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The Equilibrium Piston Technique for Gun Tunnel Operation

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SUMMARY

A modified technique for the operation of a gun tunnel is suggested based on experimental results. If the piston mass and the initial barrel pressure are chosen correctly, then the peak pressures associated with the gun tunnel may be eliminated. Under these conditions the piston is brought to rest with no overswing. Some measurements of the piston motion using a microwave technique are reported which confirm this idea.

The wave diagram associated with this mode of operation is shown, and some calculations of the stagnation pressure are given which show that during the suggested running time, the stagnation pressure may be considerably greater than the driving pressure if the driving chamber cross-sectional area is large compared with that of the driven section. For a uniform shock tube the stagnation pressure will always be less than the driving pressure. The use of air, helium and hydrogen as driving gases has been considered.

Experiments in a gun tunnel are reported which show that the equilibrium piston technique enables steady stagnation pressures to be achieved over a time of approximately 15 mS using air as the driving gas. The expansion caused by the piston acceleration is shown to interact with the stationary piston, but this is found to produce only a small drop in stagnation pressure.

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1. Introduction

Considerable evaluation of the hypersonic gun tunnel as a device for producing hypersonic flows has taken place[1]. Early calculations based on ideal shock tube performance using real gas equilibrium properties of the driven gas, predicted temperatures up to 4,000°K using air, and 8,000°K using helium as the driving gases. A large amount of experimental data has been amassed using air as the driving and driven gases, and this has shown that the final stagnation temperature is considerably less than predicted. Temperatures slightly in excess of 1,500°K have been the maximum measured.

The reduction in performance has been attributed to several effects, including piston friction, viscous attenuation of the primary shock, and loss of temperature due to a high rate of heat transfer from the heated gas to the cold barrel walls.

Some measurements of heat transfer rate deduced from spark velocity measurement and calorimeter gauge[2,3] have shown this to be of the order of 10 BTU/ft^2/sec for typical conditions of $p_s = 2,000$ p.s.i. and $T_s = 1,500$°K. In terms of temperature loss this gives approximately 10,000°K/sec, i.e., a loss of temperature of 200°K during a run of 20 mS. This effect will be worse for small facilities since a scale factor appears in the analysis.

From these measurements it would appear essential to restrict running times in order to avoid excessive loss of stagnation temperature.

The final temperature attained has also been limited by piston design. It has so far proved impossible to develop a piston

that/

that will withstand conditions corresponding to more than 1,500°K. It should be noted that with the mode of operation outlined in Ref. 1 the piston is subjected to pressures and temperatures considerably greater than the steady state values as a consequence of the high peak pressure developed during the piston overswing. In practice it is found that the peak conditions do not add appreciably to the final tunnel stagnation conditions, and should be eliminated if possible. The following method of operation is suggested to give a hypersonic flow with constant stagnation conditions for times of order 15 mS using air as the driver gas.

2. Description of Equilibrium Piston Technique and Associated Wave Diagram

The s - t wave diagram of the gun tunnel process is shown in Fig. 1.

When the piston slows at the end of the barrel a compression wave C_1 is formed on its rear face. The primary shock S_1 reflects several times between the piston face and the end of the barrel and on each reflection is weakened by the expansion generated by the retarding piston; the limiting condition being a weak compression (sound) wave. The compression C_1 then moves back towards the diaphragm station from which it will be reflected as a rarefaction R_3 because of the area change $(A_4 > A_1)$ at the diaphragm position. During its motion interactions with the expansion waves R_1, and the reflection of R_2 from the end of the driver tube, will take place. In practice R_1 and R_2 are found to be comparatively weak. However, they will be transmitted through the compression C_1 and eventually reach the piston, thereby communicating a pressure drop to the reservoir region S. The strongest wave reaching the piston will be the expansion R_3 which will cause a large drop in stagnation temperature and pressure and will limit the running time.

For a given driving pressure there are two parameters which may be altered, namely the barrel pressure p_1 and the piston mass m. For certain values of p_1 and m the piston is decelerated in such a manner that the pressure behind the wave $C_1 (p_c)$ is just equal to the pressure ahead of the piston (p_s). In general this will not be so, and the peak pressure $(\hat{p})$ generated by the piston deceleration will be greater than the pressure behind the wave C_1. For $\hat{p}$ greater than p_s there will be a piston overswing and subsequent oscillation. These two conditions are illustrated by Fig. 9 (c) and (a).

Referring to Fig. 1, consider a given driving pressure and piston mass and let the barrel pressure p_1 vary. If a high barrel pressure is used, the pressure p_c is larger and hence the piston experiences a greater retardation at the point α. The expansion produced by the decelerating piston will be correspondingly stronger, and hence the subsequent shocks will be weakened. For a lower value of p_1 the piston will experience a smaller deceleration at α and a greater deceleration at β. Thus as the barrel pressure p_1 is increased the characteristics of the piston reversal change. (For higher values of p_1 the mean piston deceleration will be smaller.) Thus there should be a value of p_1 for which the piston comes smoothly to rest. This condition will be referred to as "equilibrium piston" operation of the tunnel.

In considering the quasi-steady pressure and volume relationship in the stagnation region and using the relationship

$$pv^{\gamma} = \text{constant}$$

we/

we obtain
$$\frac{dp}{p} = -\gamma \frac{dv}{v}$$

where $\frac{dp}{p}$ and $\frac{dv}{v}$ are fractional changes in pressure and volume respectively. Since the barrel has constant cross-sectional area we may write

$$\frac{dp}{p} = -\gamma \frac{d\ell}{\ell}$$

where $\frac{d\ell}{\ell}$ is the fractional change in compression length.

