C.P. No. 949

C.P. No. 949

MINISTRY OF TECHNOLOGY

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

The Accuracy of Pressure Transducers when used in Short-Duration Wind-Tunnel Facilities-

By

L. Pennelegion, K. Wilson and Miss B. Redston

LONDON· HER MAJESTY'S STATIONERY OFFICE
1967
EIGHT SHILLINGS NET

C.P. No. 949*

October, 1966

The Accuracy of Pressure Transducers when used in Short-Duration Wind Tunnel Facilities

-By-

L. Pennelegion, K. Wilson and Miss B. Redston

SUMMARY

Calibrations have been made of some pressure transducers in the pressure ranges 0-20, 0-100; and 0-760 mm Hg. The pressure step was applied in a time of 2-3 ms. Standard deviations have been computed and are used for comparisons, and for estimation of accuracies in a shock tunnel flow. A few measurements are presented of acceleration sensitivities.

---

*Replaces N.P.L. Aero Report 1213 - A.R.C.26 577

CONTENTS

1. Introduction

Because of nozzle mass flow requirements and the rather limited mass of gas upstream of the nozzle, the majority of short-duration wind tunnels generate nozzle flows at Mach numbers greater than 8. Flat plate pressures consequently are nearly always less than 10^{-4} of the reservoir pressure (PO) and since PO may be around 3000 psi, [ϒ] one is concerned to measure pressures less than 0.3 psia on streamwise surfaces or less than 25 psia in pitot tubes.

The short flow duration requires that a pressure transducer used to measure such low pressures must be inside the wind tunnel model to avoid pipe response-time problems, and therefore the small transducer is attractive since several may be placed in a model and used simultaneously. Several centres have manufactured highly satisfactory transducers from their own designs (Cornell, AVCO, AEDC, PIBAL), but there are others who have to rely upon commercially available transducers. Suitable transducers available at NPL fall into two classes; piezo electric and unbonded strain-gauge. Though the piezo electric transducers were of a suitable size they were designed for use at pressures up to a few thousand pounds per square inch.

The investigation discussed in the present note was concerned with evaluating the transducers, using DC systems. Recognising that when the transducers are used in short-duration wind tunnels their output has to be recorded on an oscilloscope, this investigation was mainly concerned with providing a valid assessment of the overall accuracy of a typical measuring chain. It was hoped that the large number of measurements made with each transducer would result in a sensible comparison of relative merits of the transducers. The data from about 450 measurements are presented in this

[ϒ] 1 atm. = 14.695 psi = 101,325 N/m^2

report, though over three times this number of calibration measurements have been made during shock-tube and solenoid-valve development, and in the comparison of different transducers of the same type. The measurements presented in this report were made in the period Nov. 1965 - July 1966.

2. Methods of calibration

There is ample evidence that some pressure transducers [1,2] exhibit a calibration constant that varies with rate of application of the pressure pulse. Now whereas dynamic pressure measurements behind strong shock waves or in high temperature plasmas must be obtained within, say, 10 μs, in reflected shock tunnels the total running time is in the range of 4 - 10 ms and the required initial response time in the test section is not usually less than 1 or 2 ms due to nozzle flow establishment and cavity response times. In free-piston gun tunnels the running time is usually in excess of 25 ms and therefore pressure rise times of up to 10 ms may be tolerated in some circumstances. It seems realistic therefore to use a calibration pulse whose rate of pressure rise corresponds with that in the environment to be measured.

Fast rate pressure pulses (i.e. of the order of a microsecond) can only be obtained in a shook tube. If the shock wave Mach number does not exceed 2, then ideal one-dimensional shock wave calculations may be employed, and the calculated pressure behind the incident shock wave used for calibration. The technique requires a measurement of shock wave velocity and the initial pressure and temperature in the shock tube channel. Some problem may arise due to the bandwidth of the electrometer or charge amplifier, though if the same chain of equipment is used in the calibration as in the problem under investigation then the bandwidth is not so important.

Moderate rate pressure pulses (i.e. of order 1 ms) can now be obtained with rapidly-opening valves. Such valves can be operated electrically and synchronisation with the oscilloscope recording is not usually a problem. These 'semi-dynamic' calibrators have the advantage that the initial and final pressures are directly adjusted under steady-state conditions. The pressure pulse rate can be deliberately decreased by using an orifice ahead of the transducer, (e.g. reducing a 0.1 in diameter orifice to 0.010 in diameter ahead of a 701 S transducer increased the pressure rise time from 2 ms to 300 ms.)

Slow rate pressure pulses (500 ms and longer) would conveniently be obtained by manually opening a valve connecting the two pressure levels, the tank volumes or valve opening being adjusted to suit the required rate of pressure rise.

At the N.P.L. it was necessary to make test-section pressure measurements in both shock and gun tunnel facilities. The rate of pressure rise was known to be in the region of 1 to 5 ms, and therefore the most appropriate calibration equipment used a rapidly-opening valve.

2.1 Description of the NPL calibrator

The N.P.L. design of rapid-opening valve is based on an earlier version by Pallent[1] at R.A.E. Farnborough, though it is not very different in concept from the "poppet-valve" designs by Aronson[3] and Vesso[4], except that an axial motion electromagnet is used to open the valve. The response time of 1 ms is comparable with Vesso though not as rapid as Aronson (0.2 ms).

The general arrangement can be seen in Fig. 1 together with the detail of the valve port. The mushroom valve moves downwards 0.2 in when the solenoid is energised, and is cushioned by a Teflon buffer. The diameter of the hole in the top plate was chosen to suit a standard brass transducer holder that had been previously used for calibration tests in a low-pressure shock-tube.

The volume ahead of the transducer mount V_1 was made as small as possible (about 4×10^{-2} cu. in.) since this has a considerable effect on the fastest rate of pressure rise. The pressure in V_1 was evacuated through a small bore tube in the face of the mushroom valve, and brought to an external connection by a length of plastic tubing so that the valve movement was not restricted. The volume of the vessel V_2 was larger by a factor of 10^4 compared with the volume between the transducer and the valve, which ensured that the pressure in V_2 remained constant when the valve opened.

Despite the solenoid being designed for operation at 11 volts DC, satisfactory repeated operations have been achieved using a 10,000μF capacitor-bank charged to 36 volts DC and switched directly to the solenoid. The triggering voltage for the oscilloscope was taken from the voltage across the solenoid.

The fastest time for the pressure to reach a constant value was 1 ms. At pressures below 10 mm Hg, the pressure took up to 3 ms to reach its steady level, but this was still appropriate for the simulation of shock tunnel nozzle flows.

The transducers were all mounted in standard plates which contained an orifice and volume ahead of the transducer. The dimensions of the orifice were 0.1 in.(2.5 mm) diameter, 0.1 in. length, and the volume of the cavity was about 10^{-2} cu.in. (0.16 cc). The response time of this cavity was approximately 0.5 ms, and was regarded as being representative of an internal transducer fixture in a model for a short-duration wind-tunnel facility. Previous experience had shown that the size of the cavity affected the scatter of the results, so it was felt necessary to retain the same cavity volume for all the transducers. The different diameters (Section 2.3) of transducers meant that the shape of the cavity was altered to keep the volume constant. The dimensions of the cavity ahead of a Kistler 701 A are shown in Fig. 2.

2.2 Procedure for N.P.L. tests with rapid-opening valve

If we define the pressure initially ahead of the transducer in volume V_1 as P_1 and the pressure in the main vessel V_2 as P_2 then the calibration pressure jump is recorded as $P_2 - P_1$. For the routine calibration tests P_1 was 0.1 mm Hg measured on a Wallace and Tiernan 0-20 mm Hg dial gauge. The value of P_2 was read on the appropriate one of three other Wallace and Tiernan dial gauges having sensitivities of 0-20, 0-100 and 0-800 mm Hg.

Calibrations were in 1 mm Hg intervals from 2 mm Hg up to 20 mm Hg, then every 10 mm Hg to 100 mm Hg, and each 50 mm Hg, up to 760 mm Hg. The gain of the system was standardised on each combination of the charge amplifier and oscilloscope amplifier setting by using a calibrated DC source. This was fed into the calibration terminal of the charge amplifier and recorded on the oscilloscope as a low speed square wave of large deflection amplitude (5 cm) to give as great a reading accuracy as possible. The trace intensity was reduced to improve the trace definition.

The majority of the measurements used a Tektronix 564 Storage Oscilloscope with a 2A63 plug-in amplifier, the stored image being photographed after each shot. The maximum input sensitivity of this amplifier was 1 mV/cm and recourse was made to a Tektronix 502 oscilloscope when greater sensitivity was required.

2.3 Characteristics of the pressure transducers tested

The suitable and available transducers at the N.P.L. were either piezo-electric or strain gauge.

The piezo-electric transducers were all quartz except for the one loaned from Cornell Aero Labs. which was PZT, a lead zirconate-titanate ceramic which is very much more sensitive to pressure than quartz, but is not so temperature stable. Both the Kistler 701 X and the Cornell transducer were acceleration compensated.

The two absolute pressure strain-gauge transducers had flush diaphragms.

The main physical and electrical characteristics are tabled below.

Trans-ducer	Type	Sensit-ivity pC/psi	Nat. freq. kHz	Max. dynamic press (psia	Max. static press. (psia)	Approximate dimensions Face diam. mm	Length mm.
701 A	Quarts	5.0	65	3700	6000	11	22
701 s	"	8.0	50	150	150	12	22
701x	"	4.0	50	3700	6000	11	22
601	"	1.0	125	3700	7500	6	15
6QP500	"	0.5	160	4500	7500	6	15
PZ6M	"	0.4	160	2500	2500	5	15
MQ20	"	0.5	300	20,000	30,000	10	21
CORNELL	PZT	60 mV/V/psi	19	5	45	13	9
CEC 4-327	Unbonded strain gauge	0.36	12	10	20	25	40
STATHAM PA 222TC	"	0.44	7	10	15	6	15

3. Analysis of pressure calibrations

The raw data of pressure jump and output charge or voltage from the transducer were plotted directly and the method of 'least squares' used to give the equation of the most probable straight line through the points, and to deduce the standard deviation of the points and of the calibration constant. The numbers and positions of the calibration points used in each pressure calibration range were maintained for each transducer being compared, since the magnitude of the standard deviation depends upon this.

The straight-line equation obtained Prom the least-squares analysis has a value for the intercept that is not always zero. Attention was drawn to this in an earlier paper [5] where with shock-tube calibrations its value caused a large uncertainty in the interpretation of the low-pressure readings. The extent of the zero offset seems to be related to the fast pressure-loading rate obtained in shock-tube tests. The physical significance of an intercept can be understood for the case where a voltage or charge output is only obtained above a certain pressure, and this situation corresponds to a negative value for the constant term in $q = mp+b$, but shock-tube measurements by Pallent [1] show data that extrapolates to an intercept on the '+q' axis at zero pressure, (i.e. a positive value for the constant term).

The calibrations reported in Section 4, using a solenoid-operated valve, have in nearly every case implied an intercept on the pressure axis of less than 1% of the full-scale calibration at zero signal, a physical situation which seems fairly acceptable. The best assessment of the intercept is of course obtained with the lowest calibration range. It is unlikely that an abrupt threshold of output actually occurs. Far more likely is that the calibration is highly non-linear to the origin, and that the change in sign of the constant in the straight-line equation with different transducers is due to a different curvature in the non-linearity. Nevertheless, whatever the curve to the origin, the fact remains that it is not possible to assume that the calibration is linear through the origin.

4. Comment on the tabulation of pressure transducer calibrations.

To facilitate comparison of standard deviations, the slope of each transducer calibration 'm' has been normalised to unity. It can be easily shown that each original calculation of standard deviation only needs to be factored by l/m for all standard deviations in the same pressure range to be compared. The values of the standard deviations of the measured charge s_q the deduced slope s_m and the deduced constant s_b are tabulated in this way. Realistic comparisons of transducer accuracies may only be made if the pressure range and number of calibration points are identical. Four ranges of pressure have been used; 0 - 20; (Section 4.1) 0 - 100; (Section 4.2) 0 - 500; (Section 4.3) end 0 - 760 mm Hg (Section 4.4). The 0 - 500 mm Hg calibration range was used only for comparison of the CEC and Statham strain-gauge transducers since this was their maximum dynamic pressure rating.

