Test Report AL-74

A STUDY OF SHORT-TIME, LOW-PRESSURE RESPONSE
IN A TRANSDUCER SYSTEM

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Washington, D.C. 20007

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by

George S. Pick

DEPARTMENT OF AERODYNAMICS

TEST AND EVALUATION REPORT

May 1970

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SUMMARY

Existing theoretical equations have been correlated with experimental pressure-time responses in the 0.1 mmHg to 3.0 mmHg pressure range in short-time response transducer systems. Experimental investigation confirmed predicted trends but the equations required modifications to account for end effects which were neglected in the original derivations. The prediction errors of these modified equations were within an acceptable range. The results provide system design criteria for free flight instrumented models in hypersonic tunnel applications.

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NOTATION

d	tube diameter, ft
f	fraction of diffusely reflected molecules striking the tube walls
K	see Equation (6)
ℓ	length of tubing, ft
ℓ_e	equivalent tube length, ft
M	see Equation (8a)
n	see Equation (10)
p	pressure, psf
p_f	final pressure, psf
p_i	initial pressure, psf
p_m	mean pressure, psf
t	response time for continuum flow, sec
t_s	response time for slip flow, sec
V	volume of tubing, ft^3
V_{tr}	volume of transducer, ft^3
λ	time constant for continuum flow, sec
λ_s	time constant for slip flow, sec
μ	coefficient of viscosity, lb/sec-ft
ρ	density, $slug/ft^3$

INTRODUCTION

In recent years there has been a growing recognition that much high-speed wind-tunnel data are of dubious value due to model support interference. A number of researchers have advocated that strictly valid measurements can be obtained only through the use of free-flight techniques. A number of successful methods using these techniques have been reported in the literature (for example, References 1 to 10). In most of these studies, conventional wind or shock tunnels were utilized. The models were either launched into the wind stream (References 1 to 6) or fastened by threads which were in turn swept away by the starting shock (References 7 to 9).

In the measurements of aerodynamic characteristics, such as drag, lift and pitching moment, the model motion was recorded by high-speed cameras and analyzed using an automatic scanning device (Reference 10). Data was reduced to aerodynamic coefficients by computer programs. With the successful development of miniaturized, high efficiency telemetry devices, it became possible to construct small, instrumented free-flight wind-tunnel models for measurements of surface and base pressures and heat transfer distributions (References 2 to 5 and 7).

Common to all free-flight model experiments is the short time duration. Accordingly, the available time for physical measurements is very limited, in the order of 10 to 50 milliseconds, and seldom exceeds 0.1 seconds. This necessitates fast response instrumentation systems.

In hypersonic flow, surface or base pressure levels are quite low. Since the time response in general is inversely related to the pressure level, precautions must be taken in designing free-flight model pressure instrumentation systems for sufficiently short time response.

In most instances the pressure orifice is located near the transducer sensing element and they are usually connected by a short, relatively large diameter tube. The existing pressure-time response prediction theories assume the tubing is long and is of small diameter. It is therefore of importance to determine what design criteria can be used in this type of system and whether the existing theories are adequate in predicting responses.

The objective of the present investigation was to obtain pressure-time response data in the 0.1 to 3.0 mmHg differential pressure range at low ambient conditions for short connecting tube-transducer systems and correlate the data with existing analytical formulae.

THEORY

A simple pressure-measuring system consists of a transducer of constant volume connected to a tube. If the orifice of the connecting tube is subjected to a sudden pressure perturbation, a time dependent flow field is generated within the tube. The pressure in the measuring instrument will approach the new level asymptotically with time. Depending on the measured pressure level, the resulting flow in the tube may fall in the continuum, slip flow, or free molecular flow regime. The time interval between the external pressure change at the orifice and the correct indication of this change by the measuring device is called the pressure-time response. Regardless of the flow field in the measuring system, this time response depends on several common parameters. It will be shown below that the time response increases as the pressure to be measured decreases. The finite volume of the sensing transducer, the length, diameter, and the volume of the connecting tubing, and the size of the sensing orifice all affect the time response.

For most wind-tunnel applications, the time response is taken as the time interval for the transducer pressure to reach a value corresponding to 97 percent or 99 percent of the initial pressure difference. Because of the asymptotic behavior of the pressure-time curve, as it is illustrated in Figure 1, it is difficult to determine the time response in practice. One notices, however, that a good portion of the pressure-time curve is linear. The slope of this linear portion represents the maximum response rate to a given pressure step and it is defined as a "time constant." Figure 1 also shows the method for determining this quantity.

Below is a brief outline of the relevant time response theories and equations for continuum flow and slip flow conditions.

CONTINUUM FLOW

By definition continuum flow exists when the length of the molecular mean free path is negligible in comparison to some characteristic dimension of the flow field. In the present case, the tube diameter of the pressure measuring system is considered as the characteristic dimension. In all practical systems, the Reynolds number based on the tube diameter is low and well within the laminar range. Therefore, the flow may be classified as the Poiseuille type. Equations for the time constant and time response based on the Poiseuille equation were derived in Reference 11 as

$$\lambda = \frac{p_f - p_i}{(dp/dt)_{0< t < \lambda}} = \frac{128\mu\left(V_{tr} + nV\right)\ell}{\pi d^4 p_m} \qquad (1)$$

$$t = \frac{128\mu\left(V_{tr} + nV\right)\ell}{\pi d^4 p_m}\left[\ell n \frac{\left(p + p_f\right)\left(p_i - p_f\right)}{\left(p - p_f\right)\left(p_i + p_f\right)}\right] \qquad (2)$$

The above equations can be extended to the case of a compound tubing system consisting of various tube lengths and diameters if we use an equivalent tube system length (ℓ_e) of constant diameter tubing (d) where ℓ_e is given by

$$\ell_e = \ell + d^4 \sum_{j=1}^{j} \frac{\ell_j}{d_j^4} \qquad (3)$$

where ℓ_j and d_j are the length and diameter, respectively, of the jth tube.

R. C. Bauer (Reference 12) using Kendall's (Reference 13) experimental pressure relationship derived similar equations using a two tube system. The equivalent tube volume and tube length was defined in a somewhat different formula than Equation (3). The resulting equations are expressed as

$$\lambda = \frac{128\mu \ell_1}{d_1^4 \pi p_f K} \left[\frac{\left(V_1 + V_2\right) K + V_2}{2} + V_{tr} \right] \tag{4}$$

and

$$t = \frac{128\mu \ell_1}{d_1^4 \pi p_f K} \left[\frac{\left(V_1 + V_2\right) K + V_2}{2} + V_{tr} \right] \ell n \frac{\left(p + p_f\right)\left(p_i - p_f\right)}{\left(p - p_f\right)\left(p_i + p_f\right)} \tag{5}$$

where

$$K = \frac{1}{\left(\frac{\ell_2}{\ell_1}\right)\left(\frac{d_1}{d_2}\right)^4 + 1} \tag{6}$$

SLIP FLOW

Equations (1) to (6) are not valid in very low pressure flow and tubes of small diameter in combination, because of the existence of slip flow. W. T. Davis (Reference 14) obtained a time constant for this condition as

$$\lambda_s = \frac{128\mu\left(V_{tr} + nV\right) \ell}{\pi d^3 \left[p_m d + 2\left(\frac{2}{f} - 1\right) \mu \left(\frac{\pi p}{2\rho}\right)^{0.5}\right]} \tag{7}$$