In Ref. 11 it is inferred that the pressure at entry to the nozzle is suitable if it remains constant to ±10%. In a gun tunnel this imposes a constriction on the piston perturbation that

$$\frac{d\ell}{\ell} = \pm \frac{10}{\gamma} \approx \pm 7{\cdot}2\%.$$

Thus in a typical compressed length of 9·0 in. the piston must not oscillate greater than ±0·65 in. about its equilibrium.

The experiments reported were carried out in the University of Southampton Gun Tunnel. The principal dimensions are:-

Barrel length 114 in., barrel diameter 1·25 in., breech length 60 in., breech diameter 3·7 in. The tunnel and associated equipment has been fully described in Ref. 1.

For convenience of microwave tracking, the barrel was not connected to the usual nozzle and test section. The microwave aerial block (Fig. 4(b)) which fitted into the barrel in place of the nozzle had a hollow tube of diameter 0·087 in. to simulate an equivalent nozzle.

3. Prediction of Conditions required for Equilibrium Technique

A simple qualitative analysis may be applied to predict the required variation of parameters to give the equilibrium piston mode of operation.

The peak pressure generated in a gun tunnel is caused by bringing the piston to rest. It depends on the kinetic energy of the piston and may be written as

$$\hat{p} \sim \frac{m}{A_1} \cdot \frac{V^2}{2} \qquad \ldots (1)$$

The experimental measurements of Section 5.2 have been correlated on a basis of $\overline{m_1} = \frac{m}{p_1 A}$ and (1) may be written in terms of $\overline{m_1}$ such that

$$\frac{\hat{p}}{p_e} \cdot \frac{p_e}{p_4} \cdot \frac{p_4}{p_1} \sim \overline{m_1} \cdot \frac{v^2}{2} \qquad \ldots (2)$$

For/

For a uniform shock tube with $A_{11} = 1$, the Mach number M_3 may be calculated in terms of the driving pressure and the pressure in region (3):-

$$M_3 = \frac{1}{\beta_4 \gamma_4}\left[(p_{34})^{-\beta_4} - 1 \right]$$

$$\text{i.e.} \quad p_{43} = [1+\beta_4 \gamma_4 M_3]^{\frac{1}{\beta_4}}. \qquad \ldots(5)$$

Using equations (4) and (5) together with the relationship

$$p_{e_4} = p_{e_3} \cdot p_{34} \qquad \ldots(6)$$

then p_{e_4} may be evaluated in terms of M_3.

$$\text{Now} \quad p_{41} = \frac{1}{\alpha_1}\left(\frac{M_s^2}{\beta_1} - 1\right)\left[1 - \left(\frac{\gamma_4 - 1}{\gamma_4 + 1}\right) \cdot \frac{a_1}{a_4} \cdot \left(M_s - \frac{1}{M_s}\right)\right]^{-\frac{1}{\beta_4}} \qquad \ldots(7)$$

$$\text{and} \quad M_s = [\beta_1 (1+\alpha_1 p_{21})]^{\frac{1}{2}}. \qquad \ldots(8)$$

Thus we have expressions for p_{21} and p_{41} in terms of the primary shock Mach number M_s. Substituting (7) and (8) into equation (5) and then evaluating (6) we have the required result, p_{e_4} in terms of M_s. By a similar manipulation p_{e_4} may be obtained in terms of either p_{41} or p_{21}.

4.2 Effect on stagnation pressure of an area change at the diaphragm position

It has been shown[4] that for a given value of p_{41}, stronger shocks may be generated if the cross-sectional area of the driver chamber (A_4) is greater than that of the driven chamber (A_1).

The following calculations have been carried out to show how such an area change affects the stagnation pressure p_s for a given value of M_s. The flow in shock tubes with area change has been studied by Alpher and White[4] and will be merely outlined in this report. Some of the data used has been obtained from charts in Ref. 5.

The equations of the flow are found to be

$$g\, p_{41} = p_{21}\left[1 - \frac{\beta_4 \gamma_4}{a_{41}} \cdot u_{21}(g)^{-\beta_4}\right]^{-\frac{1}{\beta_4}} \qquad \ldots(9)$$

$$\text{where} \quad g = \left[\frac{1 + \beta_4 \gamma_4 M_7^2}{1 + \beta_4 \gamma_4 M_*^2}\right]^{-\frac{1}{2\beta_4}} \left[\frac{1 + \beta_4 \gamma_4 M_*}{1 + \beta_4 \gamma_4 M_7}\right]^{-\frac{1}{\beta_4}}. \qquad \ldots(10)$$

The area change determines the Mach numbers M_* and M_7 which

$$\text{are given by} \quad \frac{A_4}{A_1} = \frac{M_*}{M_7}\left[\frac{1 + \beta_4 \gamma_4 M_7^2}{1 + \beta_4 \gamma_4 M_*^2}\right]^{\frac{\alpha_4}{2}}. \qquad \ldots(11)$$

Note that if $A_{41} \to \infty$, $M_7 \to 0$.

The/

The function g has been evaluated for a range of A_{41}, γ_4 and M_7 in Ref. 4.

Now for a uniform shock tube

$$p_{41} = p_{31}\left[1 - \frac{\gamma_4 \beta_4}{a_{41}} \cdot u_{21}\right]^{-\frac{1}{\beta_4}} . \qquad \ldots(12)$$

Comparing this with equation (9) it may be noted that a shock tube with an area ratio A_{41}, pressure ratio p_{41} and sound speed ratio a_{41}, will generate a shock of strength equal to that in a simple constant area shock tube with pressure ratio $g.p_{41}$, sound speed ratio $a_{41}(g)^{\beta_4}$, equal γ_4 and equal γ_1.

