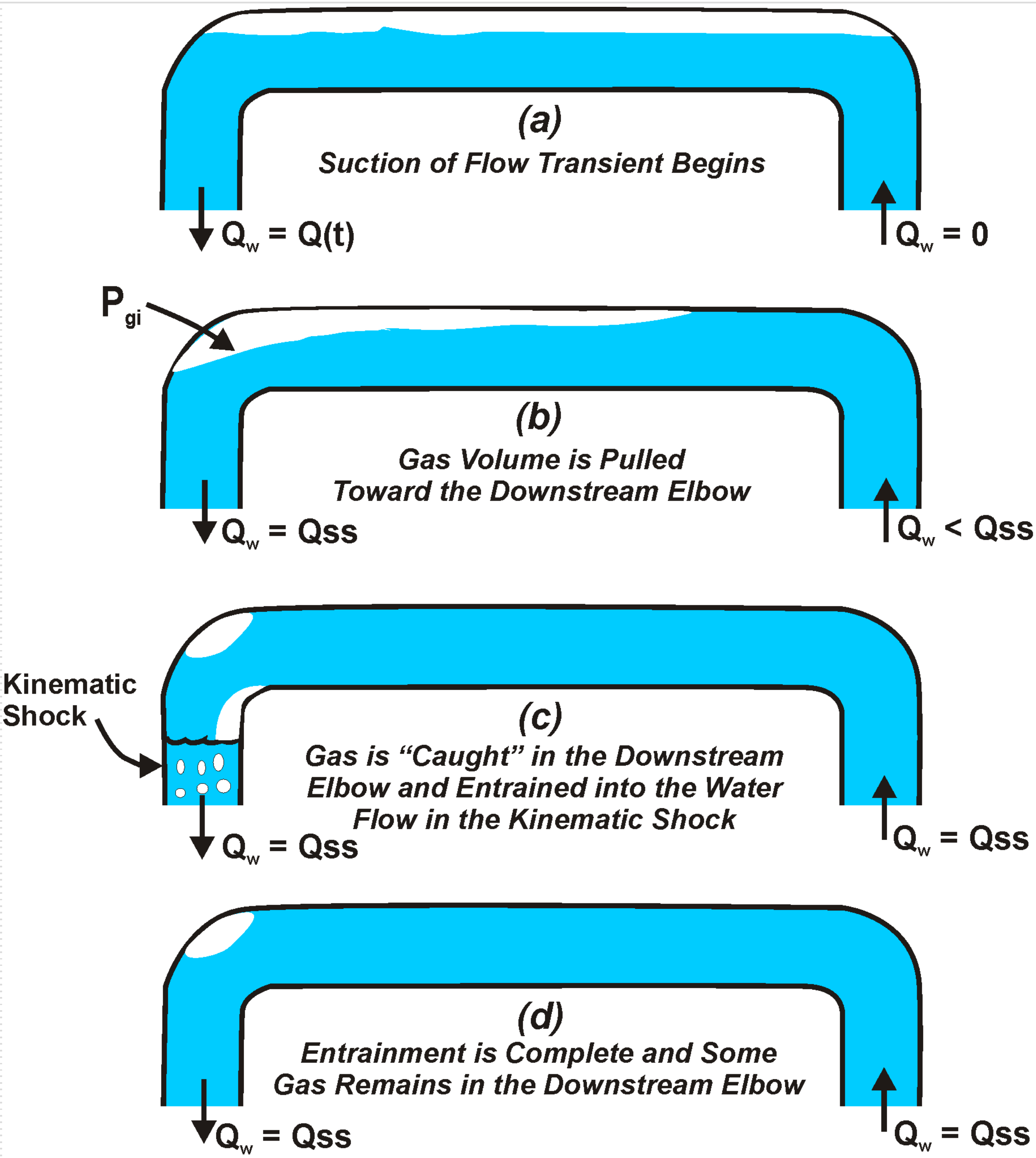
# Suction Side Issues

- The principal issue: what is the void fraction that is transferred to the pump suction for a specified gas volume in the high point piping.
- A second issue is whether a “gas slug” could be transported to the pumps.
- What is the sequence of events for the gas volume transport into the downcomer pipe leading to a kinematic shock.
- What is needed to ensure a kinematic shock will be formed to transition the flow regime to bubbly flow.

# 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) |
| Steady State Operation > 20 seconds | 40%-120% | 2% | 2% | 2% | 2% |
| Steady State Operation > 20 seconds (see Note) | < 40% or > 120% | 1% | 1% | 1% | 1% |
| Transient Operation ≤ 5 seconds | 70%-120% | 10% | | | 10% |
| Transient Operation ≤ 5 seconds (see Note) | < 70% or > 120% | 5% | | | 5% |
| Transient Operation ≤ 20 seconds | 70%-120% | | 5% | 20% | |
| Transient Operation ≤ 20 seconds (see Note) | < 70% or > 120% | | 5% | 5% | |
| Note: Further review by the Owners Groups may determine that criteria for pump operation below 70% BEP may not be required, as the conditions are bounded by the set of criteria for the 70%-120% BEP range. | | | | | |

# Transient Response of a Noncondensable Gas Volume in the Suction Piping Following Initiation of Flow

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# Sequence of Events

1. Pump starts.
2. Initial flow begins to expand and depressurize the gas space ($P_{gi}$).
3. Gas depressurization initiates the supply flow from the RWST/RWT/BWST.
4. Depressurization of about 1 psi (7 kPa) is usually sufficient for the supply flow to be provided/guaranteed.
5. Gas volume is pulled to the downstream elbow by the pump suction flow until a configuration is developed that can deliver the supply flow.
6. All gas that is not consistent with the water delivery configuration is pulled into the top of the downcomer.
7. The gas volume in the top of the downcomer develops a kinematic shock (waterfall) region that experiences gas entrainment, recirculation, disengagement and downward transport of a bubbly flow.

## What Are the Individual Features Affecting the Gas Response?

- Gas volume depressurization as the transient begins. (Discussed in FAI/09-130.)

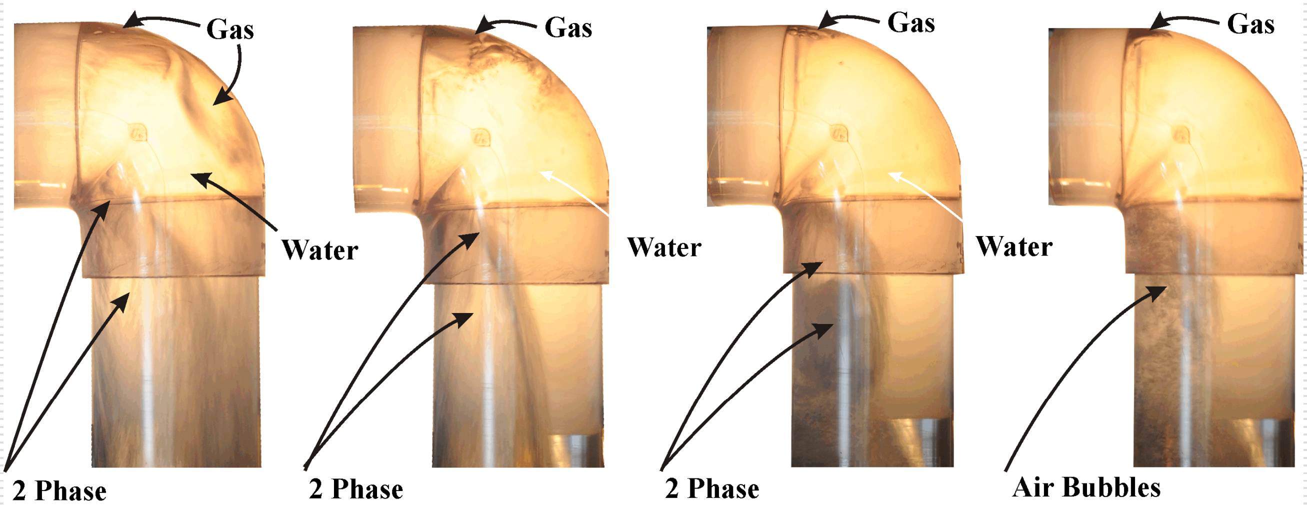
- Flow pattern in the upstream elbow. (Discussed in FAI/09-130.)

- Gas entrainment: kinematic shock. (Discussed here and in FAI/09-130.)

# What Prevents a Gas Slug From Being Transmitted?

- The formation of a kinematic shock in the downcomer pipe.
- What is a kinematic shock?  A kinematic shock is a discontinuity in the mixture density.  This discontinuity forms when a stratified gas volume is pulled into the top of the downcomer pipe.
- For a kinematic shock to form, the following conditions are needed:
  1) the gas volume can not be sufficiently large that it fills the entire downcomer pipe,
  2) the gas volume occupies the top of the downcomer pipe (due to buoyancy) and the water flow pours through the gas forming a vertical, separated flow configuration,
  3) the water flow entrains the gas and causes a flow regime transition from the vertical separated flow to bubbly flow, i.e. a discontinuity in the mixture density.

# *Kinematic Shock Development and Extinction*

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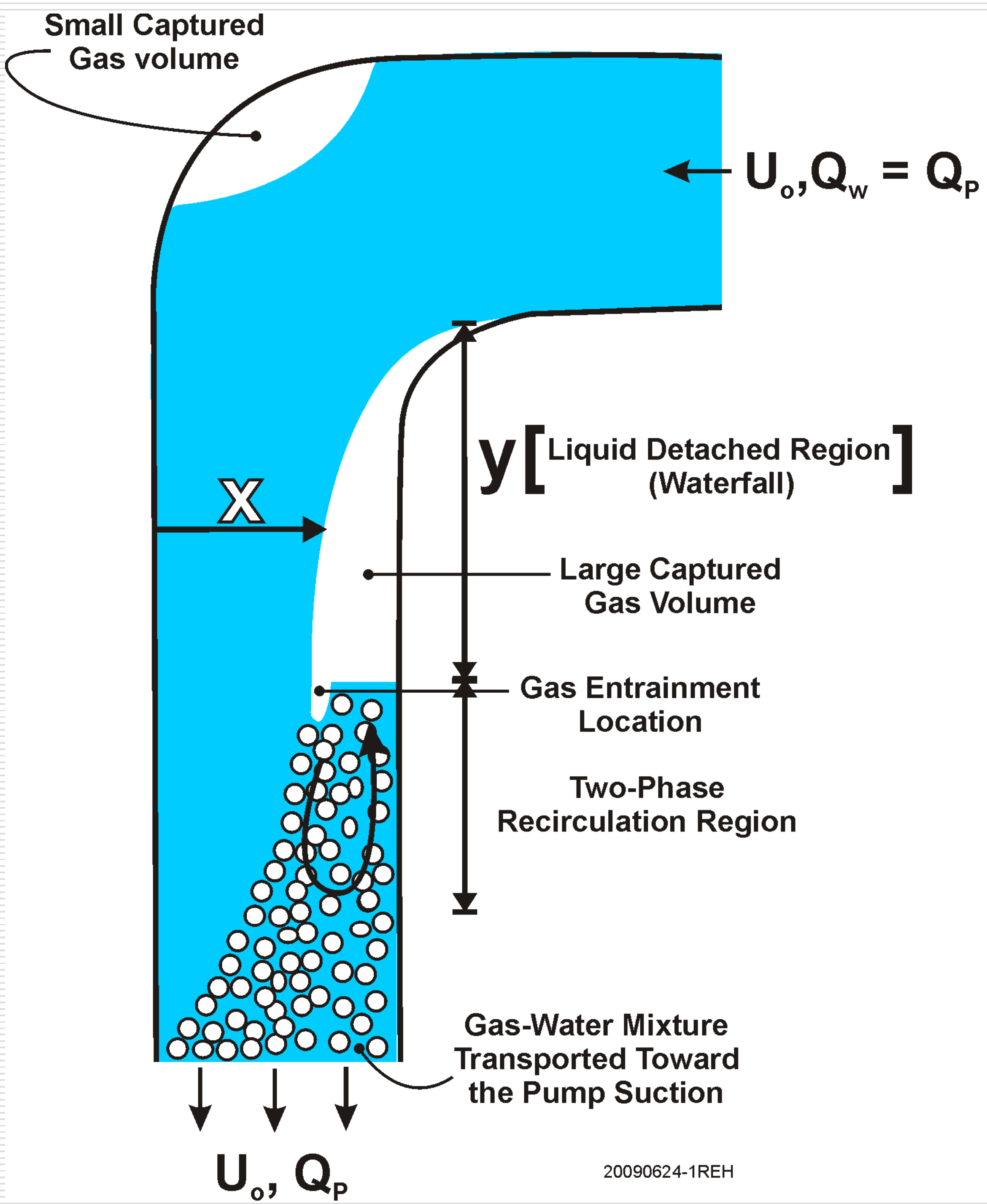


