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The Evaluation of Some Commercial and Development Pressure Gauges in a Laboratory Type Shock Tube with a View to Their Suitability for Use in Shock Tunnels

By

D. R. Stevens

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THE EVALUATION OF SOME COMMERCIAL AND DEVELOPMENT PRESSURE GAUGES IN A LABORATORY TYPE SHOCK TUBE WITH A VIEW TO THEIR SUITABILITY FOR USE IN SHOCK TUNNELS

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D. R. Stevens

SUMMARY

This note describes a simple laboratory shock tube designed to produce rectangular steps of pressure in the range 1 mm Hg to 460 mm Hg for use in evaluating and developing fast response sensitive pressure transducers primarily for shock tunnel use. Test results of three commercially available transducers are presented with brief comments on their characteristics. Two experimental gauges are described with an explanation of the philosophy followed in their design; and their performance determined. It is shown that such gauges are more suitable for our purposes although they are not of a rugged engineering nature. The course that further development might take is suggested.

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1 INTRODUCTION

The introduction of short duration test facilities for the study of hypersonic aerodynamics has made great demands on the instrument designer. This is particularly true in the field of pressure measurement. Work at the R.A.E. is concerned with the calibration of the 6 in. and 2 in. shock tubes, the measurement of pressures on models in the shock tunnel and the measurement of blast pressures. The anticipated characteristics (as seen in 1959) required of pressure transducers for these purposes are set out in Table 1. Only a perfect transducer would satisfy all these requirements. It was considered that effort should be concentrated on the low pressure range 0.5-50 mm Hg (0.01-1.0 p.s.i.) and on the fast response wide-bandwidth aspect of the requirements, since a successful gauge in this range might well be adapted to measure the higher pressures.

In order to assess and calibrate any potentially suitable gauge it was decided to design and build a small laboratory shock tube in which transducers could be subjected to rectangular pressure pulses of known amplitude and to use this to assess the performance of commercially available transducers, and as an aid to the development of possible new designs of transducers.

This note describes the calibrating shock tube and the results of tests made on some commercial transducers and on transducers being developed at R.A.E.

2 DESIGN OF A SHOCK TUBE FOR CALIBRATING PRESSURE TRANSDUCERS

At the outset it appeared that the most difficult problem would be to measure the very low pressures on models in the expanded flow of the R.A.E. 6 in. shock tunnel and static pressure variations in the test section of the 2 in. laboratory shock tube. These applications would necessitate physically small gauges with response times of a few micro-seconds and resolutions of the order of 0.5 mm Hg pressure (one one hundredth of one p.s.i.) or better. Moreover the mounted transducer would have to withstand appreciable mechanical vibration. If transducers could be found to satisfy these requirements, they or similar types could probably be used in the remaining applications.

Potentially suitable transducers would need to be proven and calibrated prior to use and a simple laboratory shock tube seemed to offer a suitable means of providing rectangular pulses of pressure for this purpose. It would appear, perhaps, anomalous to use a shock tube to calibrate gauges intended to be used for making measurements in, and assessing the performance of a shock tube. However by operating the calibrating shock tube over a very restricted range of conditions, where the shock tube performance can be confidently predicted this method can be justified.

2.1 Use of ideal gas relations

In a shock tube the shock Mach number, M1, the pressure ahead of the moving shock (initial channel pressure) p_1, and the pressure of the gas behind the shock, p_2, are related by the equation

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma + 1} M_1^2 - \frac{\gamma - 1}{\gamma + 1} \qquad (1)$$

assuming 'ideal' gas conditions. This assumption may be justified if γ remains sensibly constant, and this is the case if the temperature of the gas behind the shock does not rise unduly.

For weak shocks, i.e. up to Mach 4 in air, the temperature ratio across the shock does not exceed 4. Hence if the gas in the channel ahead of the shock is at room temperature, the temperature of the gas behind the shock will not exceed 1200°K at which temperature γ for air has changed only from 1.4 to 1.39.

Thus for an air to air shock tube operated in the Mach 1 to 4 range the relation given in equation (1) may be used. If M_1 and p_1 are measured when the tube is operated, p_2 may be calculated. If a transducer is located in the channel wall of such a shock tube it will be initially at pressure p_1. When the shock arrives the pressure will jump instantaneously to the value p_2.

2.2 Vacuum requirements and tube dimensions

Shock Mach number is determined by the ratio of the driver pressure to the initial channel pressure p_4/p_1. If we choose the driver pressure as atmospheric pressure (760 mm Hg) and plot M_1 versus p_1 we get the curve reproduced in Fig.1. The curves and values used in this section are based on charts and tables for air to air ($\gamma = 1.4$) ideal gas shock tube performance published by Lukasiewicz[1].

Thus we find the range of initial channel pressures necessary to produce shocks up to Mach 4, and, in particular, the lowest channel pressure which is approximately 4×10^{-2} mm Hg. This can be readily obtained with a small rotary vacuum pump.

From Fig.1 and equation (1) we are able to express p_2 directly in terms of p_1 (Fig.2) for an air to air shock tube with atmospheric driver.

A transducer under test and mounted in the side wall of the channel of the shock tube will be initially at p_1 and the 'step' in pressure it will 'see' on arrival of the shock will be $p_2 - p_1$. The value of $p_2 - p_1$ is plotted in Fig.2 and it may be seen that the value of the pressure step reaches a maximum at approximately 150 mm Hg (3 p.s.i.) and no advantage will be gained from running the tube with initial channel pressures above 100 mm Hg. The lower end of the test pressure range is dictated by the limit imposed on Mach number and is approximately $p_2 - p_1 = 1$ mm Hg (0.02 p.s.i.). Hence the test range is approximately 1 mm Hg to 150 mm Hg pressure (0.02 p.s.i. to 3 p.s.i.).

Somewhat larger pressure steps could be obtained if the need arose, by using the pressure behind the shock after it is reflected from the end wall of the test section. If the transducer under test is mounted in the end wall, it will measure a step in pressure equal to $p_{2_R} - p_1$. Values of p_{2_R} and $p_{2_R} - p_1$ are also plotted in Fig.2. The reflected shock pressure 'step' peaks in the same way as $p_2 - p_1$ but at approximately 460 mm Hg (9 p.s.i.). Thus tests in the range 150 mm Hg to 460 mm Hg (3 p.s.i. to 9 p.s.i.) might be made by mounting the transducer in the end wall of the test section. It would not be advisable to make use of the pressure step across the reflected shock at a station in the side wall of the test section since the reflected shock will be advancing into the boundary layer developed behind the primary shock wave, and may produce at the wall a fluctuating pressure. The pressure history behind the reflected shock is currently the subject of further investigation[2].

There remains the question of the duration of the pressure step at the test position. This is determined by the arrival there of the contact surface, when pressure fluctuations occur, or by the return to the test position of the shock after reflection from the end wall of the test section or by interference from the reflected head of the rarefaction wave from the end of the driver section of the tube. With an atmospheric air driver the last can be readily avoided by making the driver section sufficiently long. The duration determined by the return of the reflected shock will depend upon the distance of the test station from the end of the test section. The duration determined by the arrival of the contact surface will depend upon the length of the channel from the primary diaphragm to the test station. In both cases the duration will be a function of shock Mach number

The velocity of the contact surface U_2, given by:

$$\frac{U_2}{U_S} = \frac{2}{\gamma + 1}\left(1 - \frac{1}{M_1^2}\right) \qquad (2)$$

where U_S is the velocity of the shock relative to the tube, has been plotted in Fig.1 and the resulting duration of the test pulse at stations 6, 9, 12 and 15 ft from the primary diaphragm is plotted as a function of Mach number in Fig.3. It appears that a minimum testing time of 500 μsecs can be obtained with a channel length of 12 ft. This will coincide with the lower limit of test pressure i.e. $p_2 - p_1$ approximately 1 mm Hg (0.02 p.s.i.). Available testing time increases rapidly with increasing test pressure (decreasing shock Mach number).

The velocity of the reflected shock U_R is given by:

$$\left|\frac{U_R}{U_S}\right| = 1 - \frac{3 - \gamma}{2}\frac{U_2}{U_S} \quad . \qquad (3)$$

Putting $U_S = a_1 M_1$ where a_1 is the speed of sound in region 1 (1117 ft/sec) and using (2) above, we find

$$U_R = 372\left(M_1 + \frac{2}{M_1}\right) \quad . \qquad (4)$$

From values of U_S and U_R we find the time taken for the primary shock to travel to the end of the test section and be reflected back to the test station, and, thus the testing time as determined by the arrival of the reflected shock. This is plotted for test stations at various distances from the end of the test section in Fig.4. Clearly a station 9 in. from the end of the test section will yield testing times in excess of 500 usecs at allpressure levels.

We now have a guide to the channel length, position of test stations and the range of initial channel pressures required for an air to air calibrating shock tube, driven by atmospheric pressure, that will provide test pressure pulses of from 1 mm Hg to 460 mm Hg (0.02 p.s.i. to 9 p.s.i.) and of a minimum duration of 500 micro-seconds.

3 THE 3 IN. x $1\frac{1}{2}$ IN. CALIBRATING SHOCK TUBE

The general arrangement of the 3 in. x $1\frac{1}{2}$ in. calibrating shock tube is shown in Figs.5 and 6. The tube is made from approximately 20 ft of 3 in. x $1\frac{1}{2}$ in. brass waveguide, split into three sections, each of which is provided with integral flanges for coupling the sections together.

The driver section is 4 ft long and can be sealed at its free end to permit operation of the tube with driver pressures up to 80 p.s.i. or with a driver gas other than air should the need arise. It carries the knife used for mechanical rupturing of the diaphragm. The whole section slides in its cradles to permit removal of the diaphragm block.

The diaphragm block houses a light diaphragm of 0.0005 in. thick Melinex, or of cellophane and is held in position, between the driver section and the manifold, by spigots and four quick release bolts.

The manifold carries connections to the vacuum pump, to the channel pressure dial and Pirani gauges and to an exhaust valve; and is bolted in turn to the 12 ft long channel section.

The final test section is 3 ft 6 in. in length and contains accurately spaced bosses to accommodate shock detectors and gauges for test and calibration. There are ten bosses in the side walls of the test section and one in the end face. Eight of these will accommodate 0.5 in. diameter plugs and are intended primarily to house shock detectors. The remaining three, at Stations 2, 9 and 11 will accommodate 1.0 in. diameter plugs and are intended primarily for mounting gauges under test. For the majority of applications the gauge to be assessed is mounted at Station 2 and the speed measured between Stations 1 and 3, (see para 3.1). Simultaneous comparison of two gauges may be made by mounting a second gauge at Station 9, directly opposite to Station 2.

All the flange junctions, manifold junction, diaphragm block and the test stations are provided with 'O' seals to ensure vacuum sealing, and the channel and test section can be evacuated to about 10 μ crons Hg in roughly two minutes. The diaphragm can be replaced in less than one minute so that a high frequency of operation is available.

3.1 Measurement of shock velocity

To measure the shock velocity in the calibrating shock tube the shock is detected by platinum thin film temperature gauges, mounted in the side wall of the test section. For weak shocks and low initial densities the instantaneous temperature rise of such a gauge on arrival of the shock wave, is very small. Approximate values of this temperature step δT_F may be obtained from the relation:

$$\delta T_F \doteqdot \frac{T_2 - T_1}{1 + \sqrt{\dfrac{\rho_g K_g c_{p_g}}{\rho_2 K_2 c_{p_2}}}} \qquad (5)$$

where T_1 and T_2 are the gas temperatures ahead of and behind the shock respectively; ρ_2, K_2 and c_{p_2} are the density, thermal conductivity and specific heat of the gas behind the shock; and ρ_g, K_g and c_{p_g} are the same properties of the gauge substrate.

Since the instantaneous temperature rise of the gauge is very small we may assume the room temperature values of ρ, c and K for the gauge substrate (soda glass) which give $\sqrt{\rho_g c_{p_g} K_g} = 2.66 \times 10^{-2}$. T_1 will be 288°K;

$\rho_2 = \frac{\rho_2}{\rho_1} \times \frac{p_1}{760} \times 1.23 \times 10^{-3}$ gms/cc (density ratio across the shock times initial density), $C_2 = 2.4 \times 10^{-1}$ cal/gm/°C and $K_2\ (f(T_2)) = \frac{K_2}{K_0} \times 5.77 \times 10^{-5}$.

For the range of operation we are considering the square root term in the denominator of (5) is large compared with 1, and equation (5) may be written.

$$\delta T_F \approx \frac{T_2 - 288}{5620} \sqrt{\frac{\rho_2}{\rho_1} \times p_1 \times \frac{K_2}{K_0}} \ . \qquad (6)$$

For a given shock Mach number, M_1, p_1 may be obtained from Fig.1; T_2 and $\frac{\rho_2}{\rho_1}$ from tables of $\frac{T_2}{T_1}$ and $\frac{\rho_2}{\rho_1}$ versus M_1 (Ref.1) and $\frac{K_2}{K_0}$ from tables of $\frac{K_2}{K_0}$ versus T (Ref.3).

δT_F versus M_1 is the upper curve plotted in Fig.7. It appears that the thin film gauge must detect temperature steps of the order of 0.1°C.

The gauge, of resistance R_o; is energised by a constant current I_o. On arrival of the shock the gauge resistance will increase fractionally and the resulting increase in voltage across the gauge will be

$$\delta V = I_o R_o \alpha \delta T_F \qquad (7)$$

where α is the temperature coefficient of resistance of the thin film, and has been found to vary with film thickness. For the gauges commonly used as shock detectors $\alpha \approx 0.0007$; I_o is 20 mA and R_o is 60–80Ω. Thus the lower limit of δV is approximately

$$\delta V_{MIN} = 20 \times 10^{-3} \times 60 \times 7 \times 10^{-4} \times 0.1 = 84\ \mu\text{Volts} \ .$$

The signal from the gauge is fed to a fast rise time, low-noise pre-amplifier with a gain of 100 and thence to a trigger amplifier and gating circuit which produces a single positive pulse.

Two channels are used with two gauges a known distance apart in the wall of the test section and the outputs are made to start and stop a micro-second counter chronometer. Hence u_1 and M_1 may be calculated.

Since the shock wave suffers some attentuation in the channel of the calibrating shock tube it is necessary to use a lower initial channel pressure p_1 to achieve a given Mach number, than the simple theory predicts. If experimental values of p_1 are substituted in equation (6) the lower curve plotted in Fig.7 results. The values of δT_F are, of course, lower than those predicted using the theoretical value of p_1 and are in fair agreement with the experimental values of δT_F obtained from records of the output δV of the gauge reduced to δT_F using equation (7).

Typical records of the output of a thin film gauge after pre-amplification of 100 times are shown in Fig.8. The gain frequency characteristic of the pre-amplifier is not linear and the droop is due, at least in part, to the amplifier.

Considerable difficulty was experienced at first from spurious triggering of the timer caused principally by local high powered radar installations. A three stage pre-amplifier was used with a negatively biased gauge current supply to yield the positive going output required by the trigger amplifier. Fortunately the airborne interference appeared as negative going pulses at the input of the pre-amplifier. By using a positively biased gauge current supply and reducing the pre-amplifier to two stages the interference pulses are amplified without phase change and appear at the output of the pre-amplifier as negative going peaks. These cannot operate the gate unit. Other random noise sources still cause occasional spurious triggering, but are infrequent events and not a serious source of annoyance.

Mean shock velocity can be measured, it is estimated with an accuracy to better than 1% so that estimation of p_2 should not be in error by more than 2% from this source, since p_2 is proportional to M_1^2 (equation (1)).

The estimated value of p_2 is also directly proportional to p_1. p_1 is measured by means of a vacuum dial gauge or Pirani gauge depending upon the range of pressures to be used. It is doubtful if p_1 can be measured with an accuracy better than 5% with these instruments and for some purposes, it might be profitable to attempt more accurate determination of p_1.

In operation, the required pressure step $p_2 - p_1$ is chosen and the channel and test section of the calibrating shock tube is evacuated to the corresponding experimental value of p_1. The shock speed measuring equipment is reset and the diaphragm ruptured. p_2 is calculated from the measured values of p_1 and M_1.

3.2 Test equipment

High frequency amplifiers and Tektronix oscilloscopes are available for amplifying and recording the output of the gauge(s) under test. The amplifiers have the following specification:-

Gain: Switched, 1 to 10 in unity steps, accuracy ±3% at 1 Kc/sec.

Output: 68Ω impedance. Maximum linear output voltage ±1 volt.

Input: Switched input impedances of 1MΩ, 10MΩ, 100MΩ and 500MΩ
Open circuit position is not less than 2000MΩ.

Noise: With 500MΩ and 100pf input noise at output does not exceed 1mV at gain × 1.

Response: Rise-time (10% to 90%) not greater than 0.4 µsec.
Overshoot not more than 1%.
With input capacitor of 0.001 µF and at 500MΩ impedance the droop does not exceed 2% in 3 m secs.

The oscilloscopes may be triggered from the upstream shock detector trigger channel. Polaroid cameras enable an immediate record of the test gauge output to be obtained.

4 TESTS OF PRESSURE TRANSDUCERS

Three commercial and two development transducers have been calibrated in the 3 in. × $1\frac{1}{2}$ in. tube. The two transducers developed at R.A.E. and an experimental 'freely' mounted crystal gauge (section 4.5) are shown in Fig.9. No attempt has been made to make exhaustive assessment of these gauges: the tests at different pressure levels merely provide a comparison of the performance of the gauges in one typical application i.e. in measuring the static pressure in a shock tube. Considerable care has been taken to ensure that the value of the applied pressure steps has been accurately determined within the limitations described in the previous section of this note. In other applications or in a similar application in another shock tube the effects of mechanical vibration might be less or greater than here. Moreover, with minor exceptions described later, no attempt has been made to isolate the gauges from the effects of mechanical vibration.

4.1 Gauge 'X'

This crystal gauge originally designed for measurements on diesel engines consists of two semi-cylindrical quartz crystals with a steel electrode between them, contained in a stainless steel sleeve. Pressure is applied to one end via a composite diaphragm and steel anvil. The pressure sensitive end of the outer case is provided with a 14 mm thread for mounting and the makers recommend the use of a copper washer under the shoulder of the gauge body as a pressure seal. The natural frequency is 48 Kc/sec and the sensitivity 0.08 pCb per mm Hg. With a short cable and minimum capacitive loading it is thus possible to obtain a sensitivity, before amplification, greater than 1mV per mm Hg pressure.

The gauge tested was mounted in a brass plug at Station 2 of the shock tube test section and connected by a short cable to an H.F. amplifier and thence to a Tektronix oscilloscope. Values of p_1 were chosen and the tube operated to yield pressure steps of approximately 1.2, 5, 10, 20, 40 and 60 mm Hg. The gauge and mounting plug was then removed to Station 11 and subjected to pressure steps of approximately 100, 150, 200, 250 and 300 mm Hg. The true values of $p_2 - p_1$ and $p_{2_R} - p_1$ were then calculated, the recorded amplitude measured and a curve of transducer sensitivity plotted. The records are reproduced in Fig.10 and the plot of sensitivity in Fig.11.

Clearly with so much modulation of the gauge output signal it is difficult to measure the mean amplitude with any great accuracy, especially as the modulation is complex. An oscillation at approximately 40 kc/sec arising from excitation of the gauge at its natural frequency is clearly seen, but this is superimposed on a slower more ragged amplitude variation of about 5 Kc/sec frequency. This latter disturbance is believed to arise from the gauge's acceleration sensitivity to a 'hoop' oscillation of the shock tube channel initiated by the passage of the shock wave. In addition the gauge will 'feel' and probably respond to some transverse acceleration due to longitudinal disturbances in the wall of the tube generated when the tube diaphragm is ruptured. This disturbance will be able to travel ahead of the shock wave, moving at the speed of sound in the tube walls, and give rise to the pre-shock signal that appears in the records.