The performance may then be determined directly in terms of that of the equivalent constant area shock tube. Data may be obtained to plot curves of p_{41} vs M_s or p_{21}.

For the University of Southampton Gun Tunnel the area ratio $A_{41} = 8{\cdot}78$. It may be shown that the theoretical performance for such an area ratio is almost identical with that for a value of $A_{41} \to \infty$. If this is so then $M_7 = 0$ and the pressure ratio across the expansion wave is given by the following expression

$$\underline{M_3 < 1} \qquad p_{43} = (1+\beta_4 \gamma_4 M_3^2)^{\frac{1}{2\beta_4}} \qquad \ldots(13)$$

$$\underline{M_3 > 1} \qquad p_{43} = \left(\frac{1}{\alpha_4 \beta_4 \gamma_4}\right)^{\frac{1}{2\beta_4}} (1+\beta_4 \gamma_4 M_3)^{\frac{1}{\beta_4}} . \qquad \ldots(14)$$

Also the velocity in region (3) is related to the Mach number in region (3) by

$$\underline{M_3 < 1} \qquad \frac{u_3}{a_4} = \frac{M_3}{(1 + \beta_4 \gamma_4 M_3^2)^{\frac{1}{2}}} \qquad \ldots(15)$$

$$\underline{M_3 > 1} \qquad \frac{u_3}{a_4} = (\alpha_4 \beta_4 \gamma_4)^{\frac{1}{2}} \left(\frac{M_3}{1 + \beta_4 \gamma_4 M_3}\right) . \qquad \ldots(16)$$

Now

$$u_{34} = u_{21} \cdot a_{14} . \qquad \ldots(17)$$

The particle velocity behind the shock and the shock Mach number are given in terms of the shock pressure ratio by

$$u_{21} = \frac{p_{21} - 1}{\gamma_1 [\beta_1 (\alpha_1 p_{21} + 1)]^{\frac{1}{2}}} \qquad \ldots(18)$$

$$M_s = [\beta_1 (1 + \alpha_1 p_{21})]^{\frac{1}{2}} . \qquad \ldots(19)$$

By using equations (14)-(19) p_{43} may be evaluated in terms of M_s. Equations (4), (5) and (6) then give p_{e4} in terms of M_s. Similarly p_{e4} may be evaluated in terms of p_{41}.

If/

If the piston has reached an equilibrium position and if the frictional force on the piston is small then the pressure ahead of the piston is equal to the pressure behind and $p_{s4} = p_{e4}$.

4.3 Results of calculations

Curves of p_{e4} versus p_{41} and versus M_s are shown in Figs. 2 and 3 for driving and driver gas combinations of air:air, helium:air and hydrogen:air. The cases of $A_{41} \to \infty$ and $A_{41} = 1$ have been considered.

The results show that if $A_{41} = 1$ then the ratio p_{e4} is always less than unity under normal operating conditions. However, if $A_{41} \to \infty$, the ratio p_{e4} is greater than unity over a certain range of M_s, and the stagnation pressure may be as much as twice the driving pressure if helium is used as the driving gas. Since the final stagnation temperature attained is largely determined by the strength of the incident shock, Fig. 2 may be interpreted as a qualitative prediction of stagnation pressure ratio versus stagnation temperature for given gases. Using this interpretation it can be seen that air:air operation gives a higher stagnation pressure for a given temperature in the range $1 < M_s < 2$, while helium offers a considerable increase over air and a small increase over hydrogen in the range $2 < M_s < 4$. For $M_s > 4$ hydrogen gives higher ratios of p_{e4}. For all cases, a considerable increase of stagnation pressure is obtained by using a breech of large cross-sectional area compared with the barrel.

The gun tunnel on which measurements have been made has a value of A_{41} of 8·78. Theoretically this should give a performance very close to that for a value of $A_{41} \to \infty$. Some pressure measurements described in Section 5.2 show that the stagnation pressure lies between that given by theory with $A_{41} \to \infty$ and $A_{41} = 1$. The stagnation temperature will be lower than theory based on $A_{41} \to \infty$ since it has been found that the primary shock strength is below that predicted by theory[1].

5. Experimental Investigation

5.1 Description of microwave technique for measurements of piston motion

A microwave technique[6] which had been developed previously in the University of Southampton hypersonic gun tunnel[7] was used for this latter set of measurements.

This simple form of microwave interferometer consists essentially of a reflector Klystron oscillator, ferroxcube isolator, waveguide directional coupler, matching stub, coaxial transition and monitoring crystal holder connected as shown in Fig. 4. A radially symmetric (TM_{01}) mode is established in the gun barrel. The light piston has a shim metalled face, and the resultant of the reflected signal and instantaneous transmitted signal amplitude undergoes a maximum to minimum change in voltage for a change in piston position of $\lambda/4$ (where λ is the wavelength measured in the barrel).

It is convenient to measure the times at which maxima, or minima, occur and to relate these to successive displacements of $\lambda/2$ made by the piston. There is therefore a continuous record of piston motion which is independent of piston velocity. Earlier microwave measurements

made/

made at R.R.E., Malvern[8], on shock wave velocities compared the frequency of the instantaneous transmitted and reflected signals and deduced a Doppler velocity relationship. Because the piston motion in a gun tunnel has two conditions of zero velocity at which an accurate knowledge of position is needed, a displacement measurement is to be preferred.