M. J. Larcombe and J. W. Peto (Reference 15) derived the response time for slip flow as

$$t_s = \frac{128\mu\left(V_{tr} + nV\right) \ell}{\pi d^4 \left(p_f + M\right)} \left[\ln \frac{\left(p + p_f\right)\left(p_i - p_f\right)}{\left(p_f - p\right)\left(p_i + p_f\right)} + \ell n \left\{ \frac{\left[1 + \frac{2M}{p_f + p}\right]}{\left[1 + \frac{2M}{p_f + p_i}\right]} \right\} \right] \tag{8}$$

where

$$M = 8\left(\frac{\pi}{2}\right)^{0.5} \left(\frac{2}{f} - 1\right) \frac{\mu}{d\left(\frac{\rho}{p}\right)^{0.5}} \tag{8a}$$

with the value of $f = 0.8$ suggested in Reference (14) and air at 20°C

$$M \cdot d = 0.0054 (\text{lb/ft})$$

Equations (7) and (8) can be extended to the case of a compound tubing system in a manner similar to that used in Equation (3). The expression for equivalent length becomes

$$\ell_e = \ell + \sum_{j=1}^{j} \frac{\ell_j d^4 (p_f + M)}{d_j^4 (p_f + M_j)} \left[\frac{\ell n \left\{ \dfrac{199 p_f + p_i + 200 M_j}{p_f + p_i + 2M_j} \right\}}{\ell n \left\{ \dfrac{199 p_f + p_i + 200 M}{p_f + p_i + 2M} \right\}} \right] \tag{9}$$

where

$$M \cdot d = 0.0054 = M_j d_j$$

The above equivalent length has been determined on the basis that the time response is defined as the time interval for the transducer pressure to reach a value corresponding to 99 percent of the pressure difference between the initial and final pressures. It should be noted that the equivalent length is not constant for a given tubing configuration (as was the case with continuum flow) but is now pressure-dependent.

There is an inconsistency between the various authors on the value of the empirical constant to be used. Kendall (Reference 13) suggests that the full volume (n=1) of a tube should be added to the total system volume only if the diameter of the tube is greater than three times the diameter of the first tube or orifice. Davis (in Reference 14) uses n=1 for all cases. In the present study, n is handled as a variable parameter.

M. J. Larcombe et al (Reference 15) compared response times for the same pressure difference applied in opposite directions and at various initial pressure levels. Their results (illustrated in Figure 2) showed that for a constant pressure difference a pressure drop in the instrument leads to a longer response time than the corresponding pressure rise at low ambient pressure conditions. This is due to the fact that the equilibrium process takes a longer time near the lower final pressure level. However, the direction of the pressure step has little effect on the response time when the overall pressure level is increased.

DESCRIPTION OF TEST APPARATUS AND INSTRUMENTATION

The block diagram of the test apparatus and the instrumentation system is shown in Figure 3.

A specially constructed low pressure system was utilized for the present study. The main components of this system were portable high vacuum pumping station, precision variable microleak, calibrated precision electronic manometer, solenoid operated quick opening valve, transducer telemetry unit and associated electronic networks. The high vacuum system consisted of a mechanical vacuum pump which served to back up a four-inch 400 liter/sec diffusion pump with an ultimate vacuum capability of 1×10^{-7} mmHg. The high vacuum port, in the present configuration, was directly connected to a bell-jar which housed the transducer and quick opening valve assembly. A gate valve separated the bell-jar from the diffusion pump. The mechanical vacuum pump was connected to the bell-jar via a roughing valve. An ultra-stable Bayard-Alpert type ionization gauge measured the vacuum levels below 10^{-3} mmHg; above this pressure a thermocouple gauge indicated the pressure level in the bell-jar. The vacuum instrumentation was not used in the quantitative measurements of time response, but merely provided a means of observing that the system was below some prescribed critical pressure level in the initial pump-down. Furthermore, it provided information that the overall leakage rate was well within the resolution of the electronic manometer utilized for the precise determination of the initial and final pressure levels.

The bell-jar, which housed the transducer-telemetry unit and the quick opening valve, was placed on the high vacuum port of the diffusion pump. The sealing action of the Dow Corning high vacuum silicone grease between the ground glass surface of the bell-jar and the stainless steel flange of the vacuum port was sufficient to achieve vacuum levels in the order of 6×10^{-7} mmHg after a few hours of pumping.

Controlled air bleed-in was achieved through a calibrated variable "leak". The conductance of this "leak" could be varied between

$10^{-10} cm^3/sec$ to $100 cm^3/sec$ (standard pressure and temperature) with atmospheric pressure on the inlet port. When closed, the leakage was less than $10^{-13} cm^3/sec$.

The pressure standard used in the study was a variable capacitance electronic manometer (Datametrics Barocel system) capable of measuring pressures between 0 and 1.0 psi on seven consecutive scales ranging from 0.001 to 1 psi full-scale reading (zero to five volt output). A digital voltmeter was utilized to permit accurate measurements of ±0.1 percent full-scale in each range. The transient response time of the output voltage was two milliseconds with negligible hysteresis and continuous resolution. A high vacuum pumping station provided constant pressure on the reference port. This pressure was continuously monitored and did not exceed 5×10^{-5} mmHg ($\sim 10^{-6}$ psi).

During the assembly of the test apparatus, extreme care was taken to insure minimal leakage and outgassing. The combined leakage and outgassing rate was measured to be 4×10^{-6} mmHg/sec without the transducer. This rate increased to 10^{-5} mmHg/sec after the valve and transducer system installation. The leak rate was a near exponential function of time as shown in Figure 4. Due to the combined outgassing and leakage rates, the initial bell-jar pressure of 0.5 mmHg increased less than 0.1 percent within 60 seconds. Since the running times were in the order of 10 seconds, the leakage error was neglected.

The low pressure transducer-telemetry units used in the experiments were specially fabricated by JPL based on R. G. Harrison's design, Reference 16.

The telemeters utilized ultra-stable Colpitts oscillators which were operated at center frequencies of 114.3 and 116.6 MHz. The oscillators were frequency modulated by the variable capacitance-type transducers. The detail of construction and performance characteristics of these units are presented in Reference 17. The response time of the pressure telemetry units without external tubing was measured to be less than 0.5 milliseconds and their thermal stability was good. The photograph of a unit is shown in Figure 5.

The telemeter oscillator signal was beamed to a 120 MHz half wavelength folded dipole antenna matched to a coaxial cable using a matching transformer. Signal conditioning was achieved by a preamplifier and signal tapoff network before it was fed into an FM tuner. The RF and oscillator stages of the tuner were modified to provide reception in the 110 to 120 MHz band. A voltage regulator maintained the tuner line voltage within ±0.1 percent. The tuner output was then amplified by a driver amplifier and fed into a Tektronix dual trace oscilloscope equipped with a polaroid camera.

A flat faced nylon cylinder was utilized as the quick opening valve. The cylinder was fastened to a stainless steel valve rod which penetrated a double O-ring seal at the top of the bell-jar and was free to move in the vertical direction. The motion of this valve assembly was implemented via an electro-magnetic solenoid which was energized by a D.C. power supply through a switching device. The solenoid on-off switch also served to activate a 15 millisecond time delay circuit which triggered the oscilloscope. The total traverse distance of the valve varied between 0.31 and 0.34 inches. The required time for full-valve opening was less than three milliseconds.