A comparative measurement of accuracy has been made at 10 mm Hg and at full scale on each range. The pressure of 10 mm Hg has been arbitrarily adopted as being representative of flat-plate pressures in a wind tunnel at a Mach number of 9. The percentage of the standard deviation s_q to the measured charge q (or voltage from a strain-gauge transducer), at this pressure, has been tabulated for each transducer in each of the calibration ranges. This percentage is only representative of a 68% probability, and should be multiplied by 1.6 or 2.0 to give 90% or 96% probability respectively for a normal distribution. The percentage s_q/q is also tabulated for full scale calibration on each range.

4.1 CALIBRATION 0-20 mm Hg (18 calibration points)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
PRESSURE TRANSDUCER	s_q	s_m	s_b	Zero output pressure (mm Hg)	Percentage $\frac{s_q}{q}$ full scale	Percentage $\frac{s_q}{q}$ 10 mm Hg
701 A	9.7(-2)	4.1(-3)	5.0(-2)	0.3	0.5	1.0
701 3	8.1(-2)	3.5(-3)	4.2(-2)	0.3	0.4	0.8
701 x	8.7(-2)	3.9(-3)	4.9(-2)	-0.2	0.4	0.9
601	24.0(-2)	0.X-3)	15.0(-2)	0.0	1.2	2.4
6QP500	21.0(-2)	9.7(-3)	12.0(-2)	1.5	1.2	2.5
PZ6M	17.0(-2)	7.7(-3)	9.5(-2)	0.2	0.9	1.7
MQ 20	7.4(-2)	4.9(-3)	4.9(-2)	0.0	0.4	0.7
CORNELL	6.6(-2)	3.6(-3)	4.8(-2)	0.1	0.3	0.7

The points used to calculate these data are presented as calibration curves in Figs 3-10.

4.2 CALIBRATION 0-100 mm Hg (11 calibration points)

(1) PRESSURE TRANSDUCE	(2) s_q	(3) s_m	(4) s_b	(5) Zero output pressure (mm Hg)	(6) Percentage $\frac{s_q}{q}$ full scale	(7) Percentag $\frac{s_q}{q}$ 10 mm H
701 A	3.4(-1)	3.4(-3)	2.0(-1)	0.3	0.3	3.5
701 S	3.2(-1)	3.2(-3)	1.9(-1)	-0.6	0.3	3.0
701 X	4.5(-1)	4.5(-3)	2.7(-1)	+0.0	0.5	4.5
601	4.1(-1)	4.2(-3)	2.5(-1)	-0.3	0.4	4.0
6QP500	3.7(-1)	3.8(-3)	2.2(-1)	+0.0	0.4	3.7
PZ6M	8.7(-1)	8.9(-3)	5.2(-1)	1.3	0.9	10.0
MQ20	3.1(-1)	3.2(-3)	1.9(-1)	+0.1	0.3	3.2
CORNELL	4.6(-1)	4.7(-3)	2.8(-1)	-0.5	0.5	4.4
CEC 10V EXCITATION	8.3(-1)	8.4(-3)	5.0(-1)	+0.4	0.8	8.6
STATHAM 4V EXCITATION	5.4(-1)	5.5(-3)	3.2(-1)	+0.1	0.5	5.5

The points used to calculate the data of the CEC and Statham transducers are presented as calibration curves in Figs 11 and 12.

4.3 CALIBRATION 0-500 mm Hg (10 calibration points)

(1) PRESSURE TRANSDUCER	(2) s_q	(3) s_m	(4) s_b	(5) Zero output pressure (mm Hg)	(6) Percentage $\frac{s_q}{q}$ full scale	(7) Percentage $\frac{s_q}{q}$ 10 mm Hg
STATIC						
CEC 4327	3.2(-1)	7.0(-4)	2.2(-1)	3.9	0.06	5.3
STATHAM PA 222	2.2(-1)	4.9(-4)	1.5(-1)	3.2	0.04	3.2
SEMI-DYNAMIC						
CEC 4327	2.7	6.0(-3)	1.8	0.2	0.5	27
STATHAM PA 222	2.8	6.1(-3)	1.9	5.9	0.6	67

4.4 CALIBRATION 0-760 mm Hg (15 calibration points)

(1)	(2)	(3)	(4)	(5)	(6)	(7)
PRESSURE TRANSDUCER	s_q	s_m	s_b	Zero output pressure (mm Hg)	Percentage $\frac{s_q}{q \text{ full scale}}$	Percentage $\frac{s_q}{q \text{ 10 mm Hg}}$
701 A	1.9	2.3(-3)	1.0	1.7	0.3	23
701 s	3.5	4.2(-3)	1.9	-2.8	0.5	28
701 x	3.0	3.5(-3)	1.6	2.2	0.4	37
601	2.5	2.9(-3)	1.3	3.0	0.3	35
6QP500	3.0	3.6(-3)	1.6	1.6	0.4	36
PZ6M	3.1	3.7(-3)	1.7	7.2	0.4	108
MQ20	2.9	3.5(-3)	1.6	4.9	0.4	58

4.5 Discussion on comparative performance of the pressure transducers.

Our objective in making these comparative calibrations was to find if any of the transducers were suitable for the determination of low absolute pressures, in short duration facilities, and to establish their probable accuracy when used in a shock tunnel.

The percentage scatter at full scale, (Column 6)

Examination of the calibrations in Sections 4.1 - 4.4 shows very clearly that the value of s_q/q for full scale of each calibration (Column 6) is approximately the same for the semi-dynamic calibrations of all the transducers, and is around ± 0.5%. The only opportunity for comparing static and semi-dynamic calibrations was with the strain gauge transducers, and in Column 6 in Section 4.3 it can be seen that the rapid application of pressure has resulted in an order increase in scatter.

The percentage scatter at 10 mm Hg. (Column 7)

Column 7 shows that very large errors may be made by extrapolating to 10 mm Hg from a higher pressure calibration. It is common practice to accept a calibration constant obtained over a higher pressure range than is to be used, as in the case of the use of a manufacturer's calibration constant which is supplied with the transducer. The extrapolation error mainly arises from non-linearities near the origin, but is also due to the finite accuracy of the transducer chain. A useful example is for the AWRE MQ20 transducer. In Section 4.4 it is shown that a calibration over the range 0-760 mm Hg in 50 mm Hg intervals predicts at 10 mm Hg a value of s_q/q of ± 58%, whereas when calibrated in the range 0-20 mm Hg at 1 mm Hg intervals as in Section 4.1 the value of s_q/q at 10 mm Hg is only ± 0.7%.

The implied value of pressure for zero output (Column 5)

In Section 3 we have suggested that this implied threshold is merely a consequence of the straight-line equation, and that in fact the curve is non-linear close to the origin. It does however demonstrate that the linear part of the calibration is displaced from the origin and account should be taken of this. The majority of the values in Column 5 have a positive magnitude, but in the present context the physical significance of this value is not relevant. The SLM PZ6M exhibits the largest offset, but this is still only about 1% of the full scale calibration.

The standard deviation, s_m, of the calibration constant (Column 3)

The values in Column 3 Section 4.4 show that there is little difference between the transducers, all of them being near to ± 0.4%. At the lower pressure ranges (Section 4.1) then the 601, 6QP500 and PZ6M are significantly worse than the others.

The standard deviations s_q of the transducer output (Column 2)

This is the most important term in the comparisons in any one of the calibration tables, it being a measure of departure of the points from the best straight line through the points. In the highest pressure range (Section 4.4) the best transducer is the Kistler 701 A; Section 4.1 for the 1 - 20 mm Hg range shows that the Cornellis best, with the AWRE MQ20 a close second. It is not surprising that the Cornell transducer was best since it is designed to be used below 5 psia, unlike the MQ20 which is designed for use up to 20,000 psia and yet apparently operatesin a linear manner down to 0.05 psia, a remarkable operating range.

Calibration of strain-gauge transducers

The most interesting aspect to emerge from these tests was the difference in response time for the two strain-gauge transducers. In Fig. 15, on a time basis of 10 ms/div. it can be seen that a pressure jump of 100 mm Hg takes 70 ms to be recorded within the Statham transducer whereas the CEC transducer reaches its plateau within 7 ms. Providing this equilibration time is allowed, then there is very little difference between the performance of the transducers, a feature which is verified in Columns 2, 3 and 4 of Section 4.3. It certainly shows that the transient response of the Statham PA222TC is not in keeping with its quoted natural frequency of 7 kHz, (which implies a rise time of 50 μs.) It is clear now that the anomaly reported by Pennelegion[5] whereby a shock-tube calibration of a different PA222TC was only a small fraction of the static calibration, was due to this equilibration time. This type of transducer should obviously not be used in shock or gun tunnels, nor in a rapidly-sampling pressure switch.

Comment on the oscilloscope traces. (Figs. 13 - 15)

In Fig. 13 are the responses of the most sensitive transducers that were tested, to pressure steps of 10 mm Hg and 100 mm Hg. The burst of oscillation during the first 10 ma is due to mechanical conduction of vibration arising from the solenoid shaft hitting its mechanical stop. The most suitable response in Fig. 13 is from the Cornell transducer, though at 100 mm Hg the Kistler 701A and 701S, are nearly as good. It is noted that the signal from the Kistler 701X continues to climb and only just levels out at the end of the trace. This form of "creep" is most disturbing and would seem to be present with the MQ20 in Fig. 14. There is no sign of "creep" on the 701A, 701S or Cornell (0 - 100 mm Hg) in Fig. 13.

The left-hand traces of Fig. 14 are for pressure jumps of 10 mm Hg absolute. The signal/noise ratio is poor, though the plateau level can be estimated fairly closely. The improvement in the traces for a pressure jump of 100 mm Hg is seen to be very reasonable.

On a longer time-base of 10 ms/division the outputs from the strain-gauge transducers are shown in Fig. 15. They both show that the pressures take longer to indicate their steady value, and that even at 10 mm Hg the transducers take about 20 ms to indicate a steady pressure. The quality of the traces is very reasonable at a pressure jump of 100 mm Hg. No electrical filters have been employed for these tests other than the normal bandwidths of the charge amplifier and oscilloscope.

5. Repeatability of the charge amplifier,

The data presented in Tables 3-6 was obtained using a Kistler charge amplifier Type 566. Earlier work, not presented here, [5] used an SIM PV16 electrometer amplifier as an impedance converter to feed the oscilloscope. In both units a calibration DC voltage was injected into the whole system and used for normalising the results. The stability of the output voltage was superior with the charge amplifier as opposed to the electrometer, but no figures are provided in the handbooks for gain stability, which must clearly affect the calibration of any transducer using the units.

The comparison test that was devised was to apply 10 equal amplitude pressure jumps (10.0 mm Hg) to a transducer (Kistler 701S) coupled firstly to the charge amplifier, and then to the electrometer amplifier. The oscilloscope traces were read by a travelling microscope and examined for scatter. It was found that the standard deviations were 0.3% and 0.5% for charge and electrometer amplifier respectively, which suggests that a 1% scatter of data at this charge level is the worst to be expected due to fluctuations in amplifier gain,

6. Acceleration sensitivity of pressure transducers,

Most users of transducers are aware of the false signals that can be caused by acceleration forces and that these are usually present in impulsively-driven facilities. The acceleration forces can be coupled through the wind tunnel structure or may result from deflections of the model under the influence of aerodynamic forces. The signal from a pressure transducer may give no direct intimation that an acceleration component is present. Several American centres have used acceleration compensated transducers, or have located accelerometers on the principal axes of their models and fed proportional cancelling signals to the pressure recording circuits.[6] Some tests were therefore made to appreciate the extent of acceleration independence.