The resulting signals were displayed on a Tektronix 535 Oscilloscope using an external triangular time base, coupled with a "ramp" generator to provide a raster display having an equal "sweep" and "flyback" period. The total time for each line was 2 mS, and 0·5 mS markers (derived from a 1 mc/s crystal standard) were superimposed as blackout marks on the trace (Fig. 5). The total recorded time can be of order 32 mS.

The Klystron oscillator frequency used for these experiments gave a $\lambda/2$ in the 1·25 in. internal diameter of the barrel, of 1·04 in. The distance between the aerial face and the diaphragm station (i.e., the starting position of the piston) was 114·5 in., from which the skirt length of the piston was subtracted to give the available length for piston travel.

It is more convenient when drawing the "s - t" diagram to plot "number of fringes" as the independent variable rather than geometric distance, and to dimension separately any particular length that is of interest, such as "remaining volume of gas".

With the particular gun barrel dimension, and the only available Klystron, the points at which the piston position are precisely known for any given time, are at intervals of 1·045 in. Estimates can be made between any successive signal maxima, but the signal amplitude is not necessarily sinusoidally related[9]. Thus at piston reversals some doubt of piston position may exist if the actual reversal point occurs between two maxima, but since the direction of piston motion can be positively deduced, the uncertainty of piston position is within $\lambda/4$ (i.e., in this instance within 0·5 in. in 114·5 in.). Estimates of error in measurement of piston position resulting from change of permittivity due to presence of shock waves, suggest a positional error of 5% at the conditions used in this investigation.

5.2 Piston trajectory and pressure-time history results

Measurements of stagnation pressure (using an S.L.M. PZ14 Transducer) and piston velocity and position (using a microwave technique) have been made to check the proposals of Sections 2-4. Barrel pressures were measured with a transducer mounted in the side wall of the barrel just ahead of the nozzle entrance. From these measurements the equilibrium pressure p_e and the ratio of peak pressure ($\hat{p}$)) to equilibrium pressure were noted. The piston velocity and position at any instant were obtained as described in Section 5.1 simultaneously with the pressure.

Fig. 6 shows an experimental s - t diagram of the piston motion and is correlated with the pressure record for the same run. The s - t diagram shows the piston acceleration, constant speed and deceleration. For the run shown the piston comes to rest smoothly and with no overswing. It then remains steady (except for a small movement imparted by the rarefaction waves R_1 and R_2) for approximately 15 m.sec. After this time the wave R_3 reaches the piston and causes a large rearward movement accompanied by a drop in stagnation pressure.* From the records the mean

pressure/

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*The fall in stagnation pressure may be eliminated by inserting a partial blockage at the diaphragm station. The compression C_1 then passes through without disturbance and no reflected waves result. However, the partial blockage reduces the strength of the primary shock and the value of p_{e_4} and hence T_{e_4} will be smaller for a given p_{41}.

pressure (p_e) during the first 20-25 m.sec has been measured, after the disturbance due to piston overswing has decayed. The magnitude of the peak pressure attained during the shock reflection process has been noted.

A graph of p_{e4} vs. p_{14} is shown in Fig. 7 and compared with the theoretically predicted equilibrium pressures calculated in Section 4. This shows that over the range of p_4 considered (600 p.s.i. < p_4 < 3000 p.s.i.), the equilibrium pressure p_e is between 1·0 and 1·3 p_4 over the range $10 < p_{41} < 100$. Comparison with the theoretical curves shows that the equilibrium pressure p_e is greater than that which would be expected using a constant area ($A_{41} = 1$) shock tube, but less than that for a configuration with $A_{41} \rightarrow \infty$. The difference between theory and experiment is thought to be due to a combination of effects such as imperfect diaphragm opening, shock attenuation and piston friction.

Some of the scatter of results is also probably due to differences in diaphragm rupturing between runs. An incomplete opening gives an effective restriction at the diaphragm station. Some of the expansion from the driving gas is then due to a steady expansion with consequent loss of performance.

The measurements do show that slightly higher flow stagnation temperatures may be expected due to the higher stagnation pressure, if the mode of operation outlined in this report is used. They also show that some advantage is to be gained if the ratio A_{41} is large, although the increase is smaller than would be theoretically predicted.

Measurements showing the ratio $\hat{p}/p_e$ are shown in Fig. 8. Experiments have been performed over a range of values of m(3·5gm < m < 15gm), p_1 and p_{41}. The results are presented showing $\hat{p}/p_e$ plotted against

$$\overline{m_1} \left(= \frac{m}{p_1 A_1} \right)$$ for each value of p_{41}. The piston mass has been

non-dimensionalized with respect to p_1 such that motions with constant values of $\overline{m_1}$ should be similar, since the deceleration is mainly dependent on the value of p_1. For different values of p_{41} the motions for a given $\overline{m_1}$ will be different and $\hat{p}/p_e$ will consequently vary (lower values of p_{41} give higher $\hat{p}/p_e$ for constant $\overline{m_1}$ - see Section 3). Fig. 8 shows that for a given p_{41}, $\hat{p}/p_e \rightarrow 1$ as $\overline{m_1}$ becomes small. The value of m for which $\hat{p}/p_e$ is less than 1·05 may be estimated for a given value of p_{41}. If $\hat{p}/p_e$ is close to unity then the piston has been brought to rest smoothly and equilibrium piston operation has been achieved.

To achieve the low value of $\overline{m_1}$ required for this either m may be reduced or p_1 increased. A lower limit exists for the piston mass, since sufficient rigidity must be retained to avoid toppling and distortion. If p_1 is increased then p_4 must also be increased to maintain the same value of p_{41} and hence stagnation temperature. Thus an increase in driving pressure affords the best means of achieving a sufficiently low value of $\overline{m_1}$. It may be noted that a value of $\overline{m_1}$ of order 10^{-4} is required to make $\hat{p}/p_e$ less than 1·05.