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# Separated Flow

- A vertical separated flow configuration enables the water to accelerate such that

$$U(y) = U_o + \sqrt{2gy}$$

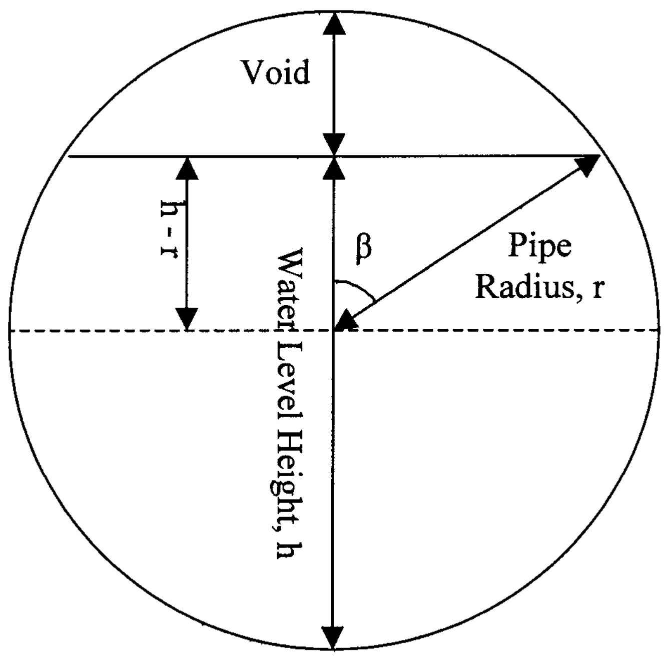
- The water volumetric flow remains constant, hence,

$$A_w(y) = \frac{Q_o}{U(y)} = \frac{A_o U_o}{U(y)}$$

- Assume the water “thickness” x can be approximated as a linear function such that the flow area can be represented as:

$$A_w(y) = \frac{\pi}{4} Dx(y)$$

# Cross-Sectional View of a Collected Gas Volume (Void) in a Horizontal Pipe Section

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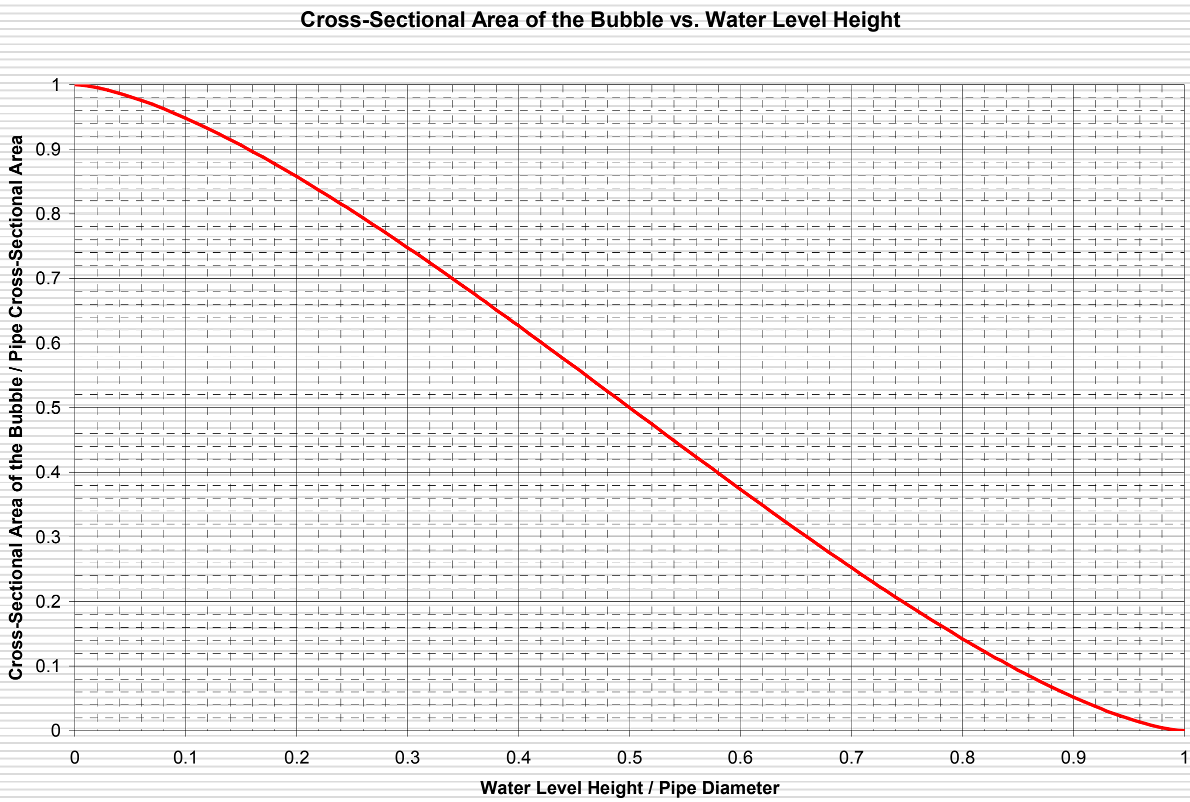
# Void Fraction vs. the Ratio of Water Level Height to the Pipe Internal Diameter

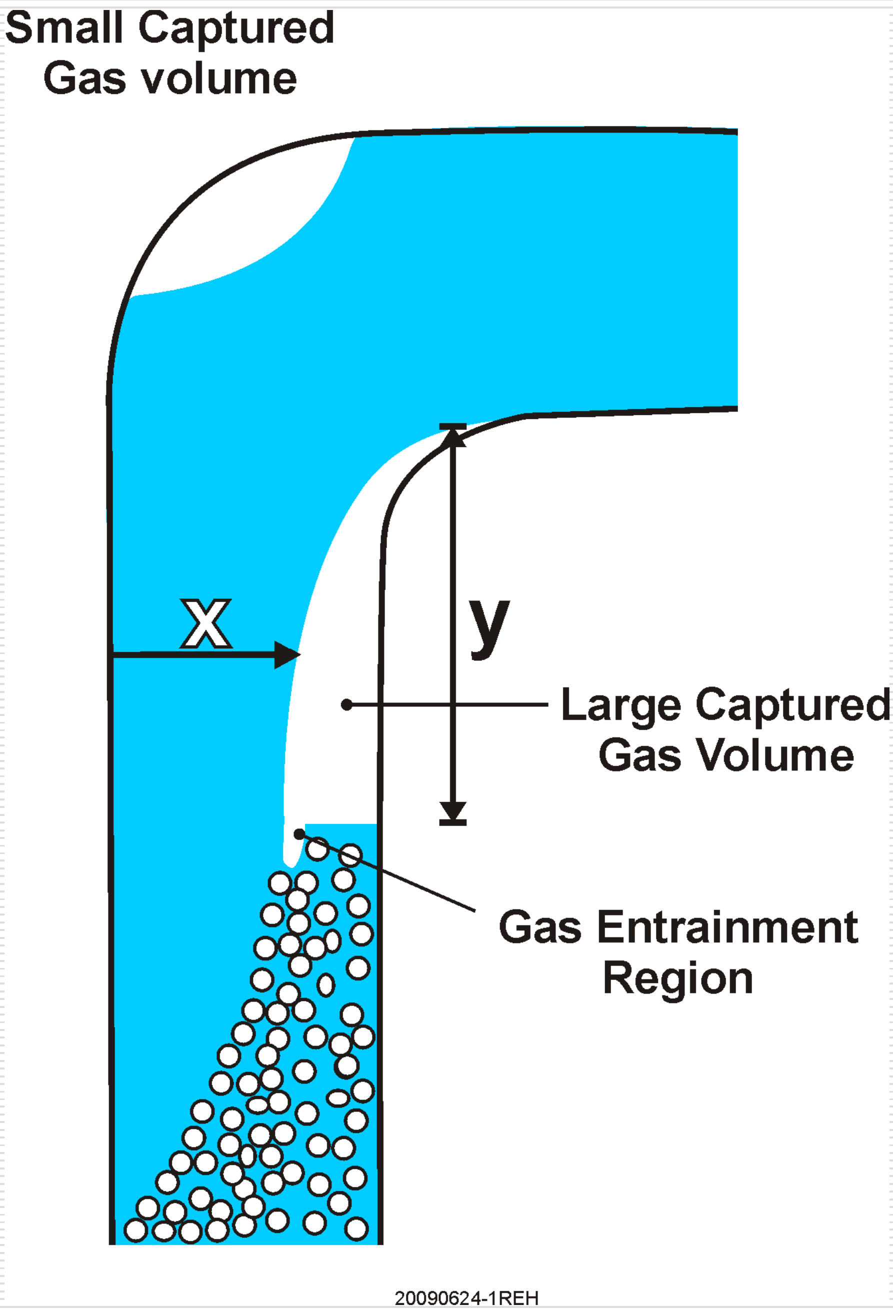


# Changing Water "Thickness"

- As the water accelerates, the thickness decreases which can be expressed as:

$$x(y) = \frac{4\,Q_o}{\pi\,DU} = \frac{4\,Q_o}{\pi\,D\left[U_o + \sqrt{2gy}\right]}$$