A measurement was made of the (output)/(peak g) and cross-axis sensitivity for five of the transducers. The cross-axis sensitivity of an accelerometer is defined as the ratio of the voltage or charge output due to acceleration applied perpendicular to the main axis, divided by the basic sensitivity, and is expressed as a percentage of the axial-sensitivity. In this instance the pressure transducer was regarded as an accelerometer and the sensitive axis as the plane perpendicular to the diaphragm. The transducers were assembled in their mounting plates as if for a pressure calibration, and the plate was then firmly clamped parallel to the table of a Pye-Ling VT 1005 vibrator. Sinusoidal table accelerations of 2 - 3 peak g were applied in the frequency range 10 - 10,000 Hz. The table acceleration was monitored by an Endevco accelerometer Model 8-2213. The same procedure was followed with the transducer plate clamped perpendicularly to the vibration axis.

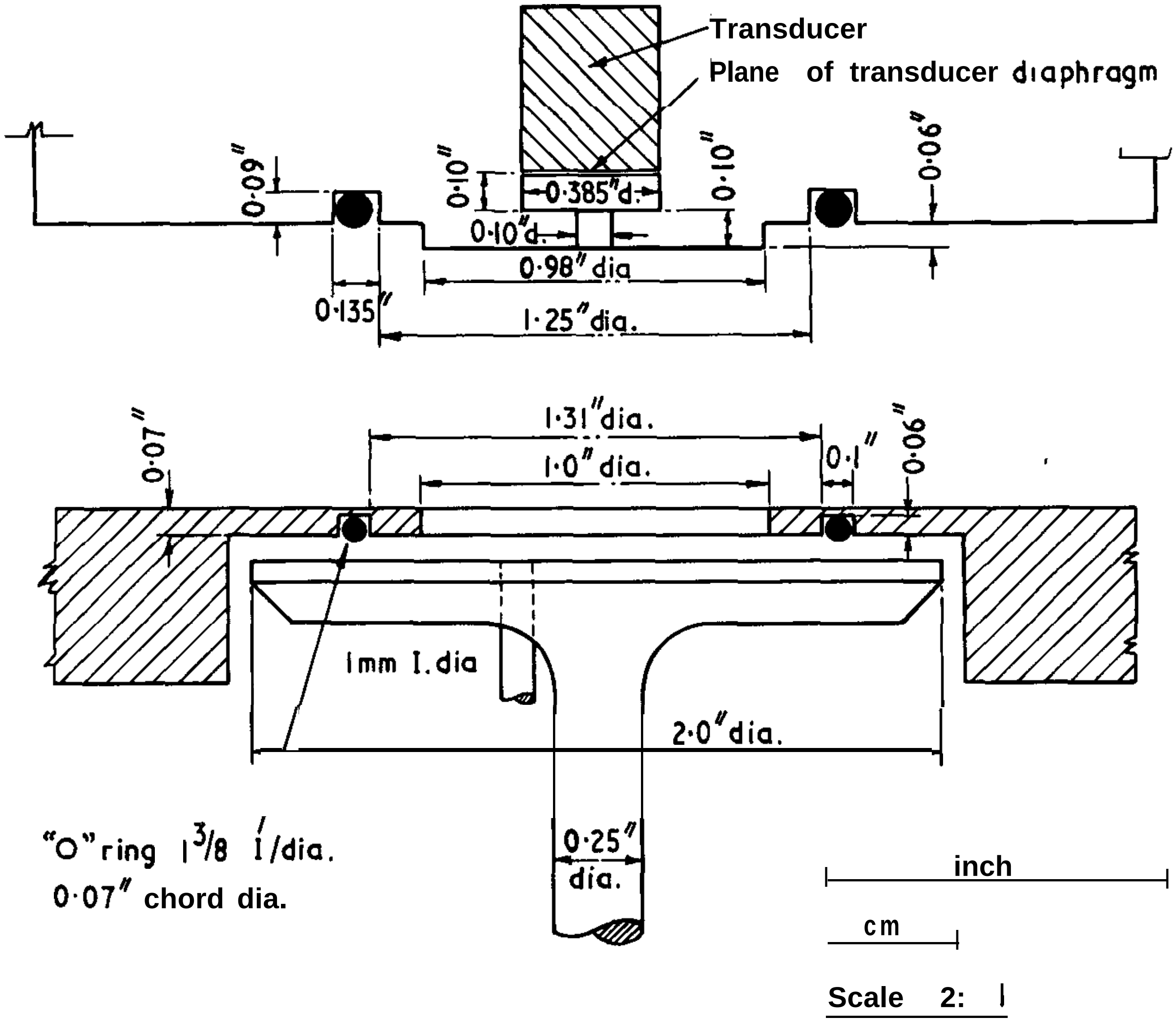
The following table compares some of the transducers for acceleration sensitivity. It will be noticed that though the two acceleration-compensated transducers have a 5:1 improvement on the uncompensated transducers along their pressure sensing axis, their cross-axis sensitivity is very much worse. It is notable that a specifically designed accelerometer has a cross-axis sensitivity of less than 5% which is considerably better than for these pressure transducers.

Transducer	Equiv. pressure peak 'g'	Cross-axis sensitivity %	
		30 - 100 Hz	100 - 1000 Hz
AWRE MQ20	1.5 mm Hg	50	50
KISTLER 701A	1.5	20	25
701 S	1.5	15	10
701 X	0.4	30	100
CORNELL PZT50-30AC	0.3	25	25

Notes (i) 701 S is shock-mounted in an '0' ring assembly.

(ii) 701 X and CORNELL are acceleration compensated.

FIG. 2



Location of transducer plate

maximum dynamic range of 10 psi absolute, and could only withstand a steady pressure of 15 psi absolute, a feature which made them unsuitable for use in the NPL 6" shook tunnel where the final equilibration pressure after a routine run was around 45 psia (3 atm.).

The Cornell transducer had no threaded portion, and no convenient stops on its body for "0" rings to locate. The recommended mounting[7] was to use a rubber annulus between the transducer and the underside of the model surface with adhesive on both sides of the washer. This removed the problem of clamping forces on the body of the transducer causing distortions which might otherwise cause non-linear response.

With all the tested piezo-electric transducers the metal case formed one electrical connection to the outer screened conductor of the coaxial cable. We have found that earth loops may be minimised if each transducer is electrically isolated from the model (this is easily achieved if "O" ring supports are used), and also from the tunnel. We ensure that the screened leads from each transducer are independently brought out of the tunnel and find their common earth in the other measuring circuits. In general the strain-gauge transducers have all four arms of the bridge isolated from the case, but need to be balanced very carefully to minimise the pick-up of hum voltages.

8. Conclusions.

We have endeavoured to assess some of the commonly available commercial pressure transducers, for response and accuracy of calibration in a short-duration facility, such as a shock or gun tunnel. Because of co-operation from Cornell Aeronautical Laboratories, Buffalo, N.Y., U.S.A., and from the Atomic Weapons Research Establishment at Foulness, Essex, we have been able to subject their 'in-house' developed transducers to the same test environment.

The conclusions are not as clear-cut as we had hoped would be the case. We believe however, that we have established a method of comparing the repeatability of transducer calibrations.

On the basis of the tabulations in Section 4, the Kistler 601, AVL 6QP500 or SLM PZ6M appear to be less satisfactory than the others at pressures in the region of 10 mm Hg, though their accuracy is quite comparable with the others at 760 mm Hg. The Cornell PZT50 - 30AC proved to be the most accurate transducer and had a full-scale probable error of ± 0.3%, which for a normal error distribution would in practice mean ± 0.5%. This figure is of course appropriate to the whole chain of measurement. The full-scale probable errors of the Kistler 601, AVL 6QP500 and SLM PZ6M were about ± 1.0% at the lower pressures, which is a working accuracy of ± 1.6%. These figures are of course pertinent to a pressure of 20 mm Hg. The sensitivity of this second group of transducers is inadequate for use at lower pressures, whereas the Kistler 701A, 701S and 701X and Cornell can go very much lower in working pressure before their signal/noise ratio deteriorates.

It is very clear that the two types of strain-gauge pressure transducers tested here should not be subjected to fast pressure pulses of short duration since they may not indicate the correct output voltage within the running-time of the wind tunnel.

9. Acknowledgements to:-

(1) Mr. S.G. Cox of R.A.E., Farnborough, Hants for the loan of the high flux solenoid that was incorporated into the NPL calibrator for these tests.

(2) Mr. K.D. Bird and Mr. T. Bell of Cornell Aeronautical Laboratory, New York, for exceptionally arranging the loan to NPL of a PZT-50-30AC transducer for testing.

(3) Mr. T. Whiteside of Atomic Weapons Research Establishment, Foulness, Essex, for arranging the loan to NPL of an MQ20 transducer for testing.

(4) Messrs. W.W. Smith and A. Cox of Aero Division Model Shop whose regular assistance was required to make special fitments for holding the various transducers, and who developed the rapid-action valve assembly used in these tests.

References.

1.	R.J. PALLANT	A note on the design and. construction of a low-pressure calibrator and a comparison with shock-tube and static calibration methods. A.R.C. C.P.947 April, 1966.
2.	M.J. DWYER	A study of' pressure waves in a pipe with reference to internal combustion engines exhaust silencers. Institute of Sound and Vibration Research, Southampton Report 114 August 1964
3.	P.M. ARONSON R.H. WASER	Pressure pulse generator for the calibration of pressure gauges. Naval Ordnance Lab. White Oak Maryland U.S.A. NOLTR 63-143 August 1963

References (cont'd)

4.	J.J. VESSO W.J. FENWICK	A calibration system for piezo-electric blast pressure transducers. Suffield Experimental Station Ralston Alberta Canada Tech. Note 89 May 1964
5.	L. PENNELEGION	Uncertainties in pressure measurements using commercial transducers in short duration facilities. A.R.C.26 737 March, 1965.
6.	J.F. MARTIN G.R. DURYEA L.M. STEVENSON	Instrumentation for force and pressure measurements in a hypersonic shock tunnel. Cornell Aero Labs. CAL Report 113 January 1962
7.	T. BELL	Private Communication. Cornell Aeronautical Labs. Buffalo N.Y. 1965

Appendix

Definition of symbols used for standard deviations in tables in Section 4

If we define the straight line equation obtained from the least-squares analysis as

$$q = mp + b$$

where
q is the developed charge (pC)
for a pressure jump P (mm Hg)
m is the calibration slope
b is a constant

we are in fact assuming that p is precise, and that all the uncertainty is contained in the 'q' values.