The motion of the quick opening valve was monitored by an electro-optical displacement follower. This device consisted of a tracker and associated power supply. A photocathode-photomultiplier tube, lense system, and signal amplifier comprised the tracker. This electro-optical system was capable of measuring extremely rapid motions of a reflecting target. The data was presented in the form of an electrical output voltage signal which was directly proportioned to the displacement distance. The response time of the device was 50 micro-seconds with continuous frequency response between 0 and 10 kc. The linearty of the signal was ±0.5 percent full scale and the output voltage six-volt D.C. full scale. The available optical system on the tracker permitted the maximum displacement measurement of two inches with a resolution of ±0.001 inch. The output signal of the optical displacement follower was fed into the oscilloscope.

Figure 6 is a close-up view of the transducer-telemetry unit and quick opening valve installation with the bell jar removed. Figure 7 gives an overview of the variable "leak", electronic manometer and transducer-valve assembly in the bell jar together with the electromagnetic solenoid. The U-shape antenna board surrounds the bell jar.

EQUIPMENT CALIBRATION

Prior to the experimental program critical components of the system were carefully calibrated.

The electronic manometer was directly compared with a unit calibrated at the National Bureau of Standards to within ±0.1 percent accuracy. The overall accuracy of the unit is ±0.3 percent. Calibration lines are shown in Figure 8 for the 0.1 psi and 0.03 psi ranges.

The FM receiver was calibrated at three points within its frequency range using the 10th and 12th harmonics of a signal generator output. Typical deviation sensitivities were found to be 71 KHz/volt and the calibration curves exhibited linearities within ±2 percent of 2.5 volts over the range from -1.5 to 2.5 volts. Slope values were within ±2 percent for repeat calibration.

The oscilloscope and driver amplifier showed typical linearities of less than ±1 percent with calibration repeatability within ±0.5 percent.

The telemeter-pressure transducer units were individually calibrated in the bell jar. Since these were differential pressure units, they were tested for both positive and negative values of pressure differential. In the calibration procedure, the system was allowed to stabilize for five minutes and then a positive or negative step pressure was introduced. This pressure was measured by both the telemetry unit and the electronic manometer and compared directly. The input time of the step pressure was in the order of three miliseconds and the pressure response of the transducer was less then ten milliseconds. Since the leakage rate of the reference port was 0.02 mmHg/sec the internal pressure change of the transducer due to this leakage was approximately 0.01 percent full scale during the duration of the calibration. This error therefore was neglected. Typical calibration lines are shown in Figure 9. Note that the pressure response of the transducer is linear. However, the slopes vary depending on whether the pressure differential is positive or negative.

The travel time of the quick opening valve was carefully determined for a distance of 0.25 inches. The increase of the solenoid excitation voltage from 17 volts to 37 volts resulted in a rather abrupt decrease of the rise time. This is illustrated in Figure 10. However, further increase of the input voltage did not result in any significant decrease of the travel time which leveled off at about three milliseconds. Further decrease would only be possible by a much larger magnetic coil. This, however, was neither practical nor necessary since the obtainable travel time was sufficiently short for the present investigation.

EXPERIMENTAL PROCEDURES

In order to verify the theoretical analysis, an experimental program was initiated to obtain pressure-time response data. Five configurations were tested. Table 1 contains the summary of the test geometries and pressure data. A close-up view of the various tube configurations used as well as the measuring system is shown in Figure 11.

The following procedure was used in each test run. The system pressure in the bell jar was initially reduced to about five microns as indicated on the thermocouple gage and the Barocel electronic manometer. At this point the vacuum roughing valve was closed and a measured amount of air was slowly admitted via the calibrated "leak". This caused the bell-jar pressure to rise to a predetermined level of initial pressure. After steady state had been reached as monitored by the Barocel electronic manometer, the quick opening valve was lowered, closing the measuring port of the transducer-telemetry system. This action isolated the pressure measuring system from the bell jar and, in turn, maintained the initial pressure level in the system independent of the bell-jar pressure. The bell-jar pressure then was quickly brought to the final pressure level either by evacuation or admittance of additional amount of air via the calibrated "leak". The final pressure in the bell jar was monitored by the Barocel electronic manometer. At this point the electromagnetic solenoid of the quick opening valve was energized and the valve opened uncovering the measuring port of the transducer. The motion of the quick opening valve was monitored by the electro-optical tracker. The telemeter signal output was conditioned by the FM receiver and various amplifiers. Both the electro-optical tracker and the FM tuner signals were recorded by a dual trace oscilloscope which was triggered by a 15 millisecond time delay circuit. The image of the oscilloscope traces was photographed by a polaroid camera. A typical photograph of the oscilloscope output is shown in Figure 12.

It should be noted that during the time interval of the final pressure build-up and the conclusion of the run, usually less than ten seconds, the reference port pressure did not change from the initial pressure level by more than one percent. The average accumulated error throughout the test program was estimated at ±7 percent with a maximum error of ±15 percent.

RESULTS AND DISCUSSION

Using four geometrical configurations and a multiplicity of initial and final pressures, a total of 70 individual pressure-time response runs were obtained. Several correlation schemes were tested and it was found that if the n "constant" in Equations (2) and (8) is replaced by

$$n = A \cdot d^{B} \tag{10}$$

then both equations predict the correct trend in the pressure-time response within the test envelope.

The measured data displays some scatter due to the difficulties in measuring very short-time responses (in all cases below 12 milliseconds) precisely.

Typical results are shown in Figures 13 and 14. In Figure 13 the final pressure is plotted as function of the time response for configuration (1). The solid line represents Equation (8). The theory overestimates the time required to reach a pressure by about 25 to 35 percent of pressures below $p_f = 0.7$ psf.

The mean pressure (p_m) is plotted as function of time response in Figure 14 for configuration (2). The theoretical line represents Equation (2). Again the data scatter is apparent but the theoretical equation seems to give satisfactory predictions within a ±25 percent error band.

Figure 15 shows the variation of the n factor with tube diameter for the mean pressure (p_m) and final pressure levels (p_f). The correlation equations for these functions are in the form of Equation (10) and are also shown in the figure.

The deviation of the theoretical equations from the measured values stem largely from end effects which were neglected in the original derivations. The end effects account for Equation (10) also.

Within the limitation of the present test, Equation (9) has negligible effects on the results.

CONCLUSIONS

A comparison of theoretical response times with measured values for several geometric configurations indicates that, for a short-time low-pressure response system, the theoretical Equations (2) and (8) modified by Equation (10) adequately predict the time for the pressure measuring instrument to reach a given final pressure. The probable error in the prediction is in the order of 25 to 35 percent. The chief reason for the deviation between measurement and theory lies in the end effects of the short tube systems used in the actual measurements to obtain short-time response but neglected in the derivation.

A note of comment should be made about the inaccuracies of the prediction equations. The average duration of a free-flight test, where these formulae would be applicable for system design purposes, is several orders of magnitude longer than the absolute value of the time response prediction which these equations would provide. Therefore, a 25 to 35 percent error in the prediction is quite acceptable.

