LOW FLOW PRESSURE DROP FLOW RATE INSTABILITIES IN A COMPRESSIBLE AIR-WATER SYSTEM

by

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ABSTRACT

Experiments were performed to investigate the pressure drop versus flow rate instability of an air-water flow through a vertical tube with a large tank of air at the entrance. An unsteady region, occurring when the slope of the pressure drop versus flow rate curve was negative, was found. In the unsteady region, periodic filling and discharge of the vertical pipe occurred, leading to large fluctuations in the pressure at the top of the bottom tank. Pressure drop fluctuations occurred about as theoretically predicted.

A minimum flow rate, at which the water flowed back into the bottom tank, was found in the unsteady region. The experimentally determined leakage limit line was compared with the analytically determined leakage line with fair agreement obtained.

Thesis Supervisor: Peter Griffith

Title: Professor of Mechanical Engineering

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NOMENCLATURE

A	Total Flow Area (ft^2)
α	Void Fraction (dimensionless)
c_o	Constant in Equation (A.3)
D	Tube Diameter (ft.)
f_1	Friction Factor corresponding to the Reynolds Number of Equation (A.5)
g	Gravitational Acceleration (ft/hr^2)
g_o	Constant (4.17×10^8 lbm-ft/lbf-hr^2)
G	Mass Flux, $\frac{(\dot{m}_f + \dot{m}_g)}{A}$ (lbm/ft^2-hr)
j_f	Superficial Liquid Velocity (ft/s)
j_g	Superficial Gas Velocity (ft/s)
L_{TOT}	Total Length of Tube (ft)
L_{UP}	Length of the Vertical Tube (ft)
$\dot{m}_f$	Liquid Mass Flow Rate, $\rho_f j_f A$ (lbm/hr)
$\dot{m}_g$	Gas Mass Flow Rate, $\rho_g j_g A$ (lbm/hr)
n	Constant in Equation (B.1)
μ_f	Absolute Liquid Viscosity (lbm/hr-ft)
Δp	Total Pressure Drop (lbf/in^2)
Δp_{fric}	Frictional Component of Total Pressure Drop (lbf/in^2)
Δp_{grav}	Gravitational Component of Total Pressure Drop (lbf/in^2)
Q_f	Fluid Volumetric Flow Rate, j_f/A (ft^3/s)
Q_g	Gas Volumetric Flow Rate, j_g/A (ft^3/s)
Re	Reynolds Number
ρ_f	Liquid Density (lbm/ft^3)

ρ_g	Gas Density (lbm/ft^3)
V	Tank Volume (ft^3)
$\bar{v}$	Average Specific Volume, $v_f + x(v_g - v_f)$ (ft^3/lbm)
v_f	Liquid Specific Volume, $1/\rho_f$ (ft^3/lbm)
v_g	Gas Specific Volume, $1/\rho_g$ (ft^3/lbm)
V_{vj}	Drift Velocity (ft/s)
x	Flow Quality, $\frac{\dot{m}_g}{\dot{m}_f + \dot{m}_g}$ (dimensionless)

INTRODUCTION

Toward the end of the oil and gas well's productive life, the pressure drop between the bottom and the top of the well begins to increase, due to the increase in the holdup, that is the volumetric concentration of the oil in the pipe. A long period dump and refill process begins to occur in the vertical pipe with a period on the order of 30 minutes. This fluctuation in the flow and pressure seems to occur because of the compressibility of the oil-gas system. After the vertical pipe is almost filled with liquid, a sudden discharge occurs. The oil-gas mixture expands and the pressure drops. The mixture surges out of the well. The sudden increase in the flow results in overloading the separators at the top of the well causing carryover.

The objective of this experiment is to discover what combinations of flow rates will cause fluctuations in the pressure and the surging of the oil-gas mixture out of the well. An air-water system will model the gas and oil. A short vertical pipe produces the negative sloping pressure drop flow rate curve, while a tank provides the compressible volume.

APPARATUS

A schematic diagram of the test apparatus is shown in Figure 1.

Shop air flows into a 2.86 cu. ft. tank. The tank has a sight gage to determine the water level (if any). The air flows out of the tank through a horizontal plexiglas tube .75 ft. long and .75 inches I.D. This tubing is joined at 90^{0} to a .25 ft. section of plexiglas (Clear plexiglas is used, so a visual check of leakage back into the tank can be made.). This plexiglas is connected to copper tubing .75 inches I.D., which forms a U measuring 5 ft. in length. Water flows into this copper section and mixes with the air from the tank. The rest of the 28 ft. vertical pipe is plexiglas with an I.D. of .75 inches. The end of the pipe feeds into a second tank which empties the air-water mixture into the drains.

A pressure gage attached to the top of the tank measures the tank pressure. A Stantham pressure transducer is attached to a tee with the pressure gage. The transducer is connected to a Sanborn WAM meter. The meter is connected to an x-y recorder to measure pressure fluctuations versus time.

The air flow rate is measured by a Fischer and Porter flowmeter model no. FP-1/2-27-G-10/55. The water flowrate is measured by a Fischer and Porter flowmeter model no. FP-1/2-21-G-10/83. Valves are located upstream of the flowmeters to control the flowrates. A Watts air pressure regulator no. 119-4 sets the supply air pressure at 30 psia.

EXPERIMENTAL PROCEDURE

Tests were performed to determine the regions of stability and instability. The pressure fluctuations in the tank were noted, as the water and air flows were varied. The regions with zero or imperceptible (less than .2 psi) fluctuations were considered steady.

Experiments were carried out to determine the maximum and minimum pressure drop in the tank for each combination of fluid and gas flow. Superficial gas and liquid velocity readings were calculated from the flowmeters. The average superficial liquid velocities ranged from $.048<j_f<.238$ ft/s, while the gas ranged from $.791< j_g <9.887$ ft/s. Pressure versus time traces were taken to get a good estimate of the maximum pressure fluctuations for each combination of air and water flows.

The leakage limit lines were determined at the same time the pressure drop data was taken. The superficial gas velocity was fixed and the lowest superficial liquid velocity was found at which leakage back into the lower tank occurred.

RESULTS AND DISCUSSION

Pressure drop readings were taken for various combinations of superficial gas and liquid velocities to determine the regions of stability and instability. These regions are shown in Fig. 2. Any fluctuation below .2 psi was considered to be negligible. Thus, any combination of flows which caused a fluctuation of less than .2 psi was considered to define a stable point. This plot was used to determine in later tests which combinations of flow rates would cause significant pressure drops.

Figure 3 shows the dependence of the pressure drops on the flow rates. As the superficial liquid velocity, j_f, increases and the superficial gas velocity, j_g, decreases, the pressure drop increases. Notice that the pressure drop is more sensitive to changes in the superficial gas velocity. According to the drift flux model (see Appendix A for further treatment), as j_f increases and j_g decreases, the pressure drop should increase. The experimental results tend to agree with this.

As j_g decreases and j_f increases, a limit to the maximum pressure drop is reached. This maximum pressure drop is approximately 12 psi. This is the pressure due to a column of water 28 ft. high that the air in the tank has to support.