# Configuration Generated by the Transport of Air Into the Downcomer Pipe

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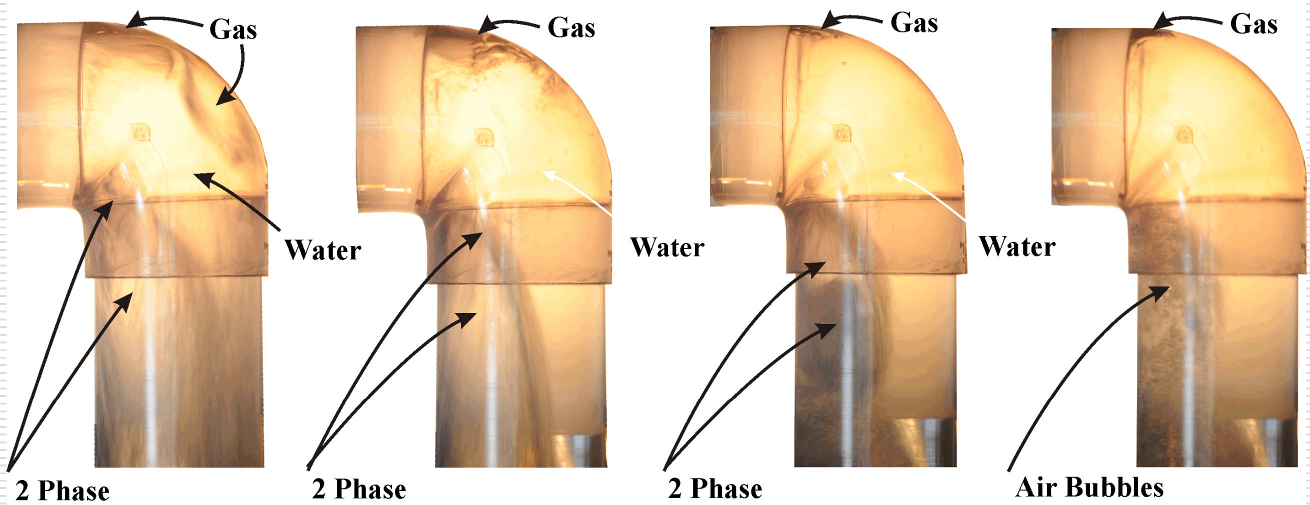
# *Kinematic Shock Development and Extinction*

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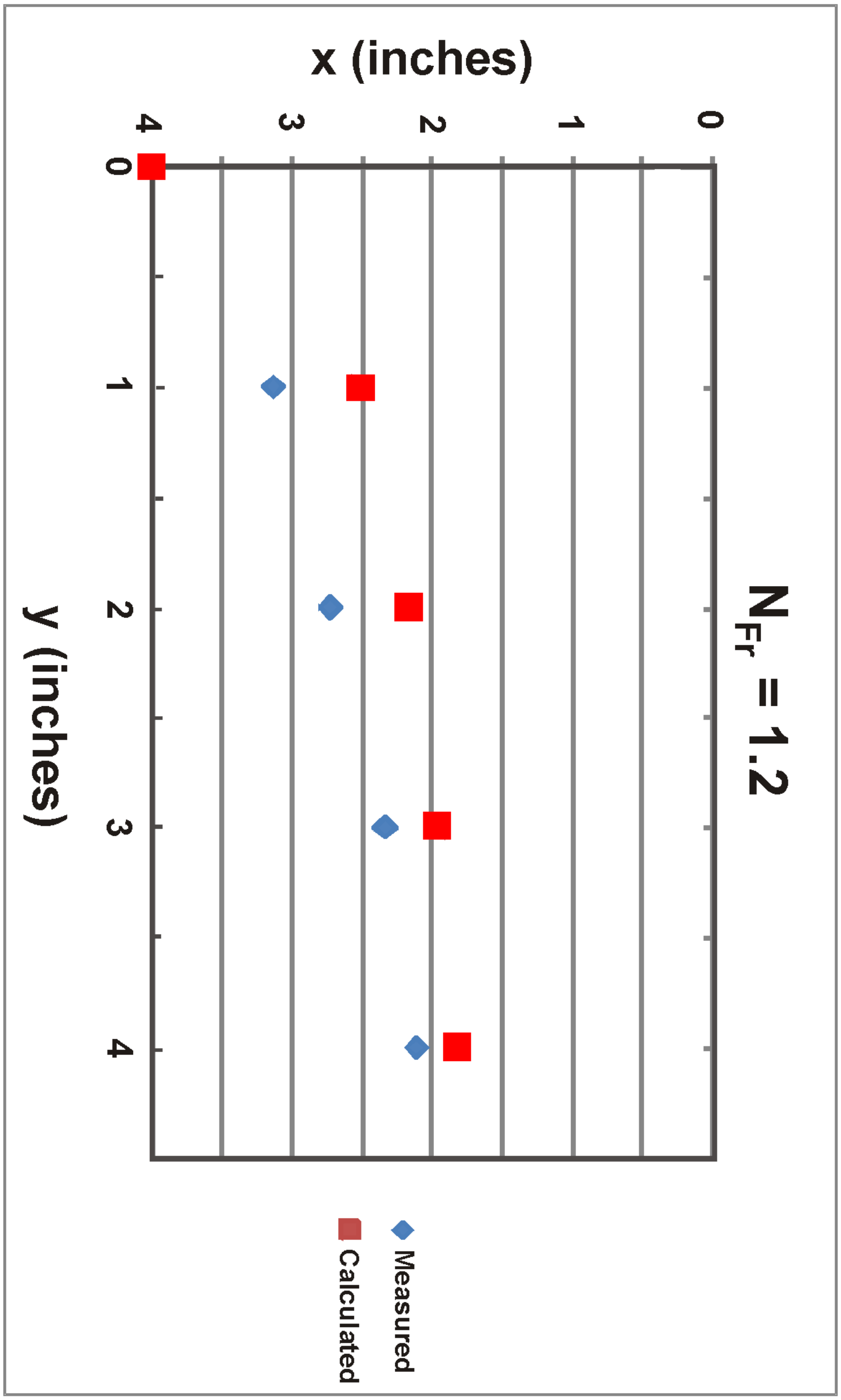
# Comparison of the Separated Water Surface with the Simplified Model

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# Depth of the Kinematic Shock

- The water volume is bounded by the bottom of the high point pipe and the location where the water jet plunges into the water filled downcomer. At this location, the water jet entrains air from the gas volume. The water volume in the separated zone can be expressed as:

$$V_w = \int_o^y \frac{\pi}{4} Dx(y)\, dy = \int_o^y \frac{Q_o}{U_o + \sqrt{2gy}}\, dy$$

## A Better Approximation

This can be solved numerically or the following approximation can be used

$$V_w = \left(\frac{Q_o}{U_o}\right) y_1 \left[1 + N_{Fr}^{-1} \sqrt{\frac{y_1}{D}}\right]^{-1}$$