Some simultaneous piston trajectories and pressure-time records are given in Fig. 9. These are for three values of $\overline{m_1}$, giving large piston overswing to no piston overswing. It should be noted that these diagrams show only the portion of the s - t and p - t diagram during and immediately after the shock reflection process.

Some typical records of barrel pressure from 4-29 mS are shown in Fig. 10. Traces (a) and (b) are for values of $\overline{m_1}$ of $6 \cdot 75 \times 10^{-4}$ and $3 \cdot 75 \times 10^{-4}$ respectively. For these values there is a large

piston/

piston overswing and hence high peak pressures. Traces (c) and (d) are for the same value of p_4 (2465 p.s.i.) but (c) has a value of $\overline{m}_1$ of $0{\cdot}74 \times 10^{-4}$ giving no piston overswing. For this condition the peak pressure is approximately equal to the equilibrium pressure.

6. Concluding Remarks

The investigation reported shows that by choice of piston mass and barrel pressure it is possible to eliminate the peak pressure which occurs using air as the driving gas in the hypersonic gun tunnel. If this mode of operation is used, microwave piston tracking has shown that the piston is brought smoothly to rest without overswing.

If the peak pressure is eliminated, the stagnation region of the gun tunnel is subjected to peak conditions no greater than the steady stagnation conditions. The problem of considerable overshoot in pressure and temperature led to the abandonment of the gun tunnel (with piston)[11]. The conditions required to produce high stagnation temperatures and pressures were such that the peak conditions generated during the compression resulted in damage to the stagnation region of the tunnel and contamination of the test gas. The elimination of overswing conditions should permit an increase in the maximum attainable stagnation conditions.

Although the equilibrium piston technique imposes less severe conditions during the piston deceleration, the piston acceleration becomes greater since lighter pistons are required. Thus the problem of piston destruction during deceleration is less severe, but for very light pistons failure may occur due to the high initial acceleration loading.

If $A_{41} = 1$, then in general the stagnation pressure will be less than the driving pressure. For A_{41} large, then calculations show that immediately after the piston is brought to rest, the stagnation pressure may be up to $2p_4$ if helium is used as the driving gas, and $1{\cdot}8p_4$ if air is used. This considerable increase in stagnation pressure (which experiment confirms) should give a slight increase in stagnation temperature, and therefore result in a worthwhile overall increase in performance.

The mechanism of the motion shows that the piston is brought to rest smoothly by the shock reflection process. The shock caused by the piston deceleration travels rearwards towards the diaphragm and is reflected as an expansion wave which interacts with the piston and limits the running time (for the U. of S. tunnel using air as the driving gas this is approximately 20 mS).

The main limitation on running time with $A_{41} > 1$ is due to the interaction of the compression C_1 reflected from the diaphragm station, with the piston. This produces a large drop in stagnation pressure. A further increase of running time is therefore possible with a constant area tube ($A_{41} = 1$), since only a very weak wave will return from the diaphragm station as a result of blockage. With no blockage, no wave will be reflected other than from the furthermost end of the driver chamber.

The expansion waves from the piston acceleration R_5 and from the expansion moving into the driving gas R_4 also interact with the piston and cause small changes in the stagnation pressure during the proposed running time.

From Figs. 9(a) and 9(c) it can be seen that some 3-4 mS of steady stagnation conditions can be gained initially by eliminating the piston oscillation.

Using/

Using the mode of operation suggested in this report the flow in a gun tunnel is almost equivalent to that in the equilibrium contact surface shock tunnel[10]. Certain advantages are to be expected using a piston since this will avoid mixing of hot and cold gas at the interface and prevent the acceleration of the contact surface. The piston also prevents contamination of the driving gas and forms a seal which enables an expensive driving gas to be reclaimed. The shock reflection compression process is slightly different, in that the reflection of a shock from a solid surface differs from the reflection from a contact surface. It would be expected for the gun tunnel that the equilibrium pressure p_c would be achieved more rapidly since the initial shock reflections would be stronger.

The measurements so far reported have considered only air as a driving gas. This means that possible stagnation temperatures will not be greater than 2,000°K. Some recent measurements[2] have shown that for a stagnation temperature of 1,600°K a fall in temperature of approximately 200°K is encountered during a run of 25 mS. Maximum pressures so far used have been $p_4 = 3{,}000$ p.s.i.

Further experiments are required to determine whether the use of helium or hydrogen result in the higher stagnation pressures and temperatures theoretically predicted. It is also uncertain if it will be possible to use the equilibrium piston technique to avoid high peak pressures when using different driving gases. Considerable development of piston design is required if it is to withstand the temperatures which should be encountered with light driving gases. Piston strength problems could possibly limit the use of a gun tunnel to air operation only. Experiments are required to investigate this. At present very little work has been carried out at pressures greater than $p_4 = 4{,}000$ p.s.i. Experiments at higher values of p_4 would be extremely useful.

Acknowledgement

To S.E. Laboratories, Feltham, Middlesex, for the loan of a Lumiscript recorder used in the early stages of this investigation.