Figure 4 shows the calculated and experimentally determined leakage limit lines. Leakage, theoretically, occurs when $\frac{Q_f \rho_f g}{A g_o} > \frac{Q_g}{V/nP}$, where Q_f is the liquid volumetric flow rate,

ρ_f is the fluid density, g is the gravitational acceleration, $g_o = 4.17 \times 10^8$ lbm-ft/lbf-hr^2, Q_g is the gas volumetric flow rate, V is the tank volume, n ≡ 1, and P is the average tank pressure. (See Appendix B for the derivation of this inequality.)

There is fair agreement between the experimental and calculated leakage limit lines. Deviations of the experimental from the analytic results could be explained by inaccurate pressure drop measurements, errors in the superficial gas velocity and superficial liquid velocity readings, an inaccurate tank volume measurement, or by the presence of friction in the real system which was not accounted for in the equations modelling the system.

Experimentally determined pressure drops and superficial gas velocities are plotted for a specific superficial liquid velocity. See Figures 5-8. Then, using the drift flux model analysis, the pressure drops are calculated and plotted against the superficial gas velocities for a given superficial liquid velocity. Refer again to Figures 5-8. See Appendix A for the equations used in the drift flux model analysis. Notice that the pressure drop versus superficial gas velocity curve is negative. According to Wallis(2), the curve is negative in the region of unstable flow. These superficial gas and liquid velocities of Figures 5-8 fell within the limits of the experimentally determined unstable region.

In Figures 5-8, there is very little agreement between the calculated and the experimental results. The pressure drops were calculated using the drift flux model. This could be an explanation for some of the disagreement in the results. The drift flux model assumes slug flow. A test run, however, had flows ranging from a solid column of water 28 ft. high to annular flow.

In Figures 5-8, both the experimental and calculated pressure drops tend toward a Δp of 2 psi. The experimental pressure, however, approaches the asymptote at 2 psi more quickly.

Figures 9-11 show traces of the pressure fluctuation with time for various flow combinations. These graphs were used to generate Figures 2-8.

Figures 9-10 show the fluctuations of the pressure with time. In both figures, notice that there seem to be 2 sets of waveforms. In determining the maximum pressure drop, the larger of the two was used.

Figure 11 illustrates the slow building up of the pressure and the rapid blowdown.

CONCLUSIONS

The regions of stable and unstable growth were found.

The dependence of pressure drop on superficial gas and liquid velocity was shown. The experimental results followed the trend of the predictions of the drift flow model, that is, as j_g decreased and j_f increased, the pressure drop increased.

The experimental leakage limit lines agreed fairly well with the theoretical calculations.

Further study on this problem could include trying to develop a better model of the system. Using the drift flux model to calculate the pressure drops gave poor results. However, it will be difficult to accurately model this system because, in the course of a run, the flow varied from a solid water column to annular flow. Refer to Wallis (2) for the equations for the pressure drop calculations for other flow regimes.

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I would like to thank Ted Fischer for coming in on Saturdays.

I would also like to thank Tiny and Fred for building and maintaining my apparatus.

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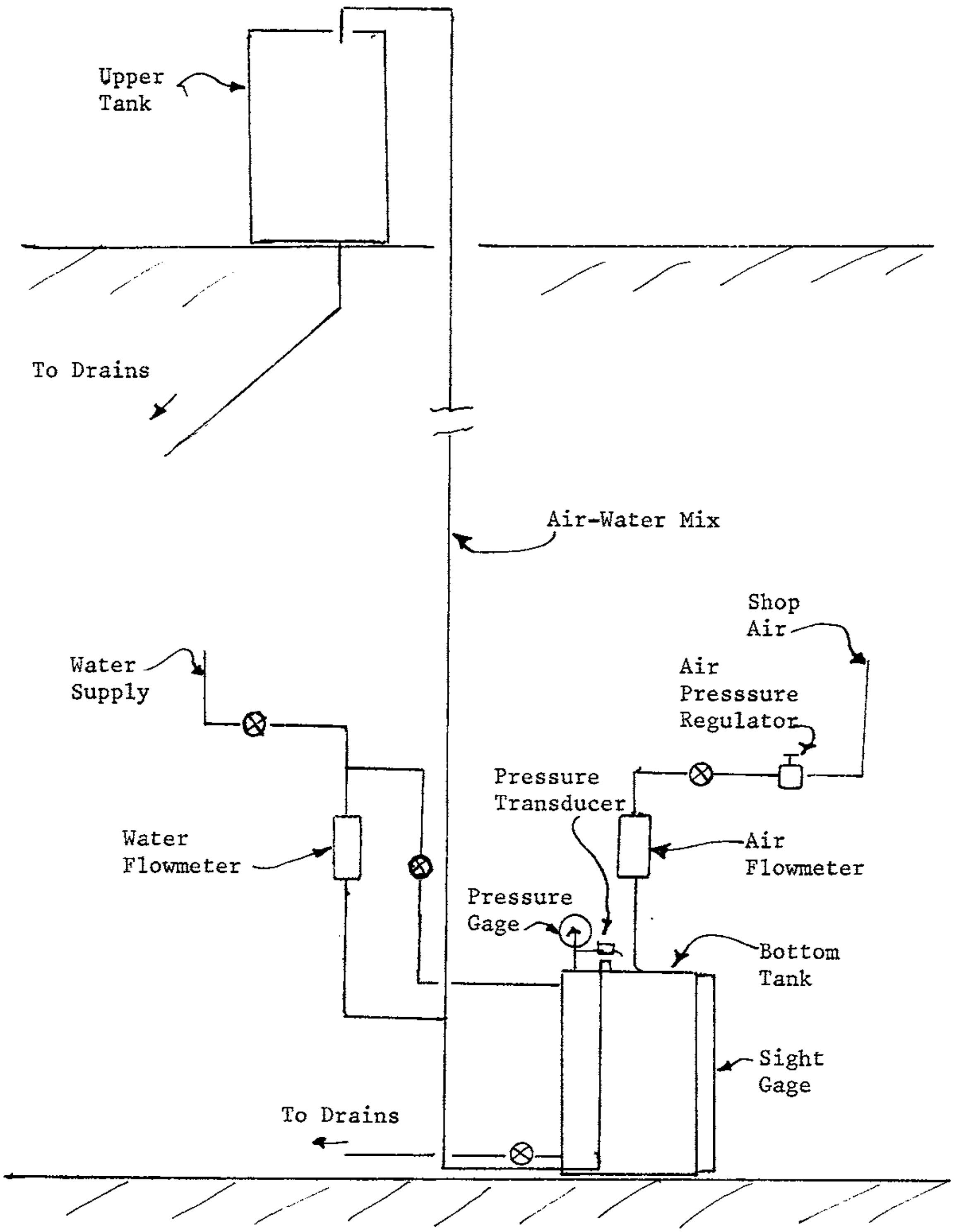