$$y_1 = \frac{1}{A_o}\left(V_g + V_w\right)$$

Let $y^* = y_1^{1/2}$

$$(y^*)^3 = \alpha_{hp} L_{hp} \left[N_F \left(D^{1/2}\right) + y^*\right]$$

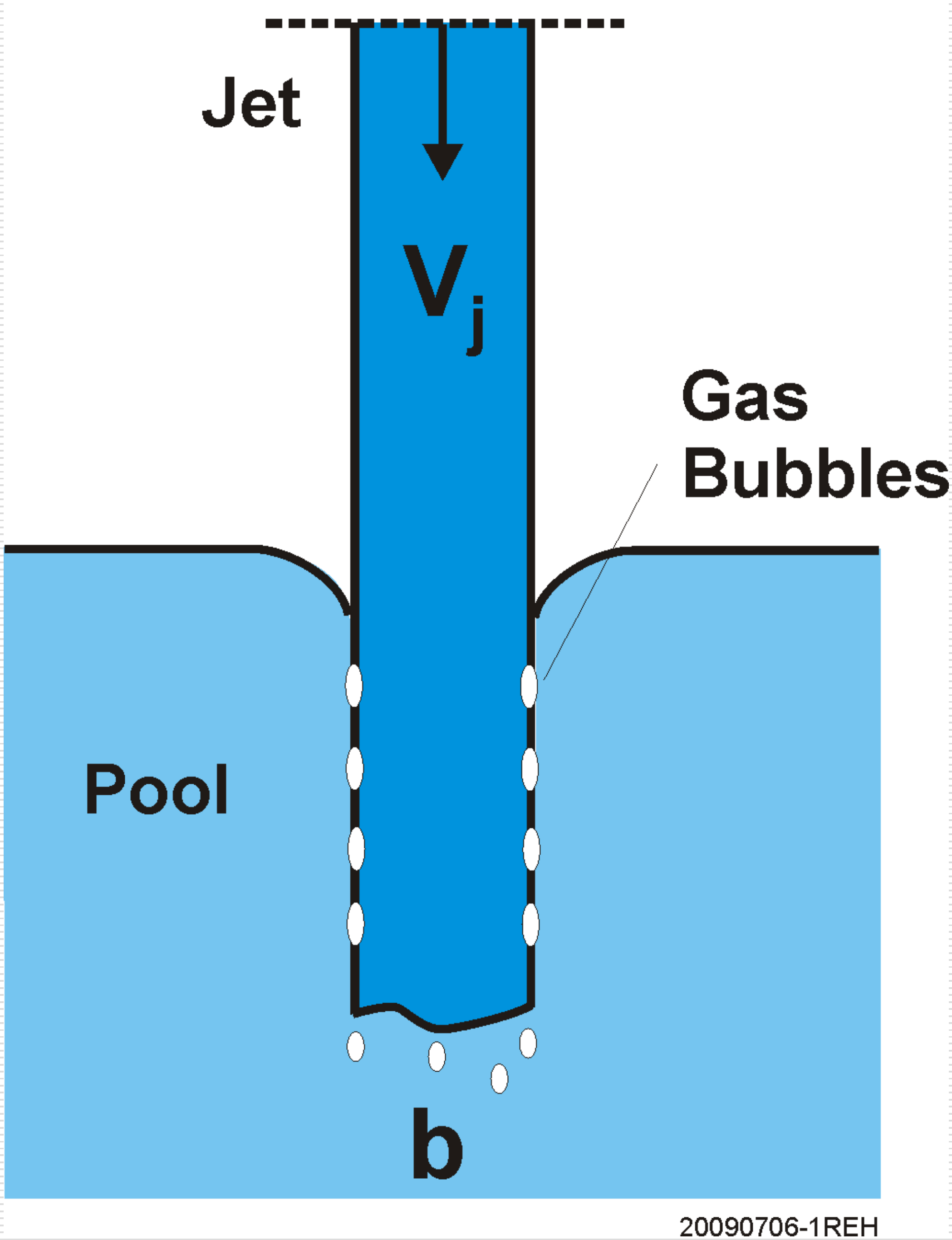
# Entrainment of the Gas Volume

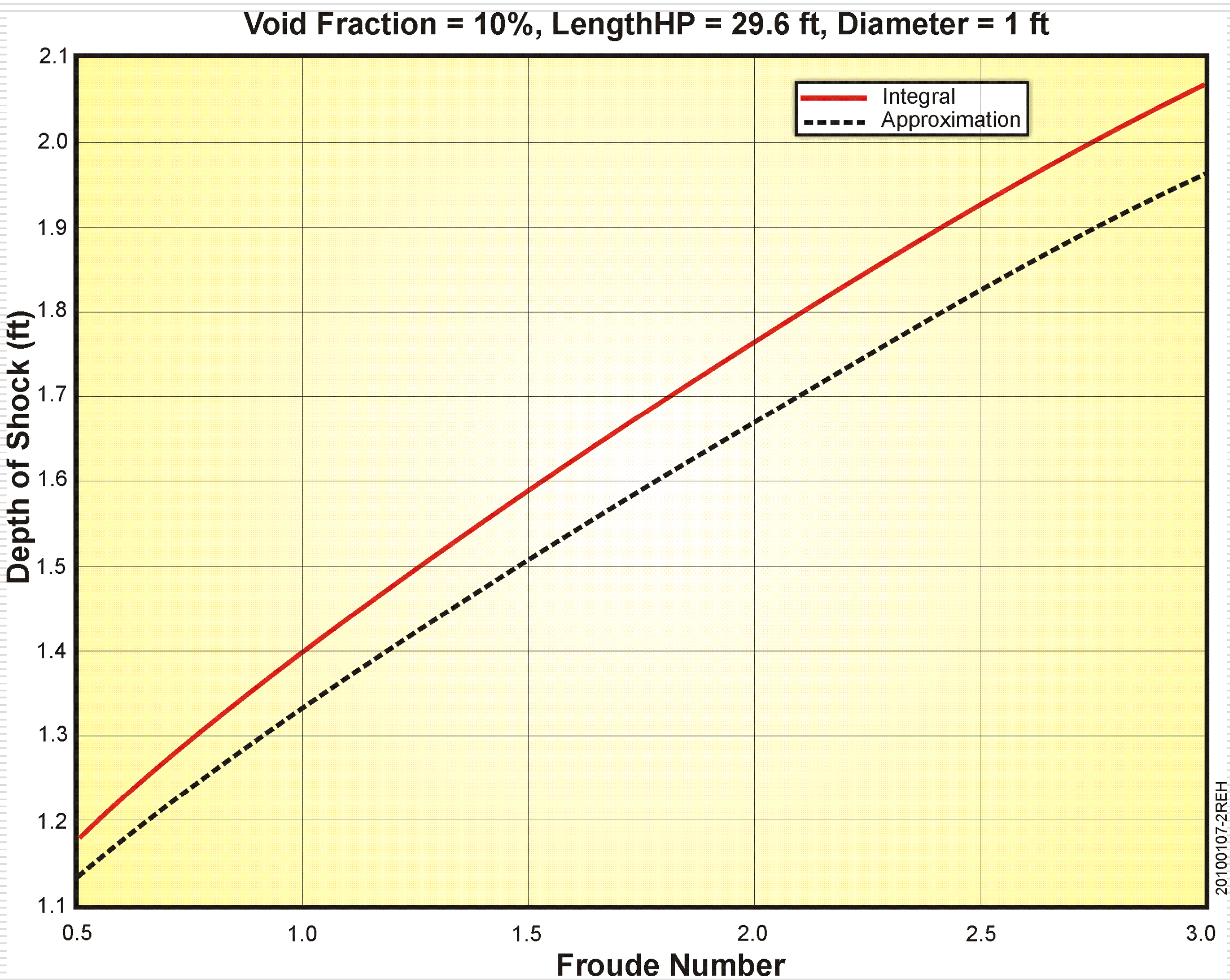
In the review article by Bin (1993), the volumetric flow rate entrainment ratio of gas for a circular water jet plunging into a water pool can be correlated by

$$\frac{Q_g}{Q_w} = K_2 \left(\frac{y}{D}\right)^{0.68}$$

where $K_2$ was found for different experiments to be in the range of 0.049 to 0.09. Since the water jet is observed to adhere to the outside wall, $K_2$ would be expected to be less than these values. As a conservatism let $K_2 = 0.049$ for these example calculations.

# Entrainment Mechanism for Plunging Liquid Jets





Void Fraction = 10%, LengthHP = 29.6 ft, Diameter = 1 ft
Integral
Approximation
Depth of Shock (ft)
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
0.5
1.0
1.5
2.0
2.5
3.0
Froude Number
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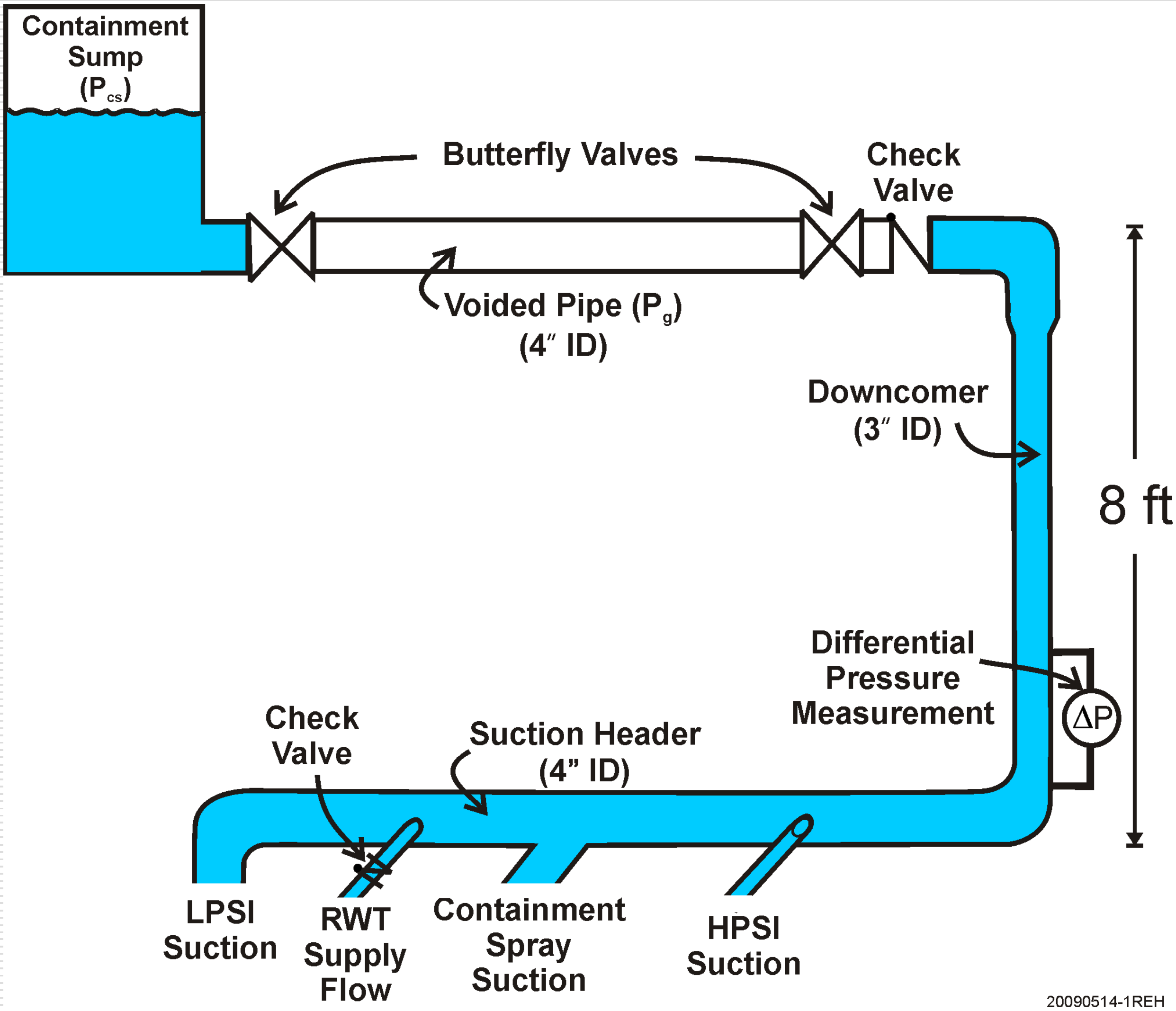
# Schematic of the Test Facility
# Reported by Hammersley et al. (2006)

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## Comparison With the Palo Verde Scaled Test Data

High Point Dia.: $D = 4 \text{ in } (0.1 \text{ m})$ ; $L = 5 \text{ ft } (1.53 \text{ m})$

$A = 0.087 \text{ ft}^2 \; (0.00785 \text{ m}^2)$

Downcomer Dia.: $D_d = 3 \text{ in } (0.075 \text{ m})$

Downcomer area: $A_d = 0.049 \text{ ft}^2 \; (0.0046 \text{ m}^2)$

$V_g = 0.6\,(0.087)\,5 = 0.261 \text{ ft}^3 \; (7.4\,\ell)$ (when the gas transfer begins)

(Froude Number in the Downcomer) $N_F = 1.2$

$U = 3.6 \text{ ft/sec } (1.1 \text{ m/sec})$ $Q_w = 0.174 \text{ ft}^3\text{/sec } (4.9\,\ell\text{/sec})$

$y = 4 \text{ ft } (1.2 \text{ m})$ $\quad y/D = 16$

$$\bar{Q}_g / Q_w = 0.029 \left( \frac{y}{D} \right)^{0.68} = 0.191 = \frac{\bar{\alpha}}{1 - \bar{\alpha}}$$

$\bar{\alpha} = 0.16$

$$Q_{g,max} / Q_w = 0.049 \left( \frac{y}{D} \right)^{0.68} = 0.323 = \frac{\alpha_m}{1 - \alpha_m}$$

$\alpha_m = 0.24$

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## Transient Duration

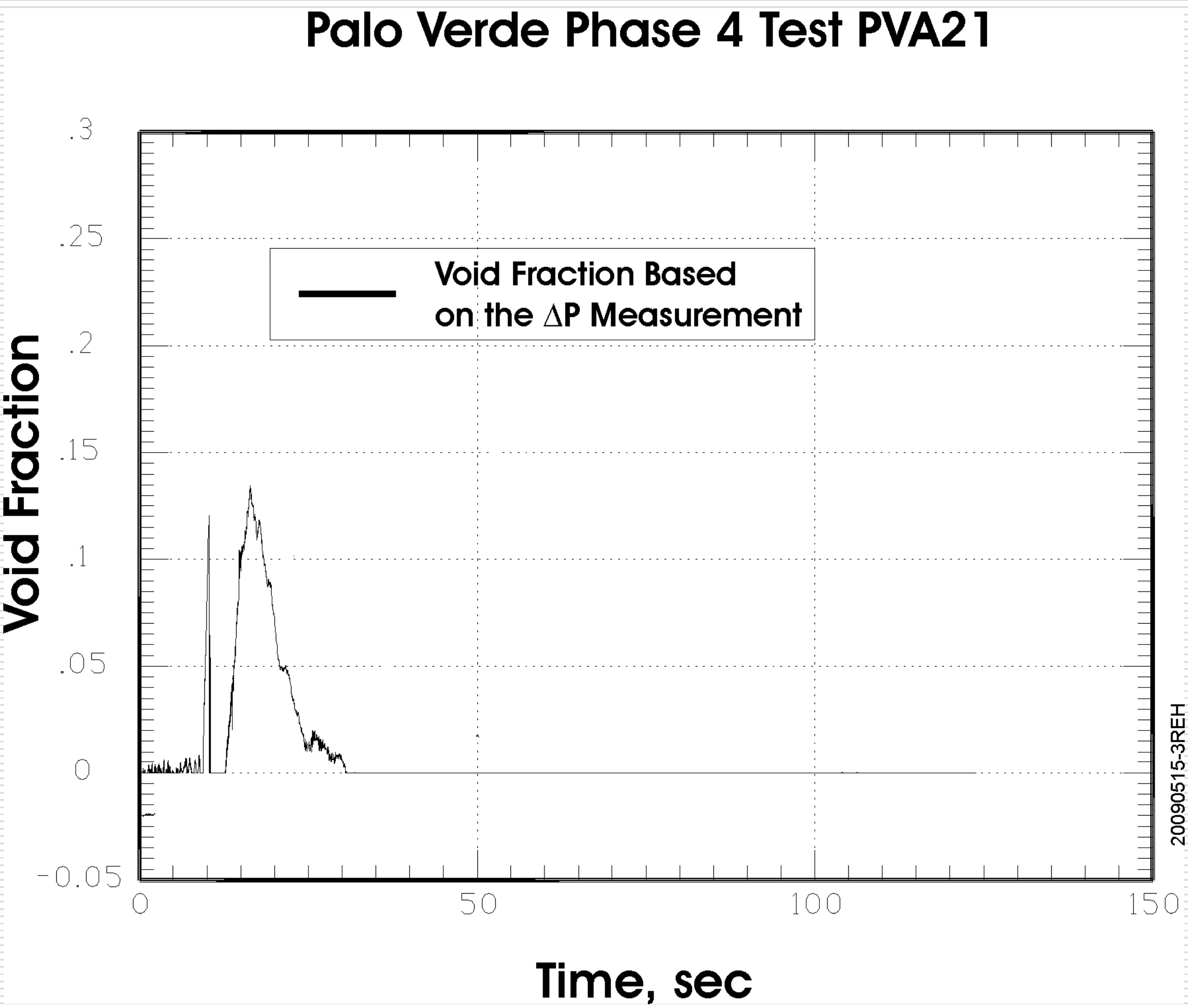
$$\bar{Q}_g = 0.191\,Q_w$$

$$\bar{Q}_g = 0.191\left(0.174\right) = 0.033\ \text{ft}^3/\text{sec}\left(0.94\ \ell/\text{sec}\right)$$

$$\Delta t = \frac{V_g}{\bar{Q}_g} = \frac{0.261}{0.027} = 7.9\ \text{secs}$$

Comparing this with the void fraction measurements for the Palo Verde scaled tests it is observed that this model conservatively underestimates the time to deplete the gas in the kinematic shock.