Pollowing usual procedure, the standard. deviations of m and b are

$$s_m = s_q \sqrt{\frac{n}{n\Sigma p_i^2 - (\Sigma p_i)^2}}$$

$$s_b = s_q \sqrt{\frac{\Sigma p_i^2}{n\Sigma p_i^2 - (\Sigma p_i)^2}}$$

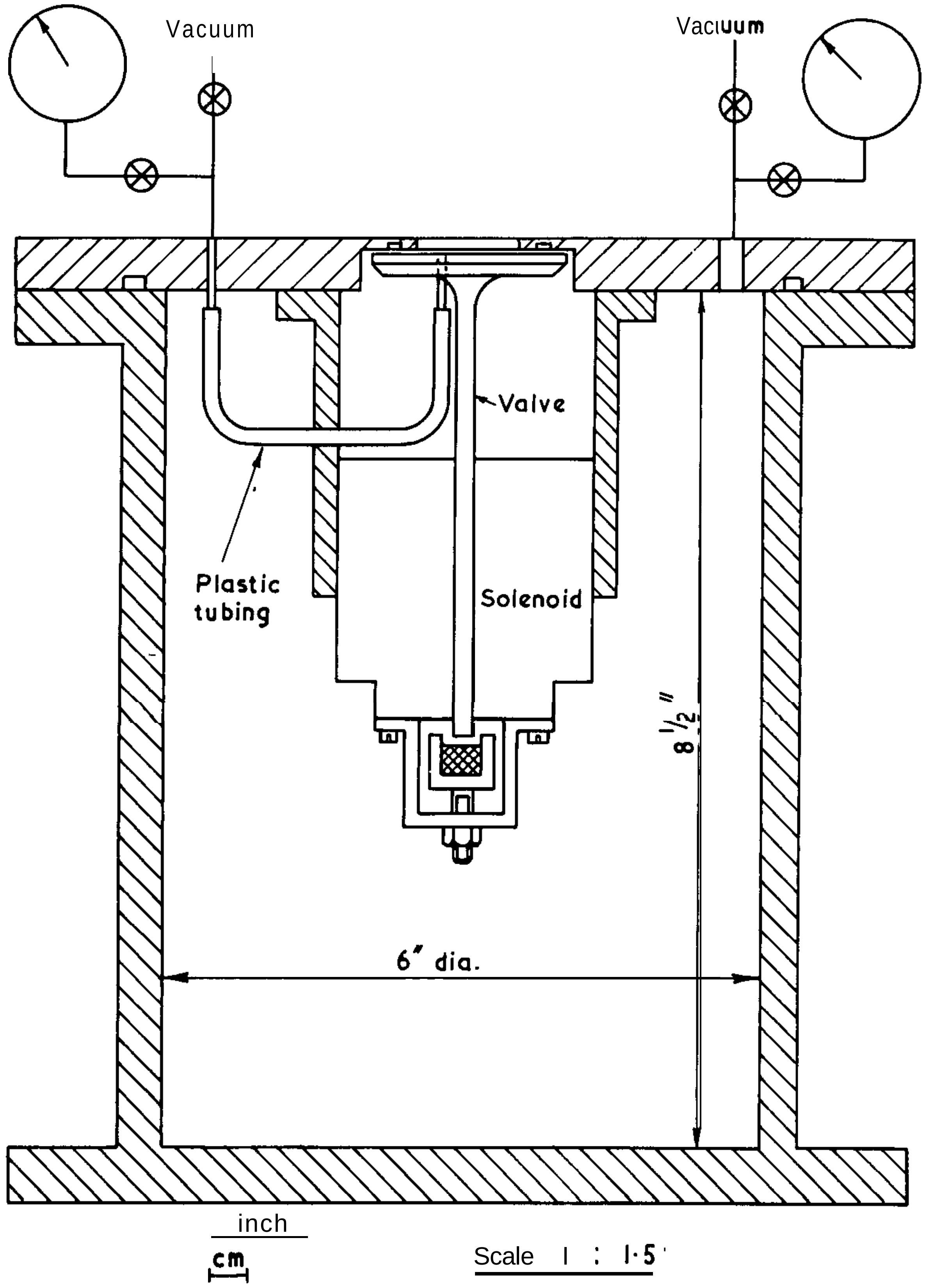
where

$$s_q = \sqrt{\frac{\Sigma(\delta q_i)^2}{n-2}}$$

and n is the number of separate points (q_i, p_i).

The values of s_m, s_b and s_q from each of the transducer calibrations has been divided by its specific value of 'm' and put into the tables in Section 4.