Further study is recommended to investigate the length effects quantitatively.

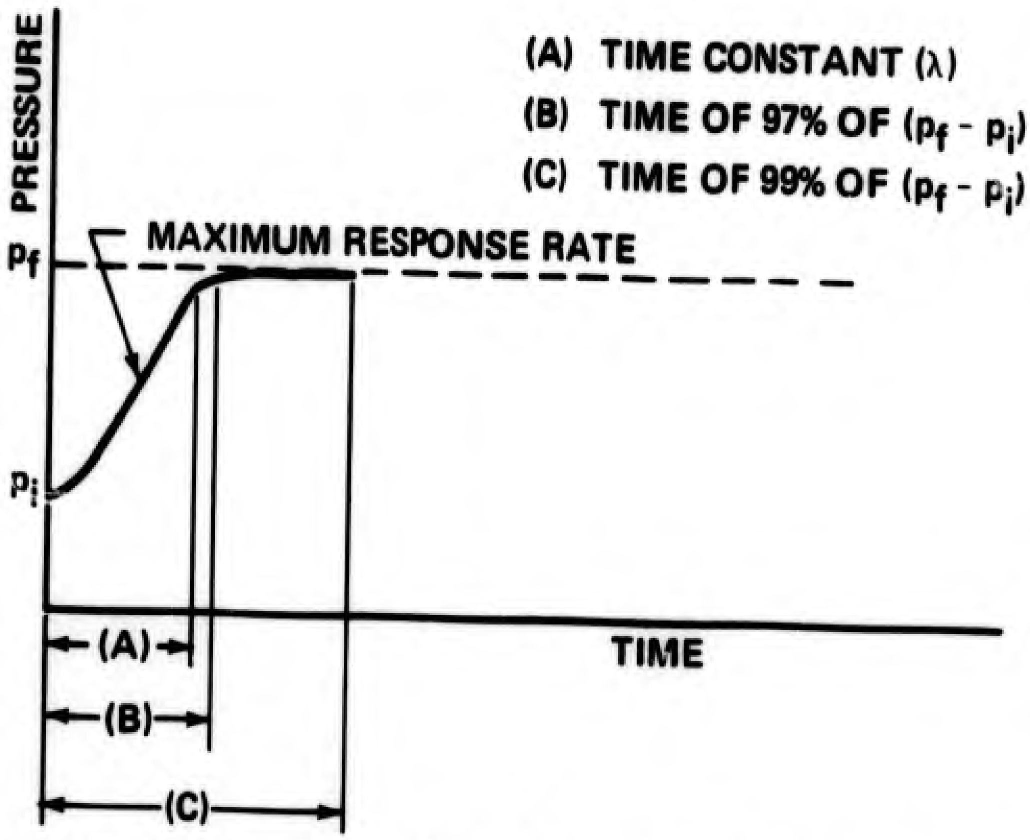

Figure 1 - Definition of Time Response and Time Constant

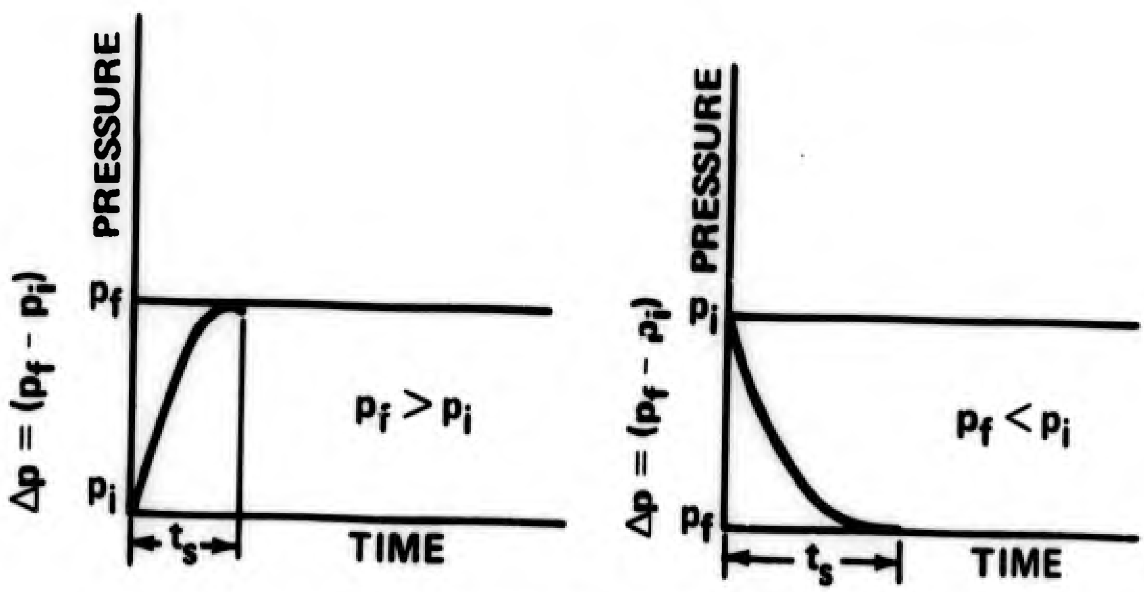

Figure 2 - Comparison of Response Times for Positive and Negative Pressure Differences

