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EXPERIMENTAL DETERMINATION AND CORRELATION OF PRESSURE-TIME RESPONSF IN MEASURING SYSTEMS

AERODYNAMICS LABORATORY

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Test Report AL-51

EXPERIMENTAL DETERMINATION AND CORRELATION OF PRESSURE-TIME RESPONSE IN MEASURING SYSTEMS

by

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SYMBOLS

d	inside tube diameter (ft)
K	configuration constant (given in Equation [A-20]
ℓ	tube length (ft)
m	mass (slugs)
M	mass flow rate (slugs/sec)
p	local pressure (psf)
r	radial coordinate
R	universal gas constant $\left(\frac{ft^2}{sec^2 \, {}^\circ R}\right)$
t	time (sec)
T	absolute temperature (°R)
u	air velocity (ft/sec)
V	tube volume (cu ft)
x	horizontal coordinate
$d\phi$	incremental angle (radians)
μ	viscosity coefficient of air (lb-sec/sq ft)
ρ	air density (slug/cu ft)
τ	viscous shear stress (psf)

SUBSCRIPTS

1	first tube
2	second tube
f	final value
i	initial value
j	value at the junction
m	maximum value
tr	transducer
x	horizontal component

SUMMARY

Existing theoretical formulae derived by Bauer have been correlated with experimental pressure-time responses in the 0.01 to 0.2 psi pressure range in single and double tube measuring systems connected to transducers. Experimental investigation, using several system configurations, indicates that the calculated and experimental data are in good agreement. It appears that for the lowest pressure level the theory overestimates the time response by 3 to 8 percent.

INTRODUCTION

Surface or pitot pressures are among the most frequently measured quantities in wind tunnel experiments. The basic principles which govern the measurement of pressure state are:

(a) pressure acts normal to a surface and

(b) it is proportional to the kinetic energy of the random molecular motion per unit volume.

The most common means of determining pressure is by the various probes and orifices. These instruments usually are connected by relatively long, small diameter tubing to transducers of some kind. When the pressures measured are low, such as the base area or the leeward side of a body in a hypersonic stream, a considerable length of time is required to approach equilibrium and obtain sufficiently accurate measurements of the probe pressure at the transducer. It is important to be able to predict and to reduce this time lag and hence achieve full utilization of the limited available running time.

The available literature on pressure-time response in various systems is mostly concerned with either high (approximately 0.1 to 20 psi) or very low pressures (a few microns of Hg).

Bauer (Reference 1) developed theoretical pressure-time response equations for single and double tube pressure measuring systems connected to manometers or to pressure transducers. Comparison of these equations to experimental values in the 0.07 to 15 psi range for three specific configurations indicated that the calculated values were within 10 to 20 percent of the measured values.

Ducoffe (Reference 2) used a one-dimensional, quasi-steady, viscous, compressible flow model in capillary tubing to derive the equation of motion. The assumptions used in the derivation included continuum flow, constant area tubing and fully developed flow over the entire tube length. The change of state of the flow was assumed to be isothermal. The resulting partial differential equation was solved by numerical step by step integration. Three numerical solutions were calculated for an idealized system. The computations were experimentally checked for 0.4 and 9.8 psi pressures and found to be satisfactory for these pressure levels. A series of experiments was also conducted. These were designed to evaluate criteria for minimum response time at rhe 0.4 psi pressure level. In brief these were:

(a) the orifice diameter should be more than one-half the model tubing diameter,

(b) the model tubing should be made as short as possible, incorporating the largest feasible inside diameter,

(c) connecting tubing should be short, with the inside diameter lying between 1.25 to 1.50 times the inside diameter of the model tubing,

(d) the volume of the pressure transducer should be minimized, and

(e) the advantage of pumping the initial line pressure to a value close to the model-surface pressure is quite small unless the initial pressure approaches the equilibrium pressure to within 1 mm Hg.

The slip flow case was also analyzed by Ducoffe and a correction factor was determined for pressures less than 0.1 psi.

Davis (Reference 3) derived a theoretical formula for pressure-time response in the slip and molecular flow region. Limited experimental results confirm the accuracy of the results to within ±10 percent for pressures higher than 0.10 psi for nearly linear pressure changes. Below this pressure, large discrepancies exist between the theory and some of the experimental points because of transient effects.

Sinclair and Robins (Reference 4) used a laminar, isothermal flow model for their calculation in determining pressure-time response in capillary tubes connected to manometers. They also determined the optimum tube diameter of a system for minimum pressure-time response. The resulting calculation showed that the optimum diameter of the capillary is independent of its length. The subsequent experimental measurements yielded reasonable agreement with theory in the 0.3 to 14.7 psi range.

Brown, et al (Reference 5) obtained data on the flow of air at pressures from 8×10^{-5} to 1.9×10^{-2} psi in copper and iron pipes of varying radii. Measurements were also presented for the resistance to flow in elbows, valves and for short sections in the pressure range of 8×10^{-5} to 1×10^{-1} psi. The data on straight copper and iron pipes, together with the measurements from the literature on glass capillaries, were correlated by the introduction of a correction factor in Poiseuille's equation. This correction factor was correlated graphically in terms of a dimensionless group representing the ratio of mean free path to pipe radius for each pipe material.

The above brief literature survey shows that there is a gap in the experimental and theoretical information in the 0.01 to 0.2 psi region. The recent upsurge of activity in measuring base pressures of bodies moving at super- and hypersonic speeds indicates considerable interest for this type of data. In the Mach number range of 5 to 10, the base pressure falls in the 0.004 to 0.2 psi range which coincides with the missing data in the literature.

The objective of the present investigation was to obtain pressure-time response data in the 0.01 to 0.2 psi pressure range and correlate it with analytical equations.