# Void Fraction History at the Bottom of the Downcomer

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## Influence of Buoyancy

- In the near vicinity of the entrainment location, the water impingement velocity is generally much greater than that corresponding to the superficial velocity caused by the pump suction flow. Therefore buoyancy is not a major influence.
- In the bottom of the downcomer pipe, the water velocity is close to that corresponding to the pump superficial velocity.
- The influence of buoyancy on the void fraction in the bottom of the downcomer can be estimated from

$$\frac{1-\alpha_e}{\alpha_e} = \frac{1}{k_{dc}}\left[\frac{1-\alpha_{dc}}{\alpha_{dc}}\right]$$

where

- $\alpha_e$ is the homogeneous void fraction in the entrainment region,
- $\alpha_{dc}$ is the void fraction at the bottom of the downcomer, and
- k is the slip ratio defined by

$$k_{dc} = \frac{U_g}{U_w} = \left[\frac{x_Q}{1-x_Q}\right]\left(\frac{1-\alpha_{dc}}{\alpha_{dc}}\right)\frac{\rho_w}{\rho_g}$$

# Influence of the Slip Ratio

- In the Palo Verde tests, the velocity through the downcomer was about 3.6 ft/sec (1.1 m/sec). Assuming a bubble rise velocity of 1 ft/sec (0.3 m/sec), the value of k (slip) is 2.6/3.6 = 0.72.

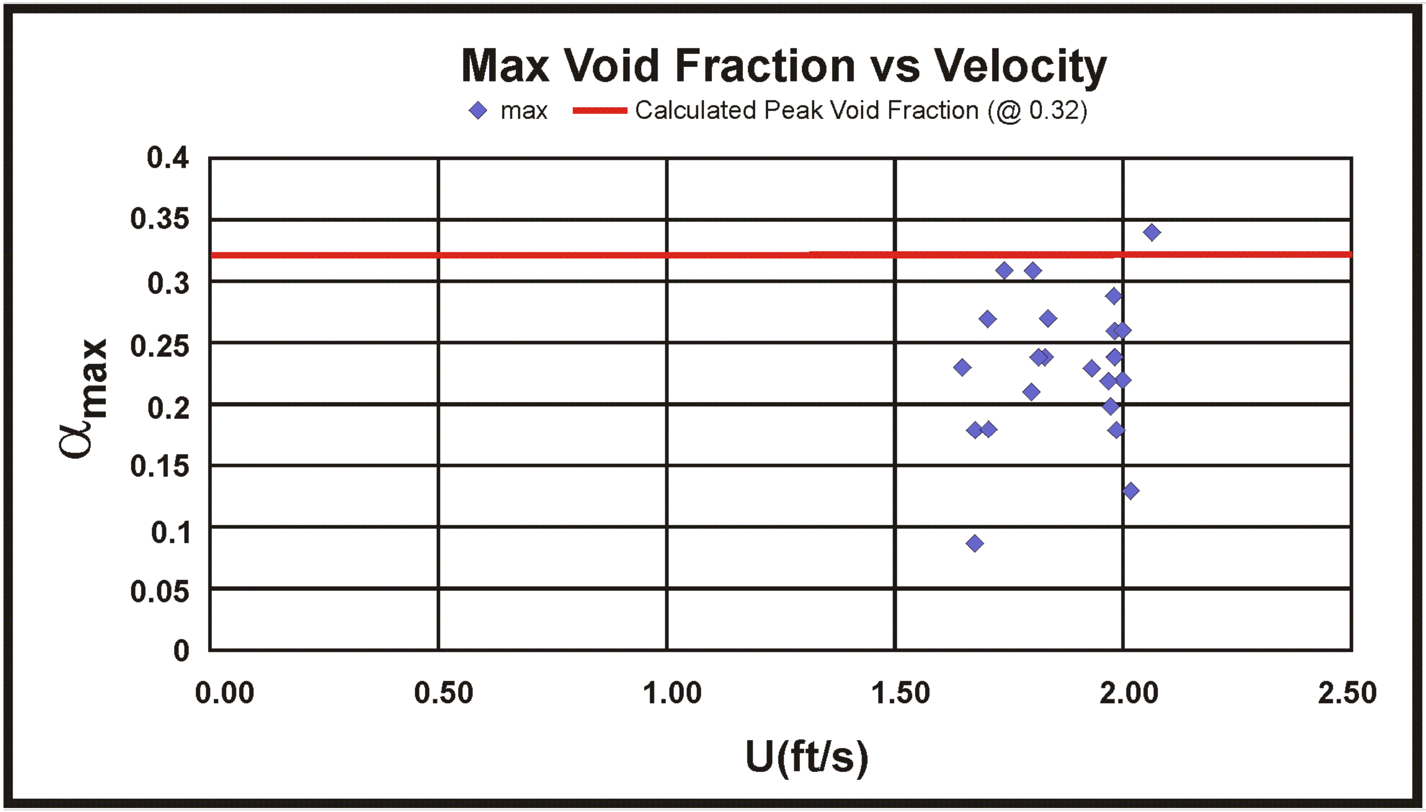
- Using this value, the calculated maximum void fraction in the downcomer is

$$\frac{1-0.24}{0.24}=\frac{1}{0.72}\left[\frac{1-\alpha_{dc}}{\alpha_{dc}}\right]$$

$$\alpha_{dc}=0.30$$

- This agrees well with the maximum values measured in the scaled Palo Verde Tests.

# Measured Local Void Fractions at the Bottom of the Downcomer for the Palo Verde Integral System Scaled Tests

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# <u>Effect of Buoyancy</u>

- The influence of the slip ratio being less than unity is only influential when comparing the calculations with the measurements of void fraction in the bottom of the downcomer.

- The consideration <u>does not</u> alter the volumetric flow rate that is transported to the pump(s).

# Conclusion From the Scaled Palo Verde Test

- The kinematic shock model is in agreement with the timing of the measured transient and the maximum measured void fractions.

- The tests and the model illustrate the importance of forming a kinematic shock to cause the two-phase flow to transition into bubbly flow.

- The tests show that the downcomer needs to be sufficiently long for a kinematic shock to develop.

# Criterion for Establishing a Kinematic Shock [Criterion Needed to Use the Simplified Equation]

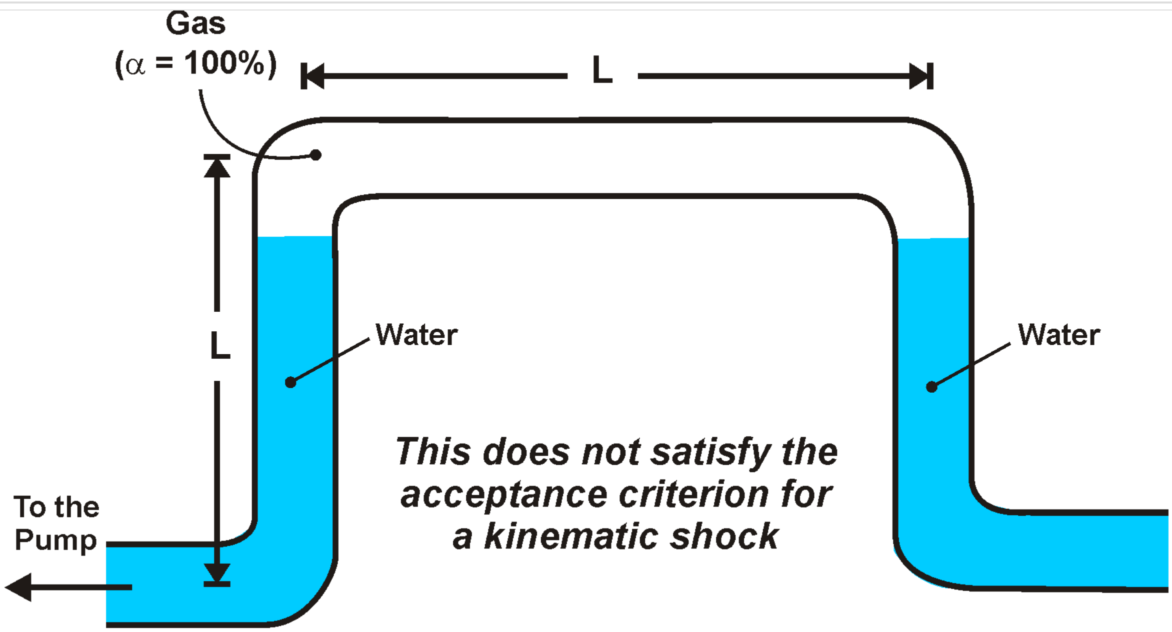
- As a conservatism, as well as to account for the two-phase flow regime details, the criterion is that the volume of the downcomer pipe should be at least 4 times the gas volume in the high point.

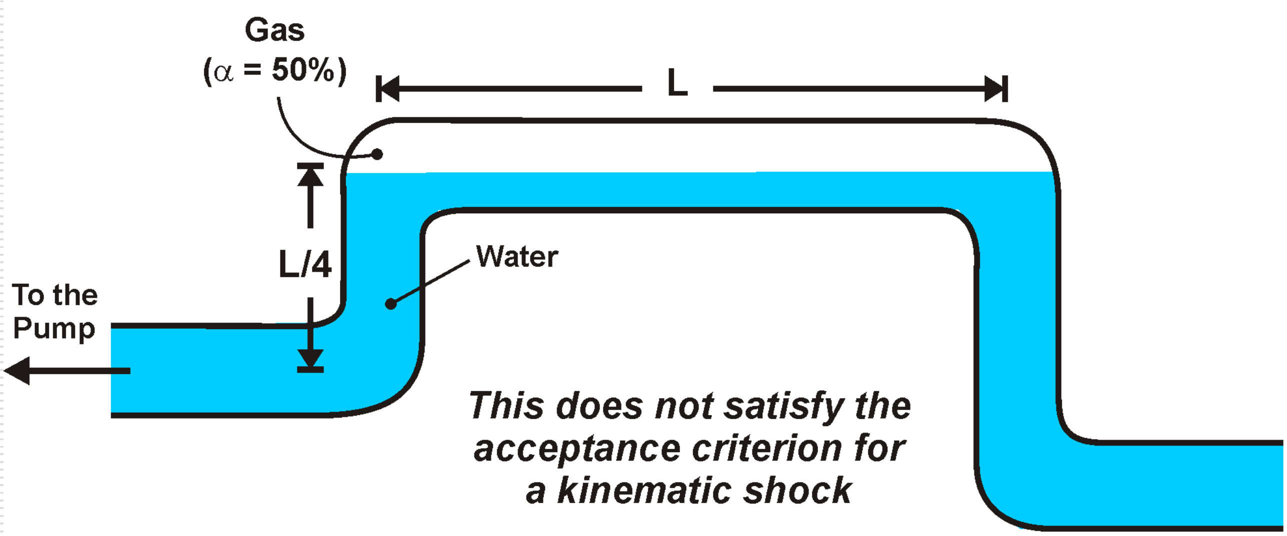
- For suction piping configurations with several steps in the downcomer piping, the maximum gas volume should be less than one-fourth of the volume of the longest step.