7. List of Symbols

a	speed of sound $\left(a_{ij} = \dfrac{a_i}{a_j} \right)$
m	piston mass
$\overline{m_1}$	non-dimensional piston mass $\left(= \dfrac{m}{p_1 A_1} \right)$
$\overline{m_4}$	non-dimensional piston mass $\left(= \dfrac{m}{p_4 A_1} \right)$
p	static pressure $\left(p_{ij} = \dfrac{p_i}{p_j} \right)$
$\hat{p}$	peak pressure generated during shock reflection
u	flow velocity $\left(u_{ij} = \dfrac{u_i}{a_j} \right)$

v/

v piston velocity

A cross-sectional area $\left(A_{ij} = \frac{A_i}{A_j} \right)$

M Mach number

M_s shock Mach number

α $\frac{\gamma+1}{\gamma-1}$

β $\frac{\gamma-1}{2\gamma}$

γ ratio of specific heats

ρ density.

The notation of suffices is shown in Fig. 1.

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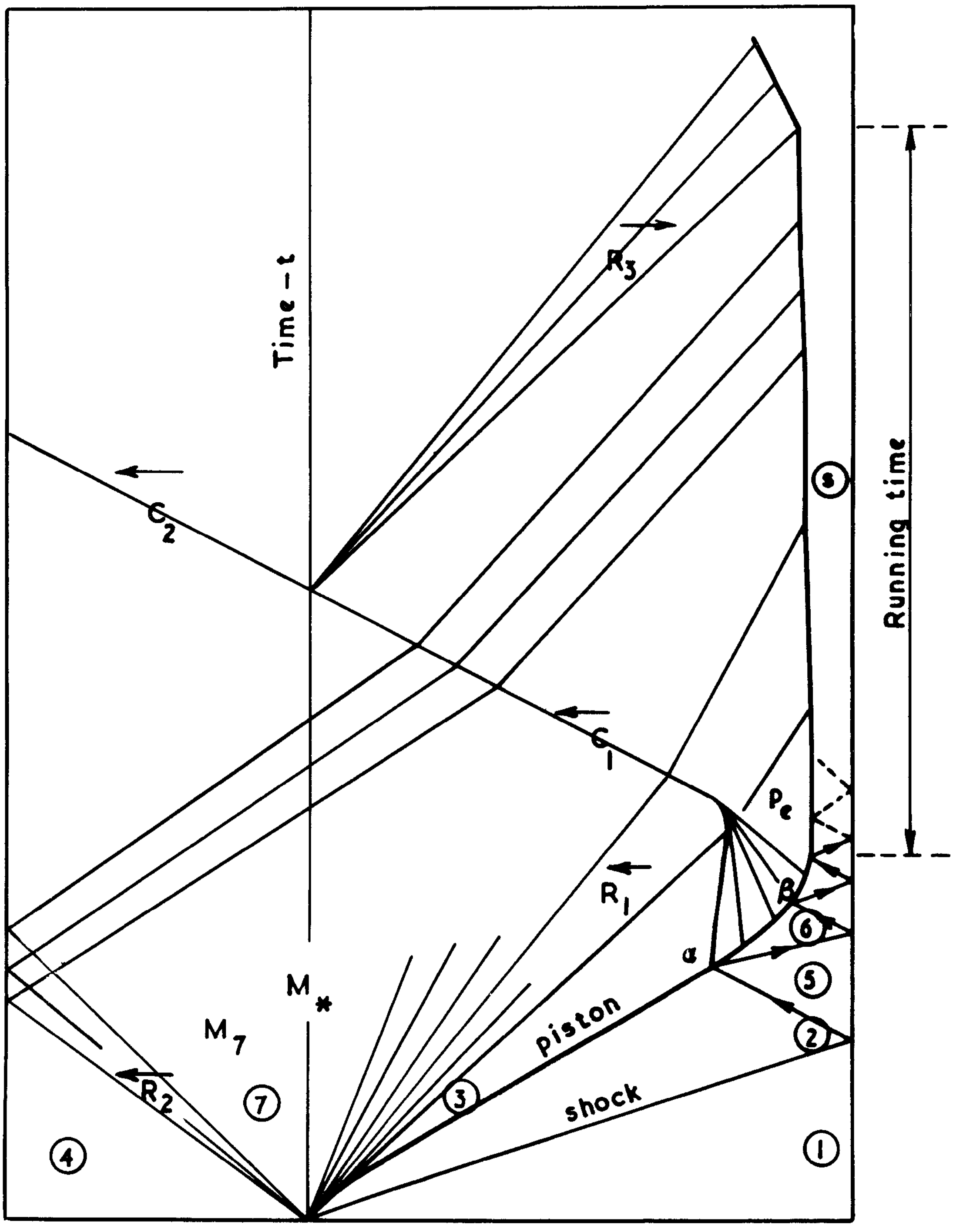
No.	Author(s)	Title, etc.
7	L. Pennelegion	Instrumentation of the University of Southampton hypersonic gun tunnel. University of Southampton Ph.D. Thesis. May, 1959.
8	J. S. Hey, J. T. Pinson and P. G. Smith	A radio method of determining the velocity of a shock wave. Nature (London) 179, 1184, 8th June, 1957.
9	G. F. Cawsey, J. L. Farrands and S. Thomas	Observations of detonation in solid explosives by microwave interferometry. Proc. Roy. Soc., Vol.248, 1958.
10	D. W. Holder and D. L. Schultz	On the flow in a reflected-shock tunnel. A.R.C. R. & M.3265. August, 1960.
11	A. J. Eggers	Discussion of papers by K. N. C. Bray et al and R. N. Cox. Proc. Colston Research Society. University of Bristol. Butterworth (London) 1959.