THEORY

Bauer (Reference 1) analyzed the unsteady flow in a two tube system and developed a theoretical pressure-time response equation. The detailed derivation of this equation is presented in the Appendix. He used the one dimensional unsteady momentum equation together with Newton's relationship for the viscous shear stresses to obtain velocity and mass flow distribution functions. Assuming isothermal compressible flow conditions the average densities in the tube system were expressed in terms of local pressures. The unsteady continuity equation coupled with the average density relationships gave the general equation for pressure-time response

$$\frac{V_1 + V_2}{2} \frac{dp_i}{dt} + \left(\frac{V_2}{2} + V_{tr}\right) \frac{dp}{dt} = \frac{d_1^{\,2} (p_f + p_i)(V_1 + V_2)}{128 \mu RT} \frac{dp_i^2}{dt^2}$$

$$+ \frac{d_1^2 (p_f + p_i)}{64 \mu RT} \left(\frac{V_2}{2} + V_{tr}\right) \frac{d^2 p}{dt^2} + \frac{d_1^4 \pi (p_f + p_i)}{256 \mu} \frac{\partial p_x}{\partial x}$$

Neglecting the second order terms an approximate solution was found to the above equation using Kendall's (Reference 7) experimental pressure relationship. The final results are:

$$t = \frac{128 \mu \ell_1}{d_1^4 \pi K p_f} \left(\frac{(V_1 + V_2) K + V_2}{2} + V_{tr}\right) \ln \frac{(p + p_f)(p_i - p_f)}{(p - p_f)(p_i + p_f)}$$

where: p_i is the initial pressure and μ is the viscosity evaluated at p_f. For a single tube system $K = 1$ and $V_2 = 0$.

COMPUTER PROGRAM*

A computer program was written in FORTRAN IV to evaluate the above equation for various two tube systems. This program also included subprograms for semilogarithmic graph plotting of the computed results. The program listing appears in Table 1.

* Note: The programming was done by Mr. Dan Dragalin.

The input data include 3 sets of ℓ_1, ℓ_2, d_1, and d_2. Six cases of p_1, one μ and fifteen p_f values in the above order. It also computes all the data for three sets of measured pressure to final pressure ratios. This ratio is usually set at .99, .98, or .97, whatever ultimate precision is desired. Results indicate that the settle-out times required for measurements better than the .99 ratio are too long to be practical. The dimensions of the required input data are given in Table 2.

The subprograms, listed in Table 3, are part of the S-C 4020 CHARACTRON system used in conjunction with the IBM 7090 computer. This system reads magnetic tape output from the computer program and produces graphical output. For the detailed description of the system the reader is directed to Reference 6. In Figures 3 to 5 three samples of the numerical computations are presented in their graphical form. The input data constants represent actual configurations used in the wind tunnel.

EXPERIMENTAL APPARATUS AND PROCEDURE

In order to compare and verify the theoretical analysis, an experimental program was initiated to obtain pressure-time response data. Seven configurations were tested - two single tube and five double-tube systems. The experimental pressure range varied between 0.01 and 0.2 psi. A calibrated Scanco transducer with a pressure range of 0.00 to 0.2 psi and accuracy of ±0.5 percent of full scale was utilized in the tests. The interior volume of the transducer was accurately determined and found to be 0.0000523 cubic feet at room temperature, which was also the testing temperature. The mean inside diameters of the test tubes were obtained by length and volume measurements. The transducer output was monitored and recorded by an X-Y plotter. The recorder amplifier was set to read 0.02 psi/inch on the vertical axis. The sweep speed on the horizontal axis was varied between 0.5 inch/sec and 10 inch/sec. The input pressure to the test apparatus was accurately measured by a Barocell electronic manometer. A block diagram of the apparatus is shown in Figure 6.

The following procedure was used in each test run. First the system was evacuated via valves B and C while valve A was kept closed. After a steady state had been reached at 10 micron Hg pressure, monitored by a McLeod gauge, valves B and C were closed and air was admitted through the control valve A to a 0.15 cubic feet settling vessel. Upon closing valve A the volume was partially evacuated via valve B to any desired pressure level, continuously measured by the Barocell. When the predetermined equilibrium pressure had been established in the settling chamber, valve B was secured in closed position. The test began by starting the X-Y recorder and opening valve C. The X-Y trace gave the pressure-time history of the test run which continued until complete equilibrium was reached. Since the volume ratio between the settling chamber and test volume exceeded 1000, the maximum error due to the volume change upon the opening of valve C was less than 0.1 percent in the measured data, well within the accuracy range of the transducer. The average error of the pressure measurements throughout test program was estimated at ±5 percent with a maximum error of ±10 percent.

DISCUSSION OF RESULT AND CONCLUSIONS

Table 4 contains all the pertinent experimental variables together with the measured and calculated data. Comparison between the theoretical formulae and experimental results for seven configurations show good agreement. The average positive deviation ($t_{meas} > t_{calc}$) is 8 percent, the average negative deviation ($t_{meas} < t_{calc}$) is 4 percent between the measured and calculated values in the 0.01 and 0.2 psi range.

The derived equation appears to overestimate the pressure-time response by 3 to 8 percent in the lowest pressure range. The inaccuracies of the theory in the lowest pressure level stem from the probable violation of the continuum flow assumption. For low absolute pressure, the equation of motion must incorporate the slip flow effects at the boundaries of the tubing. This would result in a very much more complicated expression than the one derived, with no closed analytical solution. This would necessitate numerical evaluation. However, the errors attributed to the theory, because of its oversimplification of the actual physical flow model, are small in the pressure range of interest, and in most instances are well within the limits of experimental uncertainties. For all practical purposes, therefore Equation [A-33] will yield adequate time response estimates.

In the higher pressure range, the accuracy of the pressure transducer had significantly improved but the overall uncertainty of the small time measurement had increased. The relatively large differences of the theoretical and experimental values were attributed to this uncertainty. But since the time intervals in this pressure range were small (usually less than one second), the absolute errors in all instances only amount to fractions of a second, and therefore are negligibly small.

On the basis of the foregoing, we may conclude that:

1. The calculated and experimental data are in satisfactory agreement.

2. The theory appears to overestimate the time response for the lowest pressure level by 3 to 8 percent.

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APPENDIX

DETAILED DERIVATION OF THE PRESSURE-TIME RESPONSE EQUATION

In the following development the unsteady flow in a tube system is analyzed using the approach and final results of Bauer (Reference 1). The mass flow into or out of such a system is equal to the rate of change of mass within the tubes. First the volume flow at any section of the tubes is obtained as follows.