# Implementation of the Criteria

- Since a kinematic shock is needed to cause a transition from separated to bubbly flow, the volume of the downcomer should have a volume that is at least 4 times the gas volume in the high point.

- For those configurations where the downcomer piping is divided into several steps, at least one of the steps should have a volume that is 4 times the gas volume.

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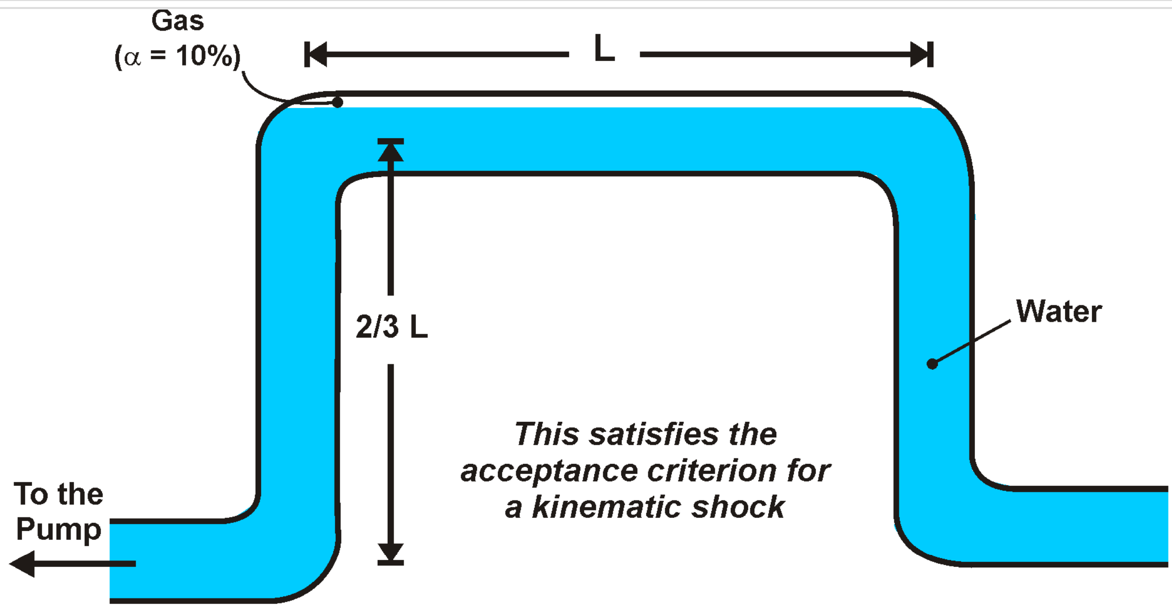
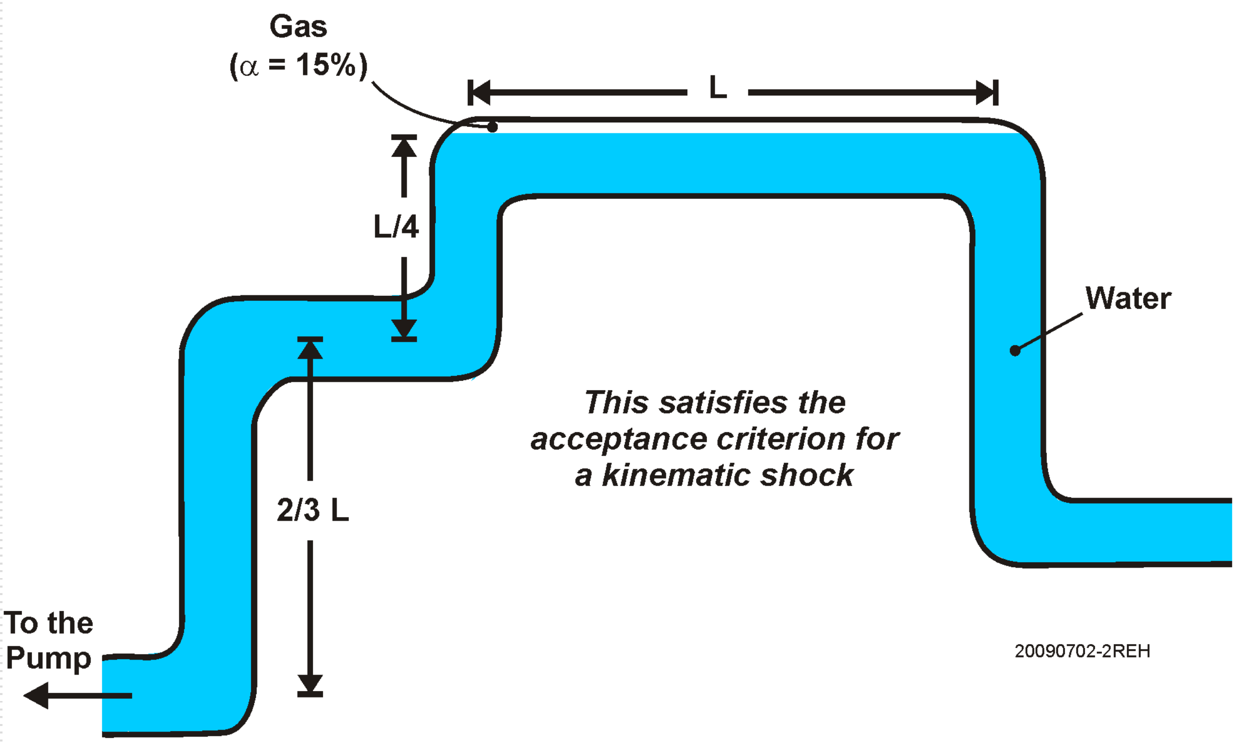

Gas
(α = 10%)
L
2/3 L
Water
This satisfies the acceptance criterion for a kinematic shock
To the Pump


Gas
(α = 15%)
L
L/4
2/3 L
Water
This satisfies the acceptance criterion for a kinematic shock
To the Pump
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## Other Relevant Experiments

The Beaver Valley gas intrusion tests provide two additional sets of experiments to compare with the kinematic shock model and the criterion for using the simplified equation.

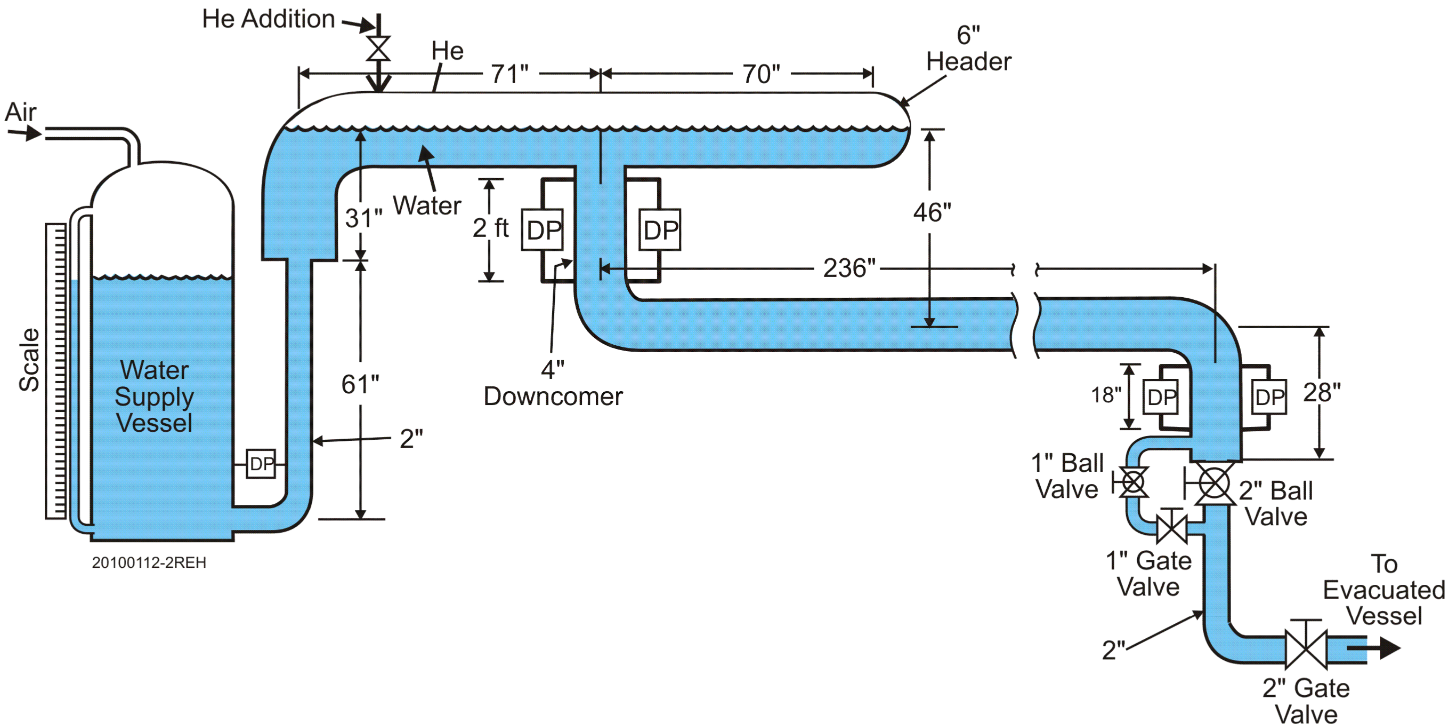
Beaver Valley Unit #1 Scaled Tests

- 6 inch diameter high point, 141 inches long
- Froude number = 0.55
- Two downcomers
- Longest downcomer 46 inches
- Void fraction measurement in each downcomer

Beaver Valley Unit #2 Scaled Tests

- 6 inch diameter high point, 168 inches long
- Froude number 0.46 to 0.95
- Single downcomer 66 inches long
- 2 void fraction measurements in the last 4 feet