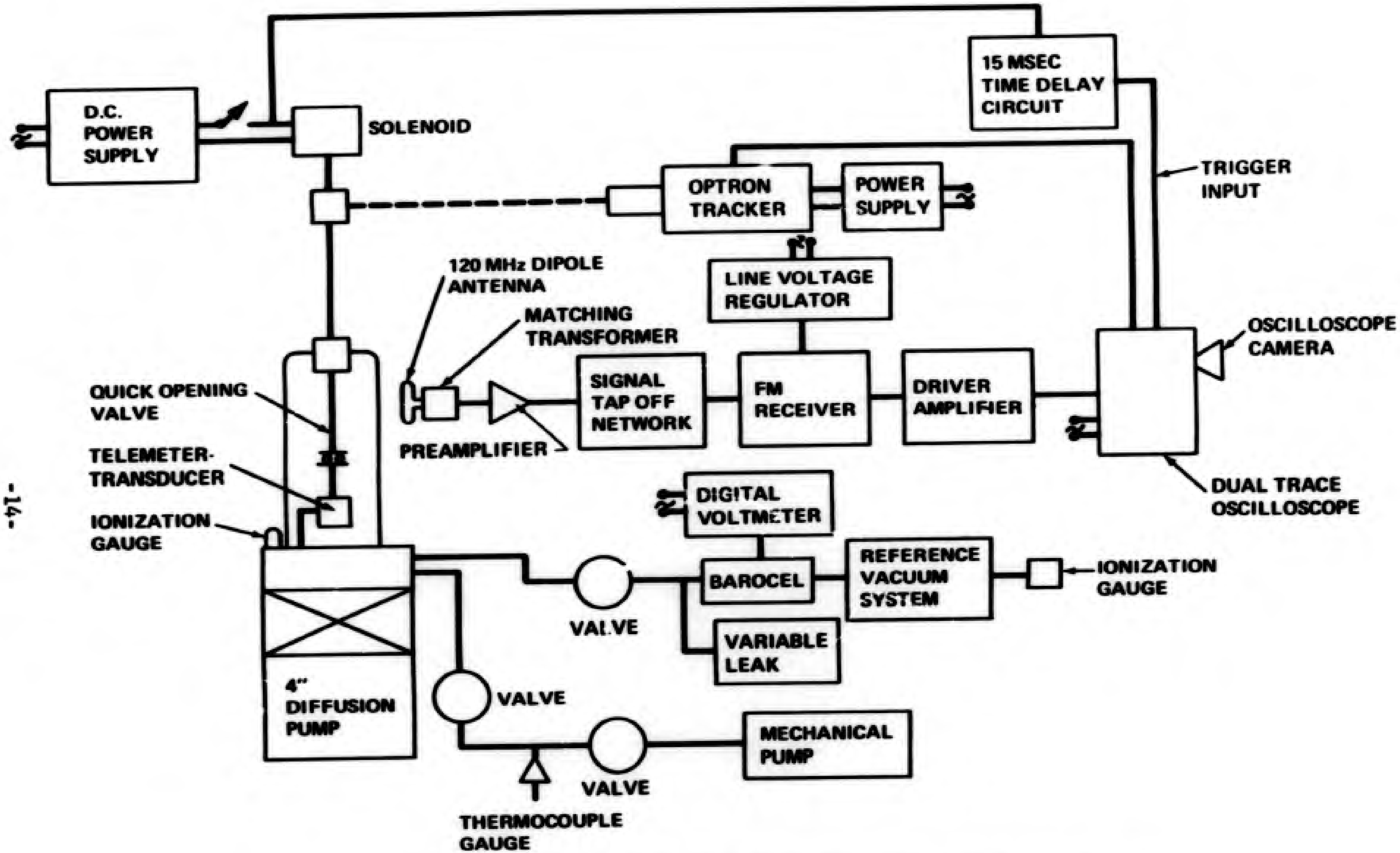

Figure 3 - Block Diagram of Test Apparatus and Instrumentation System

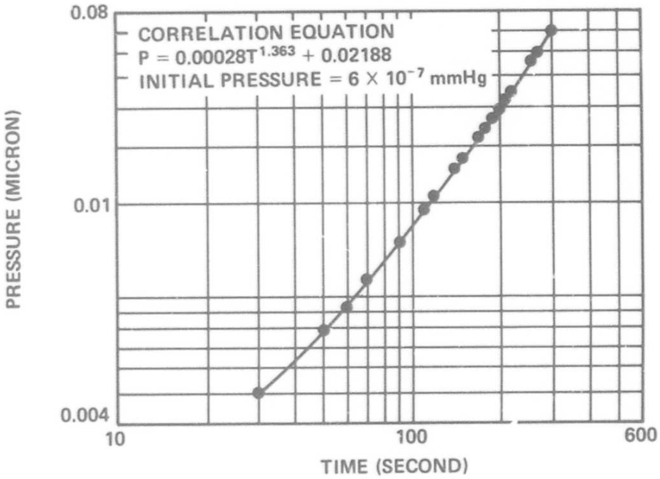

Figure 4 - System Leak Rate

Figure 5 - Close-up of Telemeter-Transducer Unit

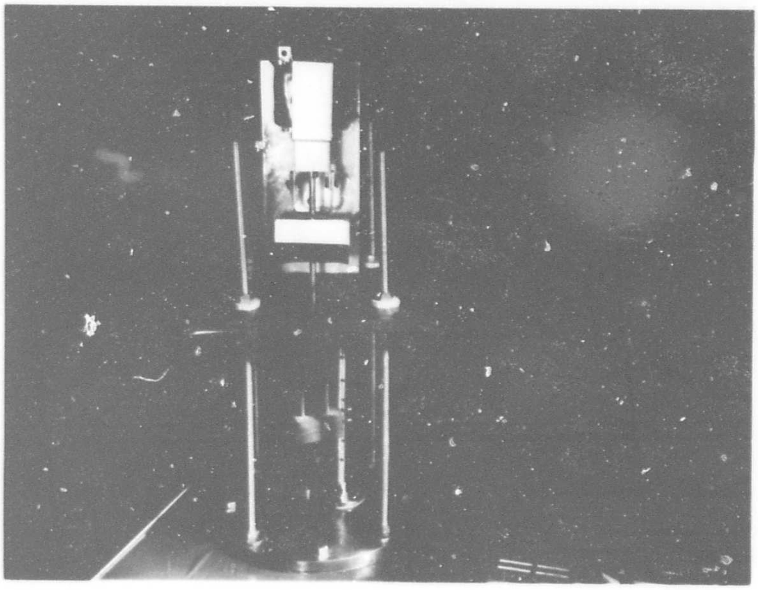

Figure 6 - Close-up of Quick-Opening Valve

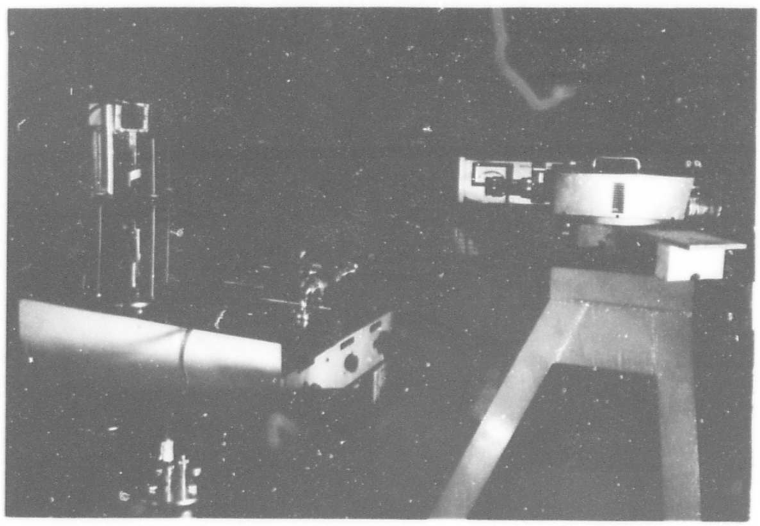