The total axial force acting on a fluid element is the sum of the pressure and friction forces. This may be expressed (see Figure 1) as:

$$- r \frac{\partial p_x}{\partial x} \, dxdr \, d\phi + \left(\tau + r \frac{\partial \tau}{\partial r} \right) dxdrd\phi \qquad [A-1]$$

The total force is also equal to the rate of change of momentum of the fluid element yielding:

$$- r \frac{\partial p_x}{\partial x} + \tau + r \frac{\partial \tau}{\partial r} = r \frac{d(\rho u)}{dt} \qquad [A-2]$$

Substituting Newton's relationship for the viscous shear stresses results in:

$$\frac{\partial}{\partial r} \left(r \frac{\partial u}{\partial r} \right) = - \left[\frac{d(\rho u)}{dt} + \frac{\partial p_x}{\partial x} \right] \frac{r}{\mu} \qquad [A-3]$$

At a given instant of time the expression in brackets on the right-hand side of Equation [A-3] can be considered constant. It is to be assumed that $\frac{d(\rho u)}{dt}$ is independent of r. Then:

$$\rho u = \frac{4M}{\pi d^2} \qquad [A-4]$$

Equation [A-3] can be expressed in terms of mass flow rate. Integration then yields:

$$r \frac{\partial u}{\partial r} = - \left[\frac{4}{\pi d^2} \frac{\partial M}{\partial t} + \frac{\partial p_x}{\partial x} \right] \frac{r^2}{2\mu} + C_1 \qquad [A-5]$$

Applying the boundary condition that:

$$\frac{\partial u}{\partial r} = 0 \quad \text{at} \quad r = o \qquad [A-6]$$

gives

$$C_1 = 0 \qquad [A-7]$$

Integrating Equation [A-5], the expression for the local velocity is obtained as:

$$u = -\left[\frac{4}{\pi d^2}\frac{\partial M}{\partial t} + \frac{\partial p_x}{\partial x}\right]\frac{r^2}{4\mu} + C_2 \qquad [A-8]$$

with boundary condition:

$$u = 0 \quad \text{at } r = \frac{d}{2} \qquad [A-9]$$

The constant of integration C_2 using the boundary condition may be obtained from Equations [A-8] and [A-9]. Substituting the value of C_2 and simplifying yields:

$$u = \frac{1}{4\mu}\left[\frac{4}{\pi d^2}\frac{\partial M}{\partial t} + \frac{\partial p_x}{\partial x}\right]\left(\frac{d^2}{4} - r^2\right) \qquad [A-10]$$

The maximum velocity at r = 0 is

$$u_m = \frac{d^2}{16\mu}\left[\frac{4}{\pi d^2}\frac{\partial M}{\partial t} + \frac{\partial p_x}{\partial x}\right] \qquad [A-11]$$

The velocity profile is a parabola as indicated by Equation [A-10]. The mean average of a paraboloid of revolution is equal to 0.5 u_m. Therefore, the volume flow at any section of the tube system is:

$$Q = \frac{\pi d^2}{4}\left(\frac{u_m}{2}\right) = \frac{d^4\pi}{128\mu}\left[\frac{4}{\pi d^2}\frac{\partial M}{\partial t} + \frac{\partial p_x}{\partial x}\right] \qquad [A-12]$$

The most common configuration of a pressure measuring system consist of two tubes of different diameters and lengths connecting an orifice to a constant volume transducer as shown in Figure 2.

The mass of air in the system at any time is:

$$m = V_1\rho_1 + V_2\rho_2 + V_{tr}\,\rho_3 \qquad [A-13]$$

The densities ρ_1 and ρ_2 vary along the length of their respective tubes. Assuming isothermal conditions the average densities may be expressed as:

$$\rho_1 = \frac{p_f + p_1}{2RT} \qquad [A\text{-}14]$$

$$\rho_2 = \frac{p_1 + p}{2RT} \qquad [14a]$$

and

$$\rho_3 = \frac{p}{RT} \qquad [14b]$$

Substituting the density relationships into Equation [A-13] and differentiating with respect to time yields:

$$\frac{dm}{dt} = \frac{1}{RT}\left[\frac{(V_1 + V_2)}{2}\frac{dp_1}{dt} + \left(\frac{V_2}{2} + V_{tr}\right)\frac{dp}{dt}\right] \qquad [A\text{-}15]$$

The mass flow into or out of the tube is equal to the rate of change of mass within a tube, i.e.

$$M = \frac{dm}{dt} \quad \text{and} \quad \frac{\partial M}{\partial t} = \frac{d^2m}{dt^2} \qquad [A\text{-}16]$$

But using Equation [A-12] and the average density in the first tube gives M as:

$$M = \frac{d_1^4 (p_f + p_1)}{64\mu RT}\frac{\partial M}{\partial t} + \frac{d_1^4 \pi(p_f + p_1)}{256\mu RT}\frac{\partial p_x}{\partial x} \qquad [A\text{-}17]$$

Differentiating Equation [A-15] and substituting the expression into Equation [A-17] yields the following general equation for pressure response time:

$$\frac{V_1 + V_2}{2}\frac{dp_1}{dt} + \left(\frac{V_2}{2} + V_{tr}\right)\frac{dp}{dt} = \frac{d_1^2(p_f + p_1)(V_1 + V_2)}{128\mu RT}\frac{d^2p_1}{dt^2}$$

$$+ \frac{d_1^2(p_f + p_1)}{64\mu RT}\left(\frac{V_2}{2} + V_{tr}\right)\frac{d^2p}{dt^2} + \frac{d_1^4\pi(p_f + p_1)}{256\mu}\frac{\partial p_x}{\partial x} \qquad [A\text{-}18]$$

An approximate solution to Equation [A-18] can be determined, by assuming that the acceleration terms are negligible. This assumption is valid for all practical cases. A qualifying condition to determine if the acceleration terms for a particular configuration can be neglected is given in Reference 1 as:

$$\frac{V_1 d_1^4 \; K \; p_f^2}{1024\mu^2 RT \; \ell_1^2 \left[\left(\frac{V_1 + V_2}{2}\right) K + \frac{V_2}{2} + V_{tr}\right]} << 1 \qquad \text{[A-19]}$$

where:

$$K = \frac{1}{\left(\frac{\ell_2}{\ell_1}\right)\left(\frac{d_1}{d_2}\right)^4 + 1} \qquad \text{[A-20]}$$

for a single tube connected transducer $K = 1$ and $V_2 = 0$.

Eliminating the higher order terms p_j can be determined; since the mass flow through the first tube (M_1) is equal to the mass flow through the second tube (M_2).