Figure 1 Schematic of Test Apparatus

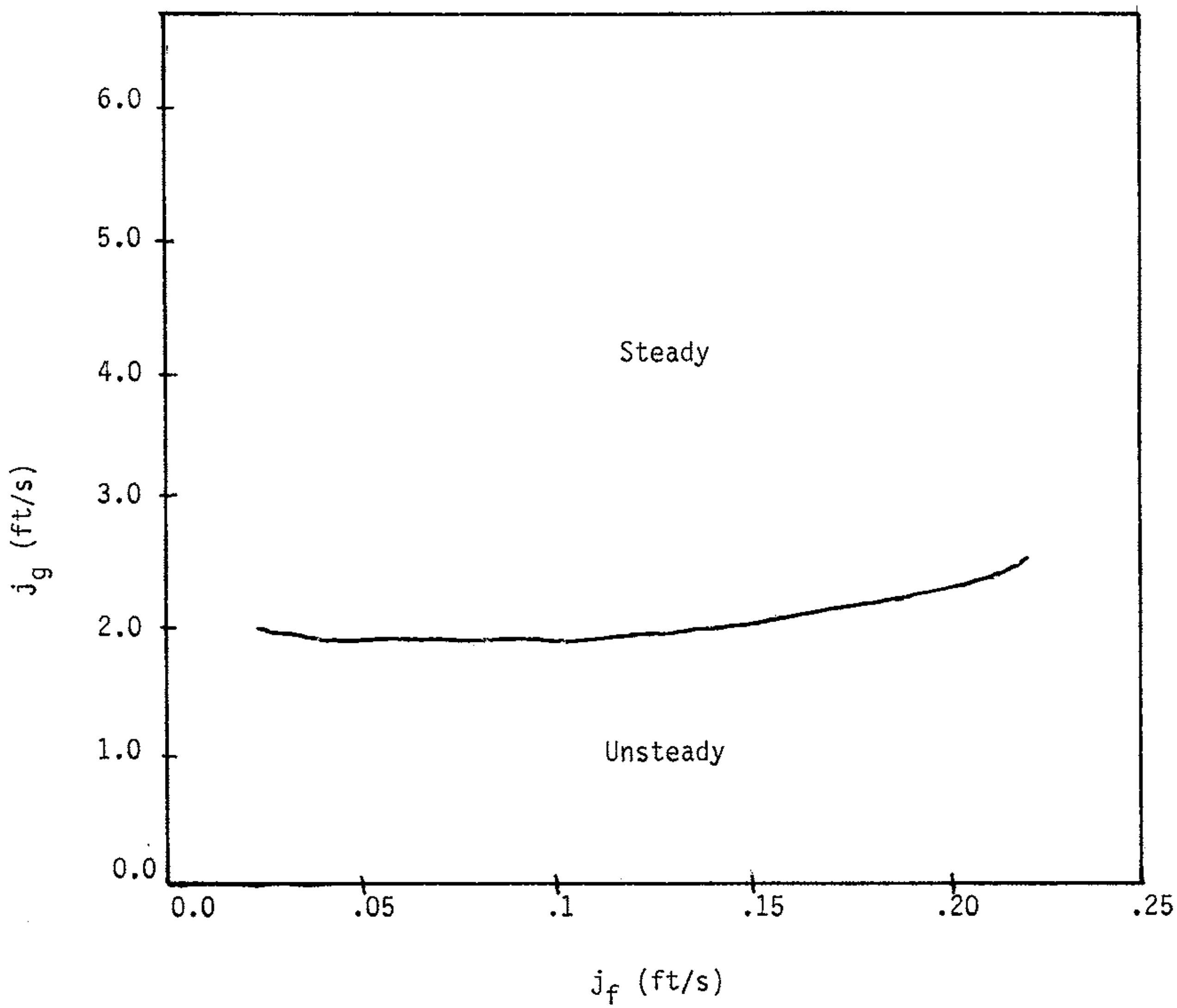

Figure 2 Steady-Unsteady Pressure Fluctuation Regions

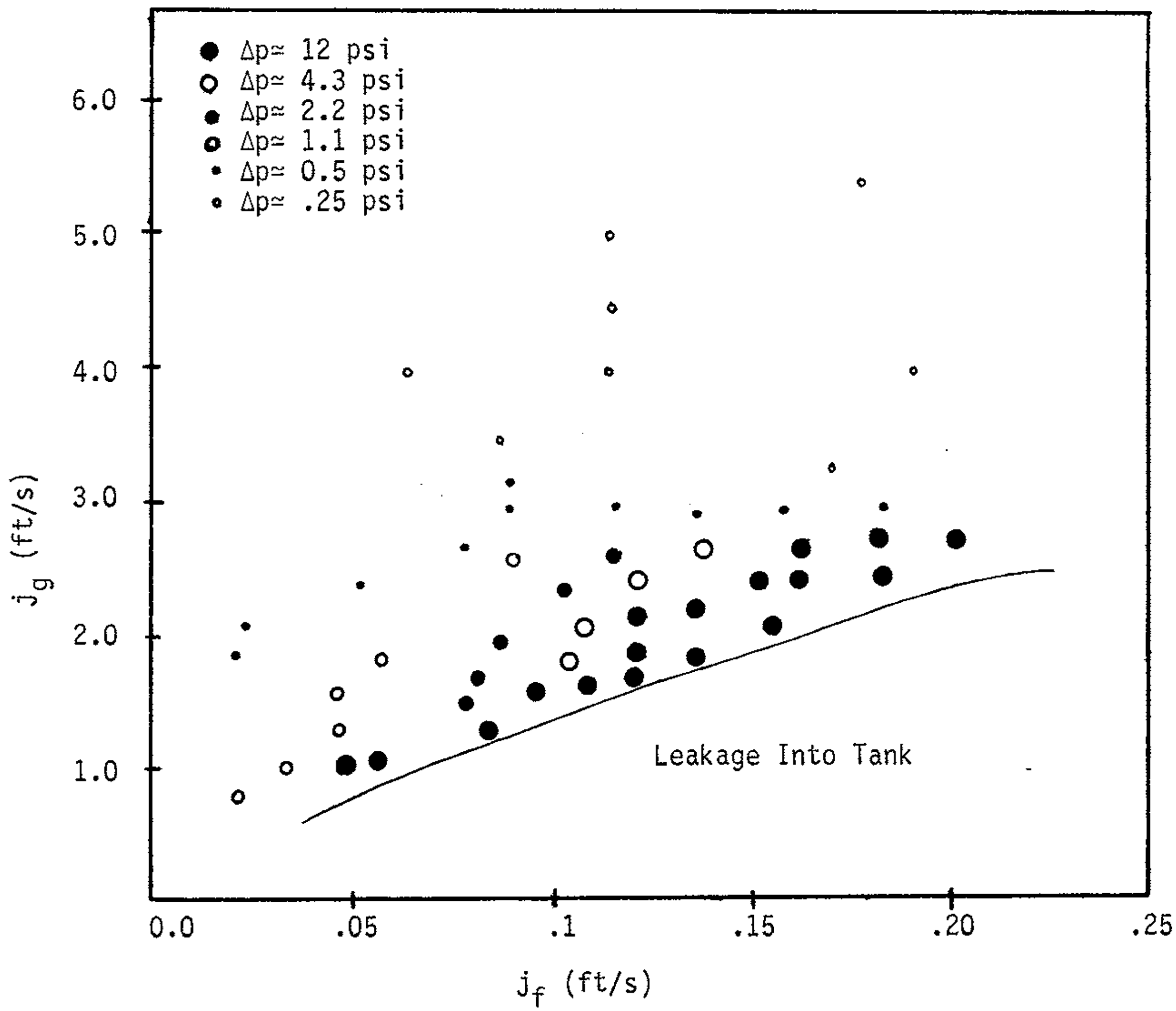

Figure 3 Experimentally Measured Maximum Pressure Drops for Various Air-Water Flow Combinations