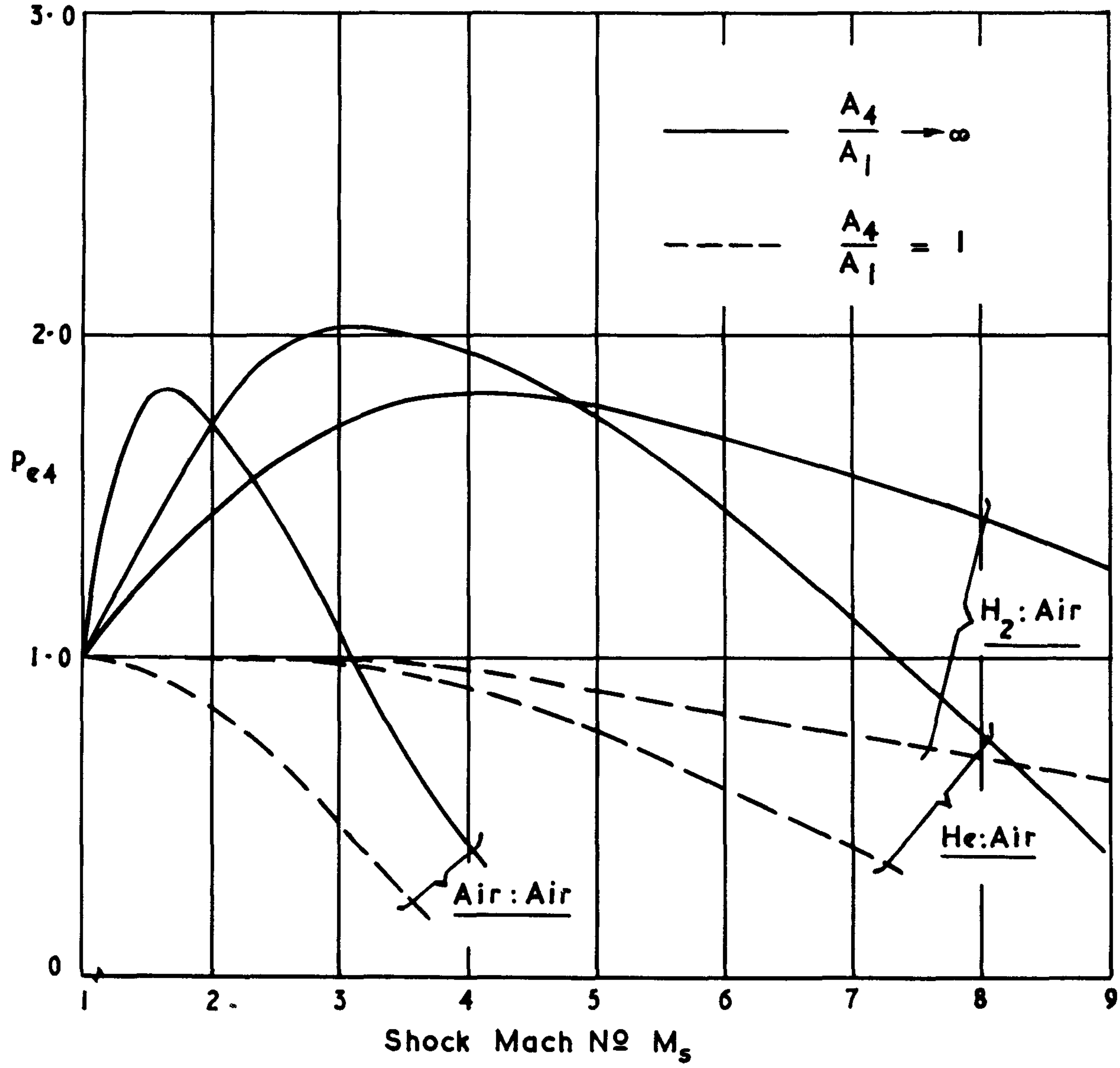
ES

FIG. 1



Sketch of wave diagram showing notation.

FIG. 2



Variation of equilibrium pressure with primary shock Mach No.