Figure 7 - Overview of the Test Apparatus

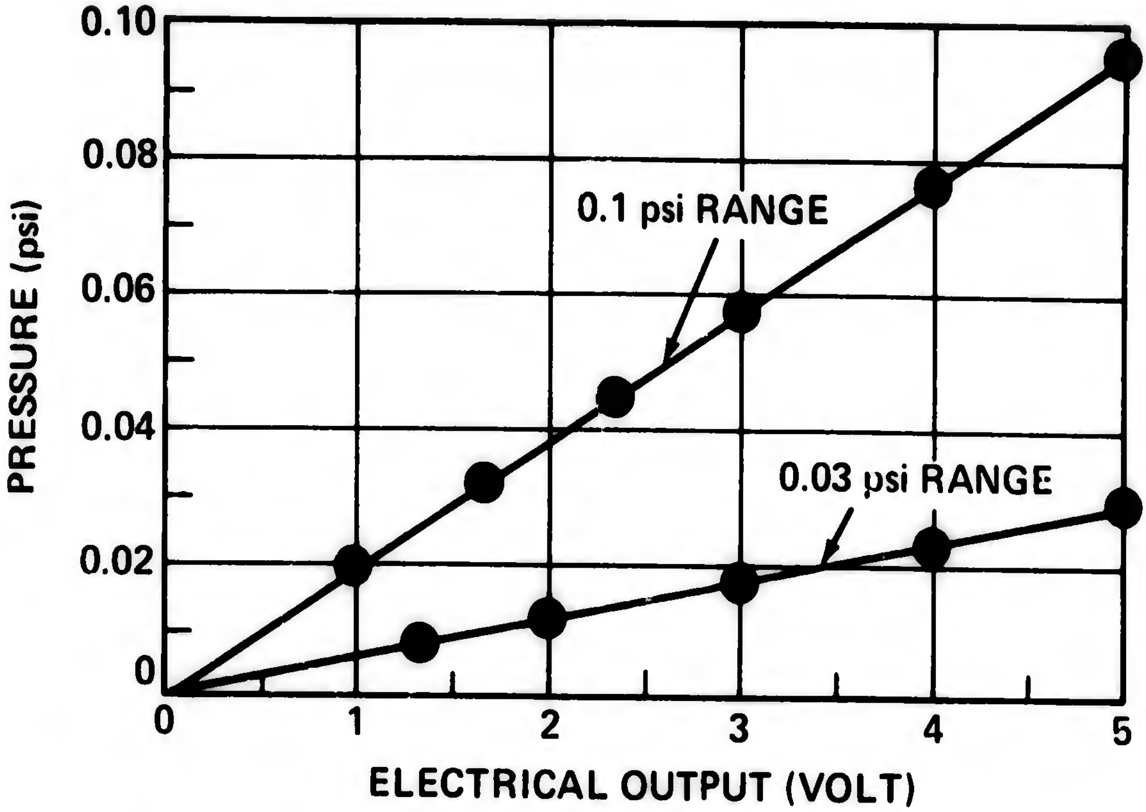

Figure 8 - Barocel Calibration Lines

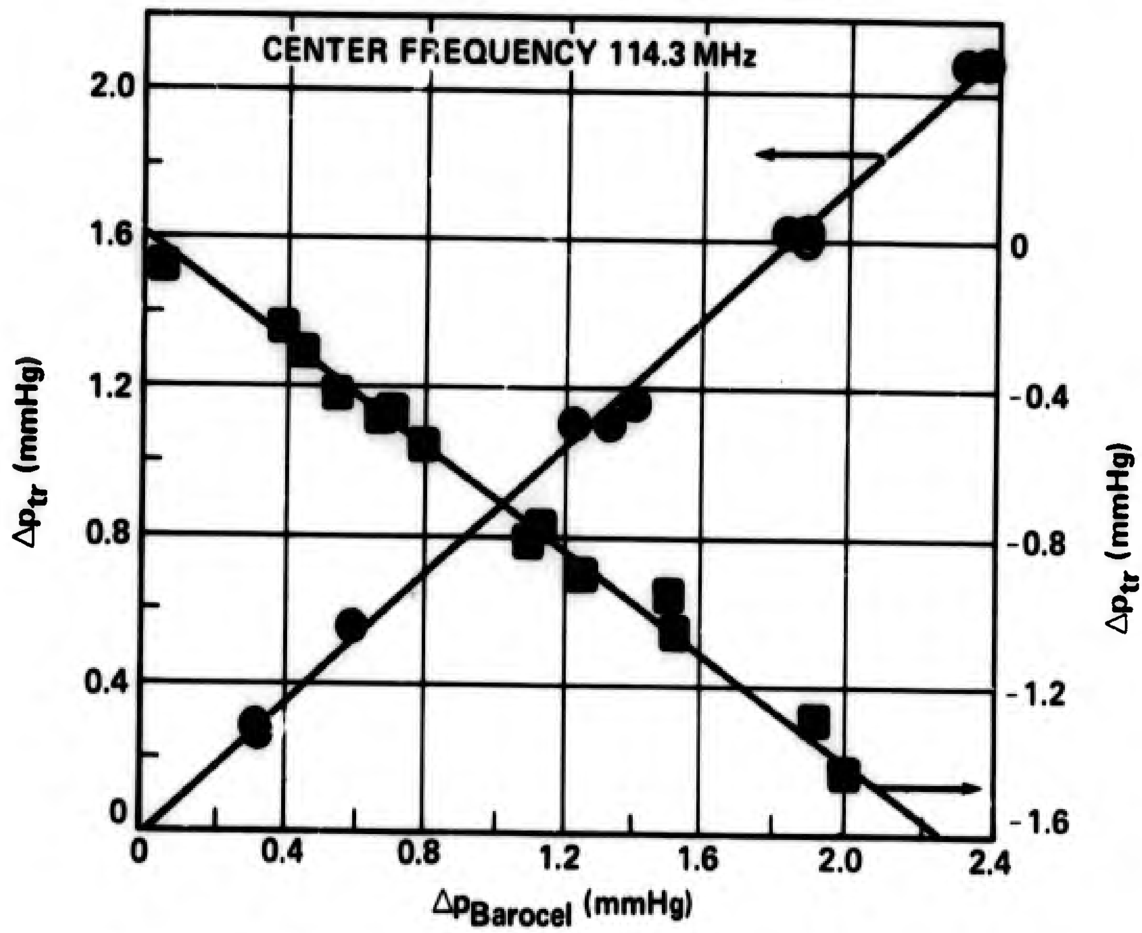

Figure 9 - Calibration Lines for Telemetry-Transducer No. 5

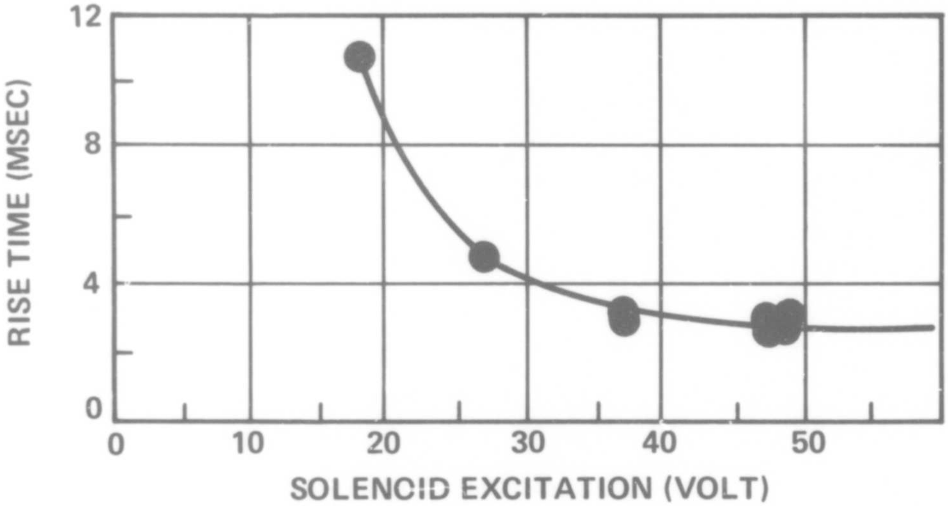

Figure 10 - Quick-Opening Valve Response

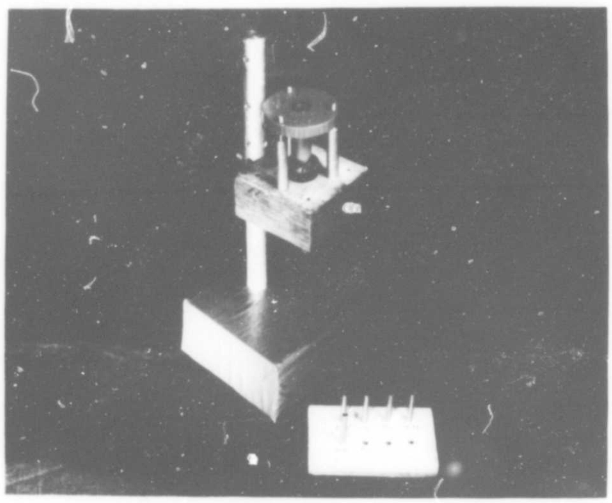