# Beaver Valley Unit 1 Test Apparatus

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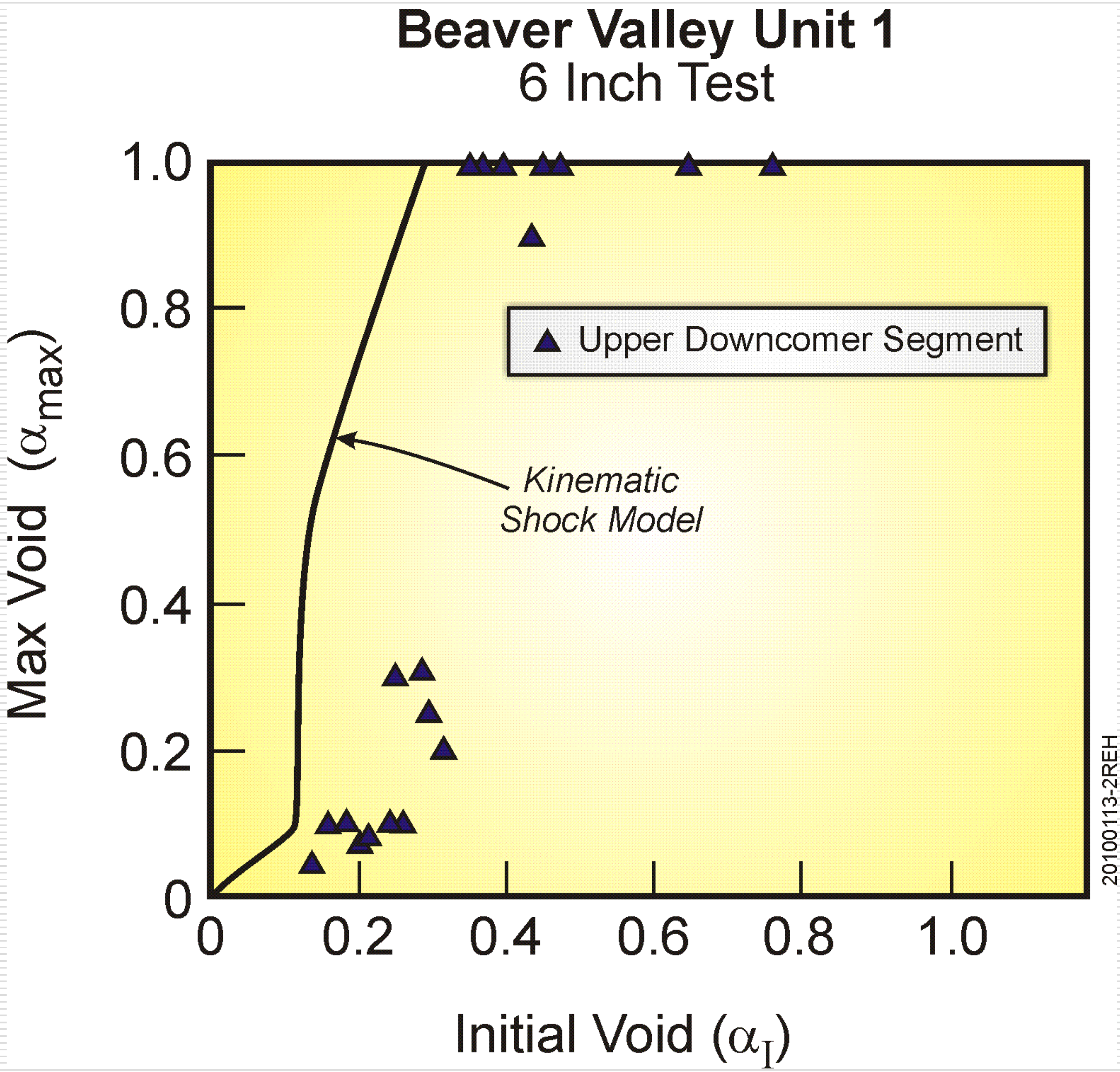
Beaver Valley Unit 1
6 Inch Test
Upper Downcomer Segment
Kinematic Shock Model
Max Void ($\alpha_{max}$)
Initial Void ($\alpha_I$)
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
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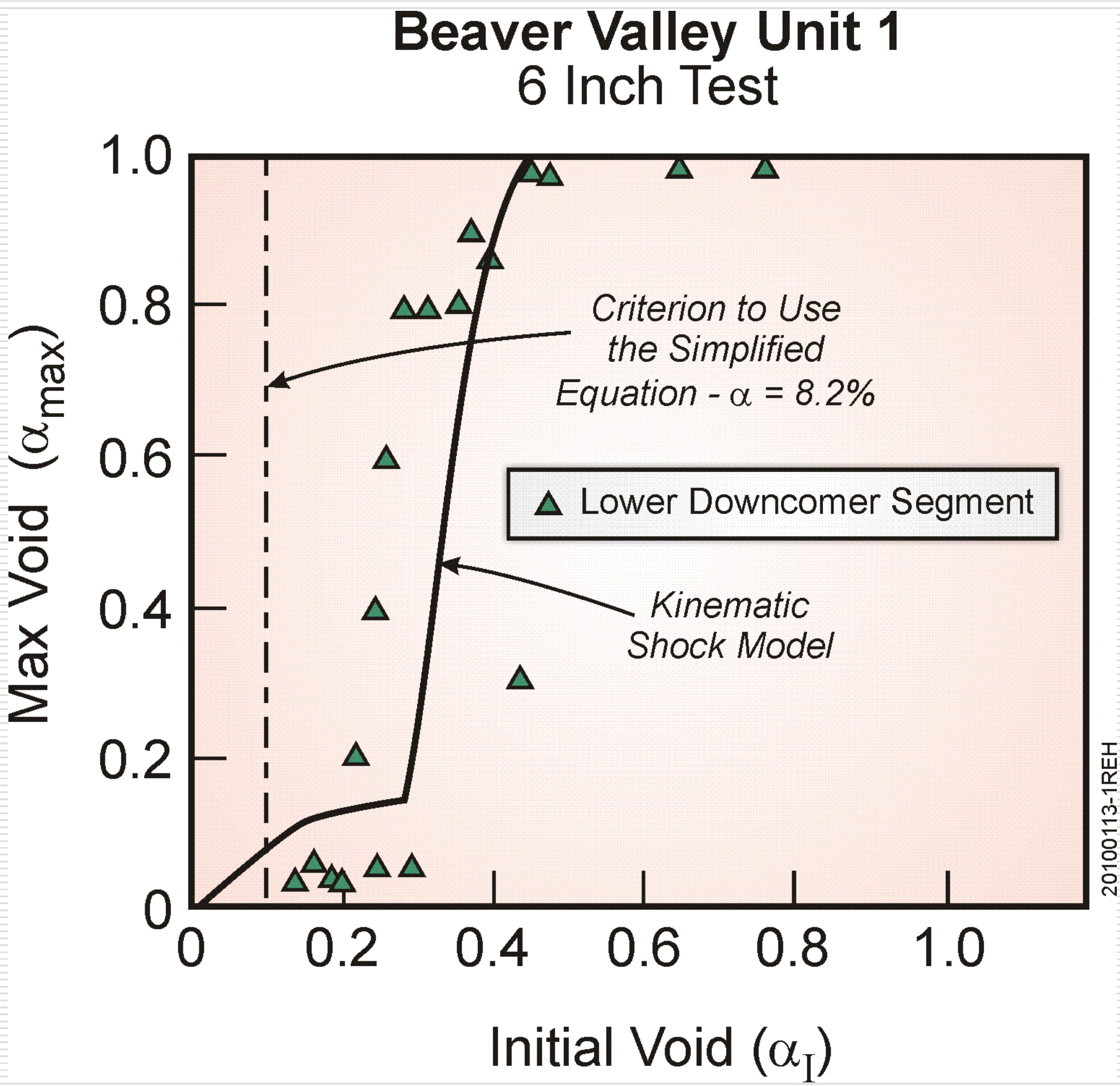
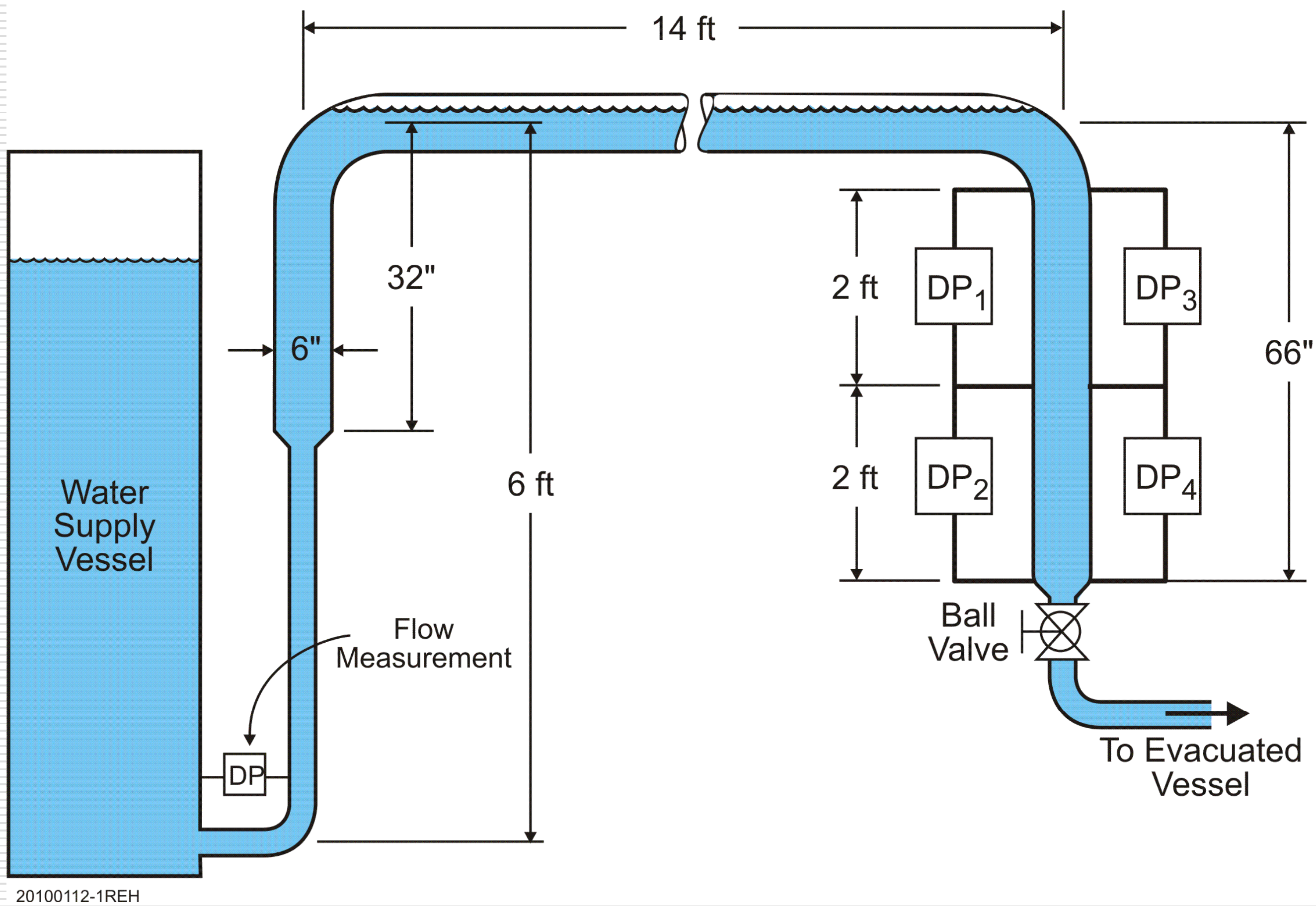

Beaver Valley Unit 1
6 Inch Test
Max Void ($\alpha_{max}$)
1.0
0.8
0.6
0.4
0.2
0
Criterion to Use the Simplified Equation - $\alpha$ = 8.2%
Lower Downcomer Segment
Kinematic Shock Model
0
0.2
0.4
0.6
0.8
1.0
Initial Void ($\alpha_I$)
20100113-1REH