The pressure at any station in a constant diameter obtained experimentally by Kendall (Reference 7) as:

$$p_x = \sqrt{(p_j^2 - p_f^2)\frac{x}{\ell_1} + p_f^2} \qquad \text{[A-21]}$$

The density is

$$\rho_x = \frac{1}{RT}\sqrt{(p_j^2 - p_f^2)\frac{x}{\ell_1} + p_f^2} \qquad \text{[A-22]}$$

$\frac{\partial p_x}{\partial x}$ may be obtained from Equation [A-21]. Substituting the values of $\frac{\partial p_x}{\partial x}$ and ρ_x in Poiseuille's equation yields:

$$M_1 = \frac{d_1^4 \pi}{256\mu RT \ell_1}(p_j^2 - p_f^2) \qquad \text{[A-23]}$$

and

$$M_2 = \frac{d_2^4 \pi}{256 \mu R T \ell_2} (p^2 - p_j^2) \qquad [A-24]$$

Therefore, by equating Equations [A-23] and [A-24], p_j can be determined as:

$$p_j = \sqrt{(1 - K)\, p_f^2 + Kp^2} \qquad [A-25]$$

Where K is given in Equation [A-20]. In order to simplify Equation [A-25], p_j is expanded into a binomial series as:

$$p_j = p_f + \frac{K\,(p^2 - p_f^2)}{2p_f} - 1/8\, K^2\, (p^2 - p_f^2)^2 + \ldots \qquad [A-26]$$

assuming that:

$$(p^2 - p_f^2)^2 << 1 \text{ and } p \approx p_f \quad \text{as } p \rightarrow p_f \qquad [A-27]$$

and since p_f = constant then:

$$p_j = (1 - K) p_f + K_p \qquad [A-28]$$

and

$$\frac{dp_j}{dt} = K \frac{dp}{dt} \qquad [A-29]$$

The mean value of the pressure gradient at any station in a constant diameter tube may be expressed as:

$$\left(\frac{\partial p_x}{\partial x}\right)_{mean} = \frac{K\,(p_f - p)}{\ell_1} \qquad [A-30]$$

Most of the pressure change occurs in the first tube since its diameter is usually small compared to the second tube. It is therefore reasonable to approximate that:

$$p_f + p_j \approx p_f + p \qquad \text{at } t \rightarrow t \qquad [A-31]$$

When Equations [A-28] to [A-30] are substituted into Equation [A-18] the following differential equation is obtained:

$$\left(\frac{V_1 + V_2}{2} K + \frac{V_2}{2} + V_{tr}\right) \frac{dp}{dt} = \frac{d_1^4 \pi K}{256 \mu \ell_1} (p_f^2 - p^2) \qquad [A-32]$$

The solution of Equation [A-31] is given as:

$$t = \frac{128\mu \ell_1}{d_1^4 \pi K p_f} \left(\frac{(V_1 + V_2) K + V_2}{2} + V_{tr} \right) \ln \frac{(p + p_f)(p_i - p_f)}{(p - p_f)(p_i + p_f)}. \qquad [A-33]$$

where: p_i is the initial pressure and μ is the viscosity evaluated at p_f. For a single tube system $K = 1$ and $V_2 = 0$.

Equation [A-33] is not a general solution of Equation [A-18]; however, if the qualifying condition given by Equation [A-19] is satisfied, it represents a close approximation to the exact solution.

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Table 1

Program Listing

```
C      COMPUTATIONS FOR PRESSURE - TIME RESPONSE USING THREE CASES
C
       DIMENSION ALEN(3), BLEN(5), ADIA(5), BDIA(5), CON(5), PF(15),
      1PI(5),TME(405)
       CALL CAMRAV(9)
       CALL SMXYV(0,1)
       KK = 1
       ICOUNT = 0
       READ(5,100) (ALEN(K),K=1,3),(BLEN(K),K=1,3),(ADIA(K),K=1,3),
      1(BDIA(K),K=1,3),(PI(J),J=1,3),(CON(N),N=1,3)
       READ(5,101) XM
       READ(5,102)(PF(L),L=1,15)
       WRITE(6,104)
       DO 50 K=1,3
       IF (K-2)5,6,7
 5     VM = ((((0.5**2*3.14)/4.0)*0.05+2.0*((0.05**2*3.14)/4.0))*2.0)/
      11728.0
       GO TO 10
 6     VM = (((0.5**2*3.14)/4.0)*0.05+2.0*((0.05**2*3.14)/4.0) + 0.114 +
      11.5*((0.07**2*3.14)/4.0))/1728.0
       GO TO 10
 7     VM = 0.114/1728.0
       GO TO 9
 9     AKON = 1.0
       BVOL = 0.0
       GO TO 12
 10    AKON = 1.0/(BLEN(K)/ALEN(K)*(ADIA(K)/BDIA(K))**4 + 1.0)
       BVOL = 3.14*(BDIA(K)/2.0)**2*BLEN(K)
 12    AVOL = 3.14*(ADIA(K)/2.0)**2*ALEN(K)
       STEPB = ((AVOL + BVOL)*AKON + BVOL)/ 2.0 + VM
       DO 50 J = 1,3
       DO 50 N = 1,3
       DO 50 L = 1,15
       STEPA = (128.0*XM*ALEN(K))/(ADIA(K)**4*3.1416*PF(L)*AKON)
       PARTA = (PI(J) - PF(L))/(PI(J) + PF(L))
       IF (PARTA.GT.0.0) GO TO 60
       GO TO 80
 60    PARTA = (PF(L) - PI(J))/(PF(L) + PI(J))
 80    IF(PARTA.NE.0.0) STEPC = ALOG(CON(N)*PARTA)
       IF (PARTA.EQ.0.0) STEPC = -1
       TIME = STEPA*STEPB*STEPC
       ICOUNT = ICOUNT + 1
       IF (ICOUNT .LT. 46) GO TO 90
       WRITE (6,104)
       ICOUNT = 1
 90    WRITE(6,103) ALEN(K), BLEN(K), ADIA(K), BDIA(K), PI(J), CON(N),
      1PF(L), TIME
       TME(KK) = TIME
       KK = KK + 1
 50    CONTINUE
       KK = 1
       DO 103 II = 1,9
       XL = 0.0
       XR = TME(KK)
```