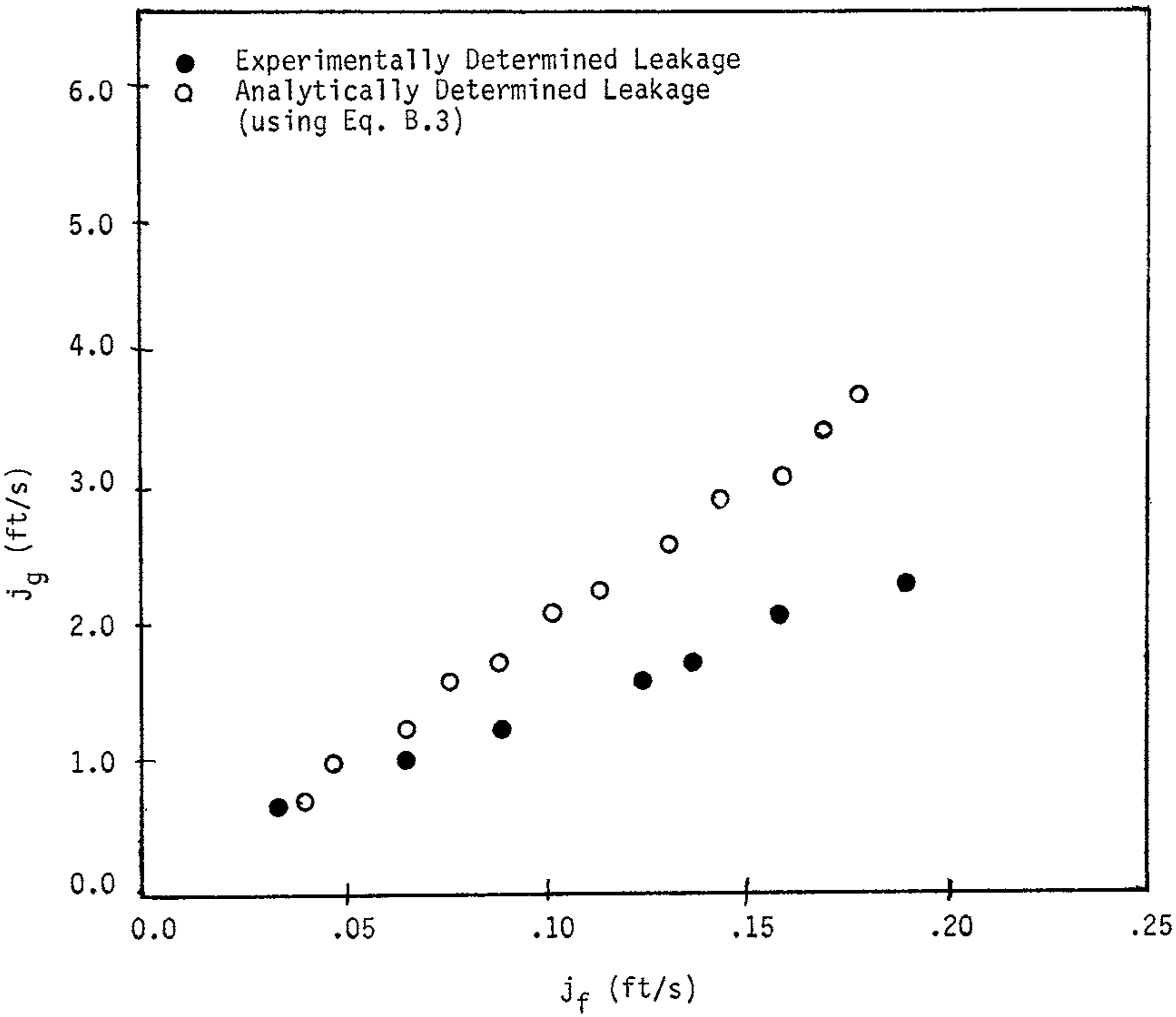

Figure 4 Leakage Limit Lines

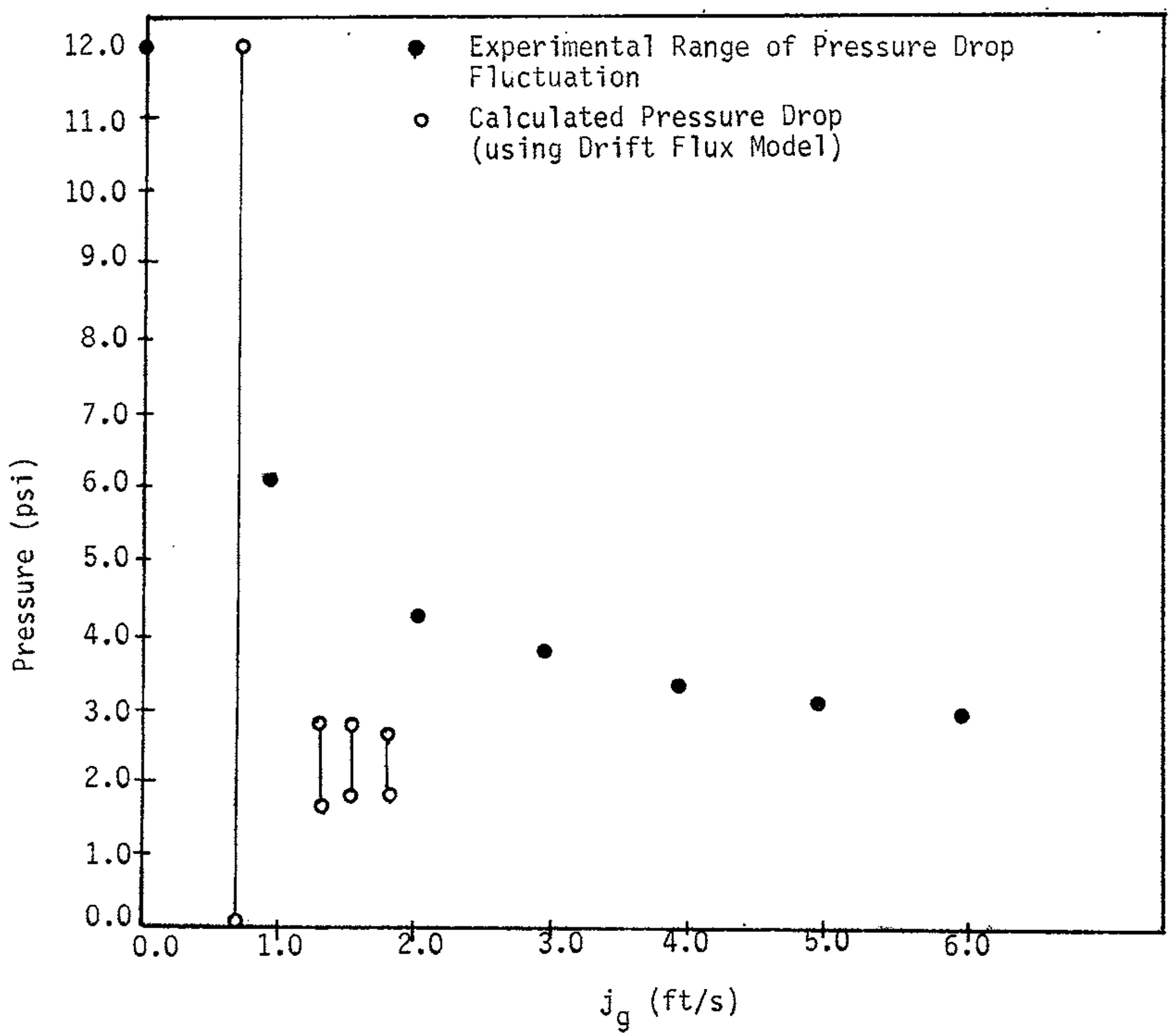

Figure 5 Experimental and Calculated Pressure Drops for j_f=.048 ft/s