The record of Fig.12 was obtained with the face of the Gauge 'X' mount covered by a brass disc to prevent the gauge from sensing the shock wave pressure step. To keep the surface of the 'blanked off' mount flush with the inside surface of the shock tube wall, the mount had to be withdrawn slightly and a packing washer inserted under the shoulder of the mount. In all other respects the test conditions were a repeat of those pertaining to the run reproduced in Fig.10F. The signal of Fig.12 is due wholly to the response of the gauge to vibration and while the signal component due to vibration is apparently reduced in amplitude when the gauge diaphragm is loaded by the shock pressure step, clearly the signal due solely to vibration coincides with the low frequency modulation of the trace in Fig.10F.

Whilst the linearity of Gauge 'X' is acceptable within the limitations of these tests and of the analysis of the records, the usefulness of the gauge at these low pressures, and in applications where it is subjected to shock loading and mechanical vibration, is undoubtedly impaired by its vibration sensitivity.

4.2 Gauge 'Y'

Gauge 'Y' intended for shock tube applications, is a smaller quartz crystal gauge having two semi-cylindrical crystals, with a central electrode between them, contained in a thin metal sleeve. The outer case and simple integral diaphragm is machined from the solid, and a cylindrical anvil transmits pressure from the diaphragm to the crystal. A lip on the top of the crystal sleeve constrains the anvil and crystal, and an external shoulder at the bottom end of the sleeve enables the crystal to be pre-stressed when the gauge is assembled. The outer case is provided with a shoulder for mounting and pressure sealing is obtained by means of an 'O' seal under this shoulder.

For various models natural frequencies are quoted between 250 and 500 Kc/sec, although from records of the self oscillation of gauges regularly used in shock tube applications the true value would appear to be somewhat lower, i.e. 120-130 Kc/sec. The sensitivity is 0.01 pCb/mm Hg and hence it is possible to obtain a sensitivity, before amplification of about 0.2 mV per mm Hg pressure.

The test configuration and procedure was similar to that described for the Gauge 'X' tests, except that some signal gain had to be obtained from the H.F. amplifier at the lower test pressures. The series of test records and the resulting calibration of the gauge are reproduced in Figs.13 and 11 respectively.

Once again the signal has both high and low frequency modulation components due to gauge self oscillation and vibration sensitivity, but these are much smaller in amplitude than in the case of Gauge 'X'. Moreover, the higher natural frequency once excited, attenuates much more quickly.

The lower sensitivity limits the use of the gauge at low pressures particularly in applications where long connecting cables are unavoidable. Unfortunately the self oscillation of the gauge prevents full advantage being taken of its very fast rise-time characteristic. The calibration linearity is comparable with that of Gauge 'X'.

4.3 Gauge 'Z'

This is a sub-miniature diaphragm gauge depending on a differential change in capacity between the diaphragm and electrodes disposed on either side of the diaphragm. One side is referenced to a steady pressure and the other side is open to the pressure it is required to measure. The gauge and its associated bridge-amplifier was designed and developed by Instrumentation Department of the R.A.E. for use in wind tunnel models and is described in Ref.4. The range is ±200 mm Hg pressure and sensitivities, dependent upon the amplifier, can be as high as 20 millivolts per mm Hg. The frequency range is from D.C. to a value determined by the bridge excitation frequency and/or the 'acoustic' resonant frequency of the pressure inlet system, which, in turn, depends on the length of the pressure inlet pipe. A very low acceleration sensitivity is claimed which makes the gauge of particular interest for shock tube applications.

Soft mounting is recommended to avoid possible distortion of the gauge body. In the following tests the gauge was clamped into a brass plug with a thin rubber pad on either side of the gauge body so that the $\frac{1}{4}$ in. long pressure inlet pipe came flush with the surface of the plug. The plug was then inserted in the shock tube at Station 2 as in the previous tests. The gauge was connected to its 400 Kc/sec bridge-amplifier, which was energised at 5V R.M.S. from a laboratory oscillator. The amplifier output was taken to a Tektronix oscilloscope. The amplifier incorporated an m-derived filter network in the output with resistive damping as described in Ref.4. The filter has a cut off frequency of 30 Kc/sec, and limits the rise-time of the output signal to about 15 μsecs.

The gauge was referenced to initial channel pressure p_1 by connecting the reference pressure inlet via a 6 ft length of pipe to an opening in the wall of the shock tube test section. The long length of pipe served to keep the reference pressure constant during the recording period while restricting the differential pressure applied to the gauge before and after the run.

A range of tests in the side wall and end wall of the shock tube was made and the records are reproduced in Fig.14. The calibration curve is plotted in Fig.11, and it should be noted that the calibration was taken rather beyond the stated range of the gauge.

The test run at 1.3 mm Hg pressure was omitted from this series since the gauge output at this pressure is comparable with the total noise level at the output. This puts a lower limit on the useful pressure range of this gauge. The slow rise-time at low pressures and limited frequency bandwidth are a further limitation to the usefulness of the gauge for transient pressure recording. At the upper end of the pressure range some degree of ringing is apparent. The source of this is almost certainly the oscillation of the column of air in the pressure inlet pipe. For a wide range of applications, however, the gauge exhibits some very desirable properties. These are its small size, steady state calibration, temperature independence and freedom from acceleration (vibration) response

It is perhaps worth noting that the inlet pipe may act as a subsidiary shock tube so that with a sudden change of pressure at the end, a weak shock may be driven down the inlet pipe. The gauge diaphragm will then see the pressure behind this weak shock after reflection, followed by a rarefaction wave when the reflected shock regains the open end of the inlet pipe. This effect has been noted in tests in which the inlet pipe was extended. Fig.15 shows the records obtained when the inlet pipe length was 1 in., 2 in. and 6 in. respectively. As the pipe length is increased the initial steps in pressure as seen by the diaphragm are rounded off, due, probably to viscous effects in the inlet pipe. In the first picture the rarefaction is seen after 150 μsecs, in the second after 300 μsecs and in the third picture the return of the rarefaction wave was made to coincide with the disturbance from the reflected shock in the main shock tube and is therefore not seen.

4.4 The cavity crystal gauge

The cavity crystal gauge evolved from some early experiments with a 'freely' supported crystal. In these experiments a lead zirconate crystal disc was supported between cellotape diaphragms in a metal wafer in the manner shown in Fig.9. It was hoped that the soft suspension would prevent mechanical vibrations from being transmitted to the crystal and that the relative absence of mass loading on the crystal would result in an output reflecting only the pressure applied to the crystal faces. By virtue of its design this gauge had to project into the flow when shock tube mounted, but by keeping the wafer thin and chamfering the edges it was expected that the gas flow would not be badly disturbed and that the gauge would 'see' something very close to the shock tube static pressure. Pressure records obtained with this gauge (Fig.16) were very encouraging. Negligible pre-shock noise was recorded; rise-time of the recorded trace corresponded to the shock transit time across the crystal diameter (4 to 5 μsecs), and the pressure plateau was encouragingly flat, especially at the lower test pressures. No attempt was made to develop the gauge in this form because of its limited usefulness, projecting as it did into the gas flow, but it was decided to engineer the gauge in a form more suitable for mounting in wind tunnel models. This led to the cavity crystal gauge shown in Fig.9. Retaining the principles of the 'freely' suspended crystal the assembly is housed in a cavity that is an integral part of the gauge. The sensitive element is a lead zirconium titanate ceramic disc 3 mm in diameter and 0.5 mm thick and the overall size of the gauge including the threaded mounting stud is 0.25 in. diameter by 0.625 in. long.

Tests of this gauge similar to the series previously described, were made, the gauge being mounted in a brass plug with an 'O' seal under the shoulder in the same manner as Gauge 'Y'. The pressure records obtained and the resulting calibration curve are reproduced in Figs.17 and 11 respectively.

The effect of the cavity is to delay the rise of pressure as seen by the crystal, and the consequent cavity 'filling' time is unacceptably long at very low pressures (below 5 mm Hg pressure). Once again an 'organ pipe' resonance is excited and the amplitude of the recorded disturbance increases with the applied pressure. This resonance can be suppressed at the expense of gauge rise-time by restricting the opening of the cavity. Examples of this are shown in Fig.18. If the optimum restriction, corresponding to the pressure to be measured, is chosen as in record D of Fig.18 the resulting rise-time will not be badly increased and while the response time of the 'damped' cavity gauge will vary with the amplitude of the initially applied pressure step, there is some evidence that once the cavity is filled to this pressure subsequent small pressure variations evoke a somewhat faster response.

The gauge as tested with a capacitive attenuator has a sensitivity of 0.6 mVolts per mm Hg pressure. The corresponding sensitivity with only 12 in.

of cable connecting the gauge to its amplifier, as in the previous tests described, is approximately 2 mVolts per mm Hg pressure. The calibration linearity is good.

4.5 The 'top hat' crystal gauge

The principle examined in this second development gauge is a simple one; namely that most of the problems of vibration sensitivity encountered with sensitive pressure gauges should be avoided if the sensitive element could be mounted in such a way that it has perfectly rigid restraint in the direction of applied pressure, a minimum of restraint in other directions, and no mass loading.

A piezo-electric crystal disc supported on a perfectly flat rigid metal block and exposed to pressure only on its front surface would have only one type of disturbance remaining. That is reflections of stress waves in the crystal from the acoustically mismatched interface between the crystal and its support and from the back face of the support block. It is possible to make the period of these reflections very short by using a suitably thin crystal and sufficiently thin support, remembering that the support must be 'rigid'. The resulting crystal/support resonance may then be filtered out without a serious compromise of gauge rise-time.

The top hat crystal gauge (Fig.9) involved a series of compromises. A thin piezo crystal disc was laid in a cylindrical clearance hole in a brass block so that its upper surface was flush with the surface of the block. It was held in place by a sellotape diaphragm placed over the surface. The back of the brass block behind the crystal was machined out until the thickness of brass behind the crystal was reduced to approximately 0.05 in.

The period for reflections within the crystal is approximately 0.6 μsec and in the brass support 1.5 μsecs. The crystal support is not perfectly rigid nor is the crystal entirely free of lateral restraint by virtue of the sellotape diaphragm, but the resulting gauge performed quite well in the series of tests shown in Figs.19 and 11.

Two constructional features that will strongly influence the behaviour of a gauge of this type may be noted. Firstly, the clearance between the side of the crystal and its support block should be as small as possible to minimise the effect of the distortion of the unsupported annulus of diaphragm. Secondly the face of the support block beneath the crystal must be perfectly flat to prevent bending of the crystal, which itself is flat to a good standard of accuracy.

5 FUTURE DEVELOPMENT

5.1 The calibrating shock tube

The present shock tube arrangement gives rise to considerable shock attenuation particularly at higher Mach numbers and lower initial densities resulting in an unsteady pressure behind the shock. In view of the very long testing time available (Fig.3) over most of the required range it is proposed to shorten the channel.

Through a large number of runs with the present tube occasional rogue runs have led to doubts about the influence of the bursting of the tube diaphragm on the resulting flow. It is not yet clear how this can best be investigated, but as a first stage it might be revealing to compare the measured shock velocity and pressure step obtained for a particular initial p_1 with various diaphragm materials and methods of rupturing them.

Efforts to measure p_1, with greater accuracy should be made. As a first step the test section is being modified to allow p_1 to be measured there by means of mercury or oil manometers.

In order to obtain the low pressure steps required it is necessary to produce shocks approaching Mach 4. Some advantage could be obtained in terms of steady flow if p_4, could be reduced appreciably below atmospheric pressure. This would introduce a diaphragm problem, but is worthy of investigation.

5.2 Development of gauges

Sellotape has been widely used as a diaphragm material in the development of crystal gauges described in this note. It tends to be fragile for use in some applications and burns readily at high temperatures. Much of its advantage as a 'soft' diaphragm comes from the cushioning effect of the adhesive with which it is backed. Other materials for, or other methods of lightly restraining the crystal will be sought.

Other approaches to the design of acceleration insensitive non-ringing gauges not reported here have been made. Of these the bar gauge described by Edwards[5] has shown promising results. In this gauge a crystal is mounted on a bar of metal chosen to have the same cross section and acoustic impedance as the crystal. Quartz and lead, and lead zirconate and zinc are examples of this. Thus the crystal and bar become acoustically homogeneous and a compression wave will propagate through the crystal and bar without reflection at the crystal/bar interface. Such a gauge does not ring at the crystal resonance but gives an output proportional to pressure until such time as a disturbance returns from the far, fixed end of the bar. Soft suspension of the bar prevents environmental vibration from reaching the gauge. To record pressure events of appreciable duration necessitates the use of an impossibly long bar. However, there is always some dissipation of the stress wave in the bar and tests have shown that this can be encouraged by choosing a suitable material (and maintaining acoustic matching by means of a change of cross sectional area); little or no reflected signal appearing in the gauge output. It may be possible to dissipate the energy in the first double traverse of the stress wave so that the bar remains compressed and does not oscillate. The crystal, which is originally set into motion, will of course, be brought to rest, and so suffers a deceleration. If this deceleration can be kept sufficiently small the resulting increasing signal from the crystal may be very nearly constant, i.e. the component due to deceleration may be very small compared with the signal due to the applied pressure. Further investigation of a dissipative bar gauge is proposed.

LIST OF REFERENCES

Ref. No.	Author	Title, etc.
1	Lukasiewicz, J.	Shock tube theory and applications. National Aeronautical Establishment, Canada Report 15, 1952.
2	Woods, B.A.	- To be published.
3	Hilsenrath, J. et al.	Tables of thermal properties of gases. National Bureau of Standards Circular 564, November, 1955.
4	Macdonald, W.R. Cole, P.W.	A sub-miniature differential pressure transducer for use in wind tunnel models. Unpublished M.o.A Report.
5	Edwards, D.H.	A piezo electric pressure bar gauge. Journal of Scientific instruments, Vol.35, No.9, p.346, September, 1958.

TABLE 1

Summary of pressure transducer requirements

1	2	3	4	5	6	7	8	9	10	11	12		
Application	Transducer location	Gas flow temperature °K	Pressure ranges covered by proposed experiments P.S.I.	Suggested ranges for transducers P.S.I.	Resolution required % full scale	Time for 1% droop when recording steady pressure micro seconds	Time to respond to a step function of pressure micro seconds	Minimum full scale sensitivity mV	Size - maximum diameter in.	Size - maximum length in.	Optimum damping required (freedom from overshoot)	Notes	Comment
Static pressure 6 in. shock tube	Channel wall	2700 - 4800	6-1000	0-100 0-1000	1	1000	1-10	100	0.25	-	Yes		Gauge should be mar resistant (to erosion by dust particles).
Pitot pressure 6 in. shock tube	Model	*2700 - 7500	60-5000	0-100 0-1000 0-10,000	1	1000	1-10	100	0.25	1.0[a]	Yes	* Stagnation temperature a Greater length could be accepted in some cases.	
Pitot pressure 6 in. shock tube expanded flow	Model		1-7	0-1 1-10	1	500	1-5	100	0.2	1.0[a]	Yes	a Greater length could be accepted in some cases.	
Static pressure 6 in. shock tube expanded flow	Wall or Model		0.03 - 0.08	0-0.1	1	500	1-5	100	0.5[b]	1.0[c]	-	b Dia limited by gauge diaphragm transit time. c Length immaterial for wall mounting.	Gauge must withstand over pressures of 30-40 p.s.i.
Static pressure 2 in. shock tube	Wall	2500	1-10	0-10	0.1	100	1	10	0.25[d]	-	Yes	d Limited by transit time effect on required resolution.	
Blast pressures	Model	300-500	15-100	0-100	1	50	1	-	0.25	1.0[e]	Yes	e Shorter for thin model sections.	Gauge preferably calibrated in situ and expendable.

Common (ideal) specification

Gauges to be:

(1) Unaffected by temperature during period of recording (col.7).
(2) Undamaged by 'soak' temperature. In general gauge will be exposed to hot gas (col.3) for 2-3 milliseconds.
(3) Independent of their mount, i.e. having little or no acceleration response in any direction.
(4) Independent of clamping effect i.e. resistant to body distortion in normal mounting.
(5) Constant in calibration.
(6) Capable of calibration statically if possible.
(7) Having an output linear with pressure (desirable but not essential)
(8) Unaffected by ionised gases and resistant to hydrogen in all but the blast pressure application.

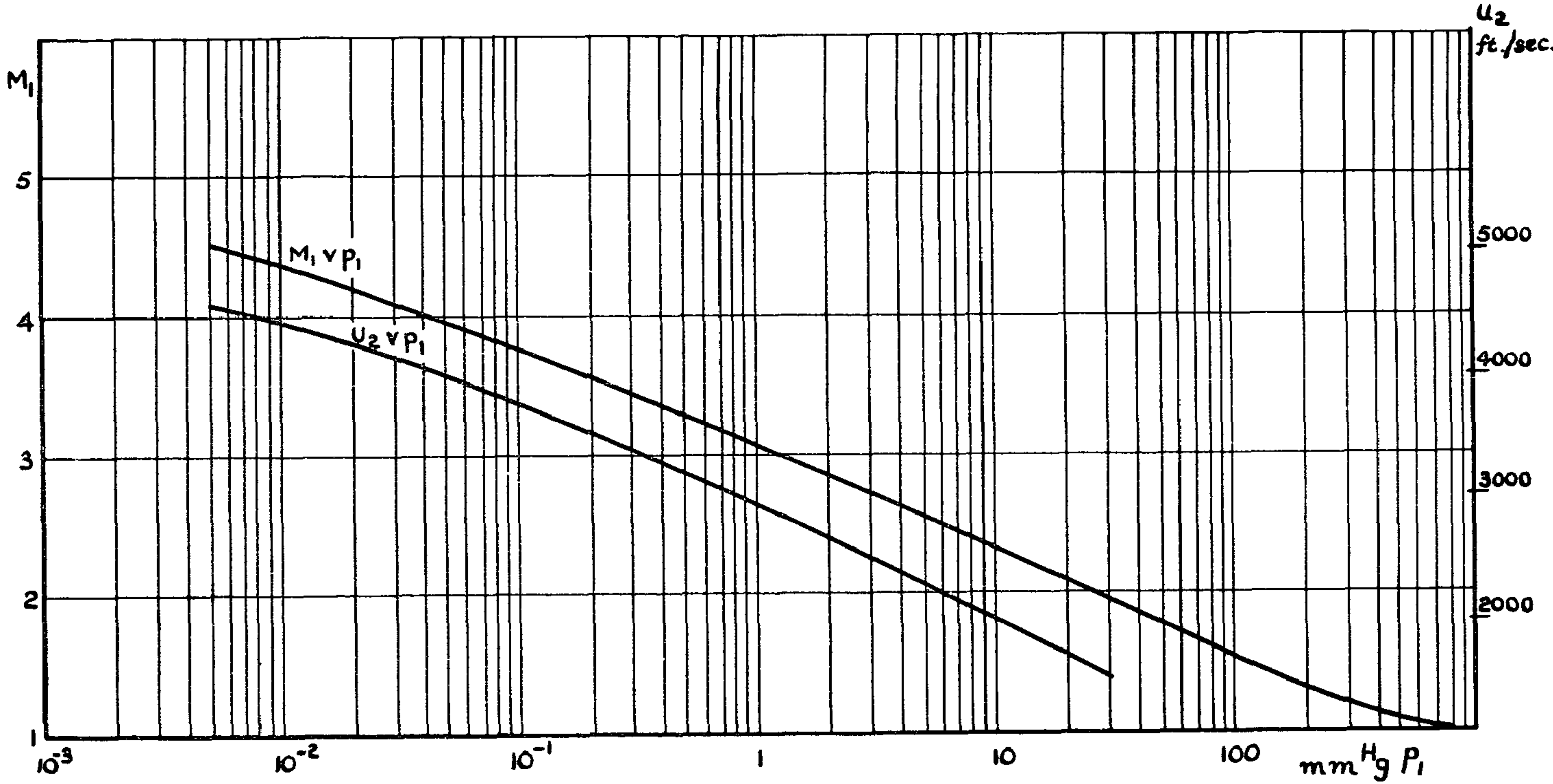


FIG. 1. INITIAL CHANNEL PRESSURE VERSUS SHOCK MACH Nº (ATMOSPHERIC DRIVER) FLOW VELOCITY VERSUS MACH Nº (ATMOSPHERIC DRIVER)