Table 1 (Concluded)

```
      KJ1 = KK + 1
      KJ2 = KK + 44
      DO 14 KJ = KJ1,KJ2
14    XR = MAX1(XR,TME(KJ))
      XR = XR + 1.0
      CALL DXDYV(1,XL,XR,DX,N,I,NX,12.0,IERR)
16    CALL GRID1V(1,XL,XR,0.1,1000.0,DX,1.0,N,1,I,1,NX,6)
      CALL PRINTV(-13,13HTIME IN SEC.    ,468,4)
      CALL APRNTV(0,-12,-11,11HPF IN PSF    ,4,576)
      DO 109 JJ = 1,3
      IF(TME(KK))20,21,21
20    KK1 = KK + 1
      NP = 14
      NP1 = 13
      KK2 = 2
      GO TO 22
21    KK2 = 1
      NP = 15
      KK1 = KK
      NP1 = 14
22    CALL APLOTV(NP,TME(KK1),PF(KK2),1,1,1,38,IERR)
17    KK = KK + 15
      DO 109 III = KK2,NP1
      KKK = KK + III - 16
109   CALL LINEV(NXV(TME(KKK)),NYV(PF(III)),NXV(TME(KKK + 1)),NYV(PF(III
     1 + 1)))
      CALL FRAMEV
100   FORMAT (3F15.6)
101   FORMAT (E11.4)
102   FORMAT (10F6.3/5F6.3)
103   FORMAT (6X, F6.3, 11X, F5.3, 11X, F7.5, 10X, F7.5, 9X, F6.3, 4X,
     1F7.2, 3X, F7.3, 5X, F14.7)
104   FORMAT (1H1, 3X, 13HLEN(1) IN FT., 4X, 13HLEN(2) IN FT., 4X,
     113HDIA(1) IN FT., 4X, 13HDIA(2) IN FT., 4X, 9HPI IN PSF, 4X,
     23HC9N, 4X, 9HPF IN PSF, 4X, 12HTIME IN SEC.//)
200   STOP
      END
```

Table 2

List of FORTRAN Symbols, Equivalent Mathematical Symbols and Their Dimensions

FORTRAN Symbols	Mathematical Symbols	Dimension
ALEN	ℓ_1	ft
BLEN	ℓ_2	ft
ADIA	d_1	ft
BDIA	d_2	ft
CON	$(p+p_f)/(p-p_f)$	--
PF	p_f	psf
PI	p_i	psf
TME	t	sec
VM	V_{tr}	ft^3
XM	μ	$lb\text{-}sec/ft^2$
AKON	K	--

Table 3

Plotting Subprograms Called in the Main Computer Program

Symbol	Function of Subprogram
CAMRAV	Selects camera
SMXYV	Produces logarithmic or semilogarithmic scale mode.
DXDYV	Produces x and y coordinates
GRID1V	Produces grid
PRINTV	Prints horizontal titles
APRNTV	Prints vertical titles
APLØTV	Plots computed points
LINEV	Connects two points by a straight line
FRAMEV	Advances the film in the camera

Table 4

Test Configurations Summary of Experimental and Calculated Data

Run No.	ℓ_1 ft	ℓ_2 ft	d_1 ft	d_2 ft	p_f psf	t_{meas} sec	t_{calc} sec
11	0.50	0.00	0.0034	0.0000	1.44	8.6	9.1
12					5.76	2.7	2.6
13					14.4	1.13	1.03
14					21.6	0.73	0.65
15					28.8	0.48	0.49
21		0.43	0.0017	0.0034	14.4	17.1	17.9
22					28.8	6.8	7.8
31	1.50	0.38	0.0058		1.44	16.0	16.0
32					5.76	4.8	5.2
33					14.4	1.75	1.71
34					21.6	1.27	1.30
35					28.8	1.09	0.96
41	1.65	0.54	0.0017		28.8	23.2	23.7
51	2.00	0.38	0.0047		1.44	14.5	15.1
52					5.76	4.3	4.4
53					14.4	1.90	1.68
54					21.6	1.21	1.11
55					28.8	0.70	0.72
61		0.43	0.0068		1.44	10.[illegible]	11.0
62					5.76	3.6	3.4
63					14.4	1.31	1.22
64					21.6	0.80	0.81
65					28.8	0.62	0.59
71	2.75	0.00	0.0034	0.0000	5.76	15.2	15.4
72					14.4	6.7	6.5
73					21.6	4.5	4.3
74					28.8	3.2	3.2

Constants V_{tr} = 0.0000523 (cu.ft.) p_1 = 0.0288 (psf)