(with j_g corrected for high pressure operation)

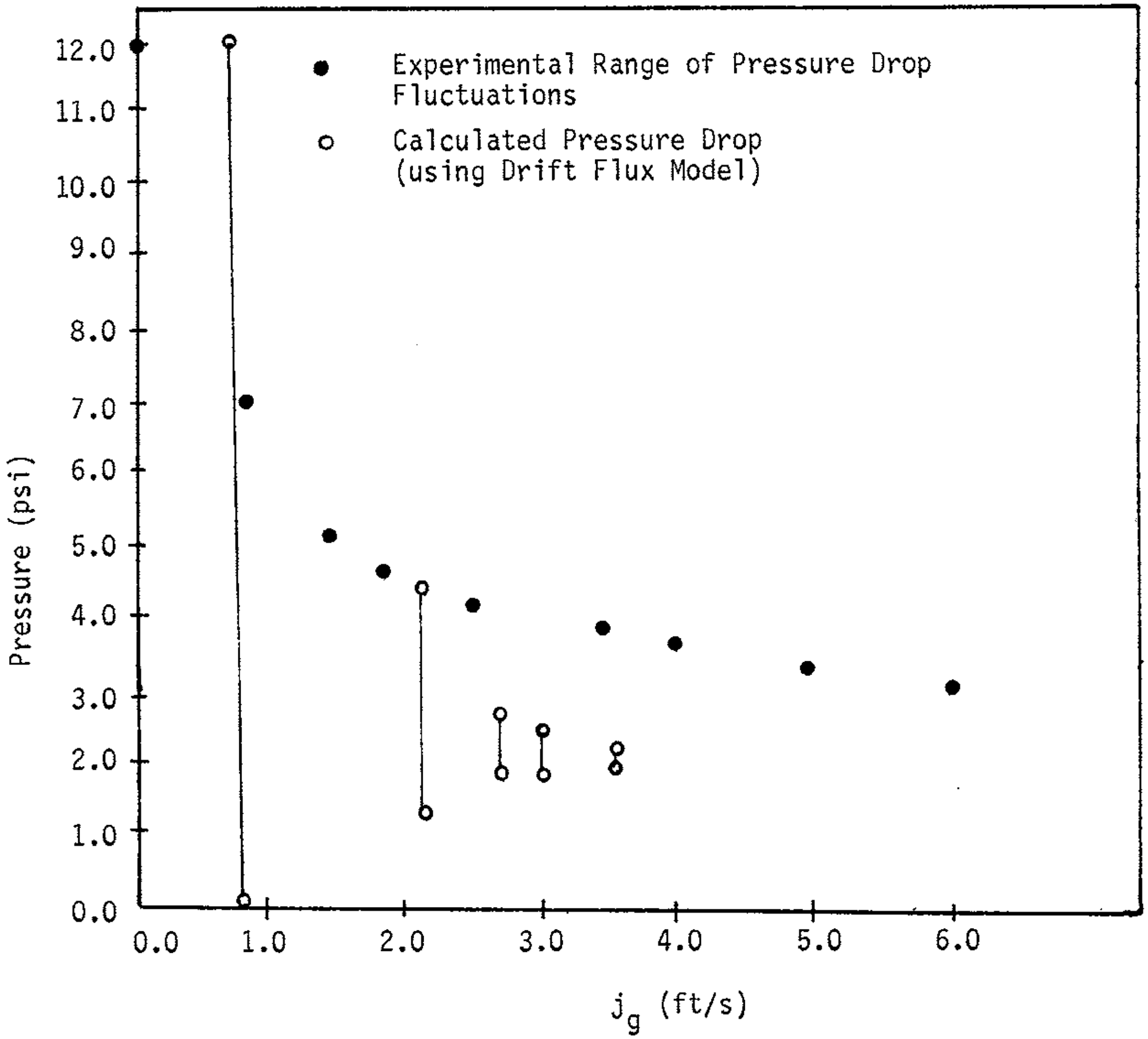

Figure 6 Experimental and Calculated Pressure Drops for j_f=.095 ft/s
(with j_g corrected for high pressure operation)