# Beaver Valley Unit 2 Test Apparatus

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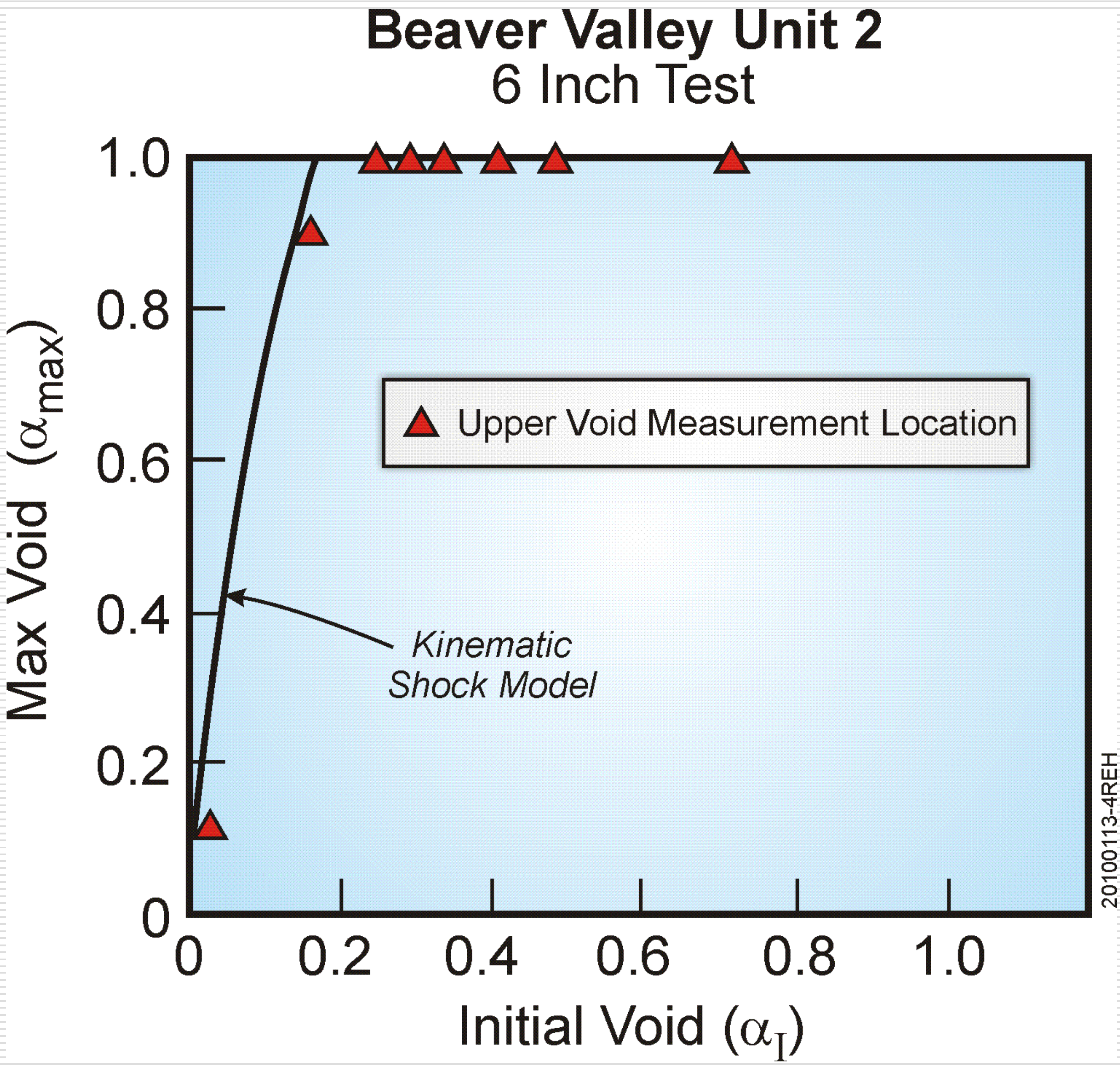


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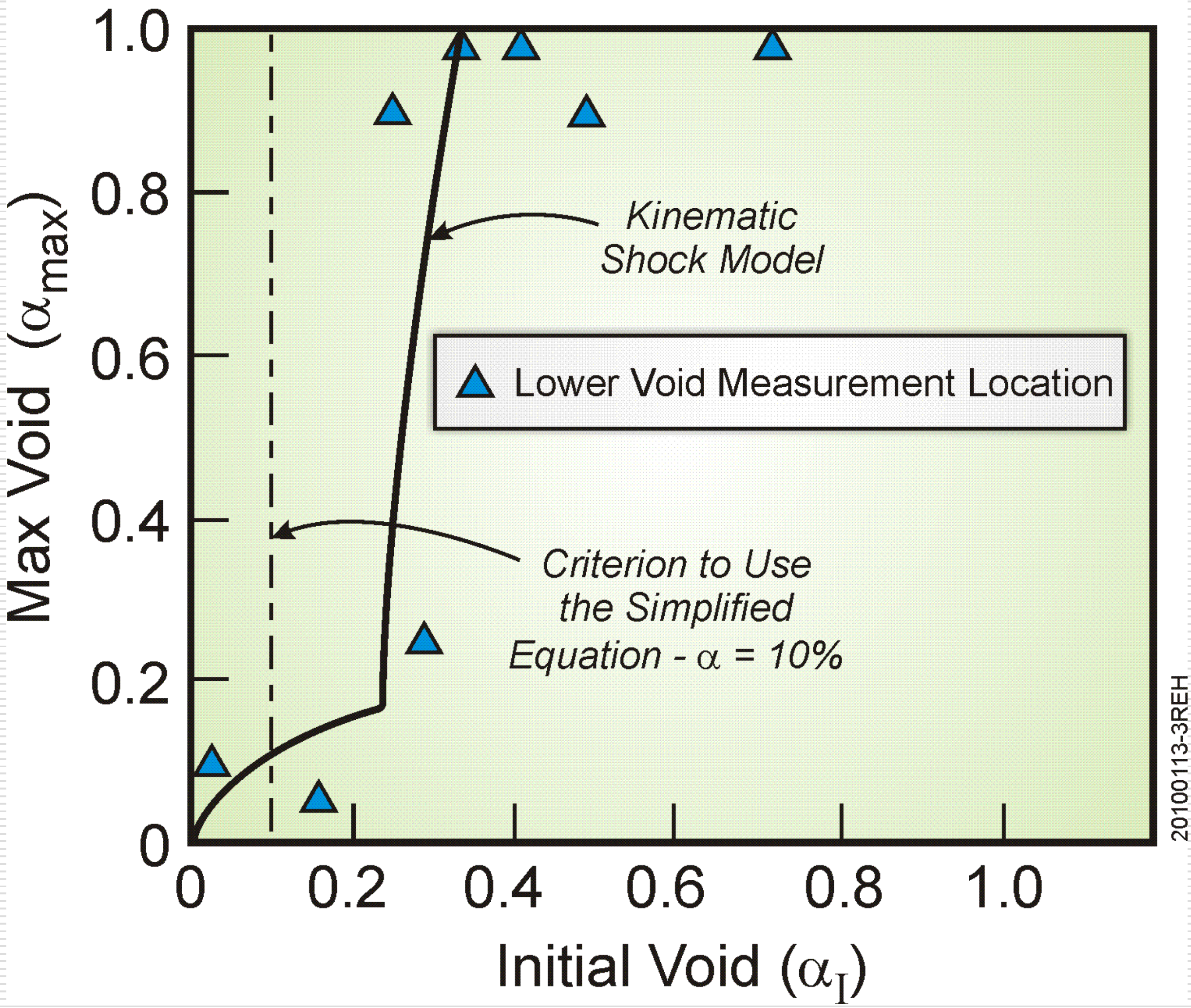
## Beaver Valley Unit 2
6 Inch Test

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# Purdue Large Scale Tests

- As part of a current PA, the PWROG data taken at Purdue University is being interpreted in a similar manner.
- The Purdue tests include large scale data with test section diameters of 4, 6, 8 and 12 inches.
- These experiments will add to the data base defining the conditions for using the simplified equation.

# Use of the Simplified Equation

- The simplified equation is based on homogeneous bubbly flow. Therefore: a kinematic shock must be formed such that the two-phase flow pattern at the bottom of the downcomer is bubbly flow.

- The gas volume introduced into a pump within a specified interval is the essential feature related to the pump operation.

- Given a bubbly flow pattern and the pump volumetric flow rate ($Q_s$), the gas volume transported to the pump can be described as:

$$V_{gp} = Q_s \, \bar{\alpha}_p \, \Delta t$$

where

- $\bar{\alpha}_p$ is the average gas void fraction transmitted to the pump suction,
- $\Delta t$ is the two-phase transition duration, and
- $V_{gp}$ is the volume of gas transported through the pump.

- Because $\Delta t$ is determined from Table 1, this has been demonstrated to bound the detailed calculation.

- Therefore, used in this manner, the simplified equation provides a bounding calculation.

## Influence of Static Head

- Approximately 2 feet (0.6 m) of water static head increases the local pressure 1 psi (7 kPa). Therefore, from a practical point of view, the static head is only important when there are at least 10 feet (3 m) or more of head difference between the piping high point and the pump suction elevation.
- Assume PV = Constant

  For static head of h, the void fraction is reduced in the following manner:

$$P_1 V_{g1} = \left(P_1 + \rho_w gh\right) V_{g2}$$

$$P_1 \alpha_1 = \left(P_1 + \rho_w gh\right) \alpha_2$$

$$\frac{\alpha_1}{\alpha_2} = 1 + \frac{\rho_w gh}{P_1}$$

If $\rho_w gh = 0.5 P_1 \qquad \alpha_2 = 2/3\, \alpha_1$

If $\rho_w gh = P_1 \qquad \alpha_2 = 1/2\, \alpha_1$

If $\rho_w gh = 0.1 P_1 \qquad \alpha_2 = 0.9\, \alpha_1$

- The corrections (reductions) are applied to the void fraction exiting the kinematic shock.

# Application of the Simplified Equation to the Scaled Palo Verde Tests

- The initial void fraction is 60% in the high point after the region pressurizes to equal the sump pressure.

- Given the water superficial velocity in the high point of 2 ft/sec (0.6 m/sec) in a 5 ft (1.5 m) long void, the simplified equation would predict the transmittal of a 60% void for 2.5 secs.

- This shows that the simplified equation provides a very conservative representation of the scaled Palo Verde tests.

- In this comparison, the difference between the simplified representation and the data is the formation of a kinematic shock and the interval over which the gas is entrained.

# Application of the Simplified Equation to the Beaver Valley Tests

I. The Beaver Valley Unit 1

- The longest downcomer is 46 inches. Hence, one-fourth of this volume corresponds to a high point void fraction of 8.2%.
- The scaled experiments show that bubbly flow is transmitted for this and larger void fractions. Hence, the simplified equation criterion provides a conservative bounding value to ensure bubbly flow transport.

II. Beaver Valley Unit 2

- The single downcomer is 66 inches long. One-fourth of this volume corresponds to a high point void fraction of 10%.
- The scaled experiments show that bubbly flow is transmitted for this and larger void fractions. Hence, the simplified equation criterion provides a conservative bounding value to ensure bubbly flow transport.

# Conclusions

| Important Features Comprising the Criteria | Technical Basis |
| --- | --- |
| 1. The gas volume is pulled toward the downstream elbow. | Palo Verde and Beaver Valley integral system scaled tests. |
| 2. A two-phase flow pattern is established with water flowing under some of the gas at the top of the elbow and the remainder of the gas is pulled into, and collected in, the top of the downcomer, i.e. a kinematic shock is formed. | Palo Verde and Beaver Valley integral system scaled tests and analytical calculations. |
| 3. The high point gas volume is $1/4^{th}$ of the downcomer volume. Criterion for using the simplified equation. | Verified by both the Palo Verde and Beaver Valley integral system scaled tests. |
| 4. When the kinematic shock criterion is satisfied, the simplified equation provides a bounding calculation of the gas intrusion to the pump. | Comparison with the kinematic shock model. |