Figure 11 - Close-up View of Test Configurations

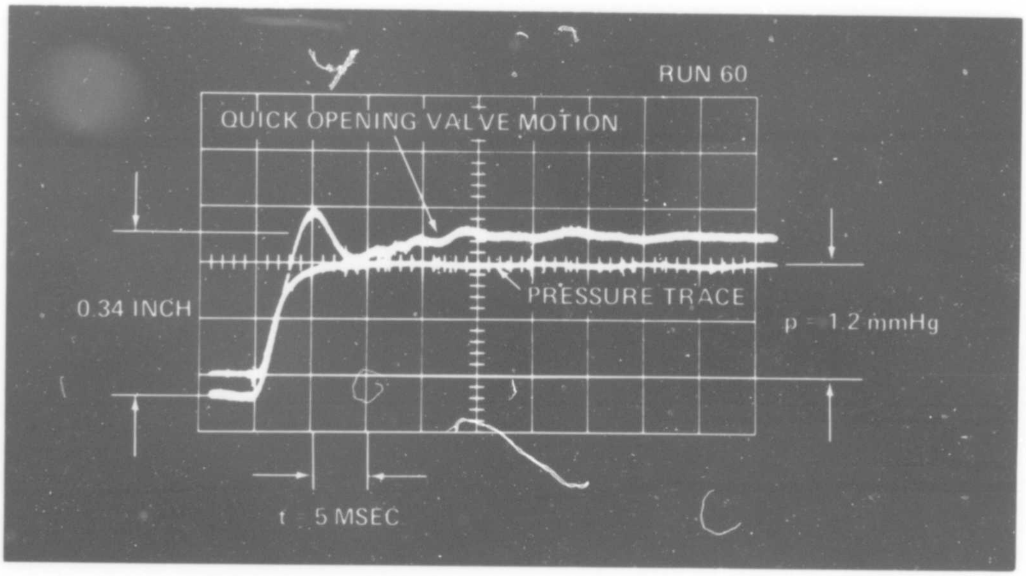

Figure 12 - Oscilloscope Trace Photograph

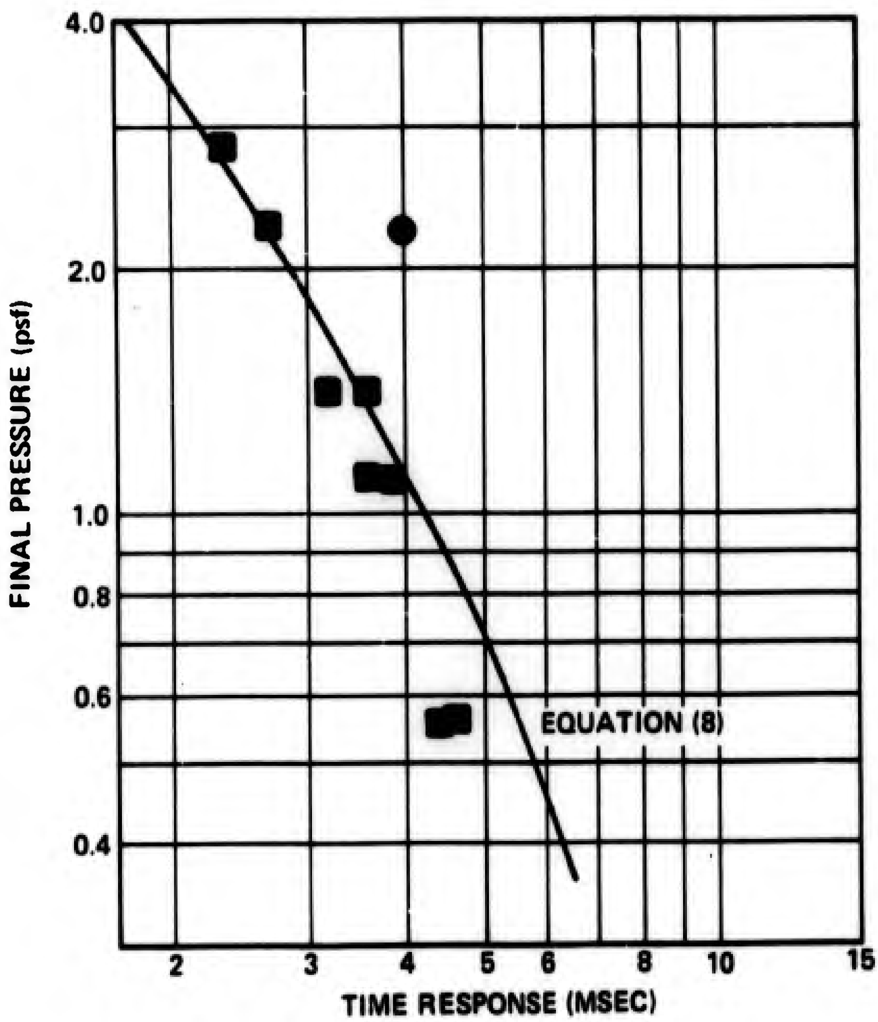

Figure 13 - Response Time Versus Final Pressure Results for Configuration (1)

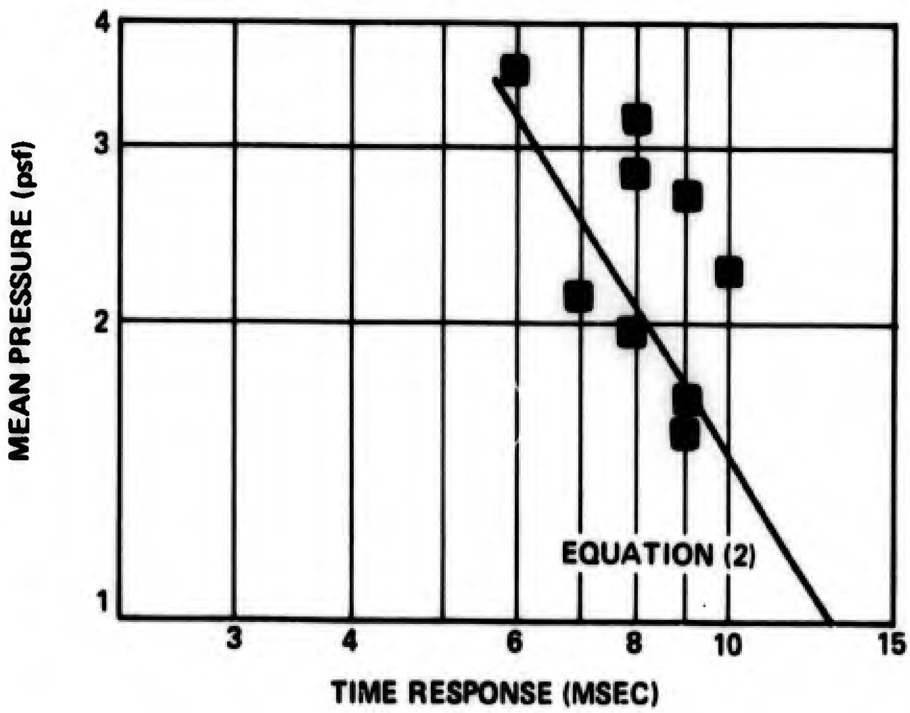

Figure 14 - Response Time Versus Mean Pressure Results for Configuration (2)