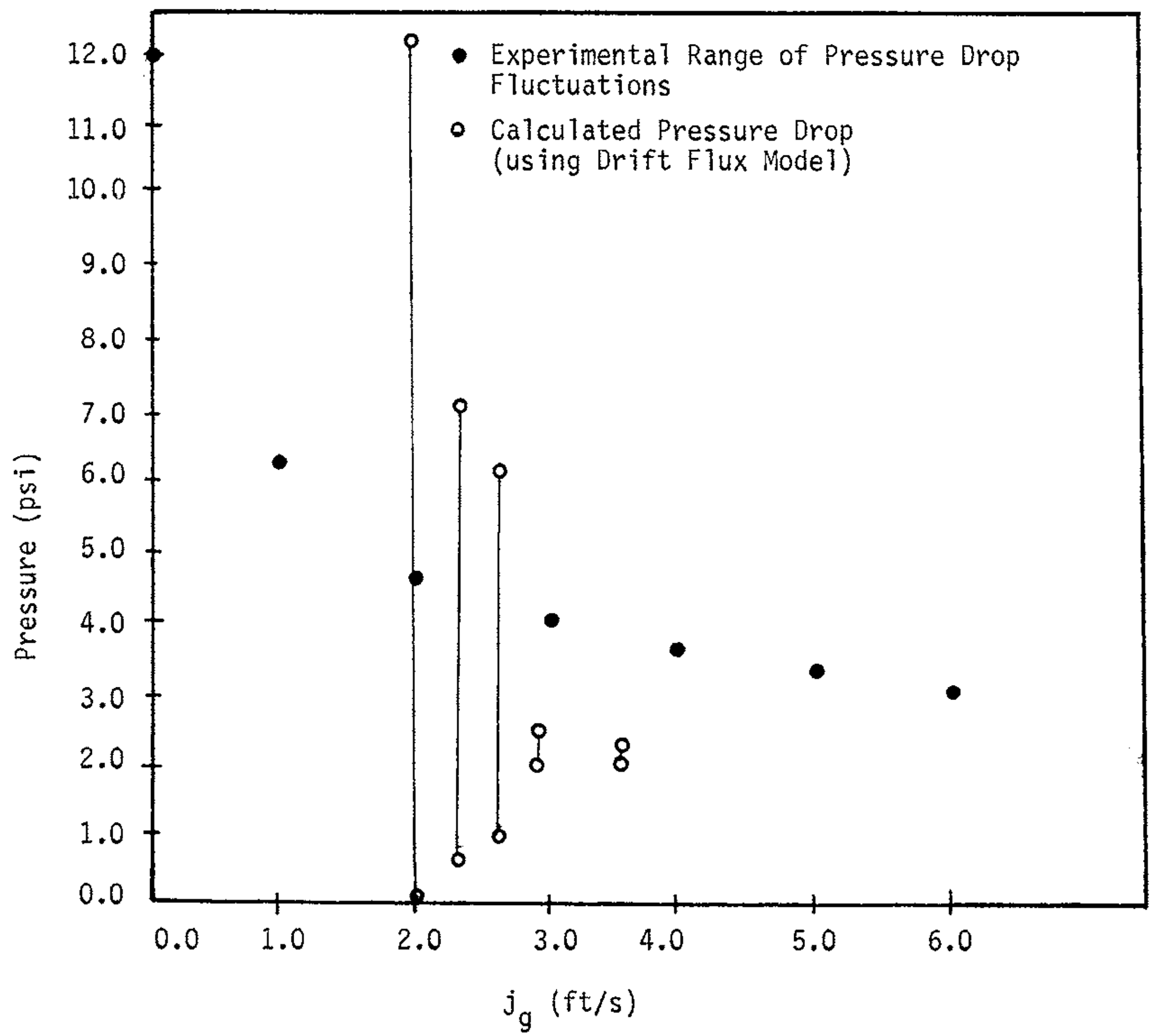

Figure 7 Experimental and Calculated Pressure Drops for j_f=.143 ft/s (with j_g corrected for high pressure operation)

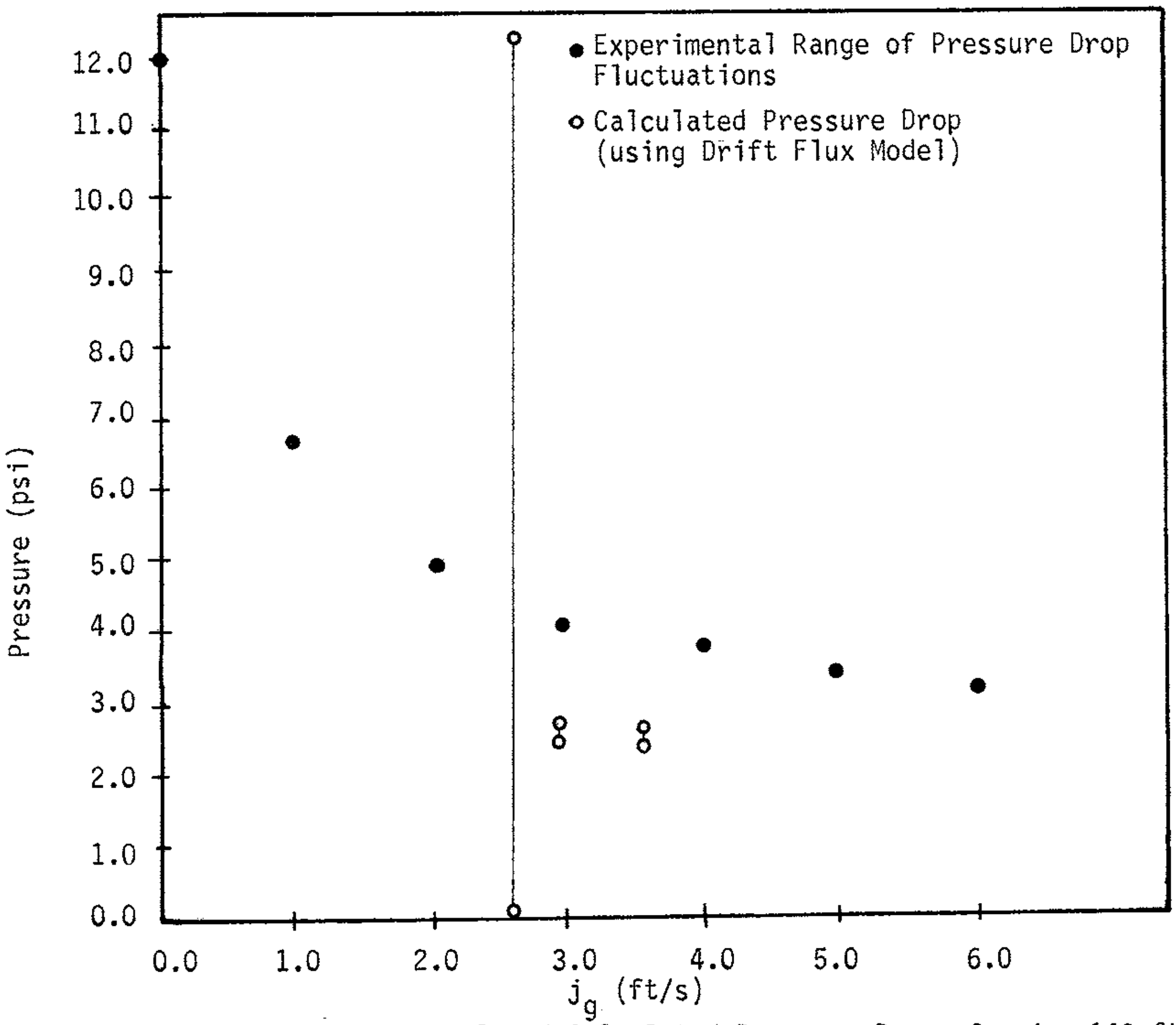

Figure 8 Experimental and Calculated Pressure Drops for j_f=.143 ft/s (with j_g corrected for high pressure operation)