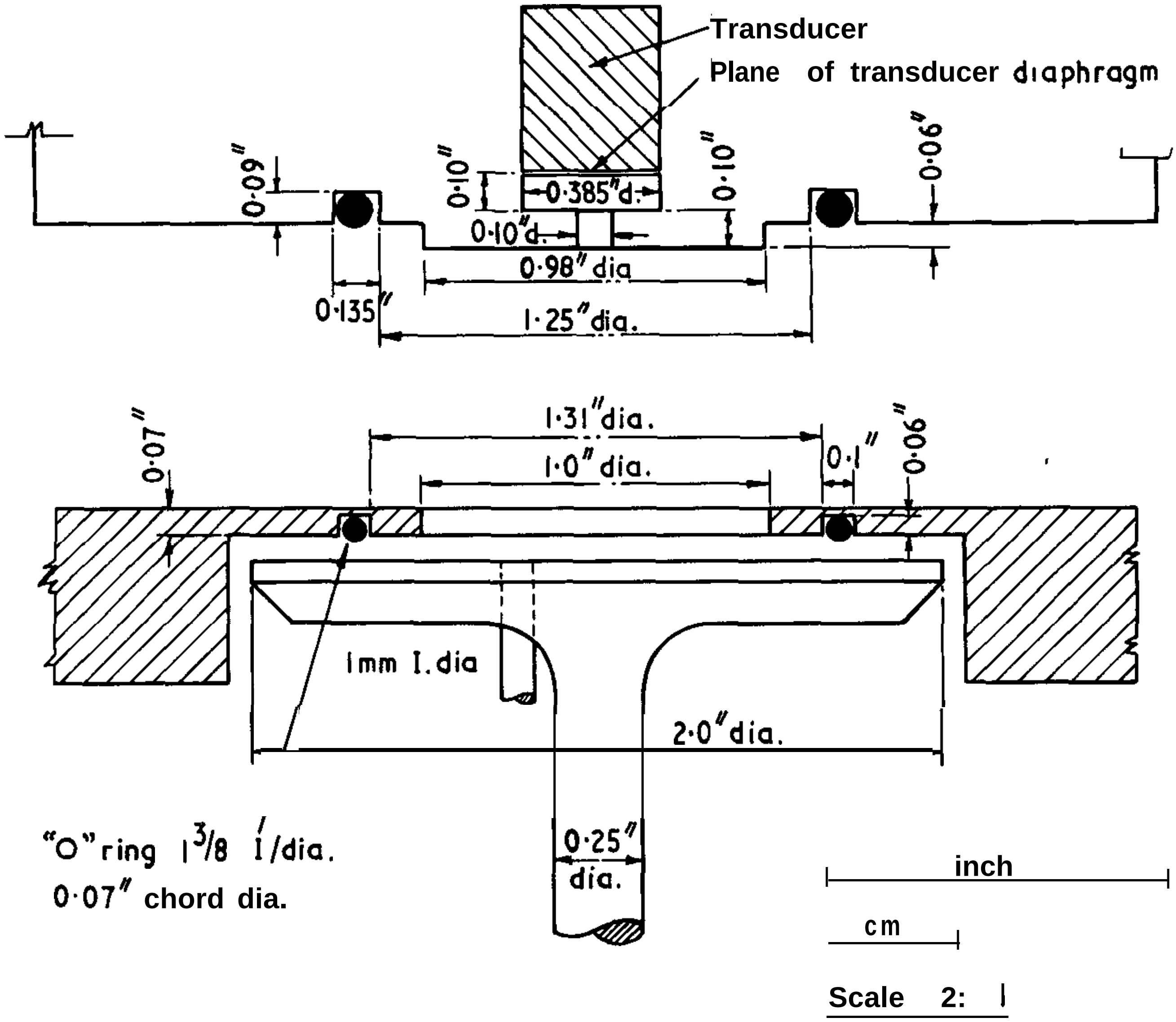
FIG. 1



Scale 1 : 1·5

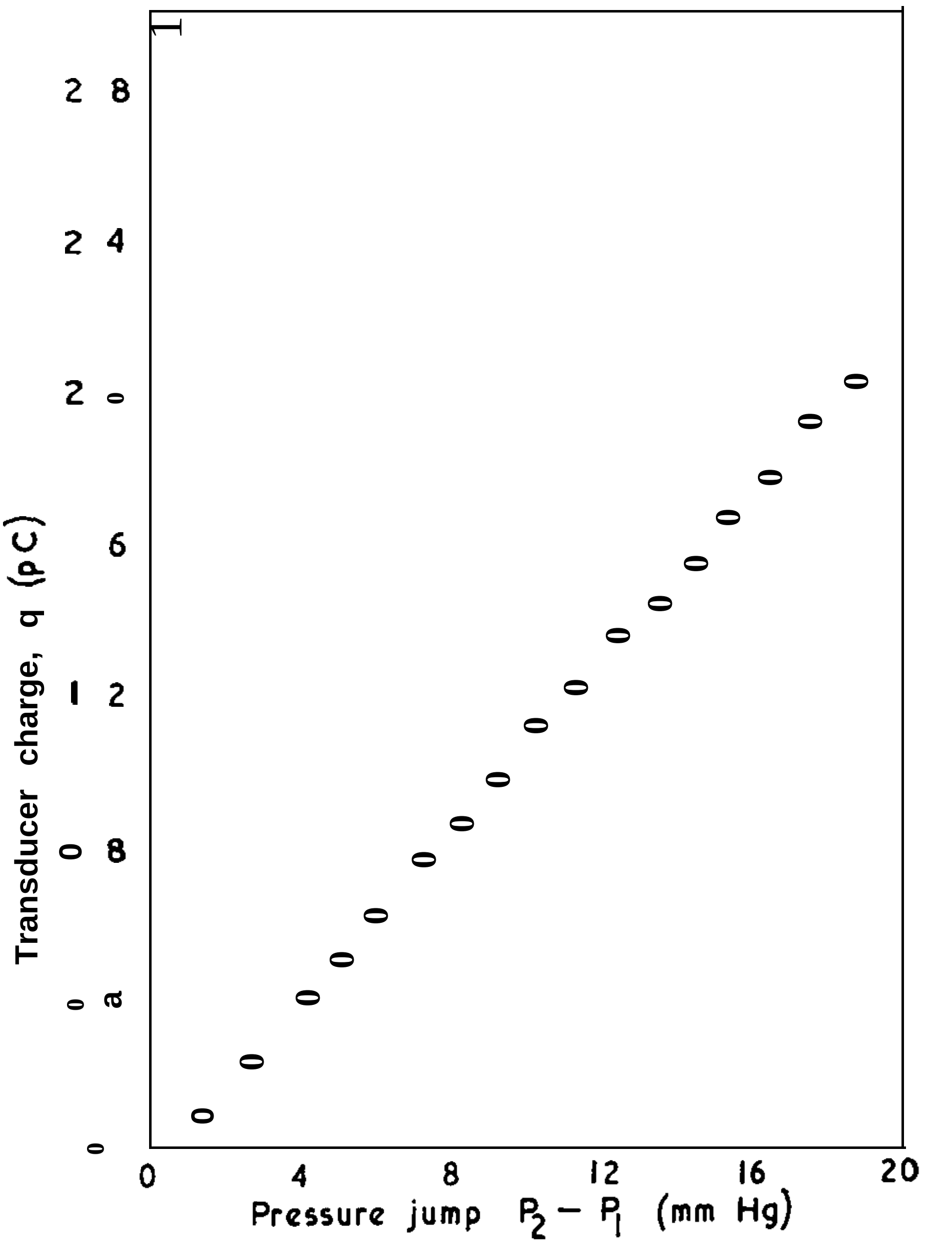
N P L semi-dynamic pressure calibrator

FIG. 2



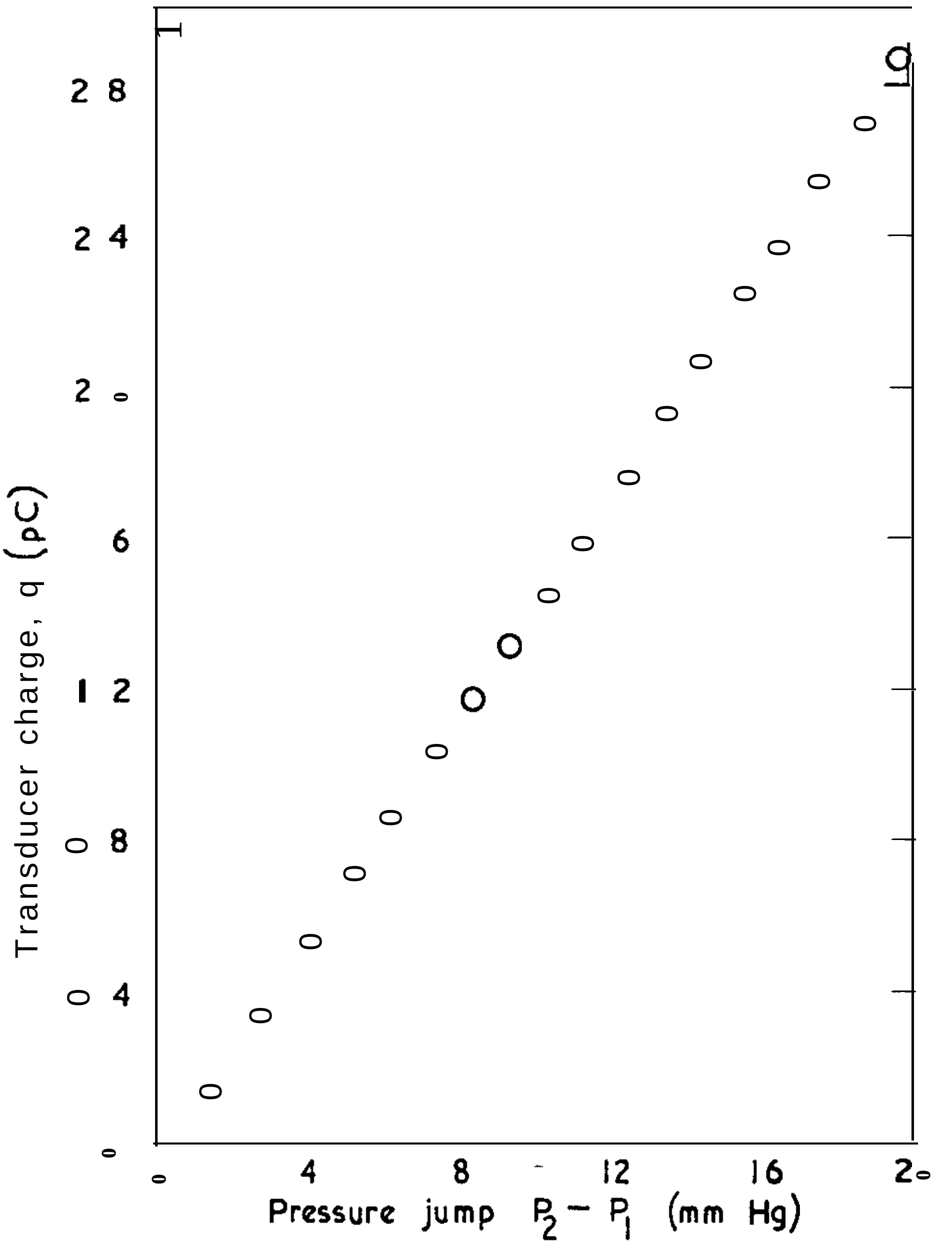
Location of transducer plate

FIG 3



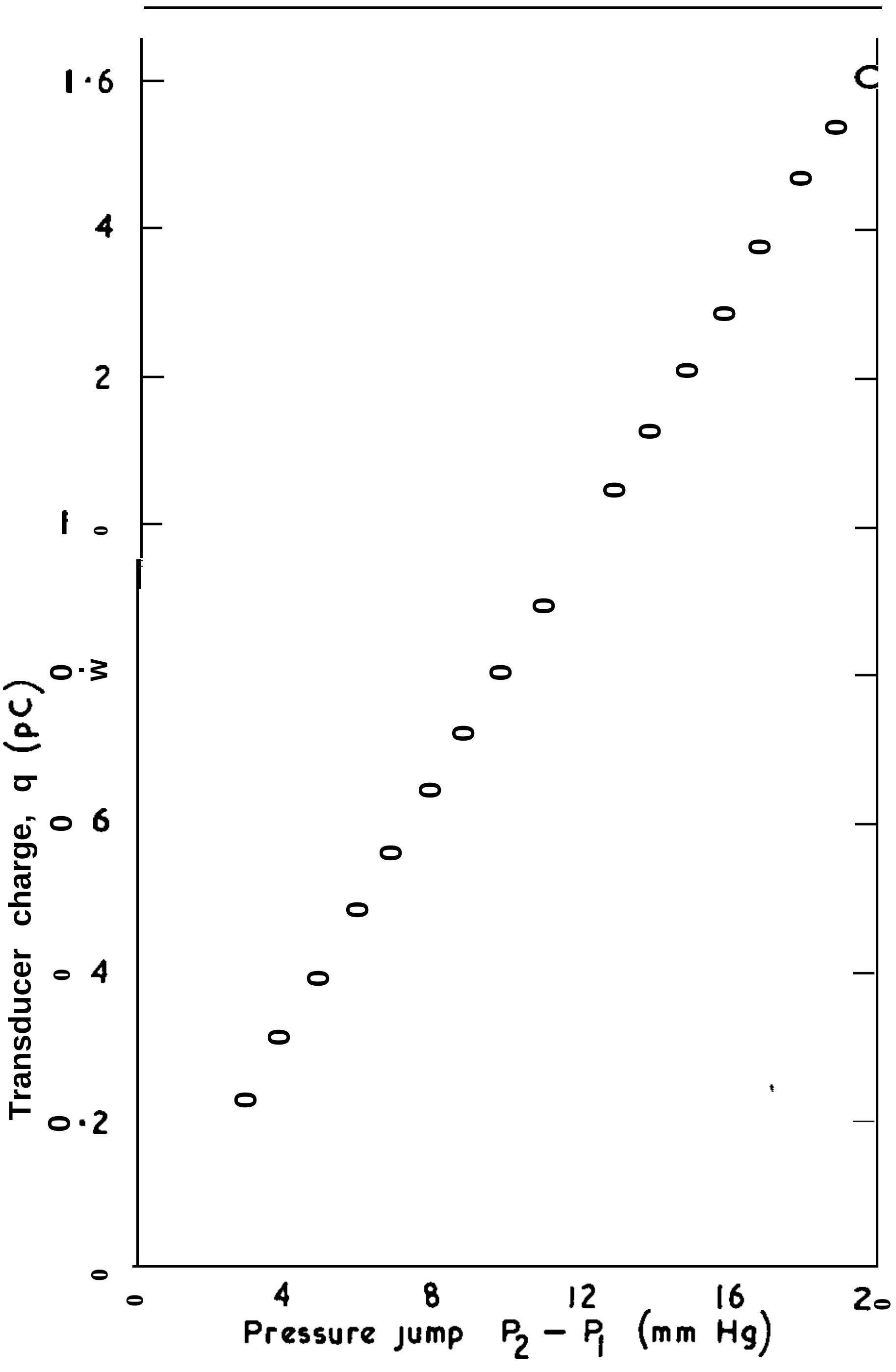
Calibration of Kistler 701 A

FIG. 4



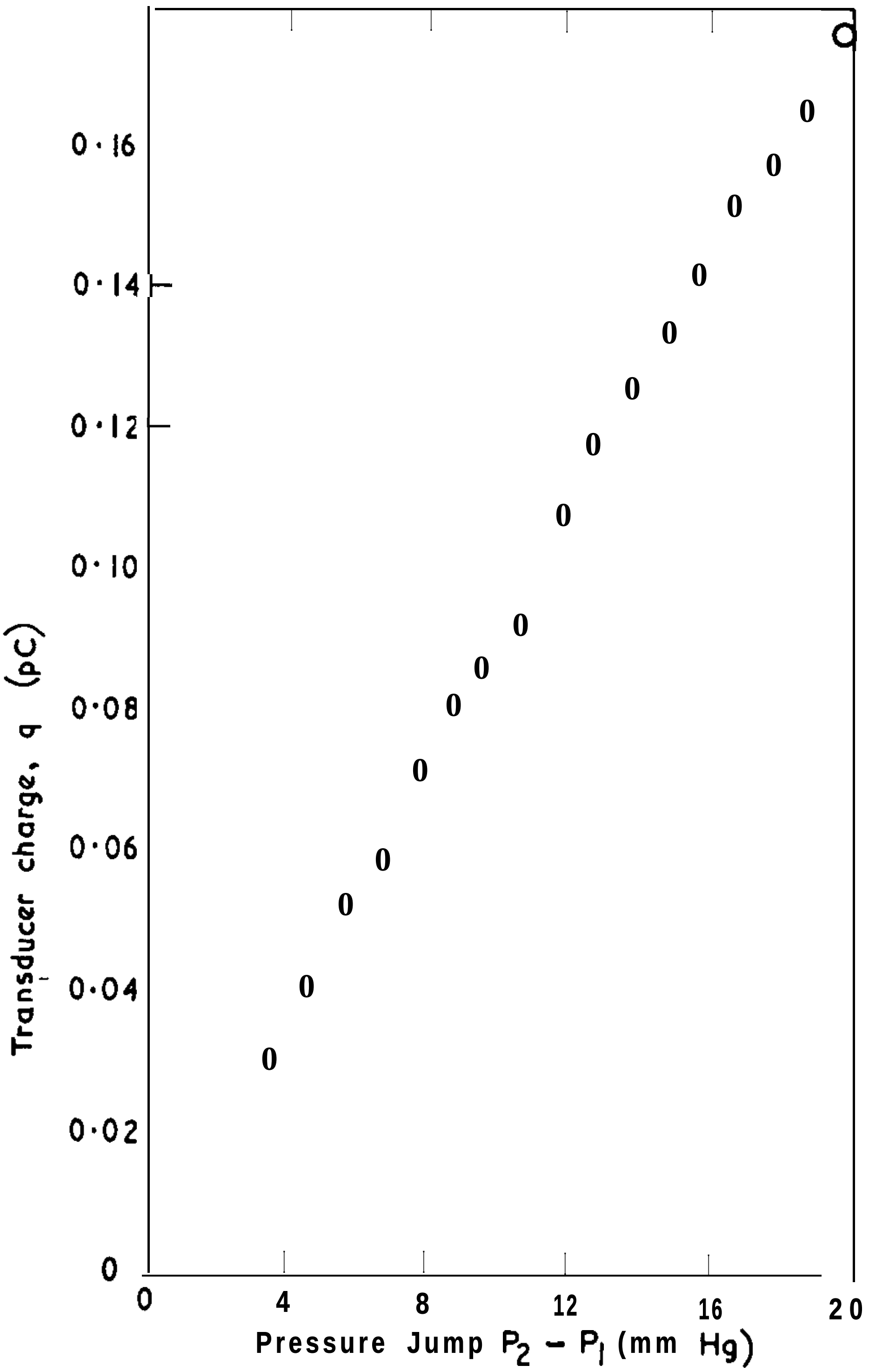
Calibration of Kistler 701 S

FIG. 5