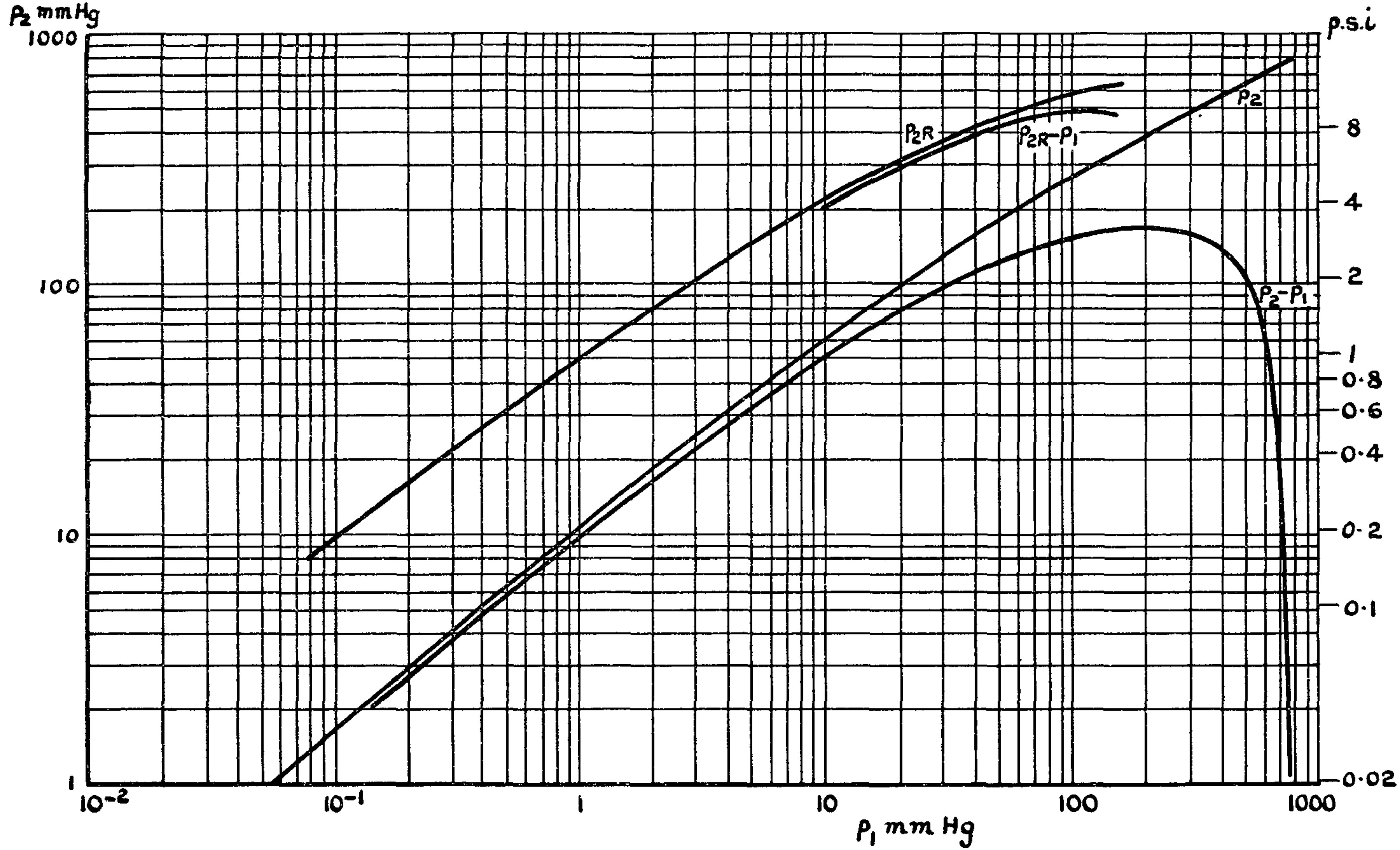


FIG. 2. INITIAL CHANNEL PRESSURE VERSUS SHOCK PRESSURE STEP.

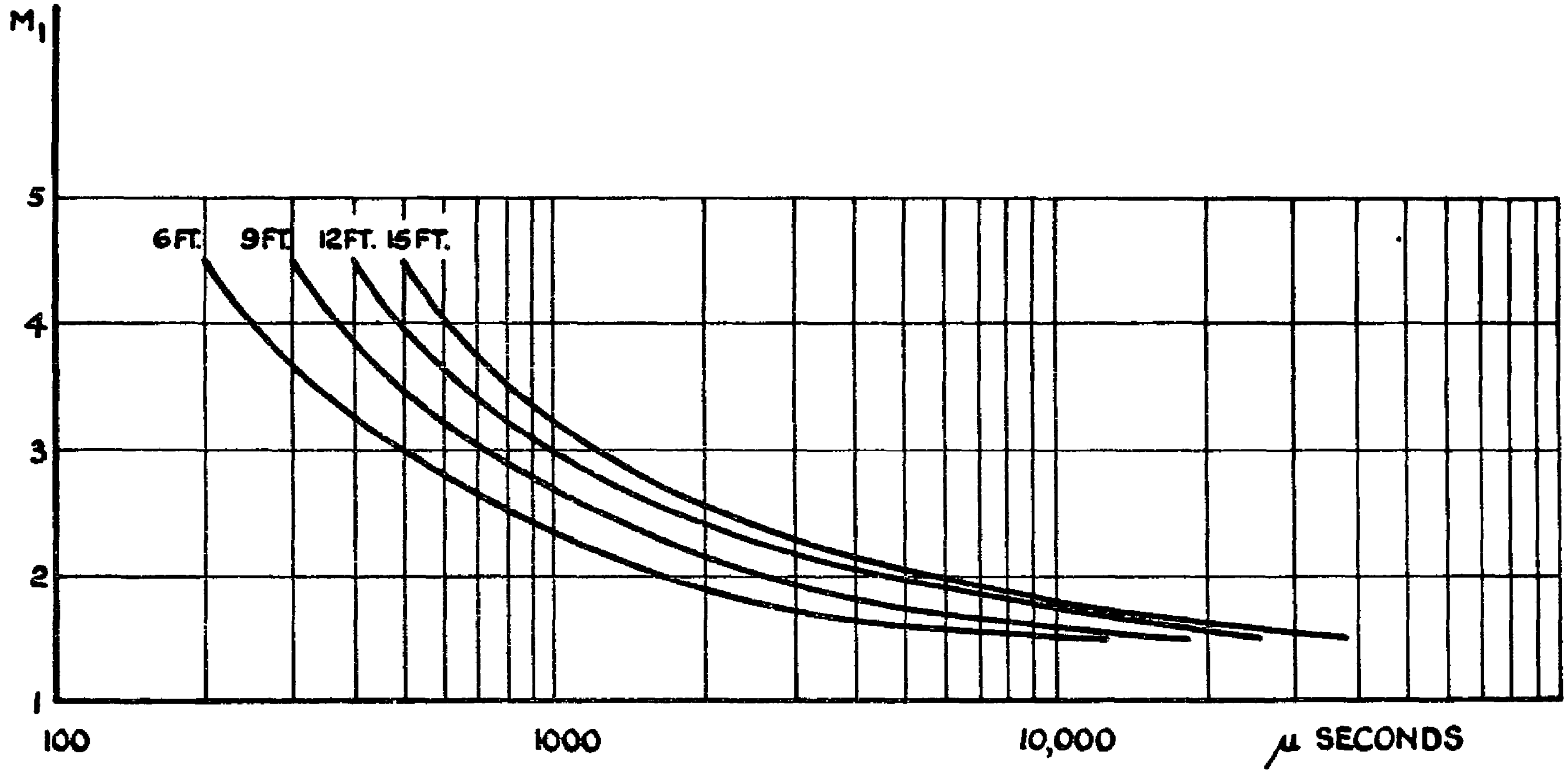


FIG. 3. TESTING TIME V. SHOCK MACH NUMBER FOR VARIOUS CHANNEL LENGTHS AS DETERMINED BY ARRIVAL OF INTERFACE.

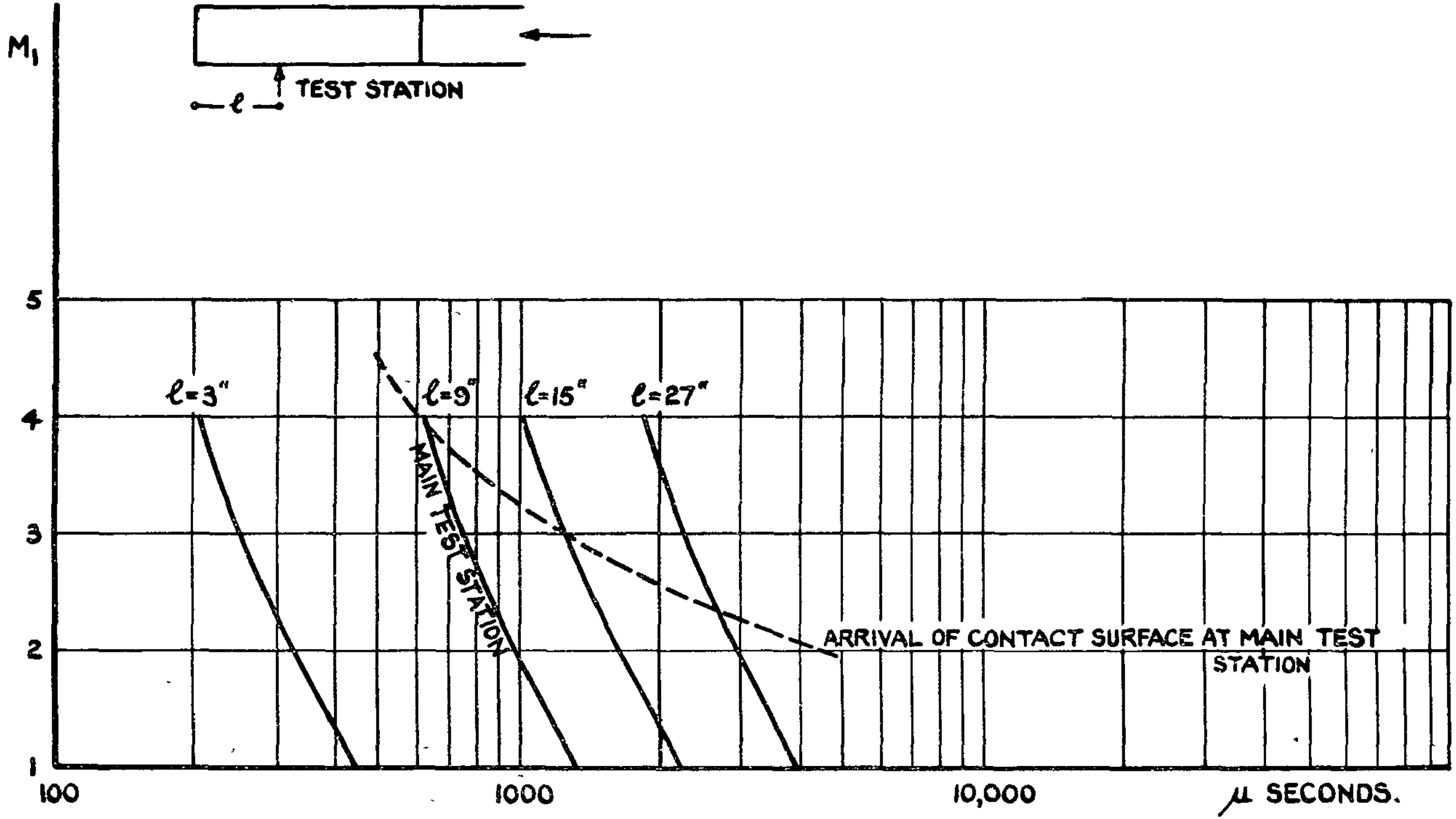


FIG. 4. TESTING TIME VERSUS SHOCK MACH NUMBER AT VARIOUS TEST STATIONS AS DETERMINED BY ARRIVAL OF REFLECTED SHOCK.