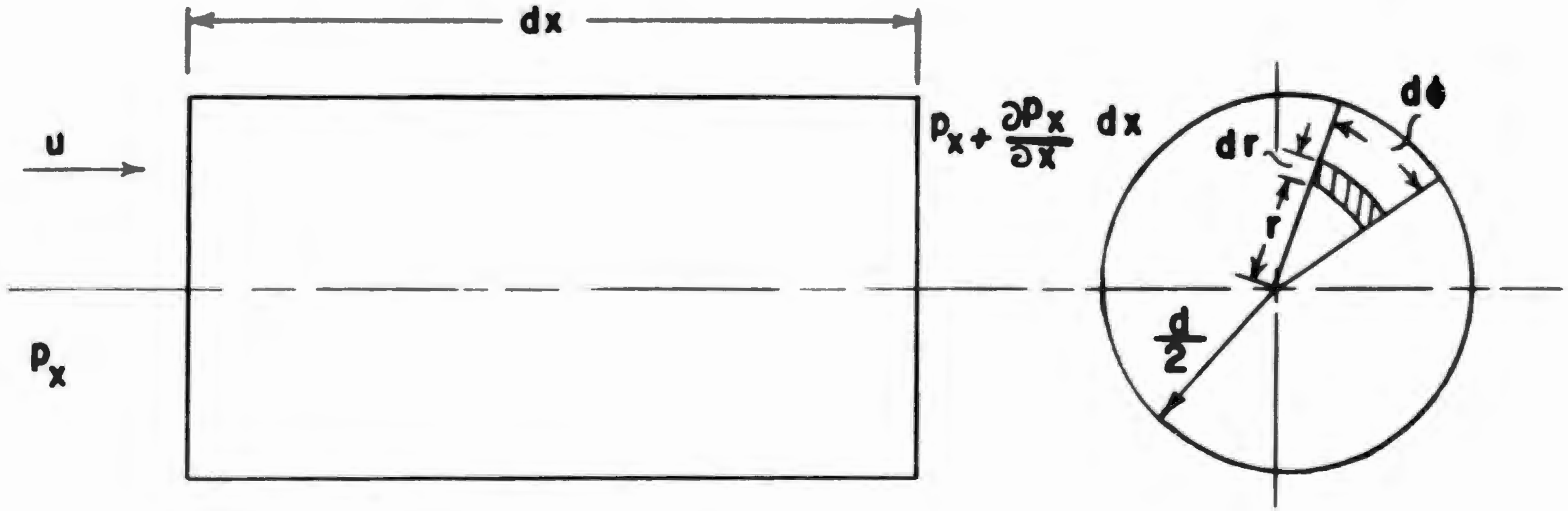

Figure 1 - Schematic Diagram of Unsteady Flow in a Tube

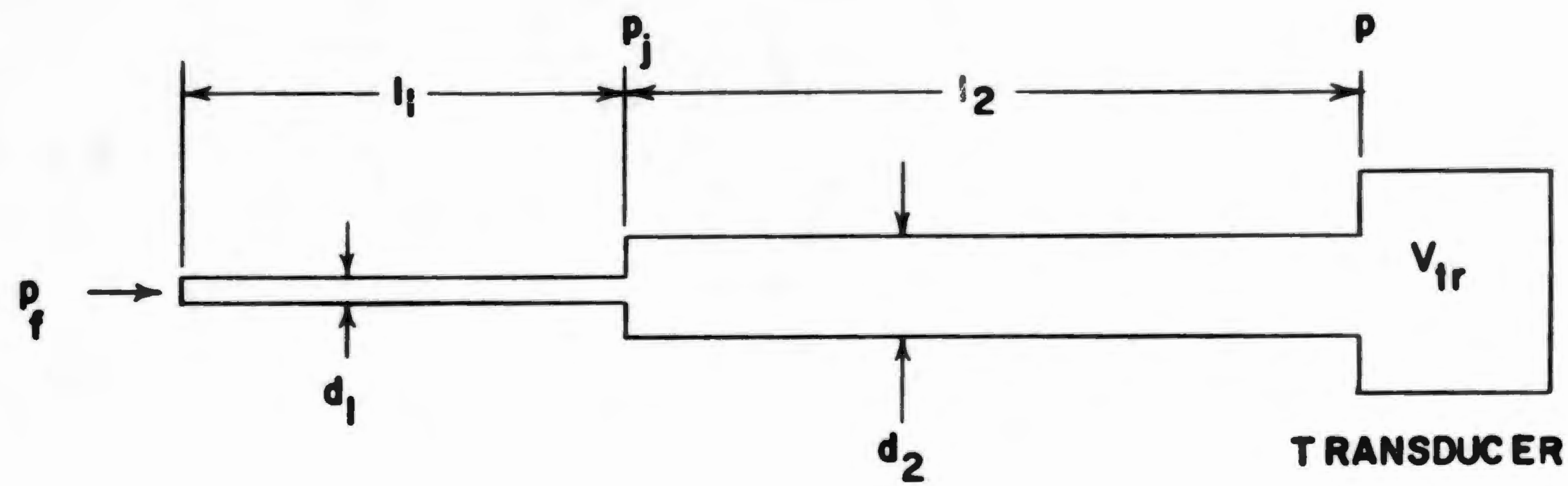

Figure 2 - Schematic Diagram of the Pressure Measuring System

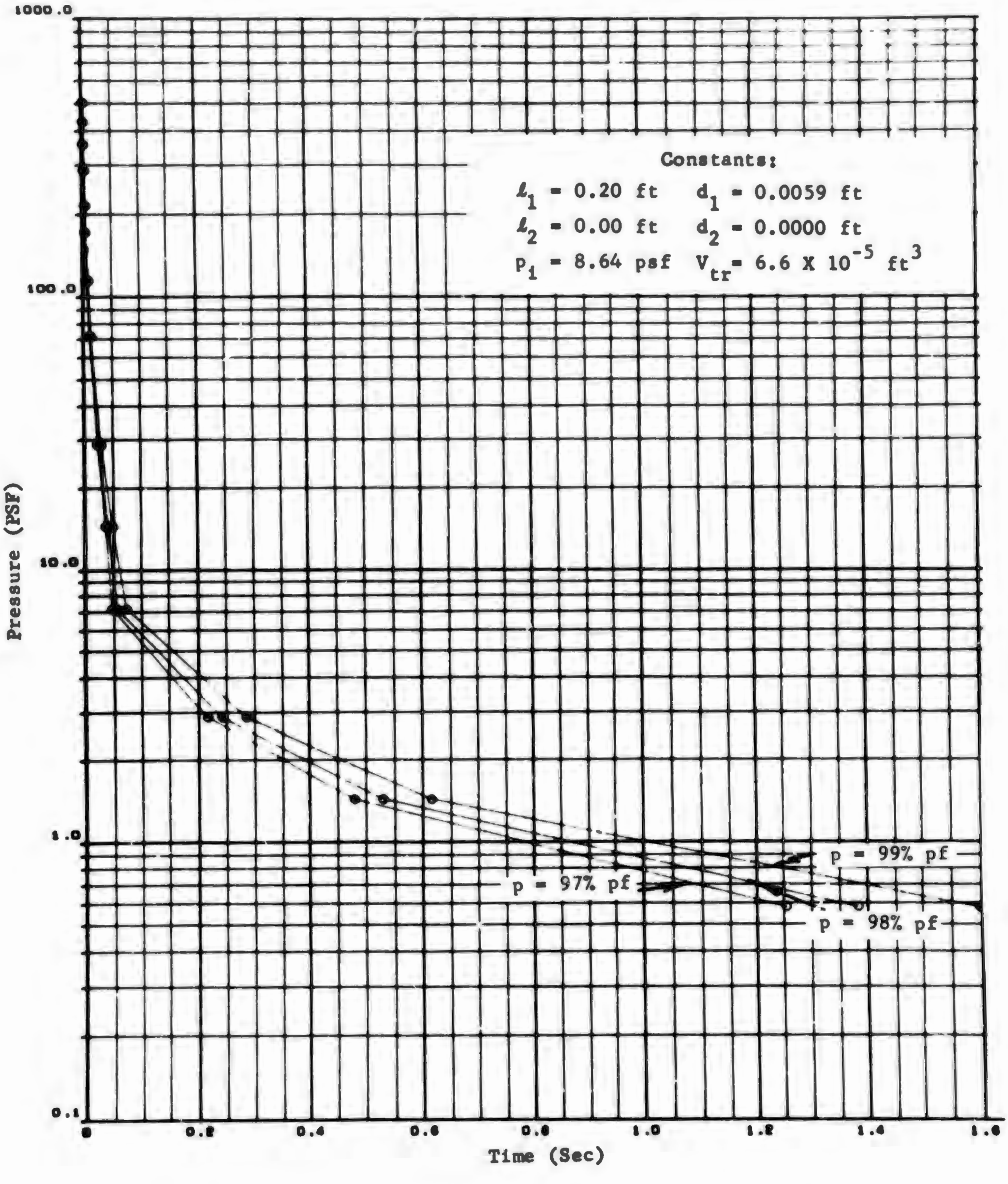

Figure 3 - Pressure-Time Response Sample Computation (Number 1)