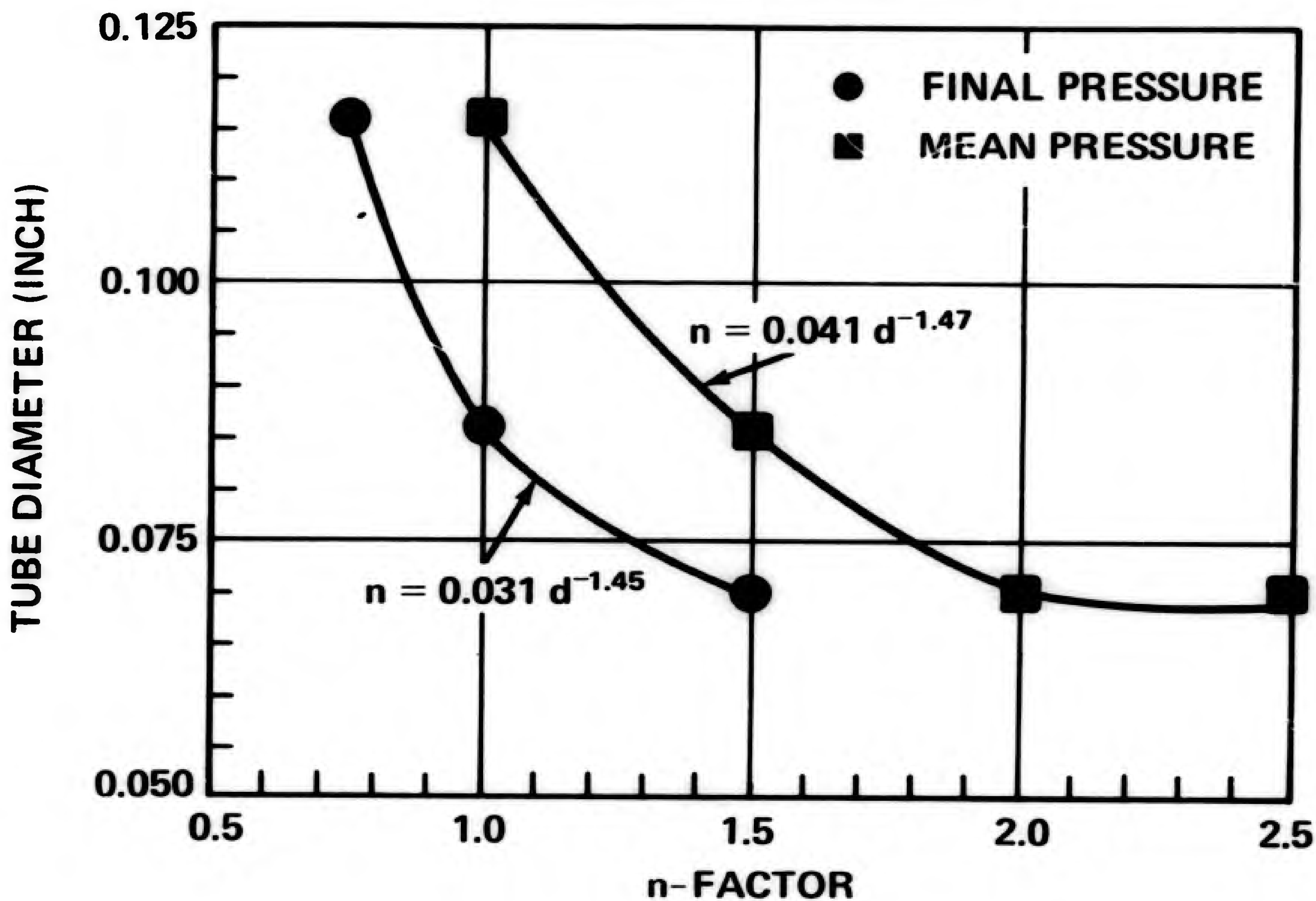

Figure 15 - n-Factor Versus Tube Diameter

TABLE 1

Test Summary

Configuration									
(1)		(2)		(3)		(4)		(5)	
l_1 (ft)		0.1083							
l_2 (ft)		0.0425							
d_1 (ft)	0.0097	0.0058		0.0072		0.0104		0.0058	
d_2 (ft)		0.005							
Pressure Data									
$P_i(\mu)$*	$P_f(\mu)$	$P_i(\mu)$	$P_f(\mu)$	$P_i(\mu)$	$P_f(\mu)$	$P_i(\mu)$	$P_f(\mu)$	$P_i(\mu)$	$P_f(\mu)$
1120	7.5	500	211	500	113	4011	415	4011	419
1010	200	1520	107		95		1334		405
1500	370	1510	947		202	2006	419		1298
500	778	1501	180		437		1305		1031
500	2600	1505	406		765				772
1000	100	1501	528		1034			3507	409
	400	1505	760		2550				770
	530	1501	978	1000	104				985
	2590	1000	107		195				1286
1500	118		204		415			2505	401
	211		406		516				766
	512		518		2580				1010
	782		781	1500	192				1286
	1040	1505	106		197			2006	412
	2580		111		405				779
					800				1019
					770				1283
					1010				

*Note: Initial and final pressures are given in microns (μ)

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Department of Aerodynamics Naval Ship Research and Development Center Washington, D. C. 20034	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

A STUDY OF SHORT-TIME, LOW-PRESSURE RESPONSE IN A TRANSDUCER SYSTEM

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Test and Evaluation Report

5. AUTHOR(S) (First name, middle initial, last name)

George S. Pick

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1970	31	17

8a. CONTRACT OR GRANT NO. WR 009.0201 b. PROJECT NO. c. TASK 10209 d. NSRDC 648-242	9a. ORIGINATOR'S REPORT NUMBER(S) Test Report AL-74 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Commander Naval Air Systems Command Washington, D. C. 20360

13. ABSTRACT

Existing theoretical equations have been correlated with experimental pressure-time responses in the 0.1 mmHg to 3.0 mmHg pressure range in short-time response transducer systems. Experimental investigation confirmed predicted trends but the equations required modifications to account for end effects which were neglected in the original derivations. The prediction errors of these modified equations were within an acceptable range. The results provide system design criteria for free flight instrumented models in hypersonic tunnel applications.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

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Security Classification

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Instrumentation						
Pressure Measurement						
Hypersonic Flow						
Transducer System Design						
Pressure-Time Response						
Low Pressure System						
End Effects						
Data Correlation						

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