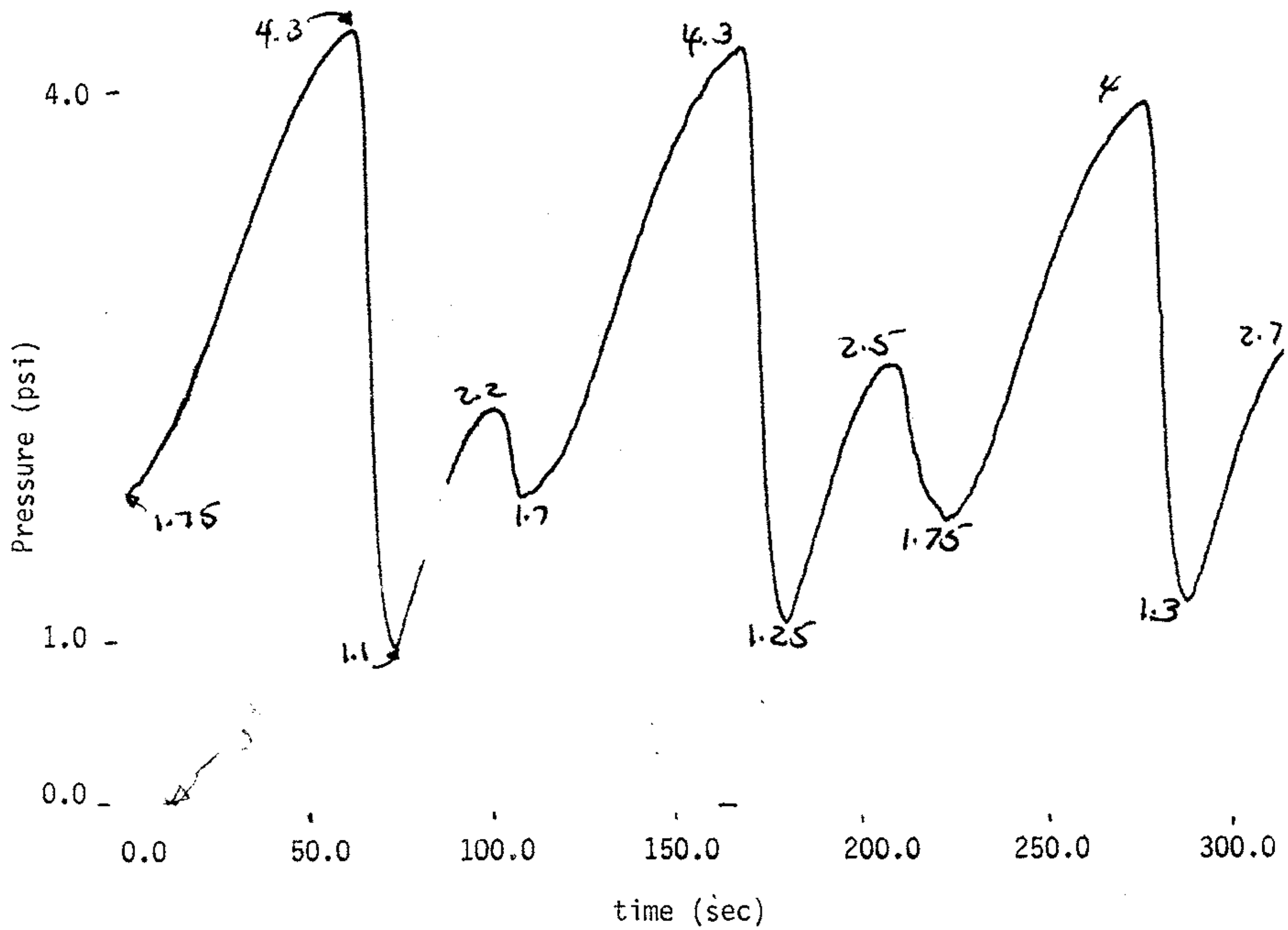

Figure 9 Sample Pressure versus Time Trace
(for j_f=.095 ft/s, j_g=2.13 ft/s)

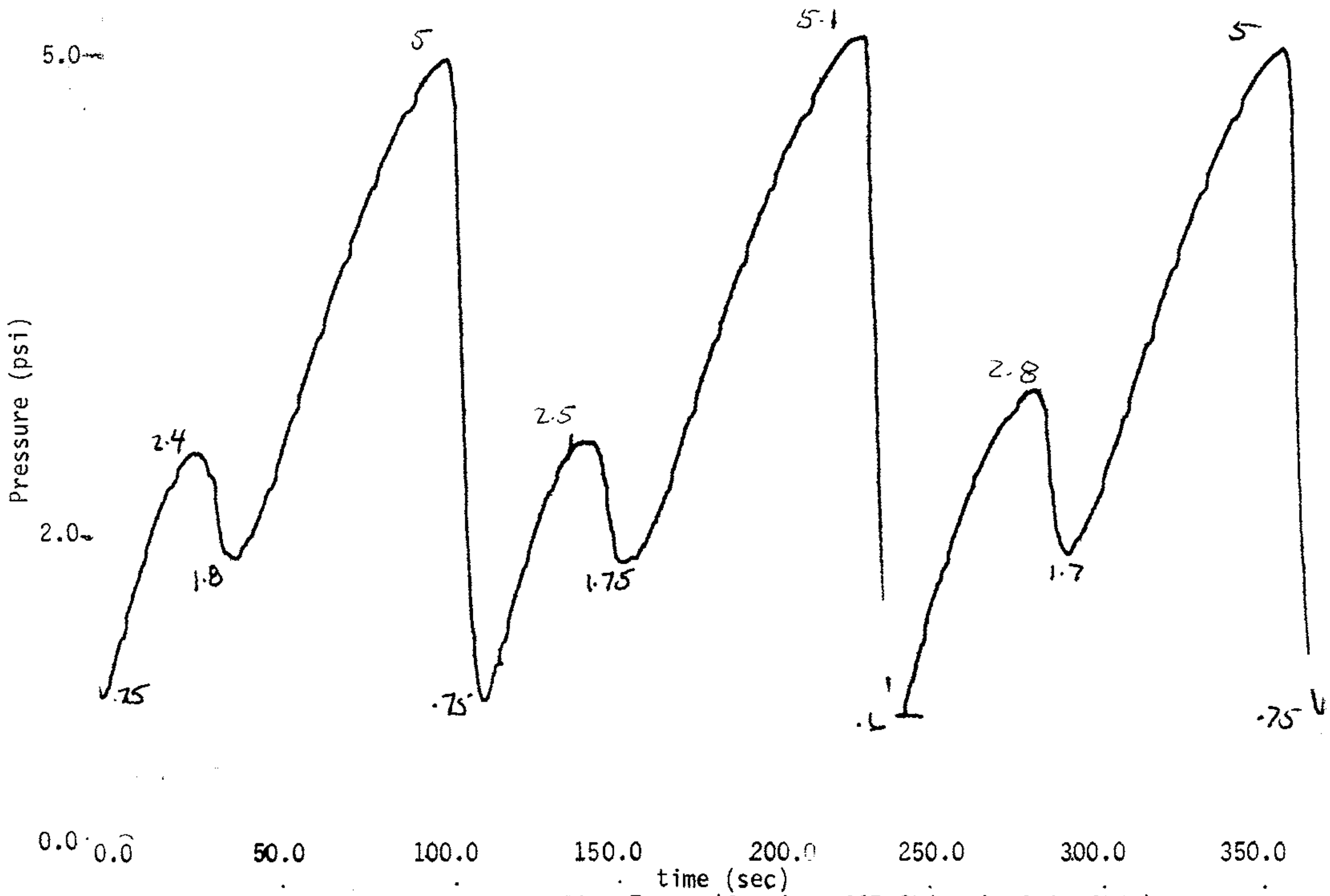

Figure 10 Sample pressure versus Time Trace (for j_f =.107 ft/s, j_g=2.13 ft/s)