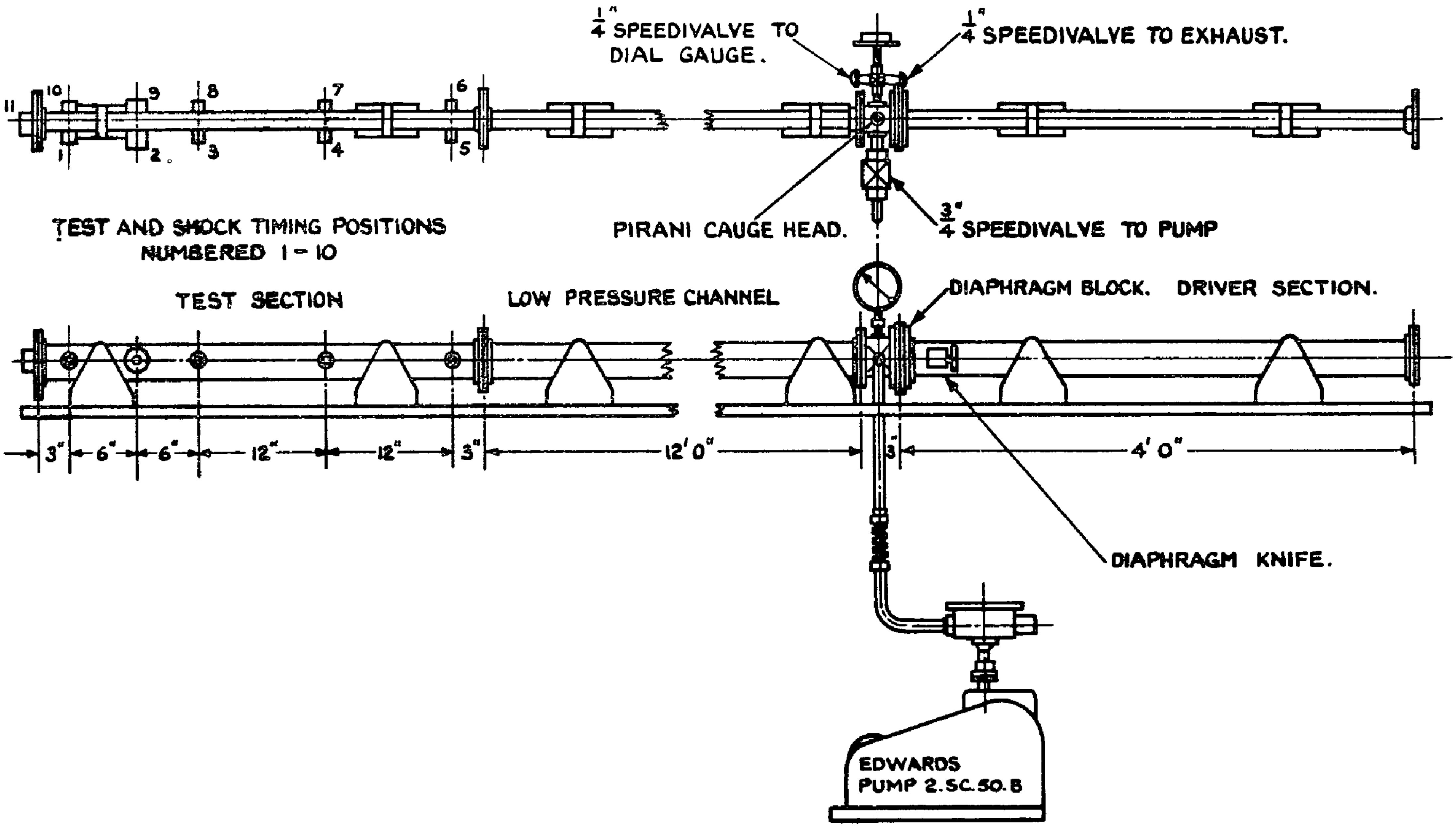


FIG. 5. GENERAL ARRANGEMENT OF 3" X $1\frac{1}{2}$" CALIBRATING SHOCK TUBE

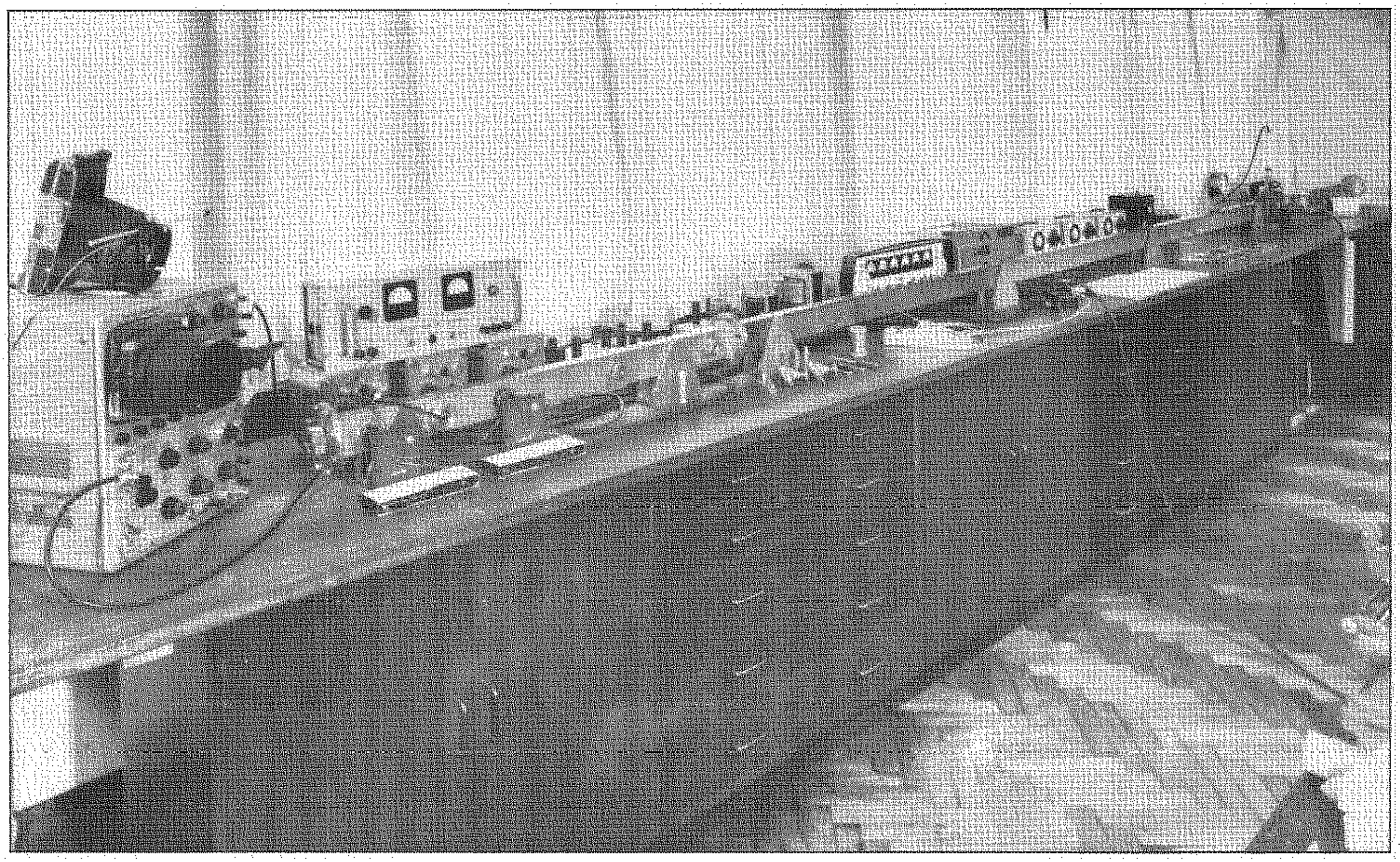


FIG.6. LAYOUT OF 3″ x 1½″ CALIBRATING SHOCK TUBE

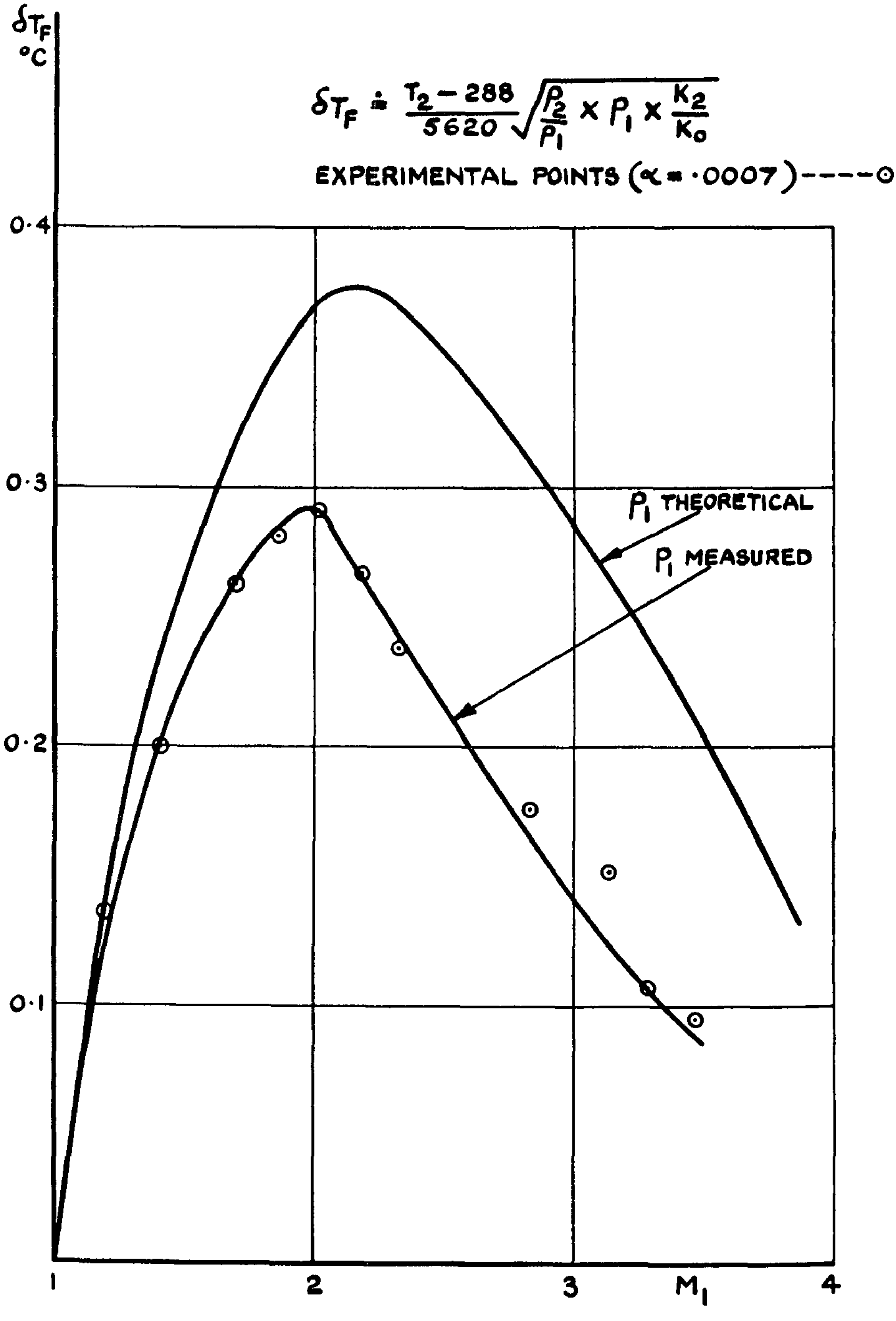
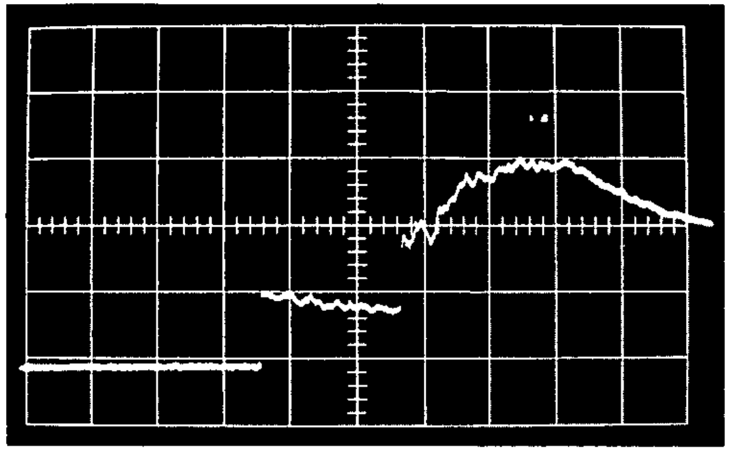
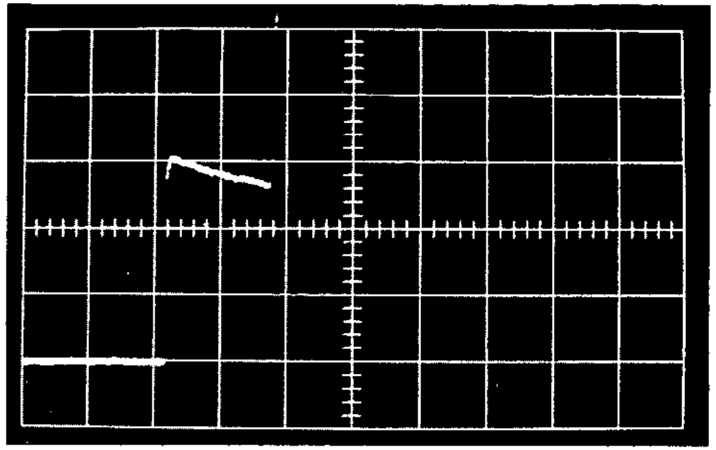


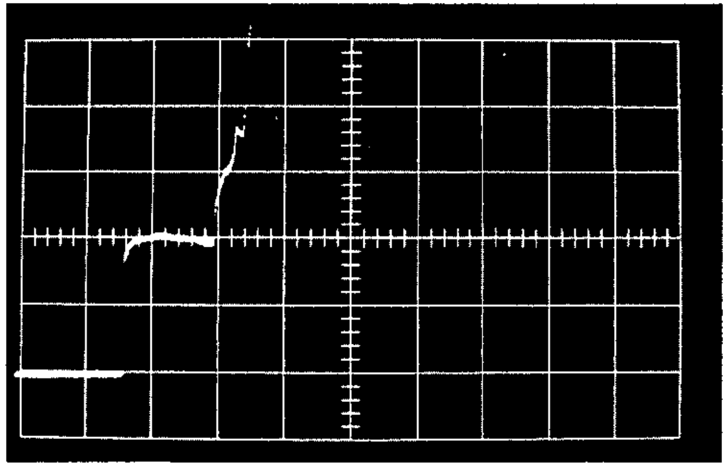
FIG.7. TEMPERATURE RISE OF THIN FILM GAUGE AT THE WALL OF THE SHOCK TUBE.



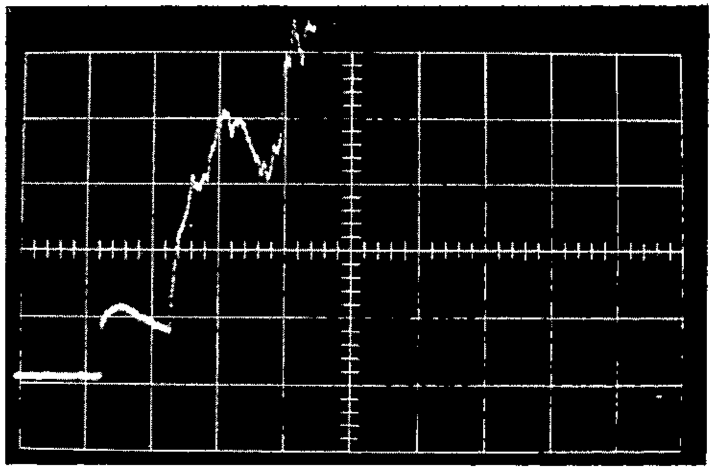
$M_1 = 1.2$



$M_1 = 2.0$



$M_1 = 2.63$



$M_1 = 3.29$

Records show sudden temperature change on arrival of incident and reflected shocks

Signal has been amplified 100 times

Vertical sensitivity 10 mV/cm
Sweep Speed 200 μS/cm

FIG 8 OUTPUT OF WALL TEMPERATURE SHOCK DETECTORS AT STATION 1

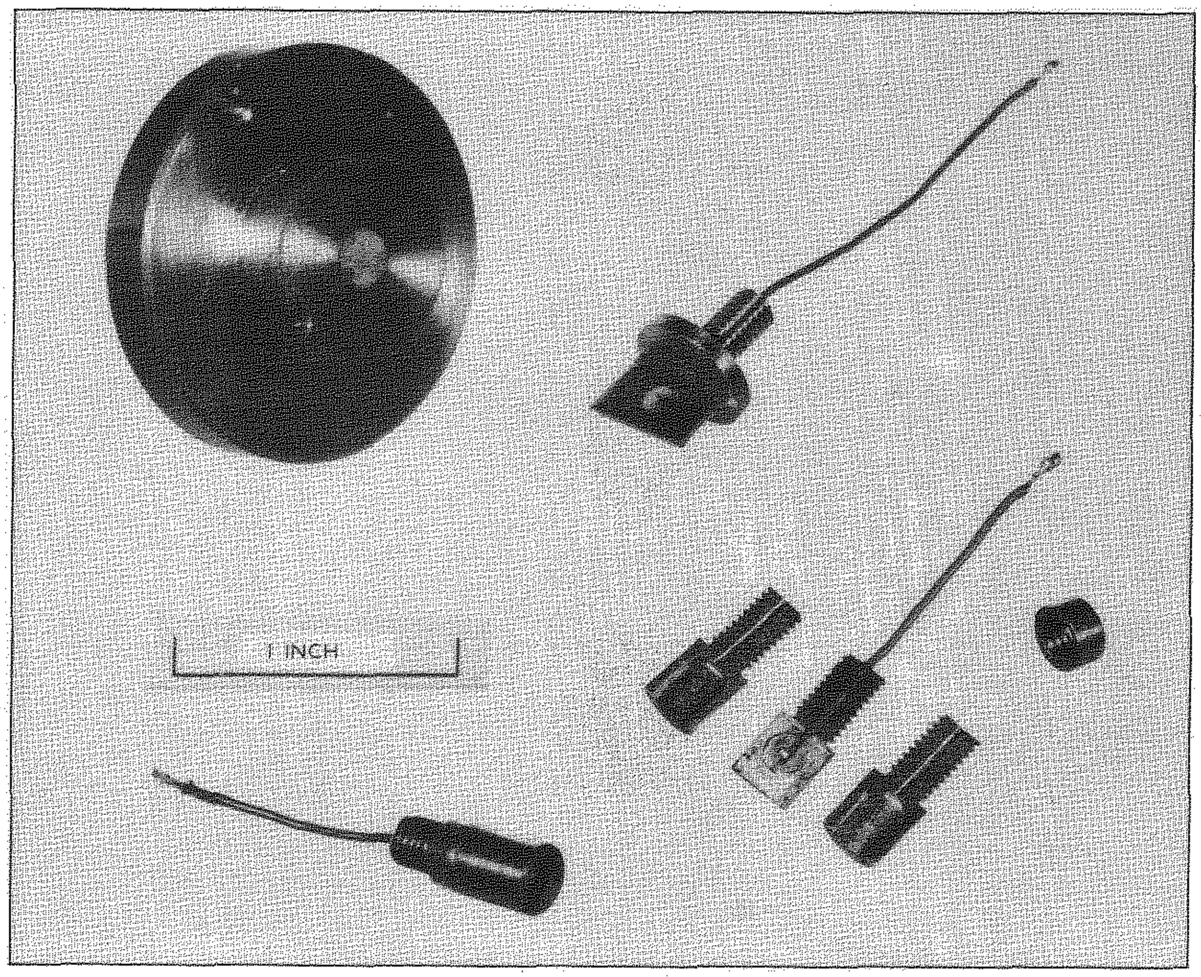
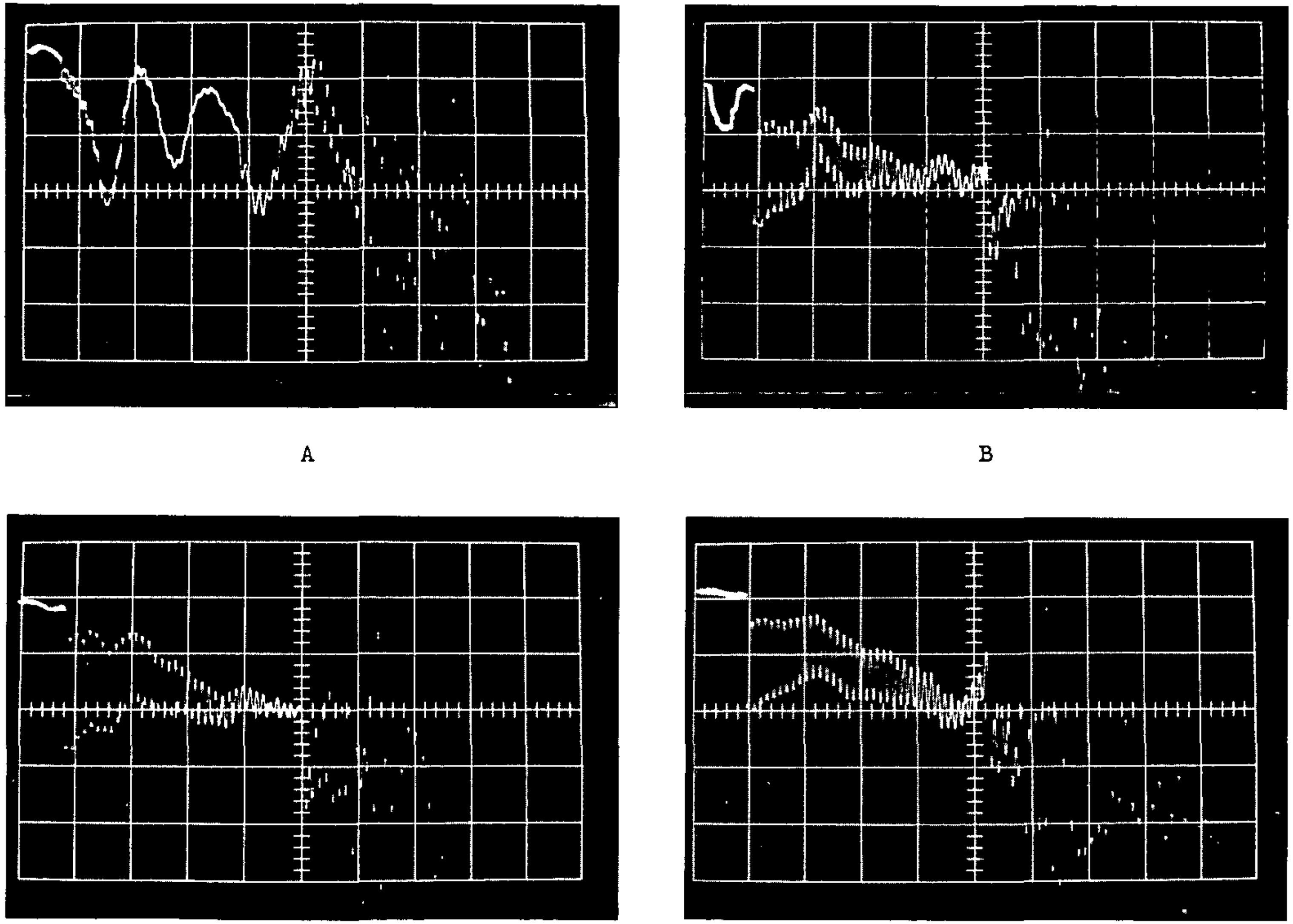


FIG.9. EXPERIMENTAL GAUGES TESTED IN THE 3" x 1½"
CALIBRATING SHOCK TUBE



A B

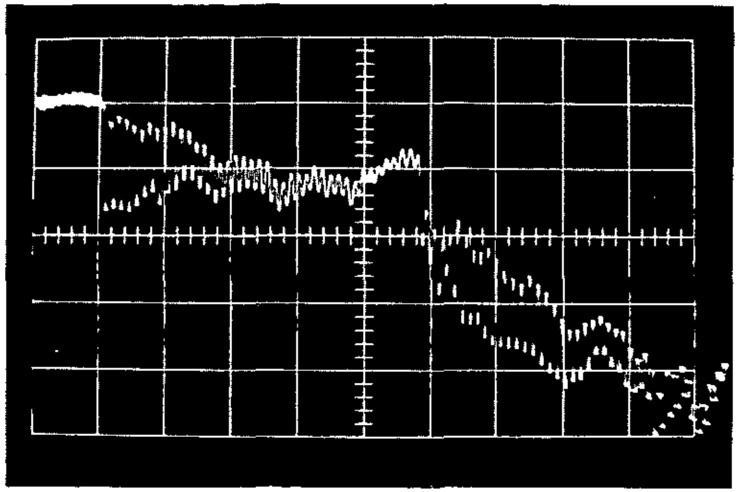
C D

A	1.36 mm Hg
B	6.43 mm Hg
C	11.7 mm Hg
D	19.5 mm Hg

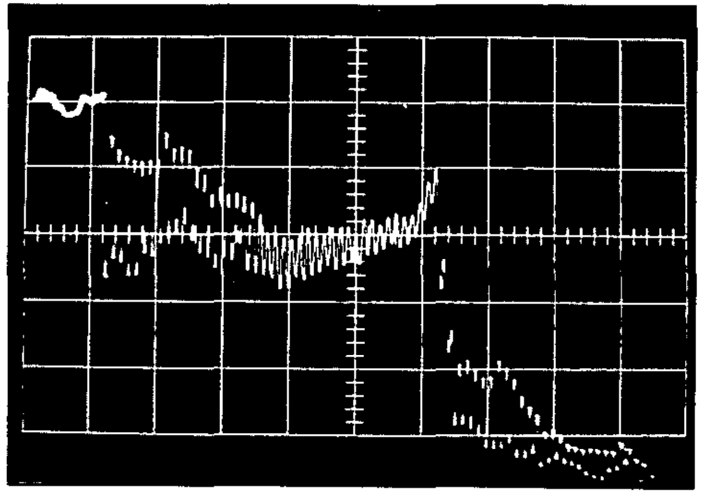
Oscilloscope Settings

A	200 μSec/cm	5 mV/cm
B	200 μSec/cm	10 mV/cm
C	200 μSec/cm	10 mV/cm
D	200 μSec/cm	20 mV/cm

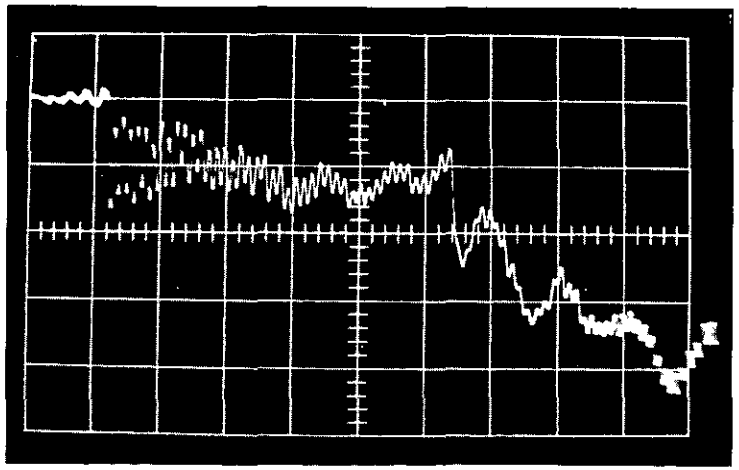
FIG 10 RESPONSE OF GAUGE 'X' TO A STEP OF PRESSURE