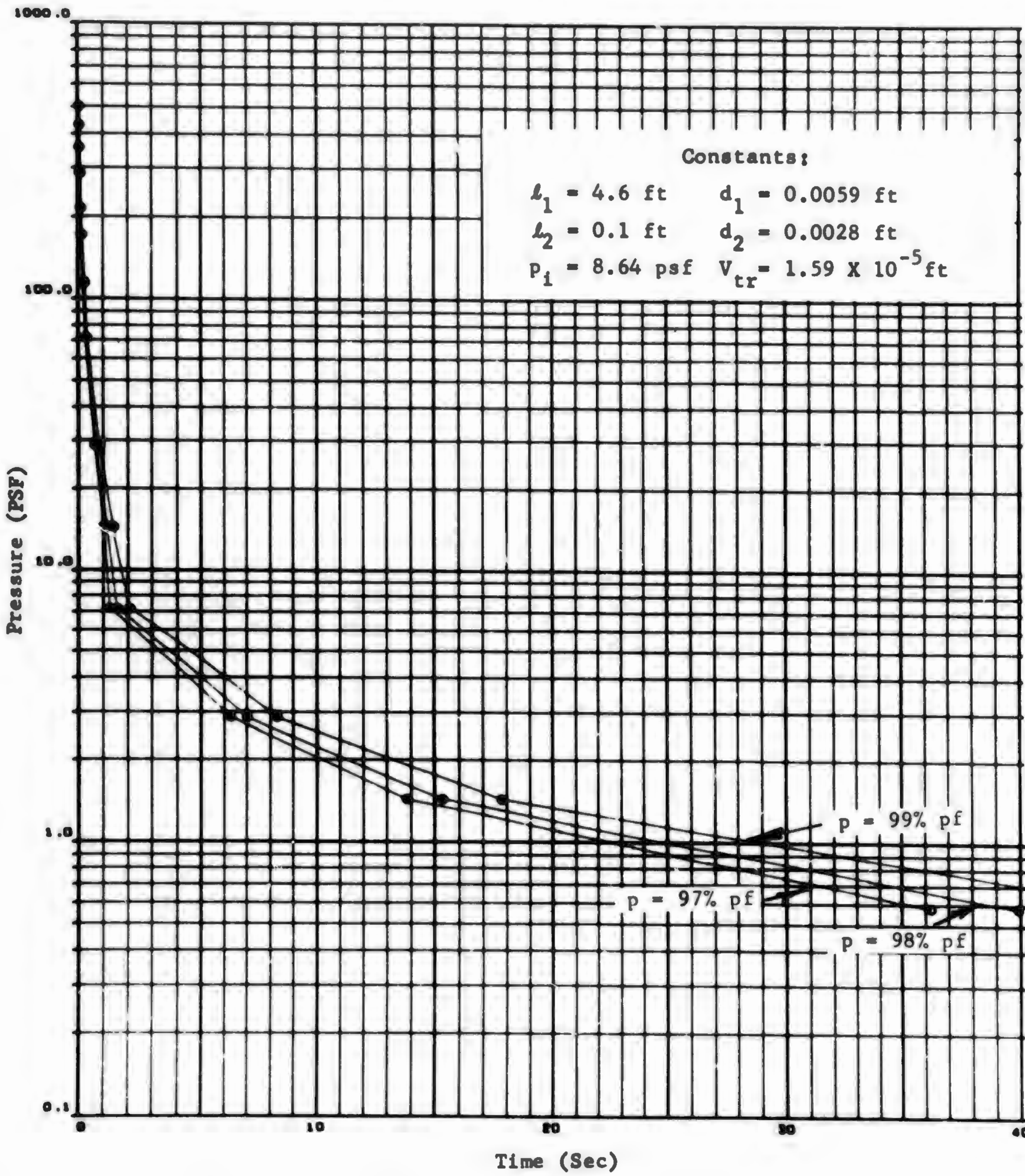

Figure 4 - Pressure-Time Response Sample Computation (Number 2)