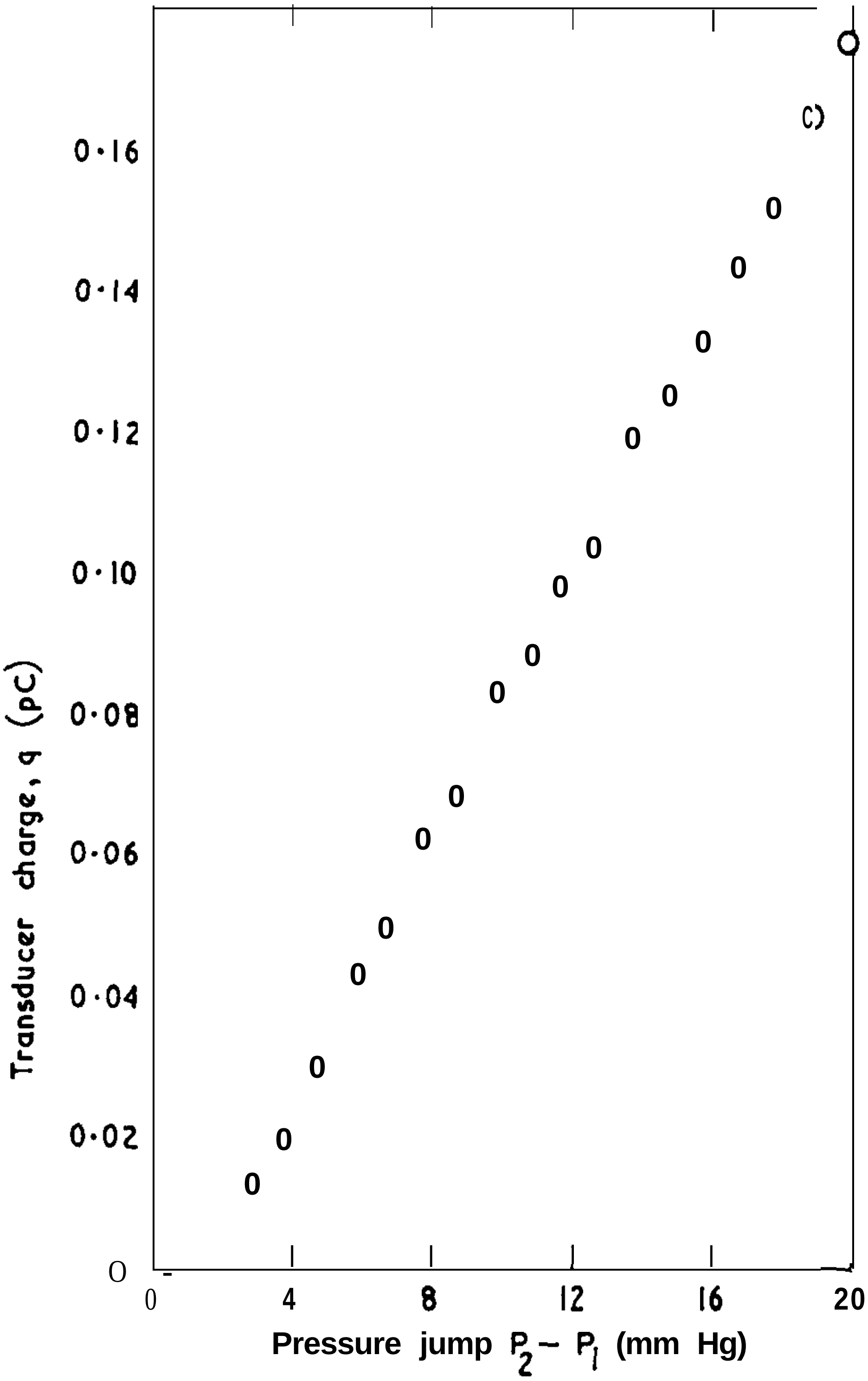
Calibration of Kistler 701 X

FIG. 6



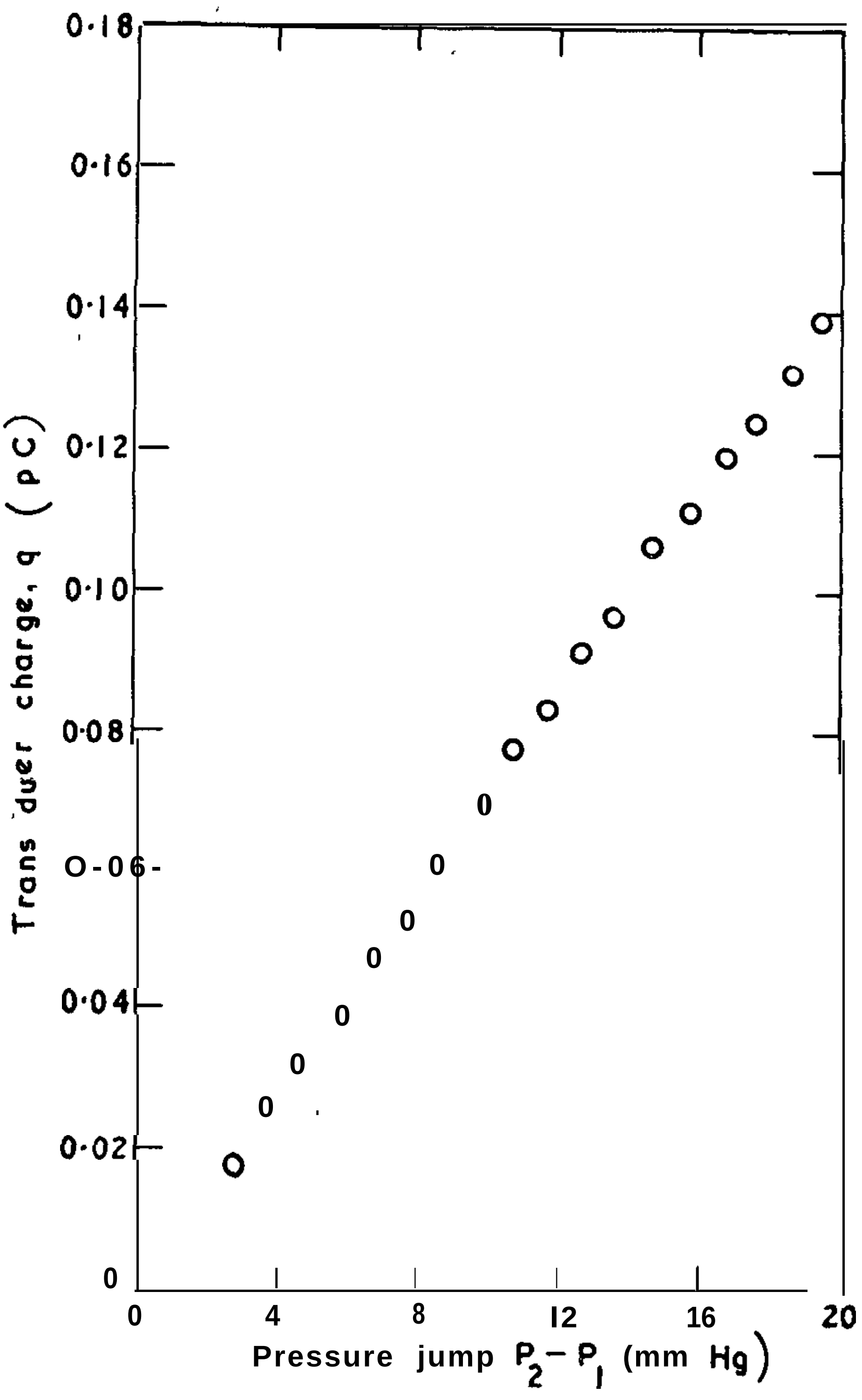
Calibration of Kistler 601

FIG. 7



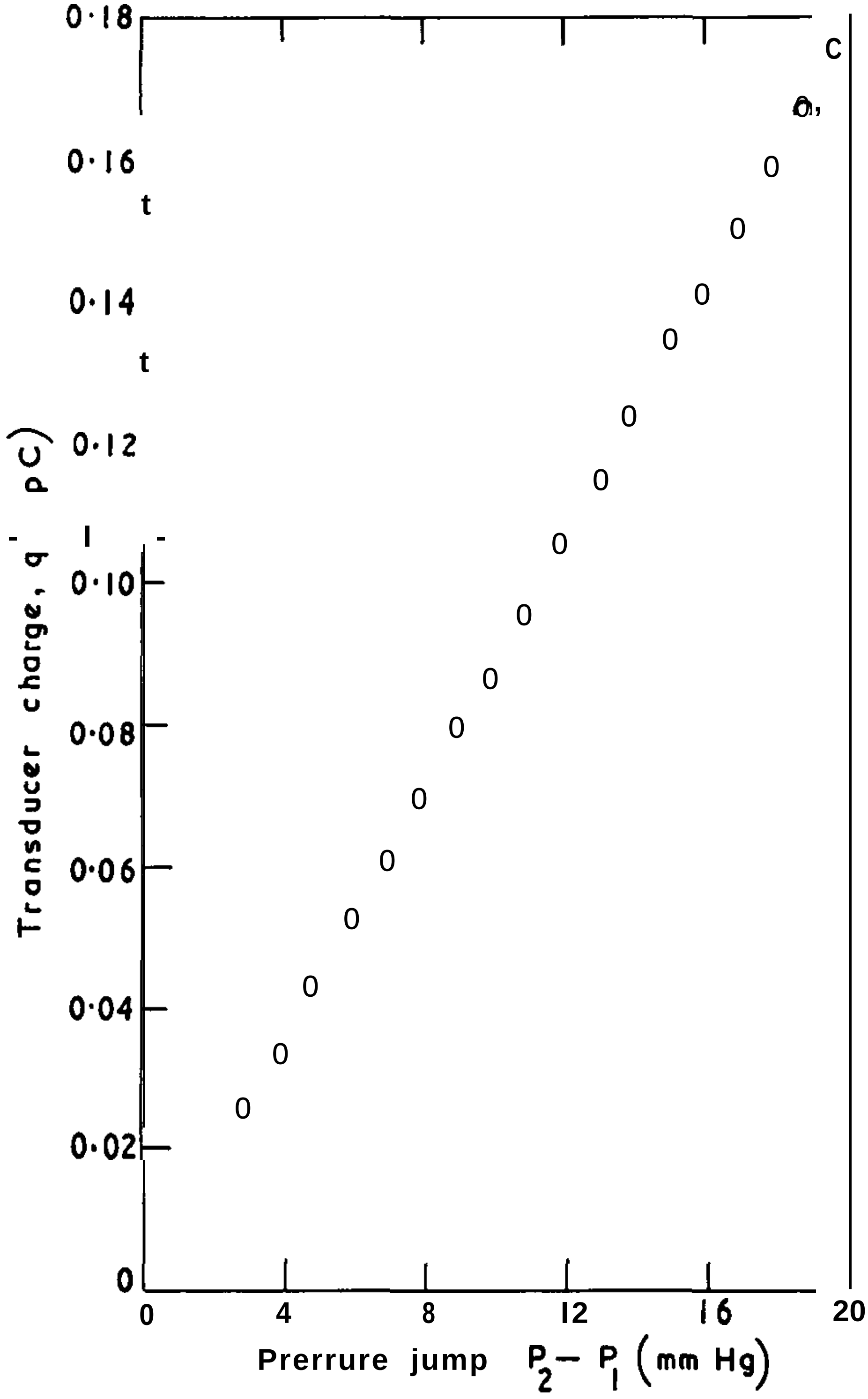
Calibration of AVL 6QP500

FIG.8



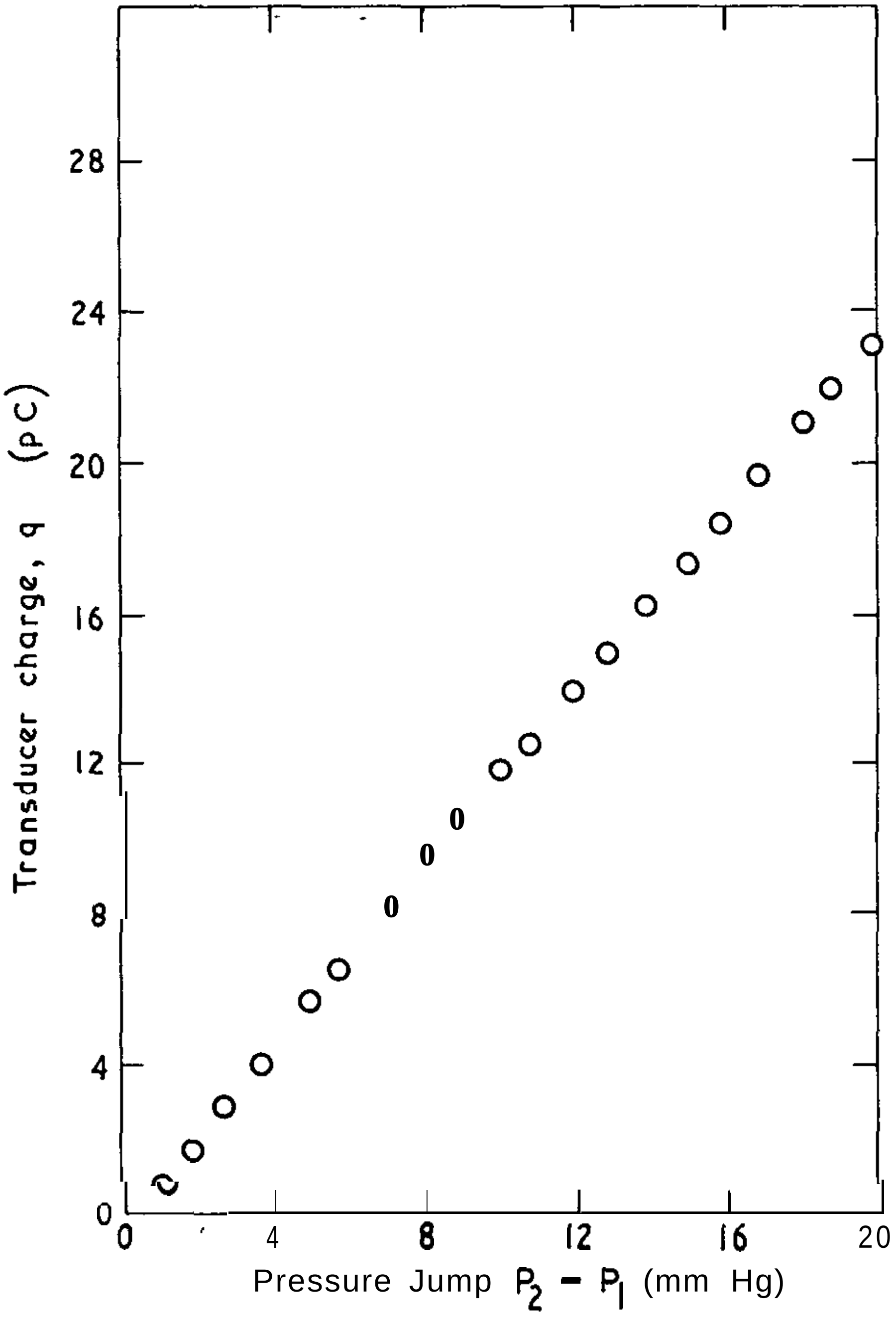
Calibration of S L M PZ6M

FIG. 9



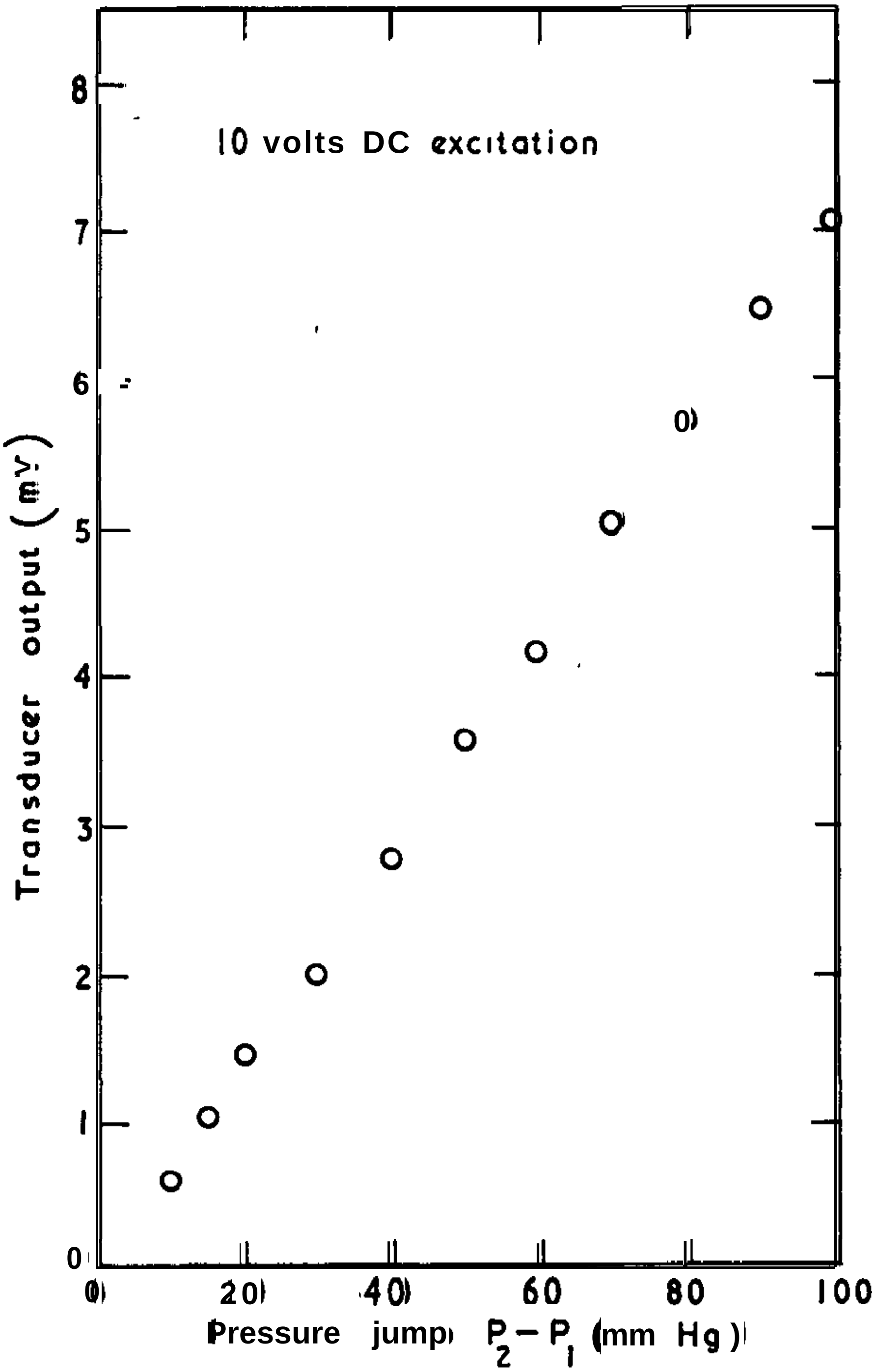
Calibration of A W R E MQ 20

FIG. 10



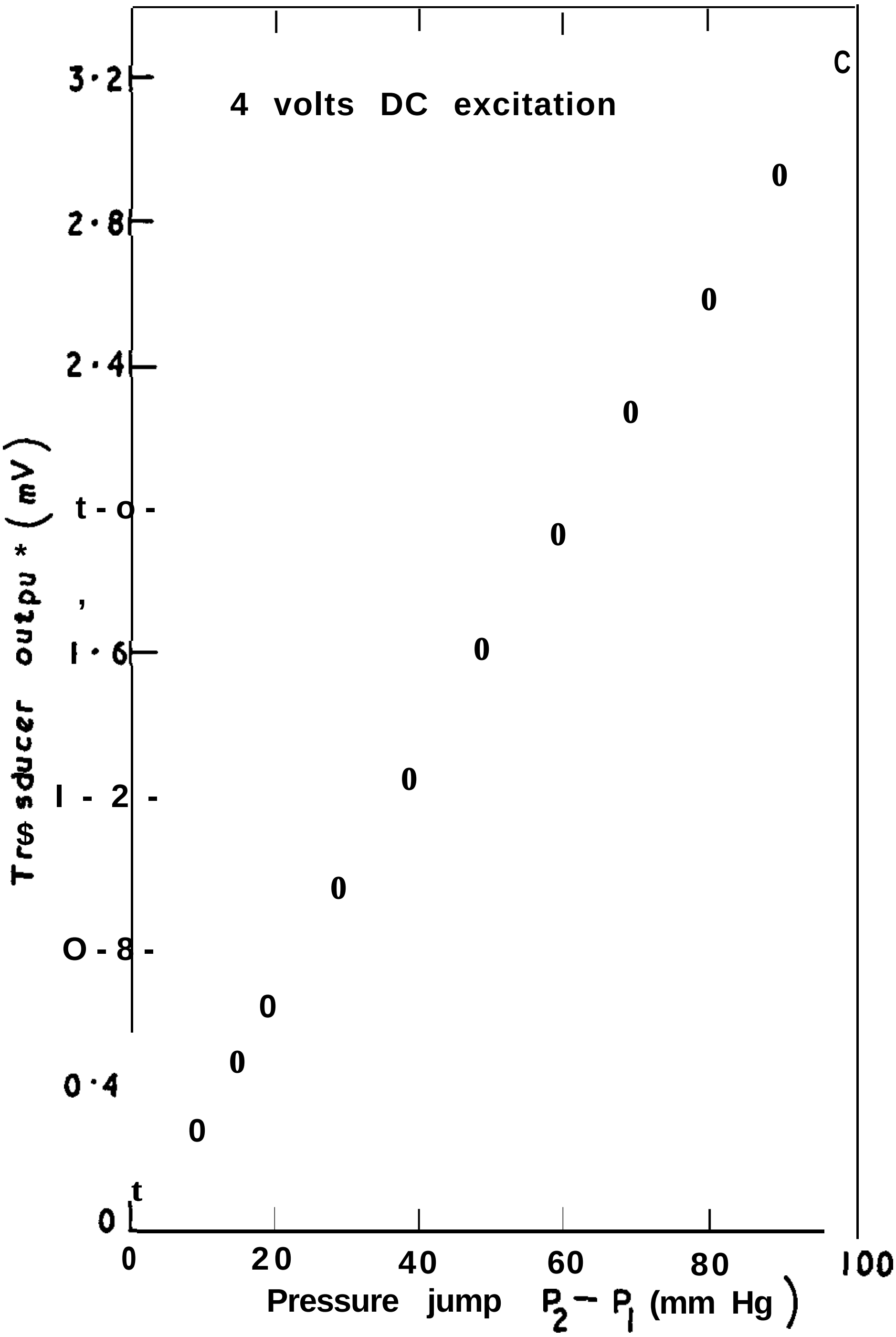