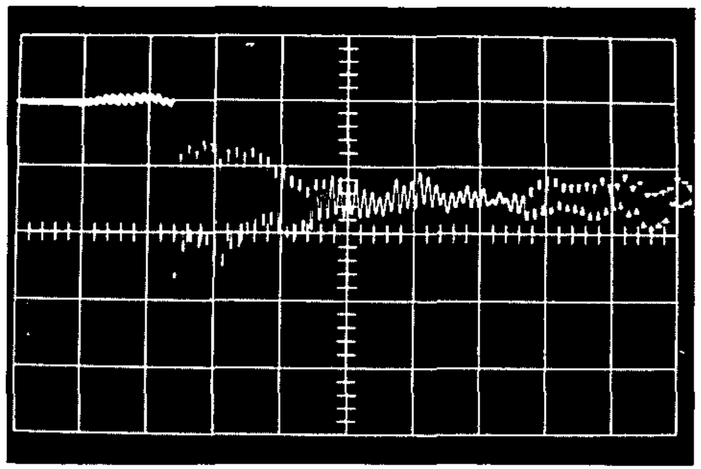
E



F



G

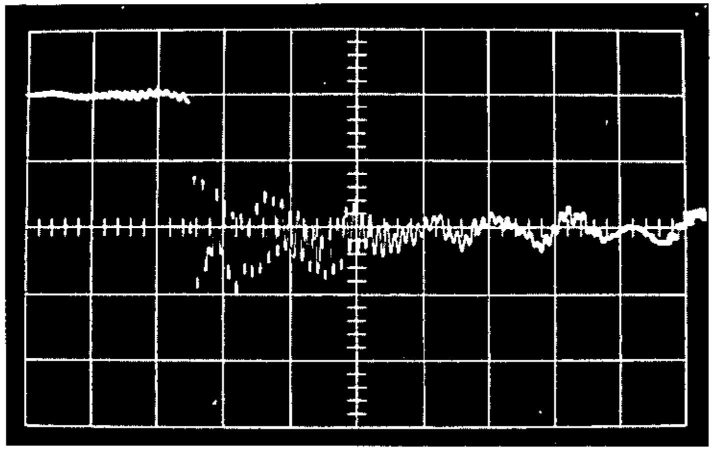


H

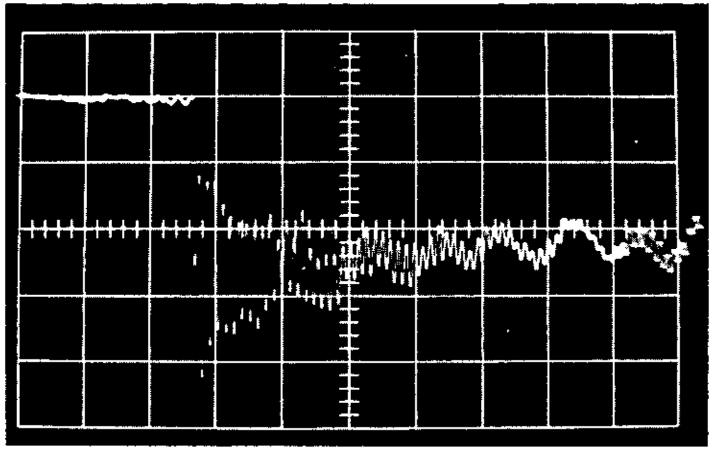
E	40.8 mms Hg
F	66.1 mm Hg
G	77.5 mm Hg
H	110 mm Hg

E	200 µSec/cm	50 mV/cm
F	200 µSec/cm	50 mV/cm
G	200 µSec/cm	100 mV/cm
H	200 µSec/cm	100 mV/cm

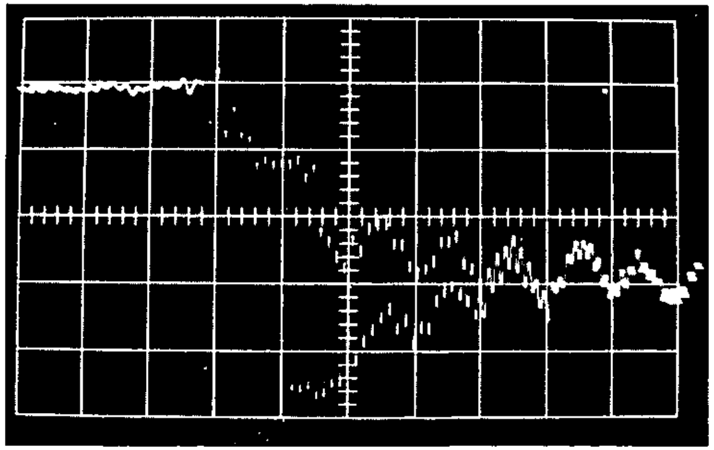
FIG.10 cont'd. RESPONSE OF GAUGE 'X' TO A STEP OF PRESSURE



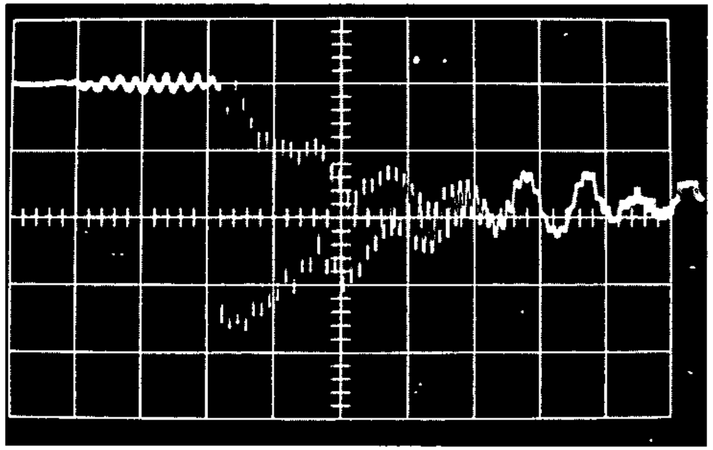
J



K



L



M

J 147 mm Hg
K 202 mm Hg
L 266 mm Hg
M 308 mm Hg

J 200 μSec/cm 100 mV/cm
K 200 μSec/cm 100 mV/cm
L 200 μSec/cm 100 mV/cm
M 200 μSec/cm 200 mV/cm

FIG.10 cont'd RESPONSE OF GAUGE 'X' TO A STEP OF PRESSURE

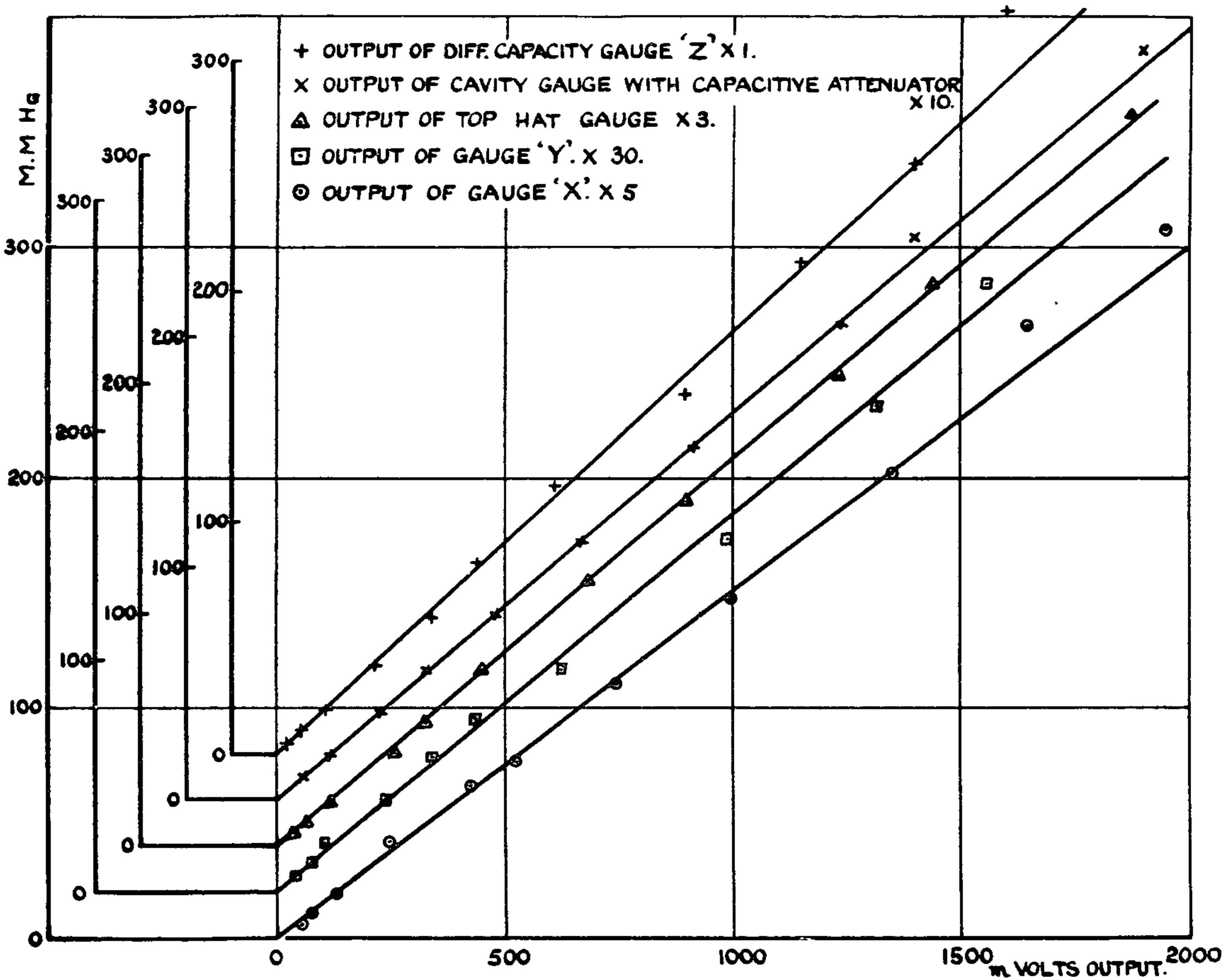
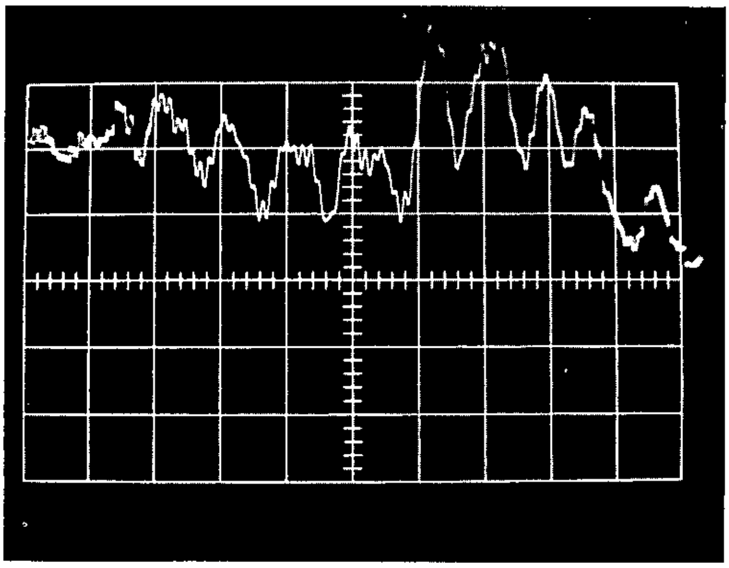
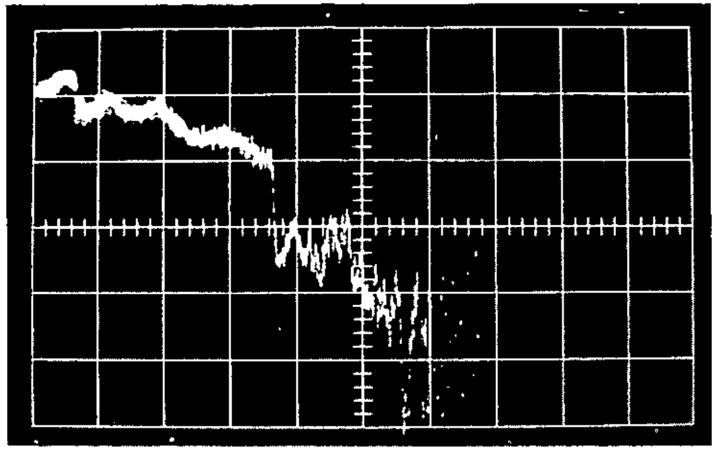


FIG. 11. CALIBRATION OF TEST GAUGES.

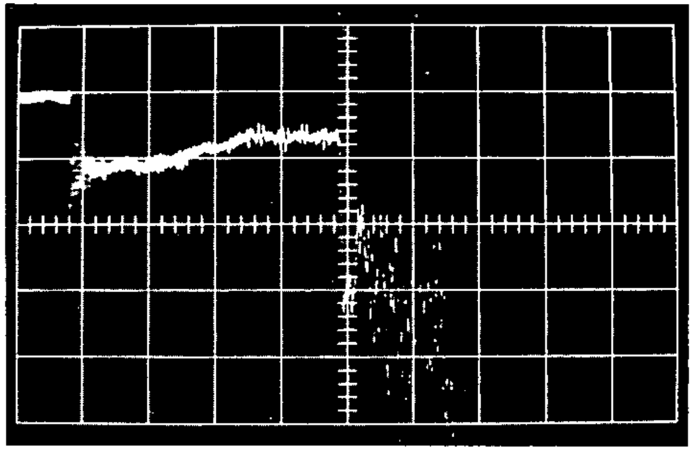


200 μSecs/cm 50 mvolts/cm $p_2 - p_1 = 60$ mm Hg

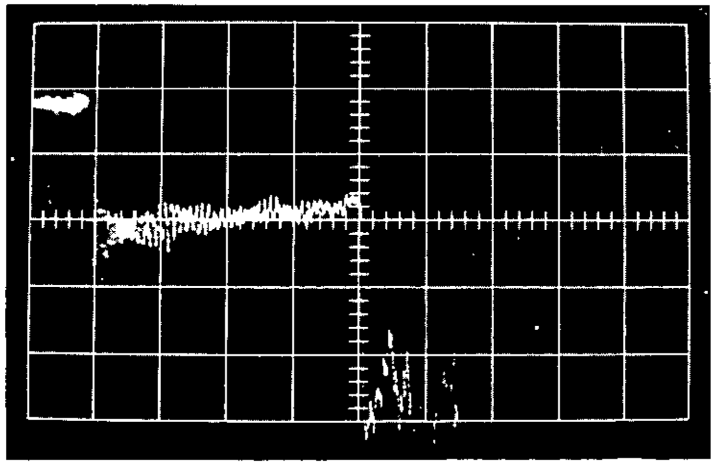
FIG.12. RESPONSE OF GAUGE 'X' IN WALL OF SHOCK TUBE TO VIBRATION - GAUGE DIAPHRAGM BLANKED OFF



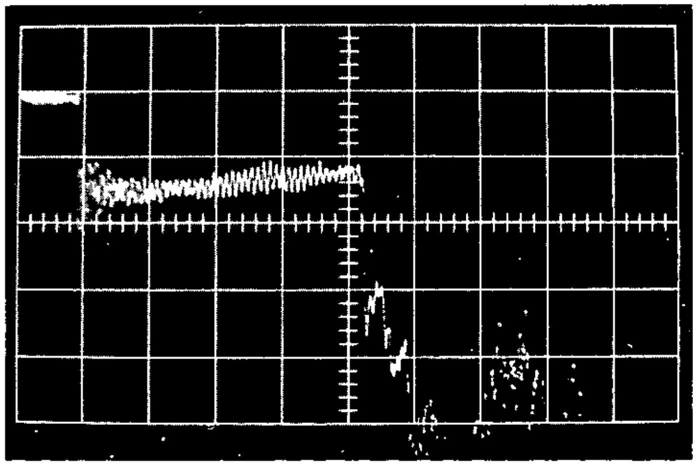
A



B



C

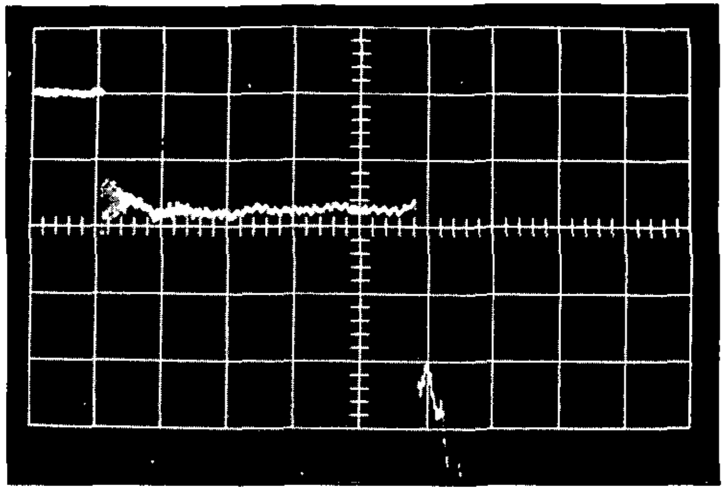


D

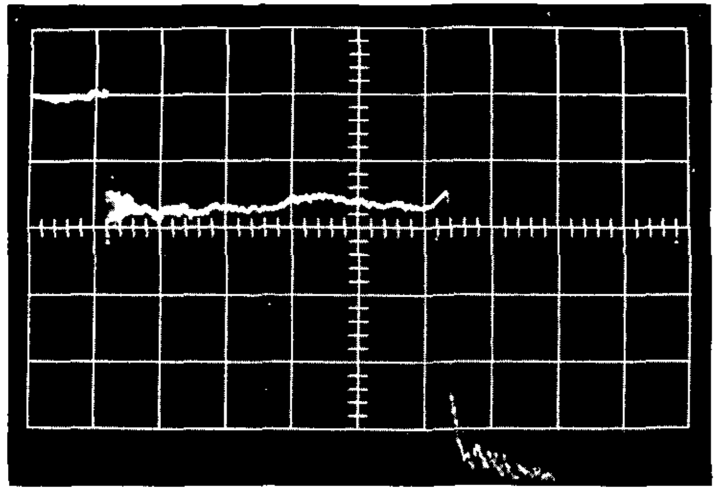
A	1.43 mm Hg
B	7.40 mm Hg
C	12.9 mm Hg
D	21.0 mm Hg

	Sweep	Amp Gain	Osc Sens
A	200 µS/cm	10	5 mV/cm
B	200 µS/cm	4	5 mV/cm
C	200 µS/cm	4	5 mV/cm
D	200 µS/cm	2	5 mV/cm

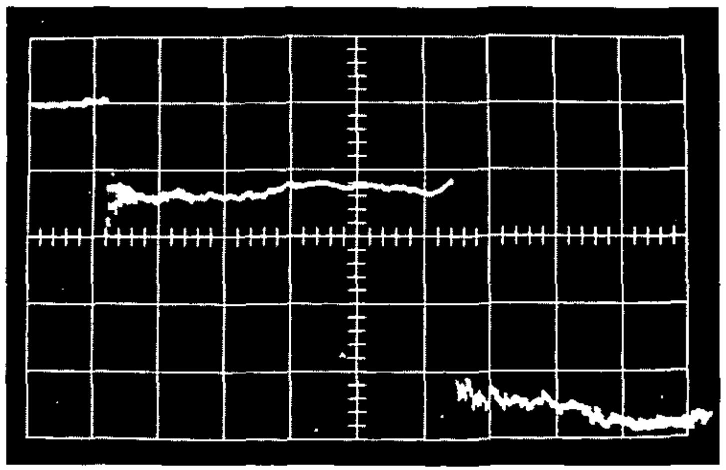
FIG.13. RESPONSE OF GAUGE 'Y' TO A STEP OF PRESSURE