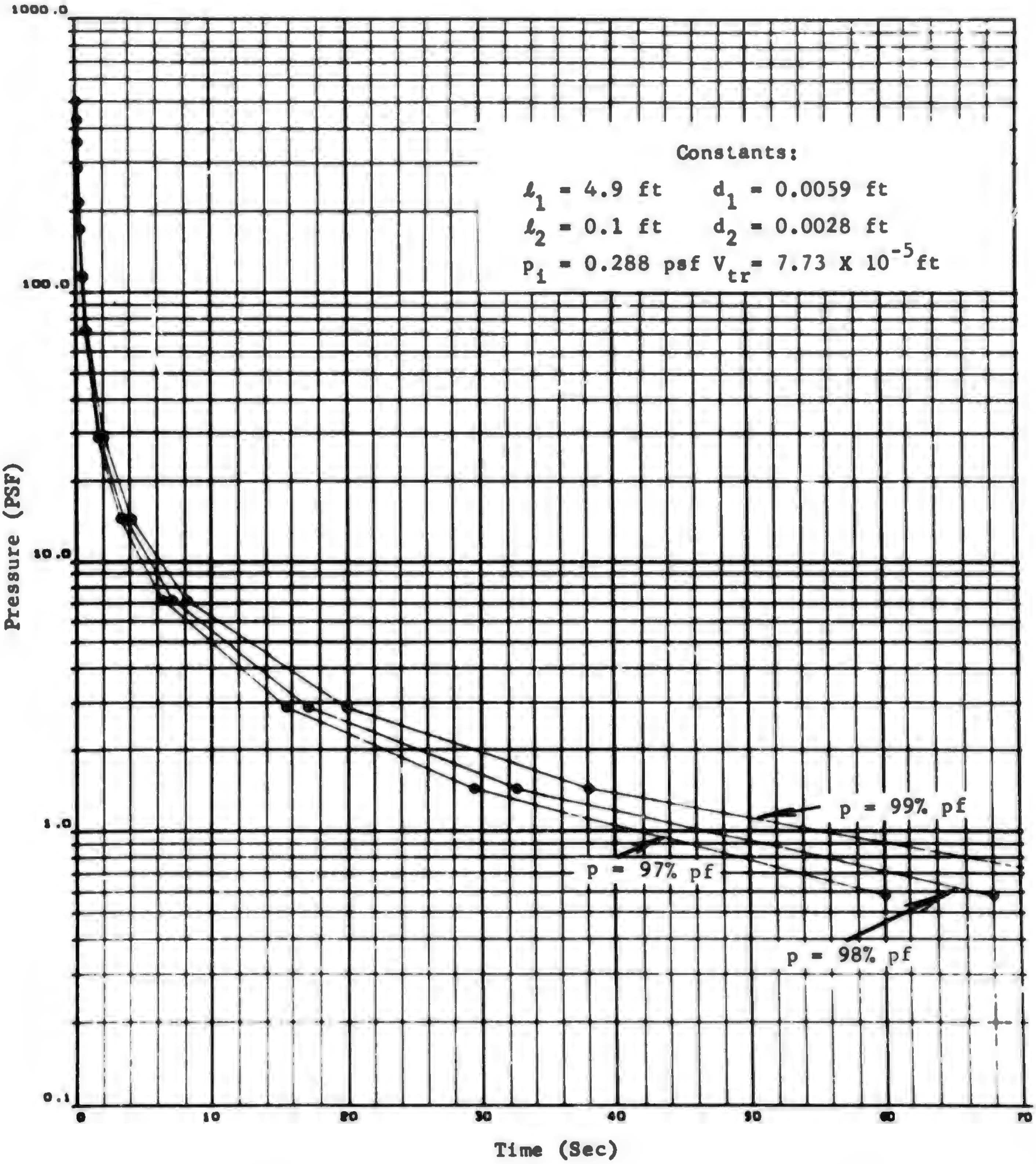

Figure 5 - Pressure-Time Response Sample Computation (Number 3)

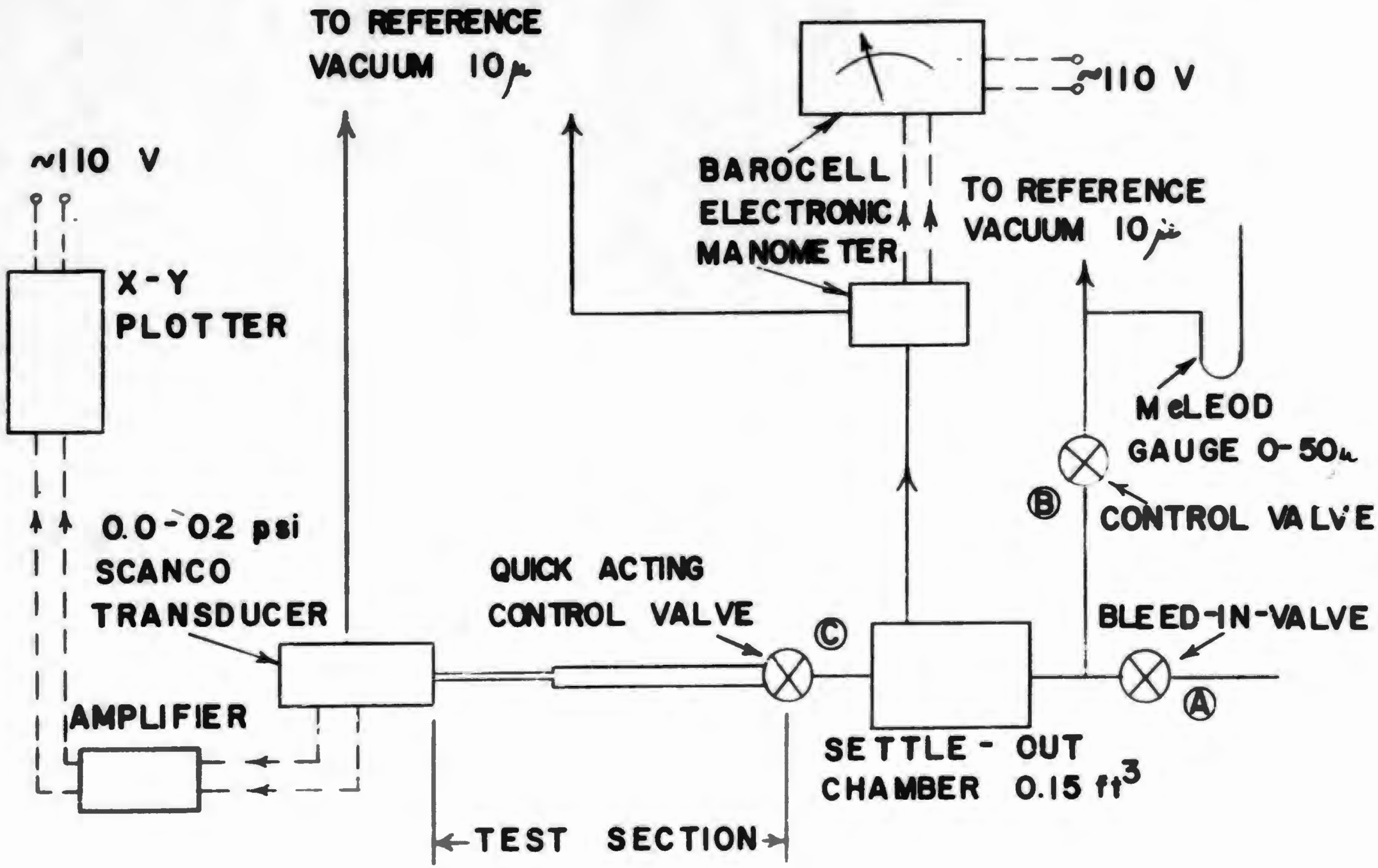

Figure 6 - Block Diagram of Test Apparatus

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13. ABSTRACT

Existing theoretical formulae derived by Bauer have been correlated with experimental pressure-time responses in the 0.01 to 0.2 psi pressure range in single and double tube measuring systems connected to transducers. Experimental investigation, using several system configurations, indicates that the calculated and experimental data are in good agreement. It appears that for the lowest pressure level the theory overestimates the time response by 3 to 8 percent.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Measuring Systems						
Pressure Measurements						
Transient Pressures						
Pressure-Time Response						