Calibration of CAL PZT-50 -30 AC

FIG. II



Calibration of CEC 4-327

FIG.12



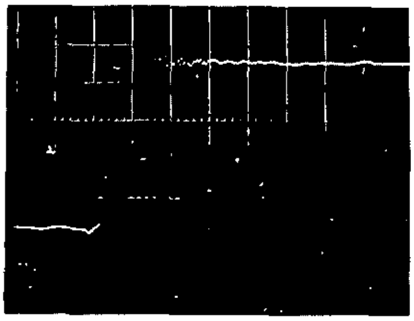
Calibration of Statham PA222 T C

FIG. 13

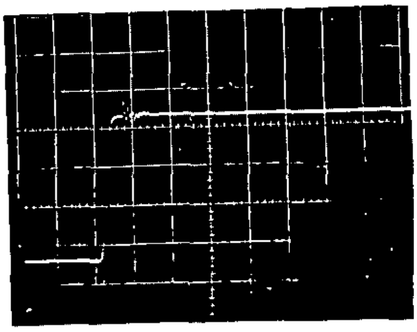
$P_2 - P_1 = 10$ mm Hg

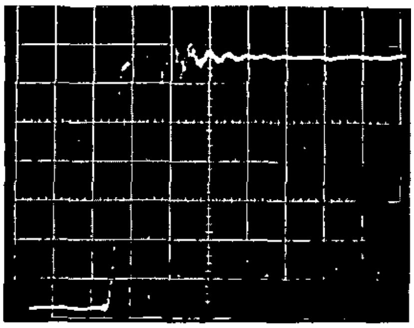
$P_2 - P_1 = 100$ mm Hg

Time base 5 ms/div

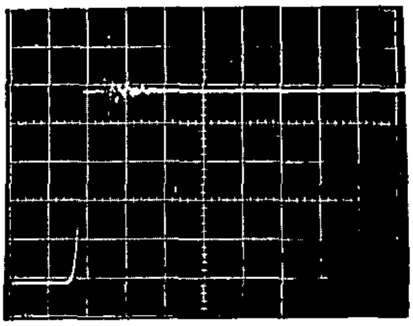


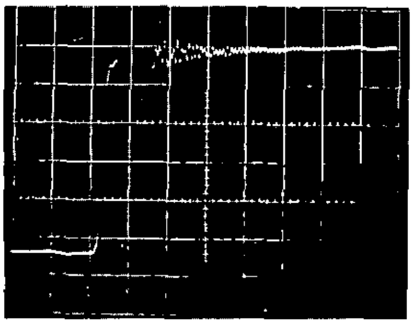
Kistler 701A.