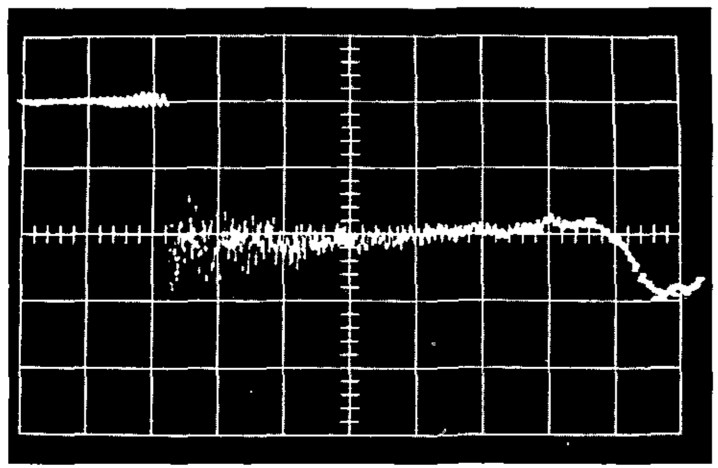
E



F



G

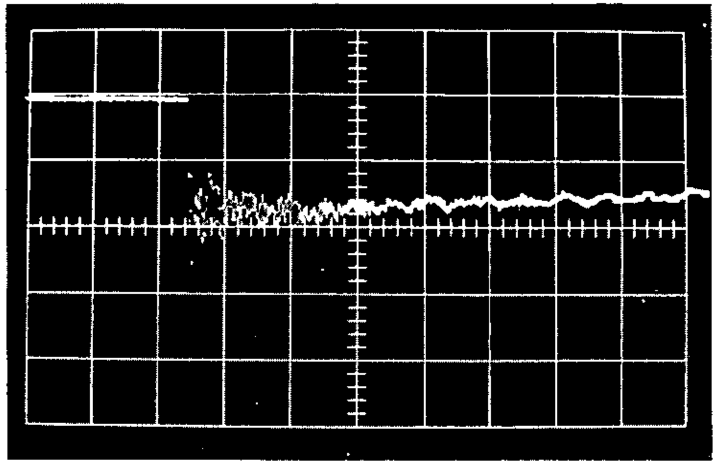


H

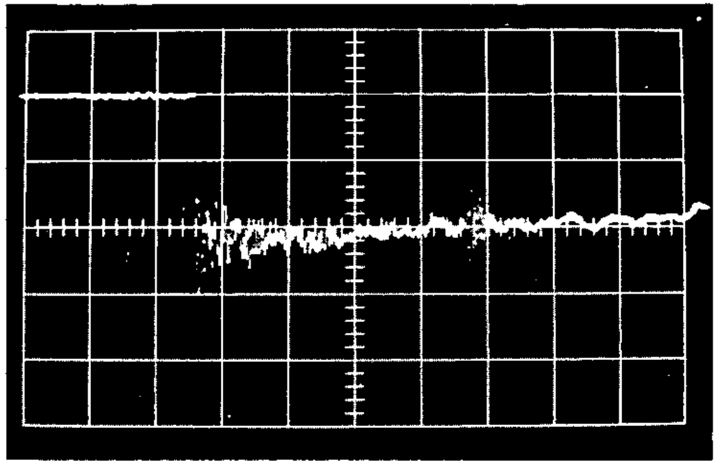
E	40.0 mm Hg
F	58.4 mm Hg
G	75.6 mm Hg
H	97.2 mm Hg

	Sweep	Amp Gain	Osc Sens
E	200 μS/cm	1	5 mV/cm
F	200 μS/cm	3	20 mV/cm
G	200 μS/cm	1	10 mV/cm
H	200 μS/cm	1	10 mV/cm

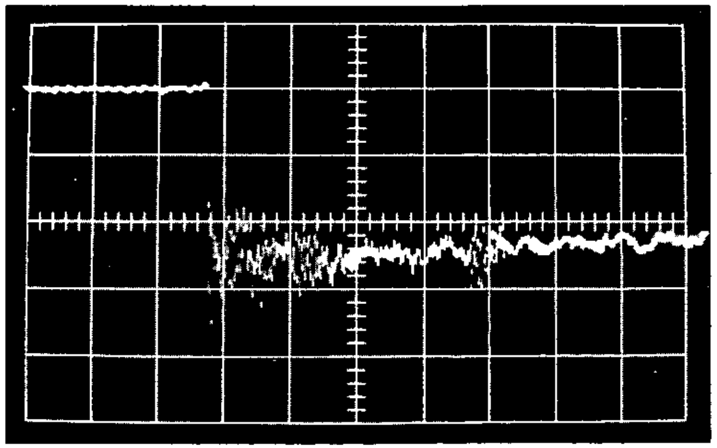
FIG 13 cont'd RESPONSE OF GAUGE 'Y' TO A STEP OF PRESSURE



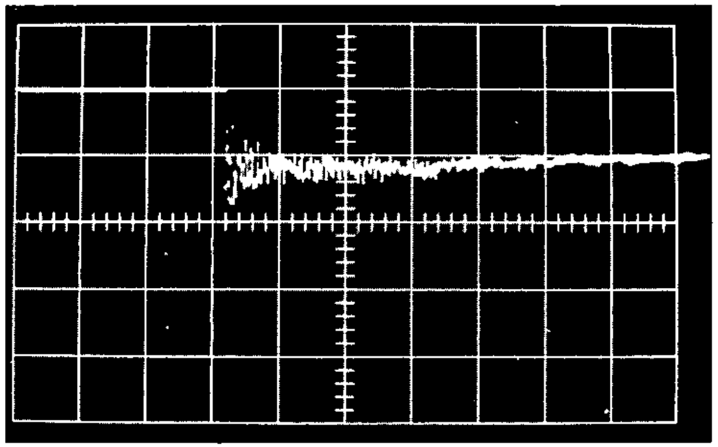
J



K



L

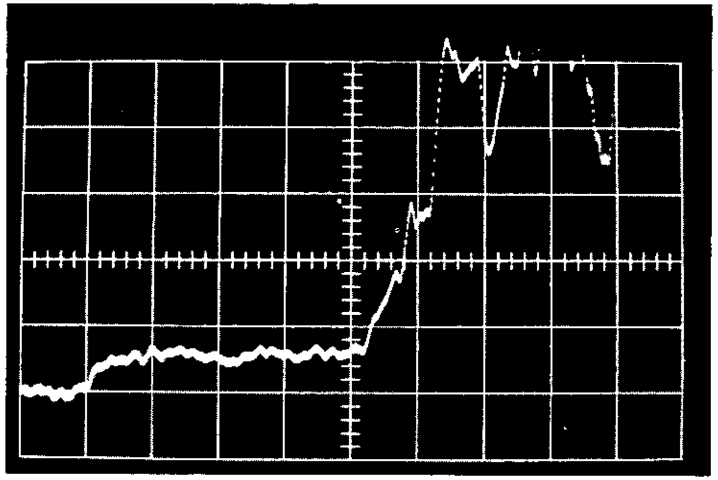


M

J	153 mm Hg
K	211 mm Hg
L	264 mm Hg
M	334 mm Hg

	Sweep	Amp Gain	Osc Sens
J	200 μS/cm	1	20 mV/cm
K	200 μS/cm	1	20 mV/cm
L	200 μS/cm	1	20 mV/cm
M	200 μS/cm	1	50 mV/cm

FIG.13 cont'd. RESPONSE OF GAUGE 'Y' TO A STEP OF PRESSURE



B

B 4.7 mm Hg

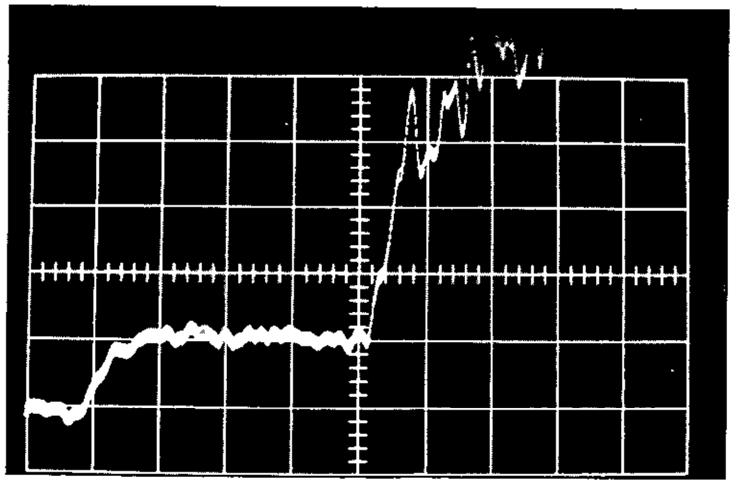
C 10.75 mm Hg

D 19.2 mm Hg

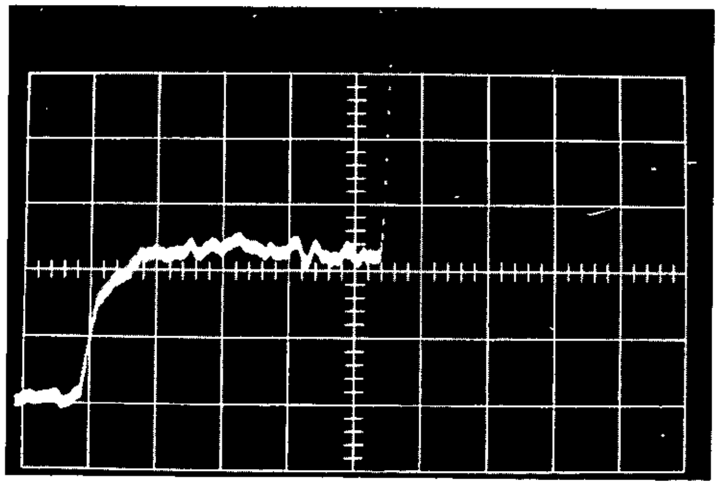
B 200 µS/cm 50 mV/cm

C 200 µS/cm 50 mV/cm

D 200 µS/cm 50 mV/cm

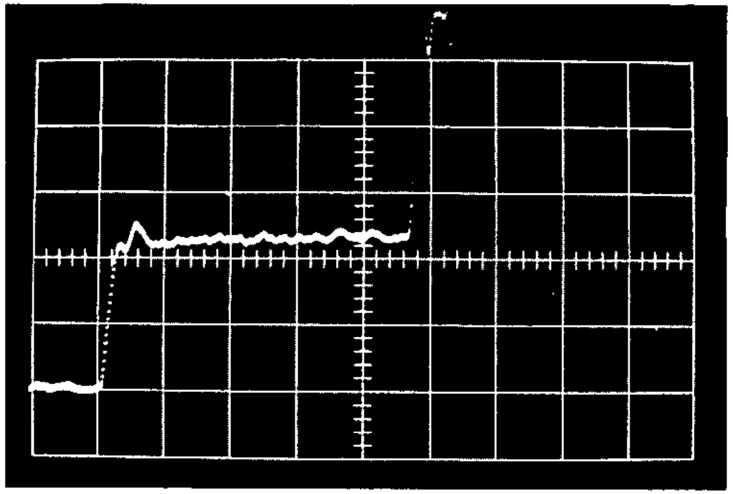


C

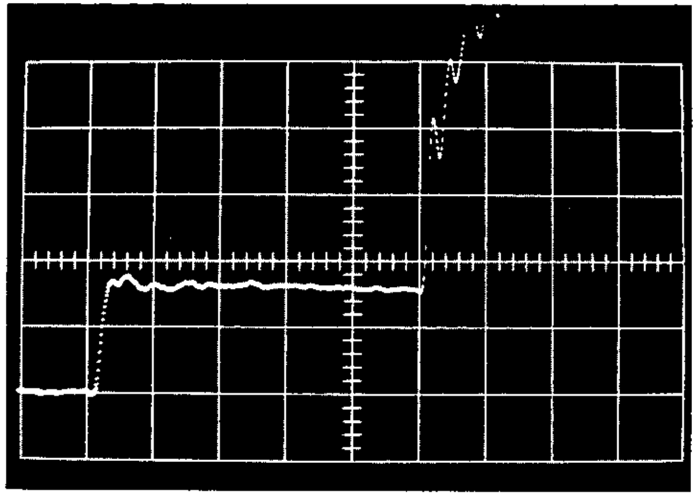


D

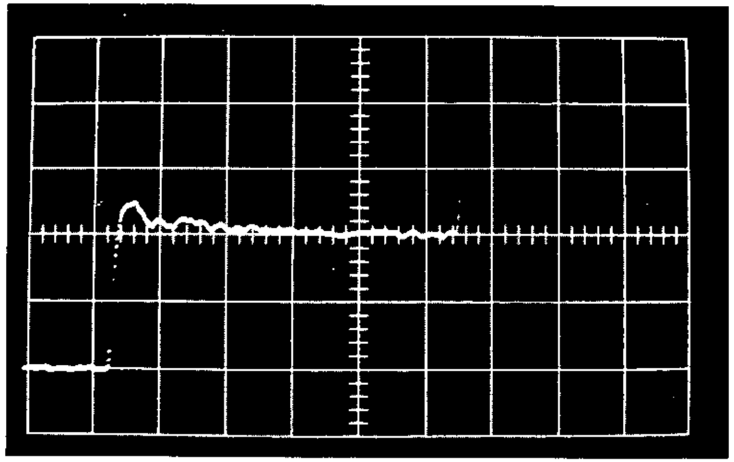
FIG.14. RESPONSE OF DIFFERENTIAL CAPACITY GAUGE 'Z' TO A STEP OF PRESSURE



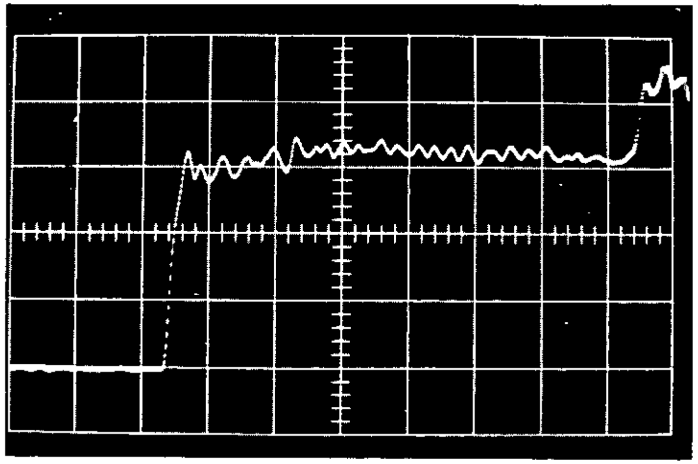
E



F



G

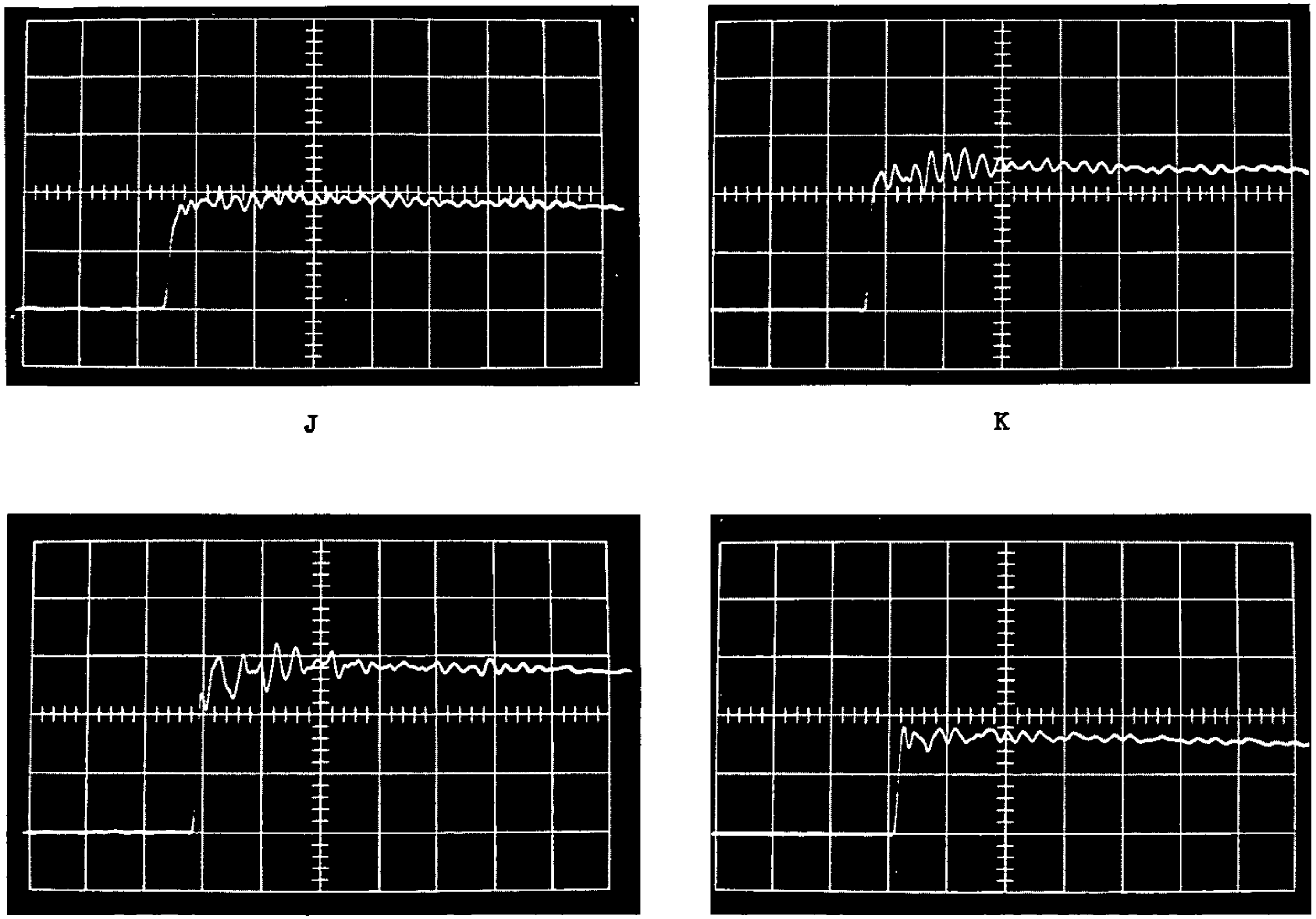


H

E	37.8 mm Hg
F	59.0 mm Hg
G	82.5 mm Hg
H	116 mm Hg

E	200 µS/cm	100 mV/cm
F	200 µS/cm	200 mV/cm
G	200 µS/cm	200 mV/cm
H	200 µS/cm	200 mV/cm