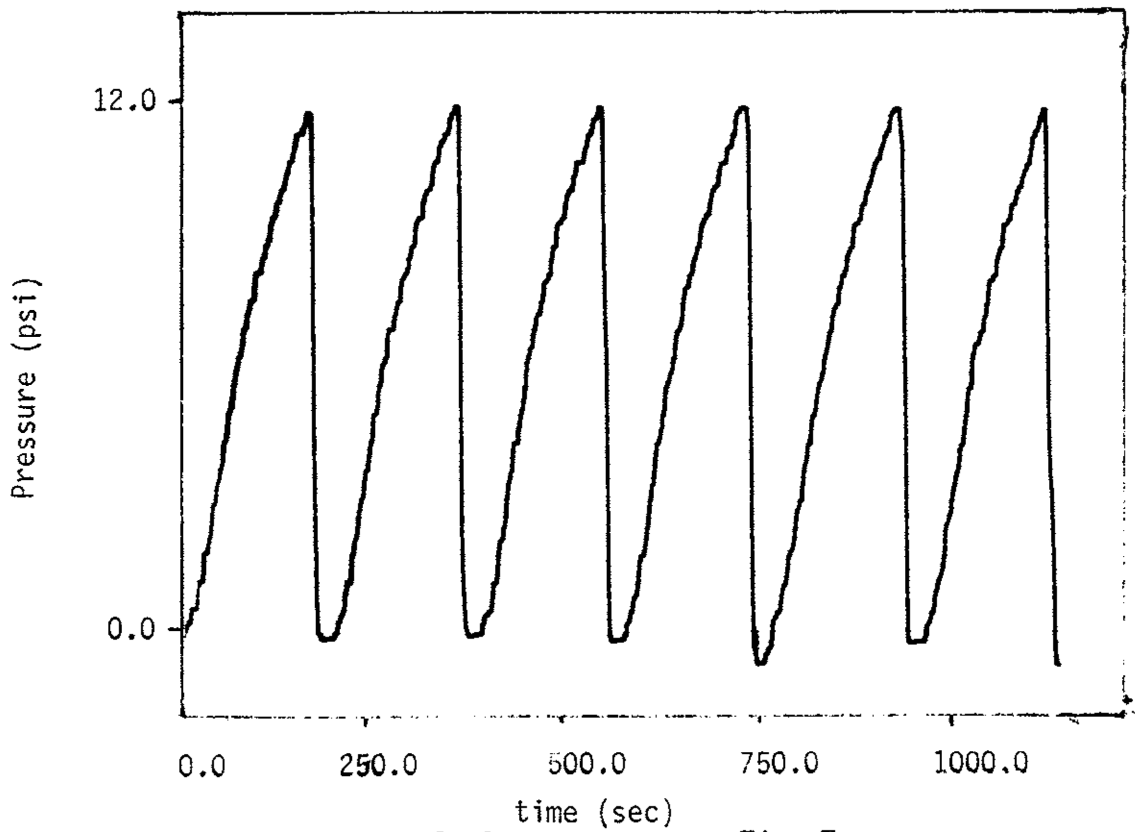

Figure 11 Sample Pressure versus Time Trace
(for j_f=.119 ft/s, j_g=2.13 ft/s)

APPENDIX A

THE CALCULATION OF THE MAXIMUM PRESSURE DROP, Δp, WITH VARIOUS COMBINATIONS OF j_g AND j_f, USING THE DRIFT FLUX MODELS.

(See References 1 and 2)

The pressure drop in the tank-tube system is a combination of a pressure drop due to friction and a pressure drop due to gravity, or

$$\Delta p = \Delta p_{grav} + \Delta p_{fric} \tag{A.1}$$

where

$$\Delta p_{grav} = (\alpha\rho_g + (1-\alpha)\rho_f) \frac{g}{g_o} L_{UP} \tag{A.2}$$

with α = void fraction, ρ_g = air density (0.0763 lbm/ft^3), ρ_f = fluid density (62.4 lbm/ft^3), g = gravitational acceleration, $g_o = 4.17\times10^8$ lbm-ft/lbf-hr^2, and L_{UP} = length of the vertical tube. The drift flux model is used to estimate the void fraction (see Wallis (2)),

$$\alpha = \frac{j_g}{c_o(j_g + j_f) + V_{vj}} \tag{A.3}$$

where c_o=1.2, j_g is the superficial gas velocity, j_f is the superficial liquid velocity, and $V_{vj}=0.35(gD)^{0.5}$ from Hsu (4) with D = tube diameter (.75 inches) and g = gravitational acceleration.

The frictional pressure drop can be found from

$$\Delta p_{fric} = L_{TOT} \frac{f_1 G^2 \bar{v}}{\alpha D g} \tag{A.4}$$

where L_{TOT} is the total length of the tube, f_1 is the Moody friction factor for a given Reynolds number

$$Re = \frac{(\dot{m}_g + \dot{m}_f)\ D}{\mu_f\ D} \qquad (A.5)$$

where $\dot{m}_g$ is the mass flowrate, $\dot{m}_f$ the liquid mass flowrate, A the cross-sectional tube area, μ_f the absolute liquid viscosity ($3x10^{-5}$ lbf-s/ft^2), $G = (\dot{m}_g+\dot{m}_f)/A$, and $\bar{v} = v_f + x(v_g - v_f)$, where $v_f \equiv 1/\rho_f$, $v_g \equiv 1/\rho_g$, and $x = \dot{m}_g/(\dot{m}_g+\dot{m}_f)$.

These equations demonstrate how dependent the pressure drop, Δp, is on the superficial gas and liquid velocities.

APPENDIX B

CALCULATION OF LEAKAGE LIMIT LINE

The system can be divided into two parts: the tank, where the pressure fluctuation with time is found using the equation (see reference (3))

$$\frac{dP}{dt} = \frac{Q_g}{V/nP} \qquad (B.1)$$

where Q_g is the gas volumetric flowrate, V is the tank volume (2.87 ft^3), $n \equiv 1$, and P is the average tank pressure; and the vertical tube, where the pressure fluctuation is

$$\frac{dP}{dt} = \rho_f \frac{g}{g_o} \frac{Q_f}{A} \qquad (B.2)$$

where Q_f is the liquid volumetric flowrate, g is the gravitational acceleration, g_o=4.17x10^8 lbm-ft/lbf-hr^2 and ρ_f is the fluid density (62.4 lbm/ft^3).

Leakage occurs when the pressure in the tube is greater than the pressure in the tank. Combine Equations B.1 and B.2 to get the inequality

$$\rho_f \frac{g}{g_o} \frac{Q_f}{A} > \frac{Q_g}{V/nP} \qquad (B.3)$$

When the lefthand side of this inequality is greater than the righthand side, then, theoretically, leakage into the tank will occur.