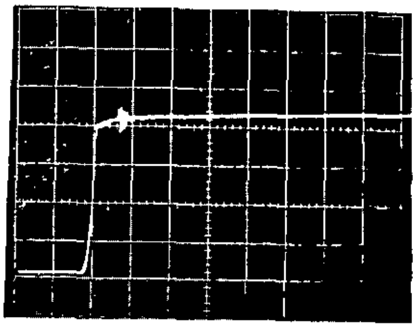


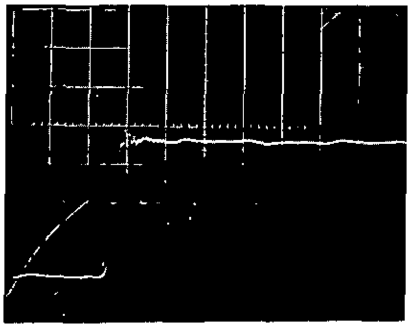
Kistler 701 S



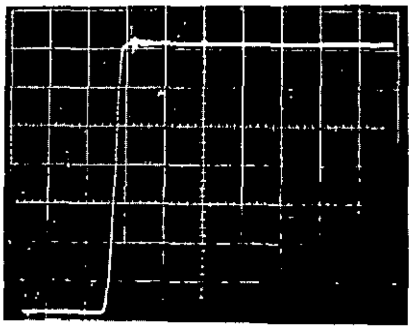


Kistler 701X



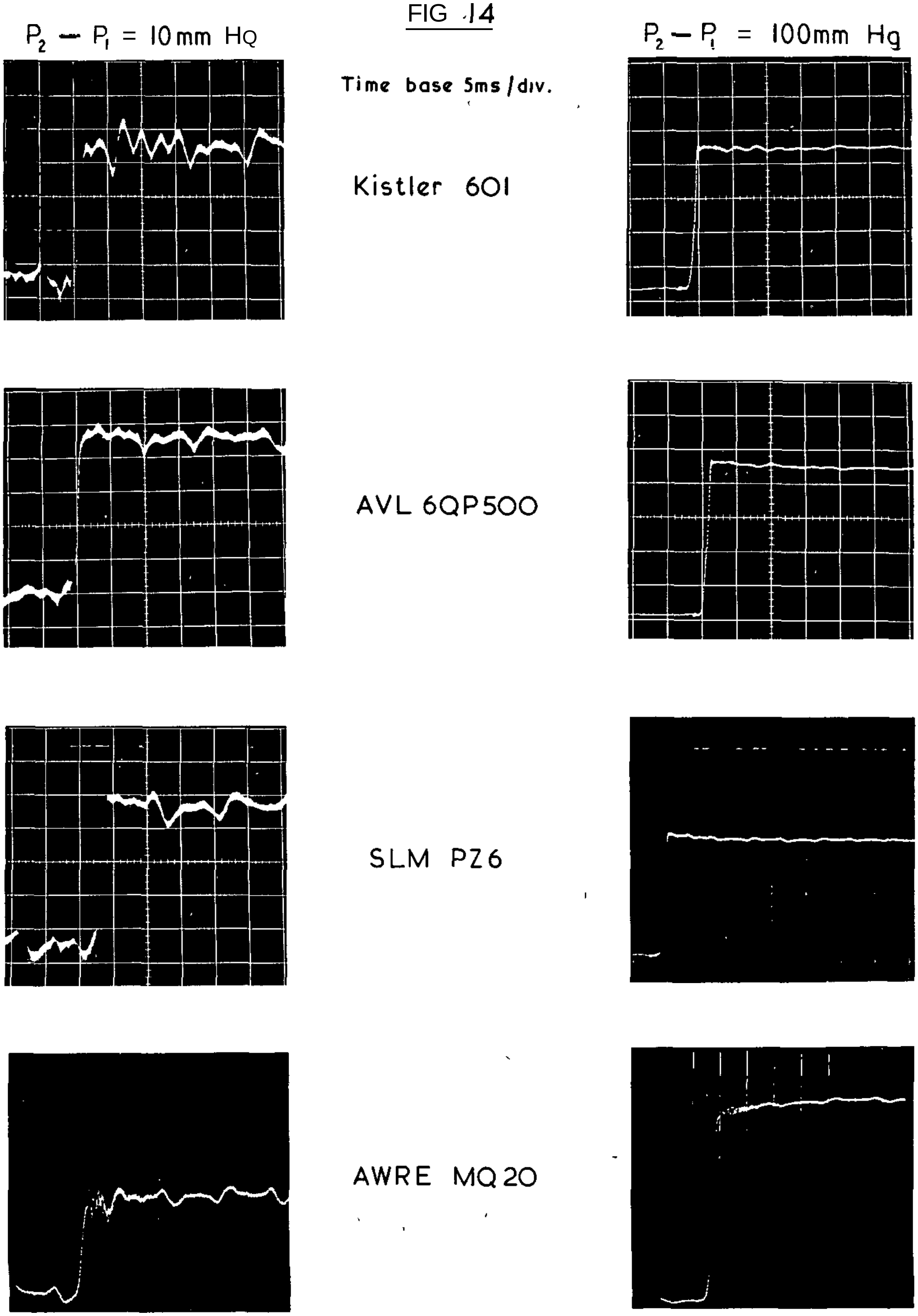


Cornell
PZT-50-30 AC



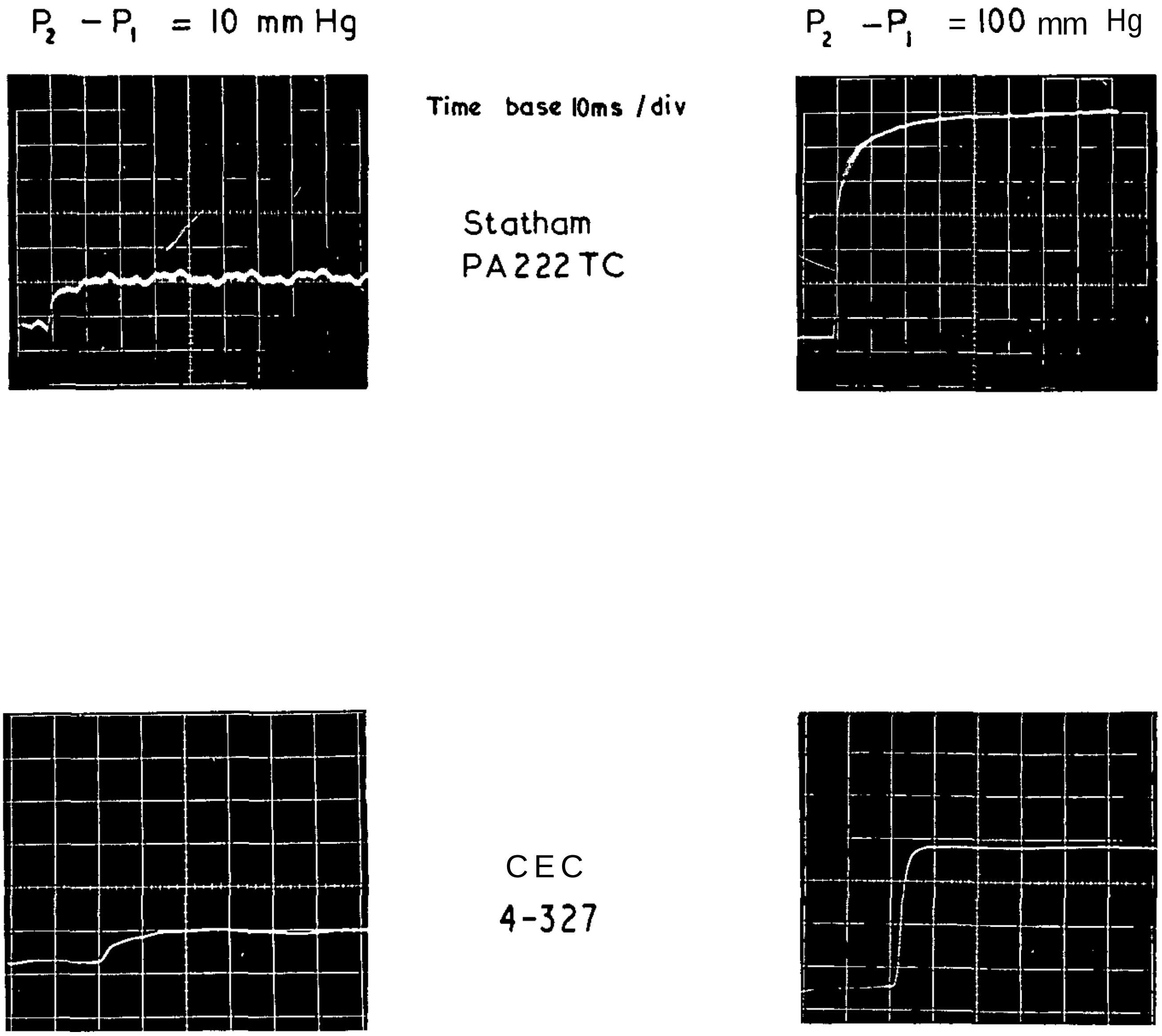
Transducer response to ‘step-change in pressure

FIG 14



Transducer response to step-change in pressure

FIG 15



Transducer response to step-change in pressure

A.R.C. C.P. No. 949
October, 1966.
Pennelegion, L., Wilson, K. and Redston, Miss B.

THE ACCURACY OF PRESSURE TRANSDUCERS WHEN USED IN SHORT-DURATION WIND TUNNEL FACILITIES

Calibrations have been made of some pressure transducers in the pressure ranges 0-20, 0-100, and 0-760 mm Hg. The pressure step was applied in a time of 2-3 ms. Standard deviations have been computed and are used for comparisons, and for estimation of accuracies in a shock tunnel flow. A few measurements are presented of acceleration sensitivities.

A.R.C. C.P. No. 949
October, 1966.
Pennelegion, L., Wilson, K. and Redston, Miss B.

THE ACCURACY OF PRESSURE TRANSDUCERS WHEN USED IN SHORT-DURATION WIND TUNNEL FACILITIES

Calibrations have been made of some pressure transducers in the pressure ranges 0-20, 0-100, and 0-760 mm Hg. The pressure step was applied in a time of 2-3 ms. Standard deviations have been computed and are used for comparisons, and for estimation of accuracies in a shock tunnel flow. A few measurements are presented of acceleration sensitivities.

A.R.C. C.P. No. 949
October, 1966.
Pennelegion, L., Wilson, K. and Redston, Miss B.

THE ACCURACY OF PRESSURE TRANSDUCERS WHEN USED IN SHORT-DURATION WIND TUNNEL FACILITIES

Calibrations have been made of some pressure transducers in the pressure ranges 0-20, 0-100, and 0-760 mm Hg. The pressure step was applied in a time of 2-3 ms. Standard deviations have been computed and are used for comparisons, and for estimation of accuracies in a shock tunnel flow. A few measurements are presented of acceleration sensitivities.

DETACHABLE ABSTRACT CARDS

C.P. No. 949

Printed and published by
HER MAJESTY'S **STATIONERY OFFICE**

To be purchased from
49 **High Holborn,** London **W.C.1**
423 Oxford Street, London **W.1**
13.4 Castle Street, **Edinburgh** 2
109 St. Mary Street, **Cardiff**
Brazennose Street, Manchester 2
50 **Fairfax** Street, **Bristol** 1
35 Smallbrook, **Ringway, Birmingham 5**
7 • 11 **Linenhall** Street, Belfast 2
or through any bookseller

Printed in England

C.P. No. 949

S 0 Code No 23-9017-49