FIG.14 cont'd RESPONSE OF DIFFERENTIAL CAPACITY GAUGE 'Z' TO A STEP OF PRESSURE



J

K

L

M

J 156 mm Hg

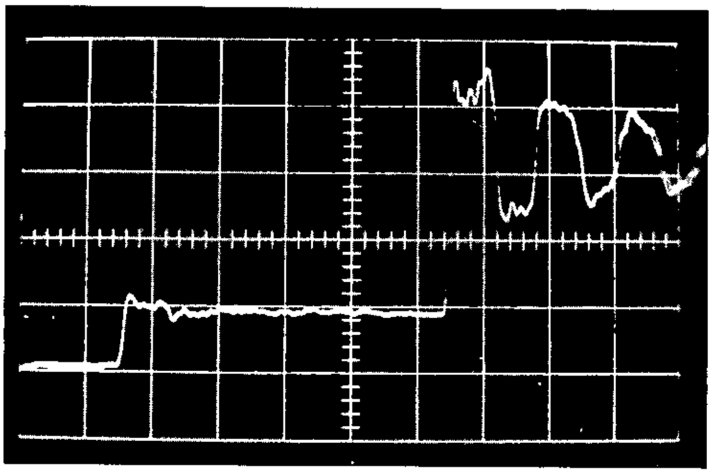
K 213 mm Hg

L 256 mm Hg

M 322 mm Hg

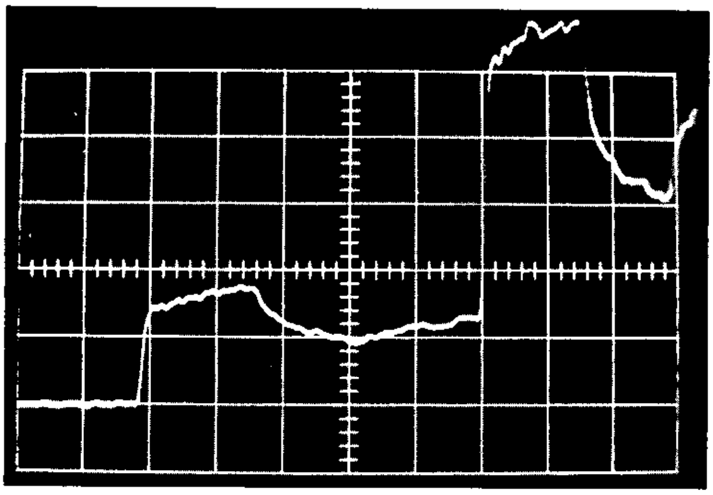
J	200 µS/cm	500 mV/cm
K	200 µS/cm	500 mV/cm
L	200 µS/cm	500 mV/cm
M	200 µS/cm	1000 mV/cm

FIG.14 cont'd. RESPONSE OF DIFFERENTIAL CAPACITY GAUGE 'Z' TO A STEP OF PRESSURE



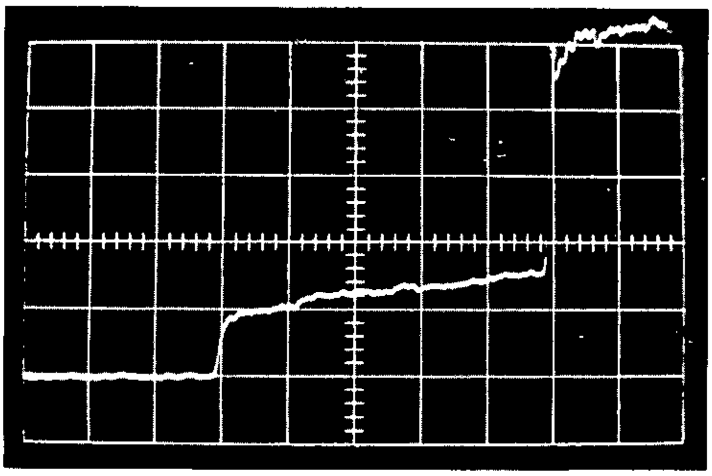
M_s 1.99
P_{step} ~ 65 mm Hg
200 μS/cm

Pressure Inlet Pipe 1 inch



M_s 1.88
P_{step} ~ 65 mm Hg
200 μS/cm

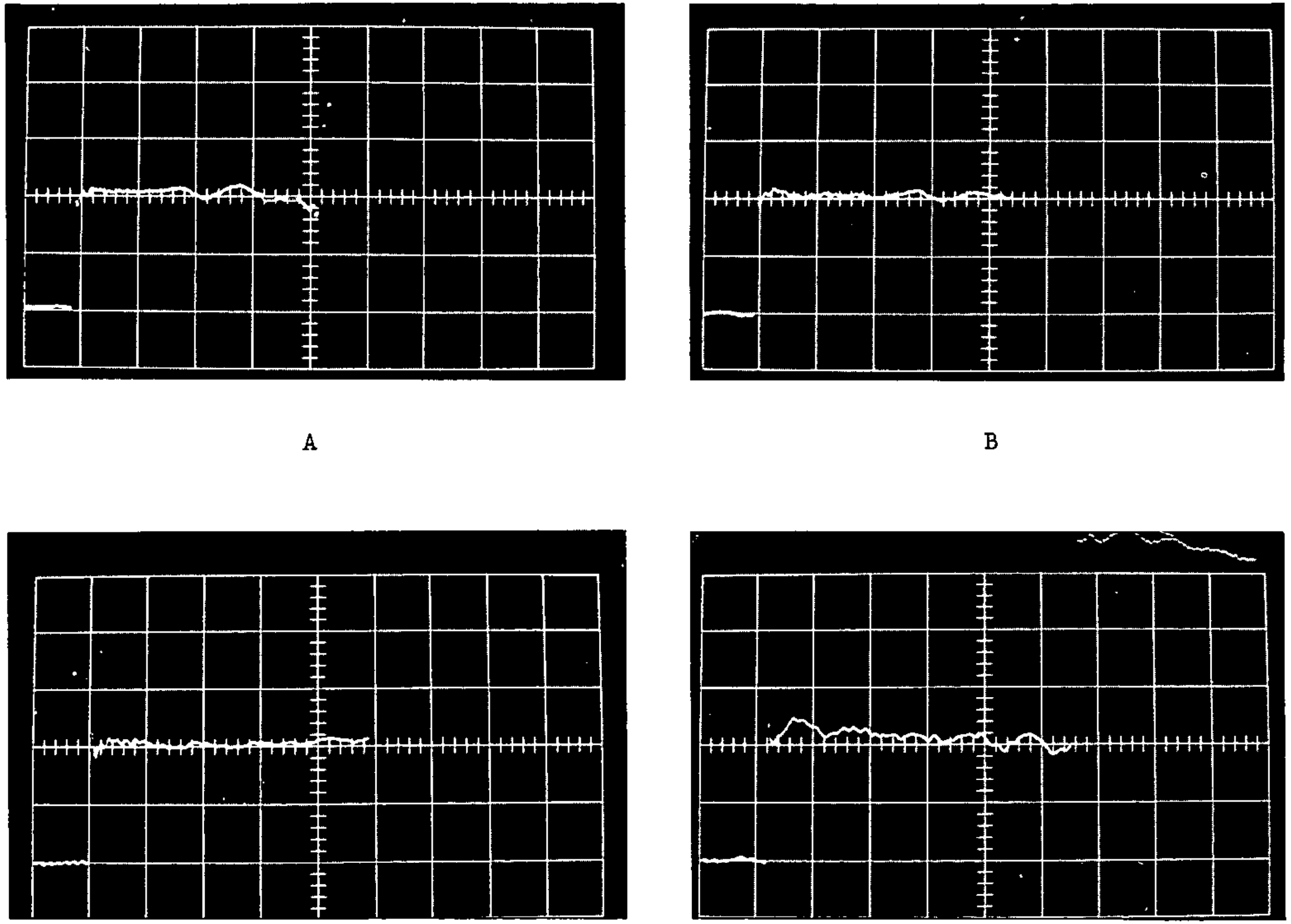
Pressure Inlet Pipe 2 inches



M_s 1.94
P_{step} ~ 65 mm Hg
200 μS/cm

Pressure Inlet Pipe 6 inches

FIG.15 GAUGE 'Z' - EFFECT OF VARYING LENGTH OF PRESSURE INLET PIPE



A B

C D

A 9.9 mm Hg

B 20.3 mm Hg

C 38.3 mm Hg

D 85.0 mm Hg

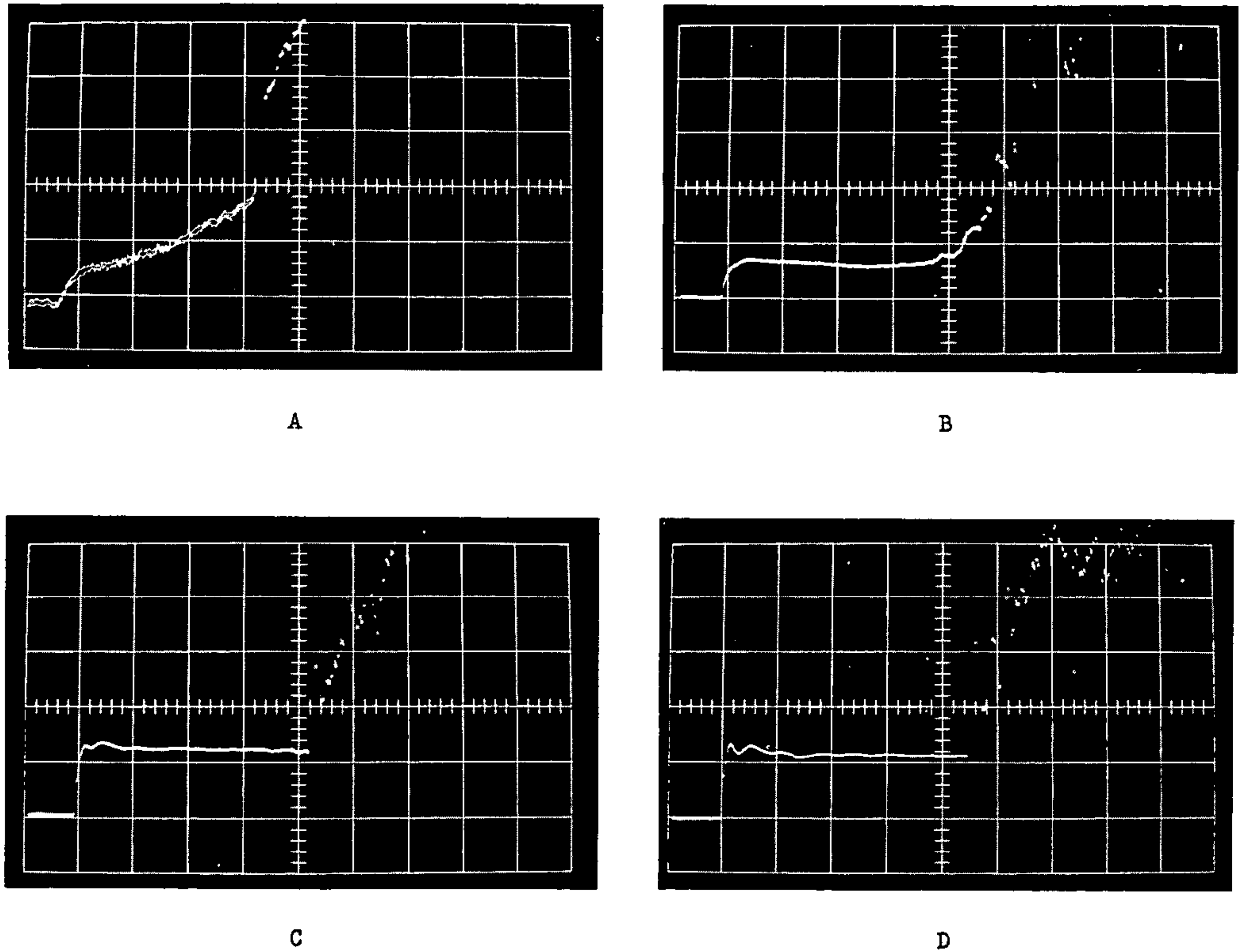
A 200 µS/cm 5 mV/cm

B 200 µS/cm 10 mV/cm

C 200 µS/cm 20 mV/cm

D 200 µS/cm 40 mV/cm

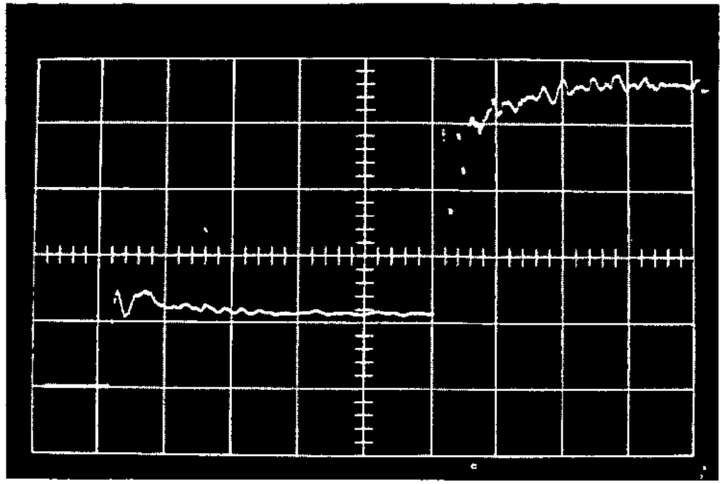
FIG 16 RESPONSE OF 'FREELY' MOUNTED CRYSTAL TO A STEP OF PRESSURE



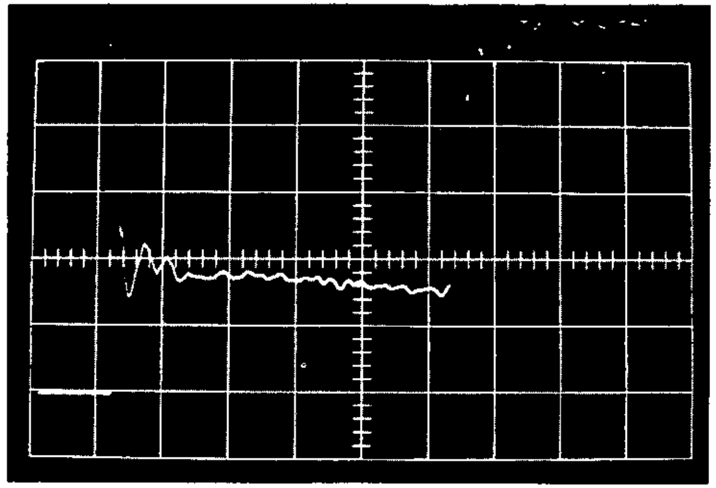
A	1.2 mm Hg	
B	5.6 mm Hg	
C	10.0 mm Hg	
D	19.7 mm Hg	

A	200 μS/cm	0.5 mV/cm
B	200 μS/cm	5 mV/cm
C	200 μS/cm	5 mV/cm
D	200 μS/cm	10 mV/cm

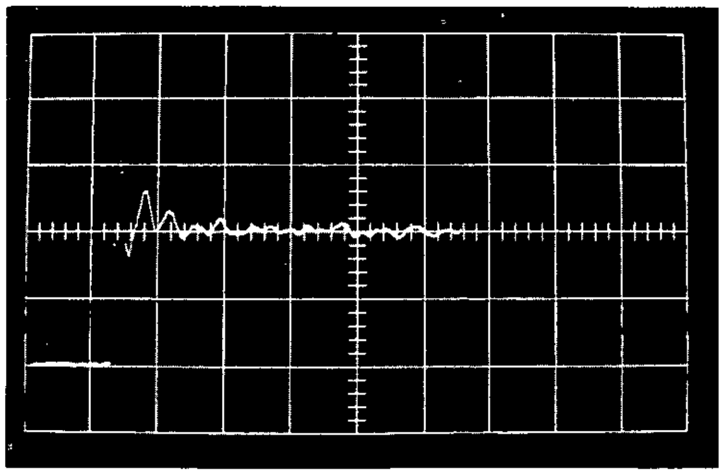
FIG.17. RESPONSE OF CAVITY GAUGE TO A STEP OF PRESSURE



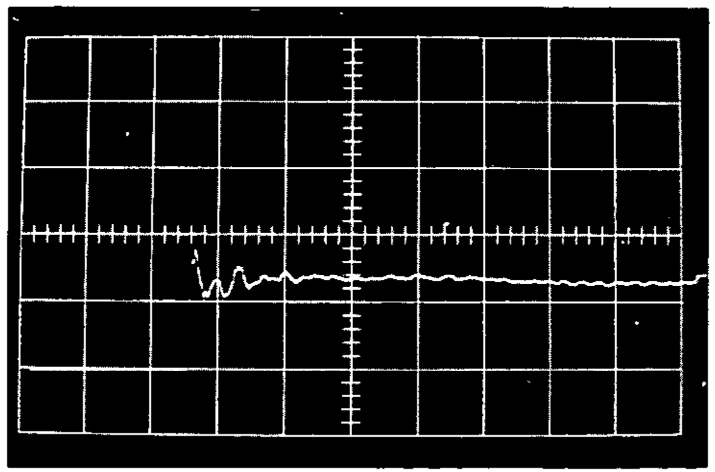
E



F



G

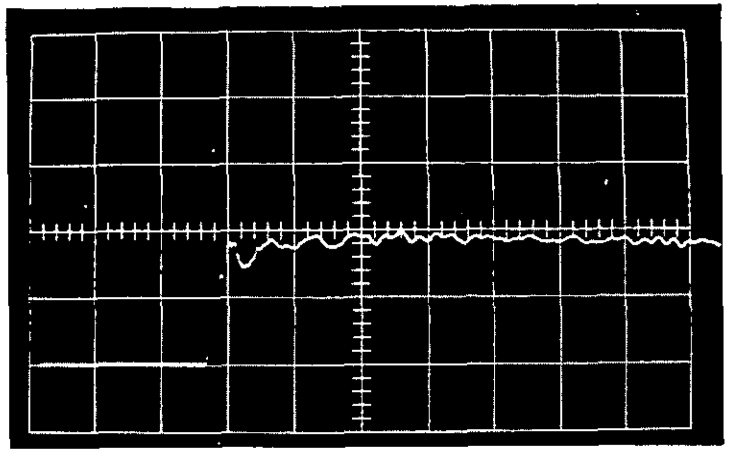


H

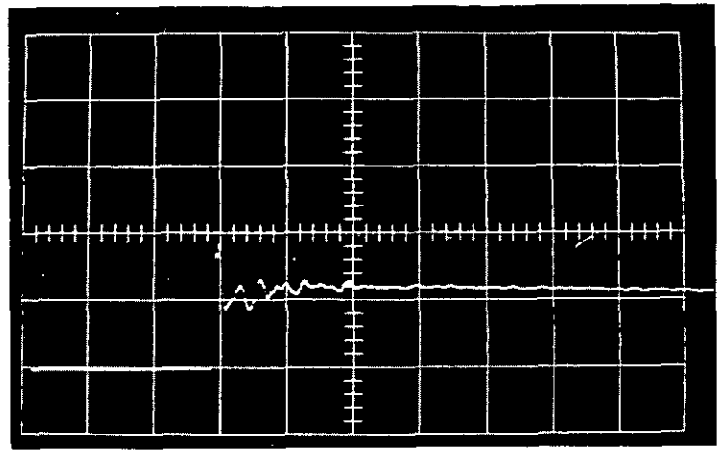
E	38.5 mm Hg
F	55.6 mm Hg
G	80.0 mm Hg
H	112.5 mm Hg

E	200 µS/cm	20 mV/cm
F	200 µS/cm	20 mV/cm
G	200 µS/cm	25 mV/cm
H	200 µS/cm	50 mV/cm

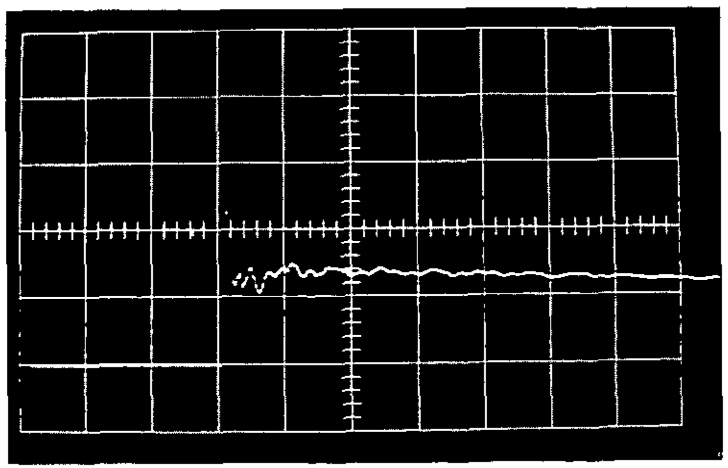
FIG 17 cont'd. RESPONSE OF CAVITY GAUGE TO A STEP OF PRESSURE



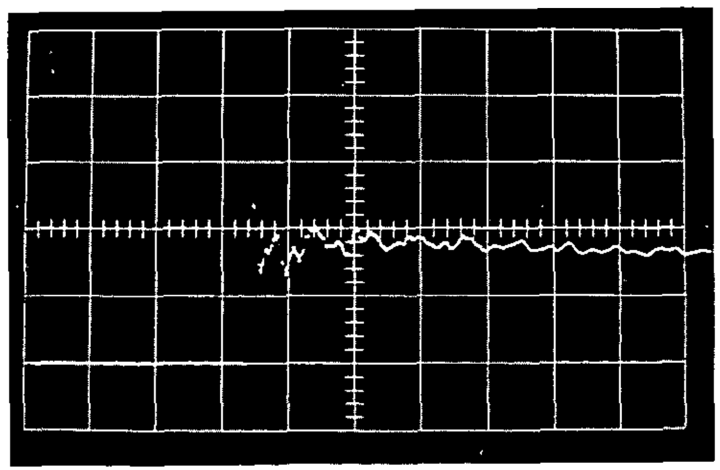
J



K



L

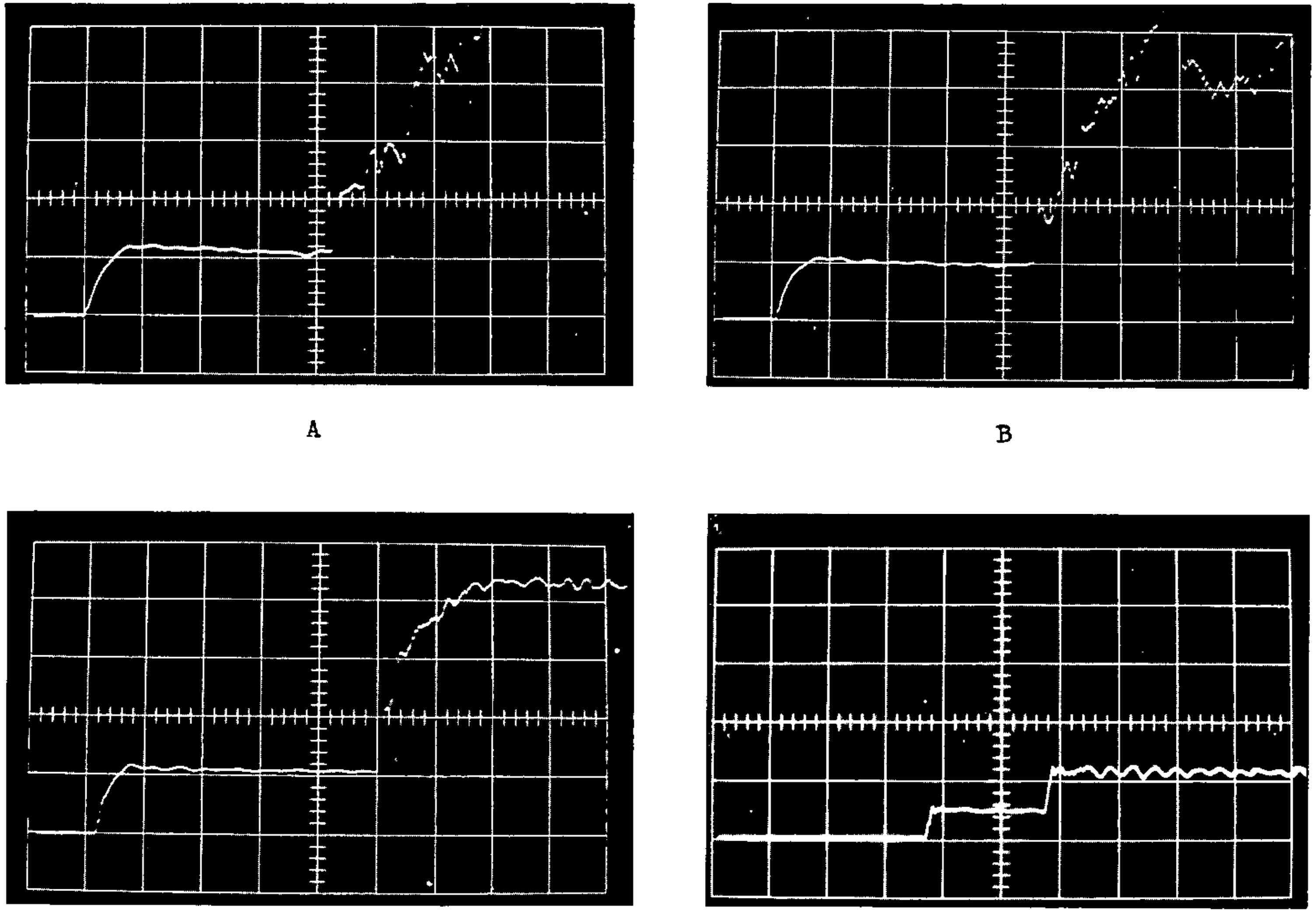


M

J 153 mm Hg
K 207 mm Hg
L 245 mm Hg
M 326 mm Hg

J	200 µS/cm	50 mV/cm
K	200 µS/cm	100 mV/cm
L	200 µS/cm	100 mV/cm
M	200 µS/cm	100 mV/cm

FIG.17 cont'd RESPONSE OF CAVITY GAUGE TO A STEP OF PRESSURE



A 10 mm Hg

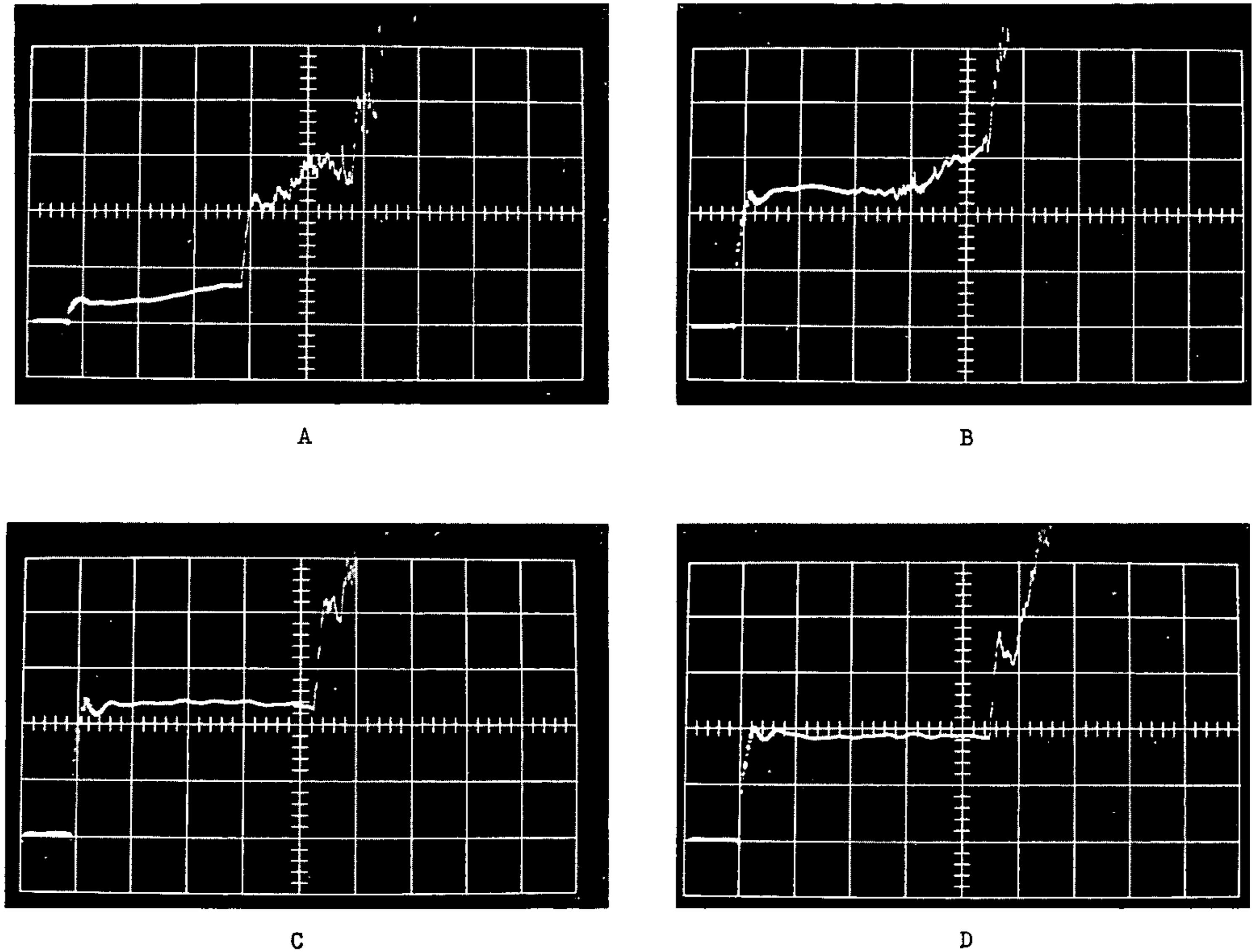
B 18.4 mm Hg

C 37.4 mm Hg

D 158 mm Hg

A - D 200 μSecs/cm

FIG.18 RESPONSE OF CAVITY GAUGE WITH BAFFLE TO A STEP OF PRESSURE



A 1.17 mm Hg

B 5.41 mm Hg

C 10.0 mm Hg

D 18.9 mm Hg

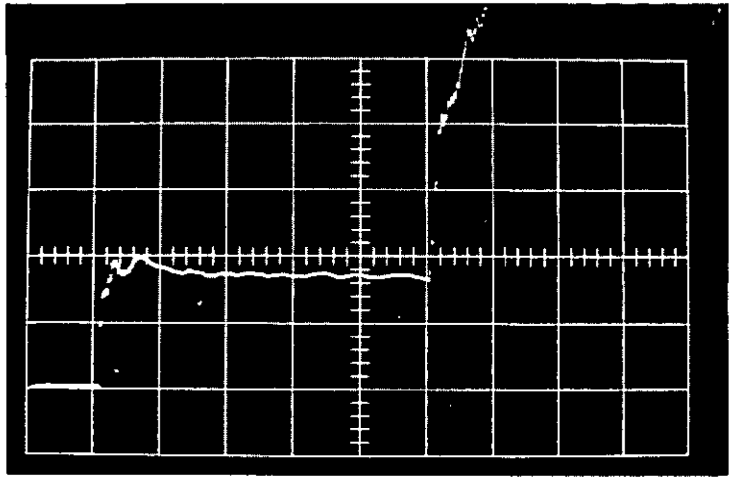
A 200 μS/cm 5 mV/cm

B 200 μS/cm 5 mV/cm

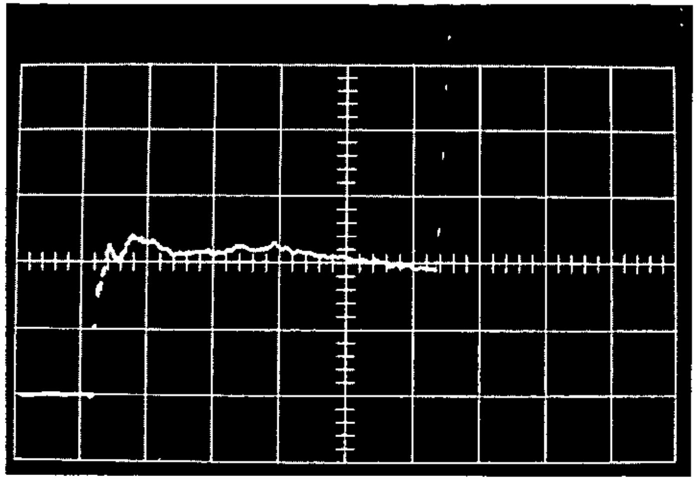
C 200 μS/cm 10 mV/cm

D 200 μS/cm 20 mV/cm

FIG 19. RESPONSE OF TOP HAT GAUGE TO A STEP OF PRESSURE



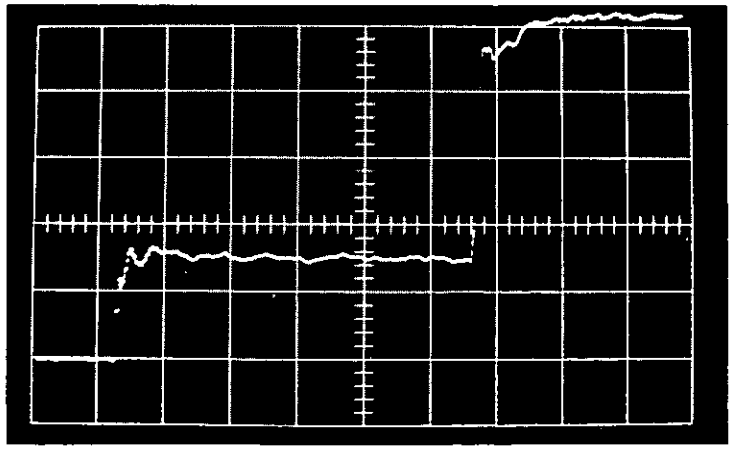
E



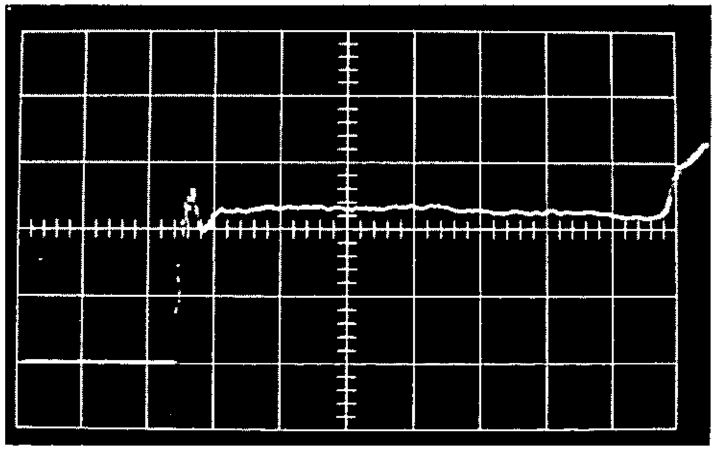
F

E	40.8 mm Hg
F	54 mm Hg
G	77 mm Hg
H	115 mm Hg

E	200 μS/cm	50 mV/cm
F	200 μS/cm	50 mV/cm
G	200 μS/cm	100 mV/cm
H	200 μS/cm	100 mV/cm

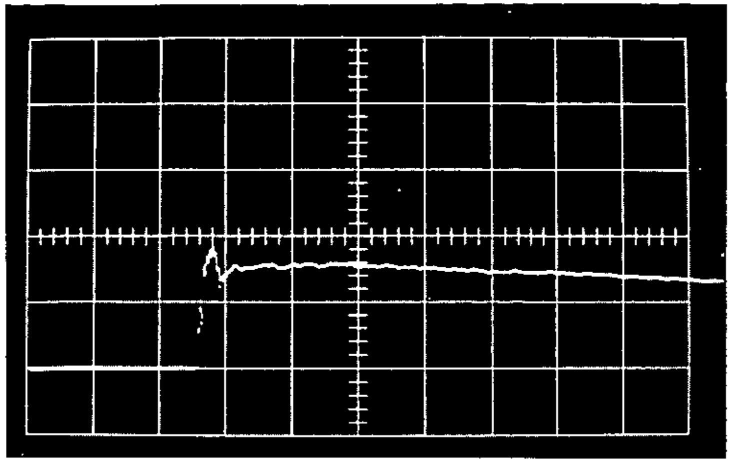


G

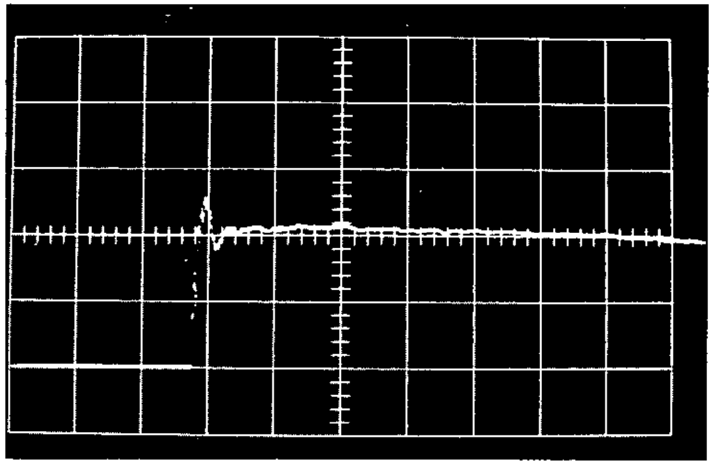


H

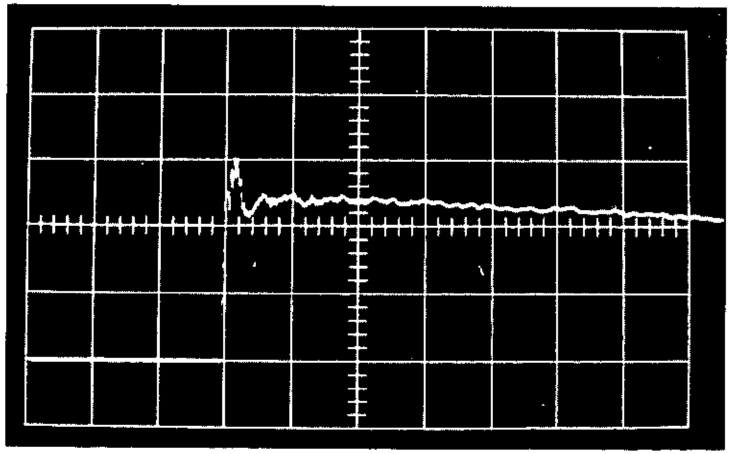
FIG 19 cont'd RESPONSE OF TOP HAT GAUGE TO A STEP OF PRESSURE



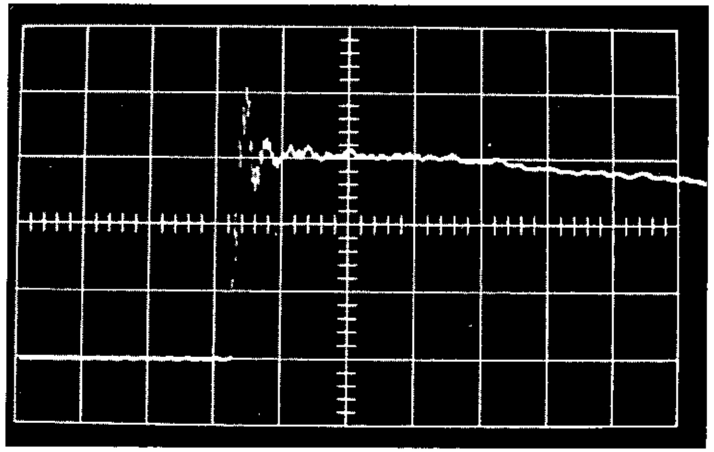
J



K



L



M

J 150 mm Hg

K 204 mm Hg

L 244 mm Hg

M 318 mm Hg

J 200 µS/cm 200 mV/cm

K 200 µS/cm 200 mV/cm

L 200 µS/cm 200 mV/cm

M 200 µS/cm 200 mV/cm

FIG.19 cont'd RESPONSE OF TOP HAT GAUGE TO A STEP OF PRESSURE

A.R.C. C.P. No. 677

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THE EVALUATION OF SOME COMMERCIAL AND DEVELOPMENT PRESSURE GAUGES IN A LABORATORY TYPE SHOCK TUBE WITH A VIEW TO THEIR SUITABILITY FOR USE IN SHOCK TUNNELS. Stevens, D.R. March, 1962.

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