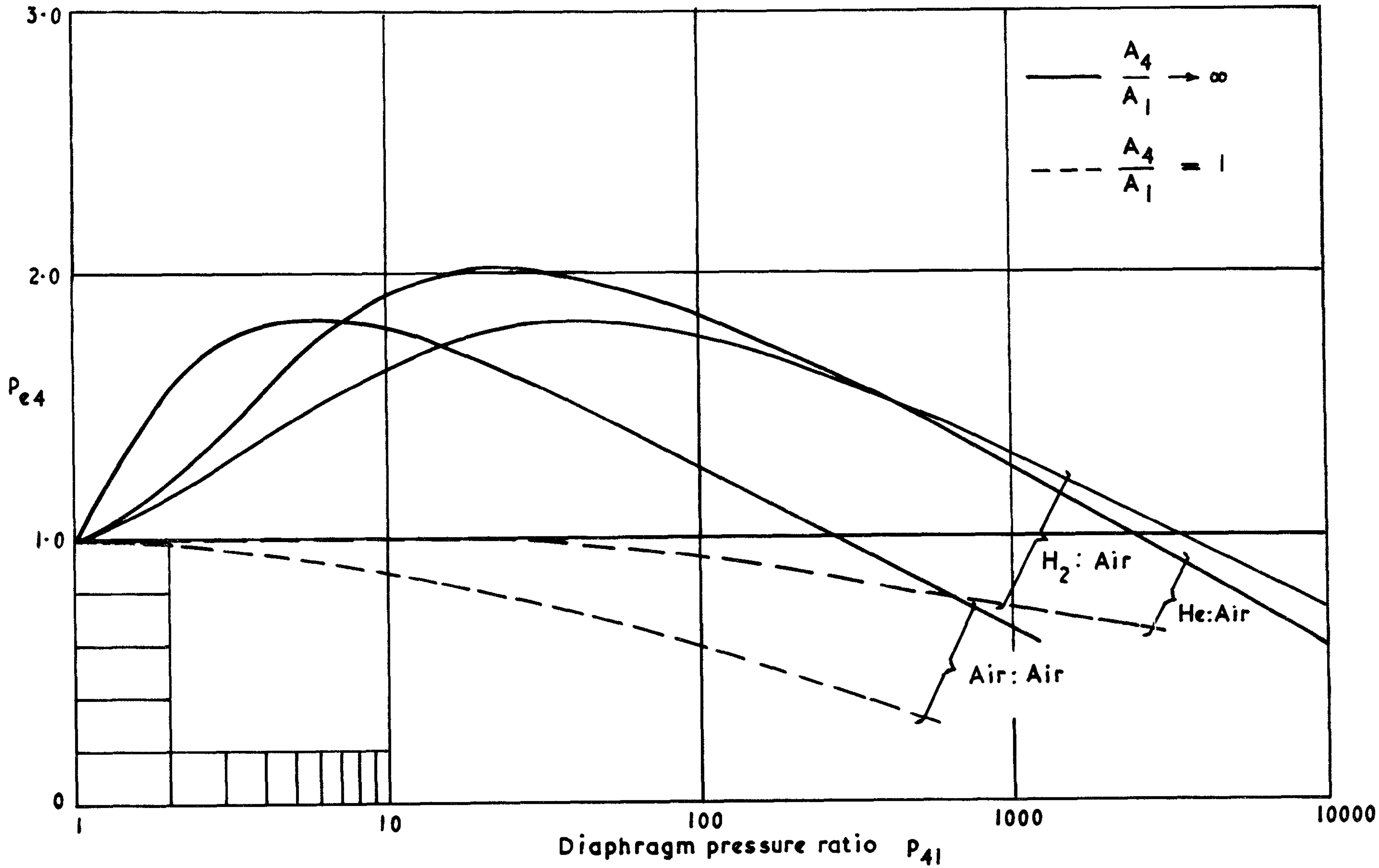
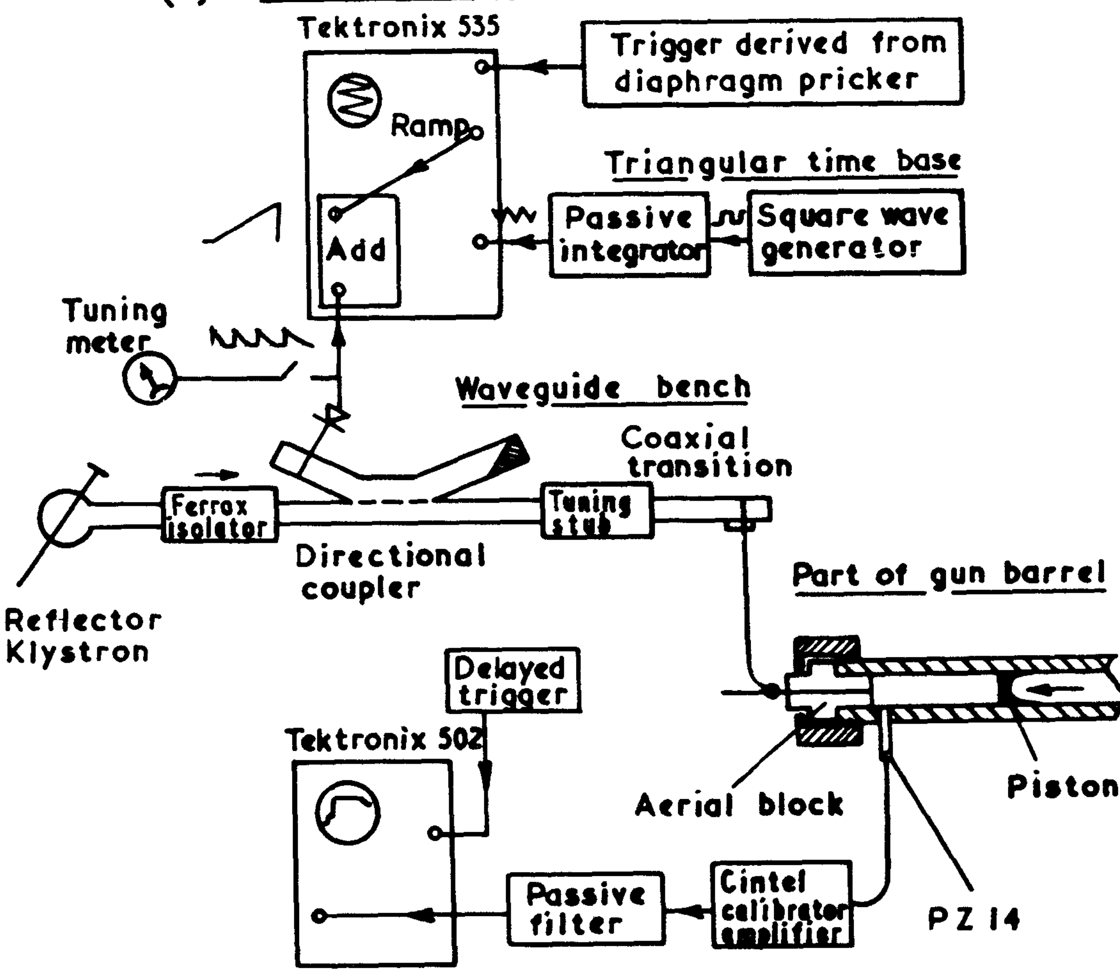


FIG. 3

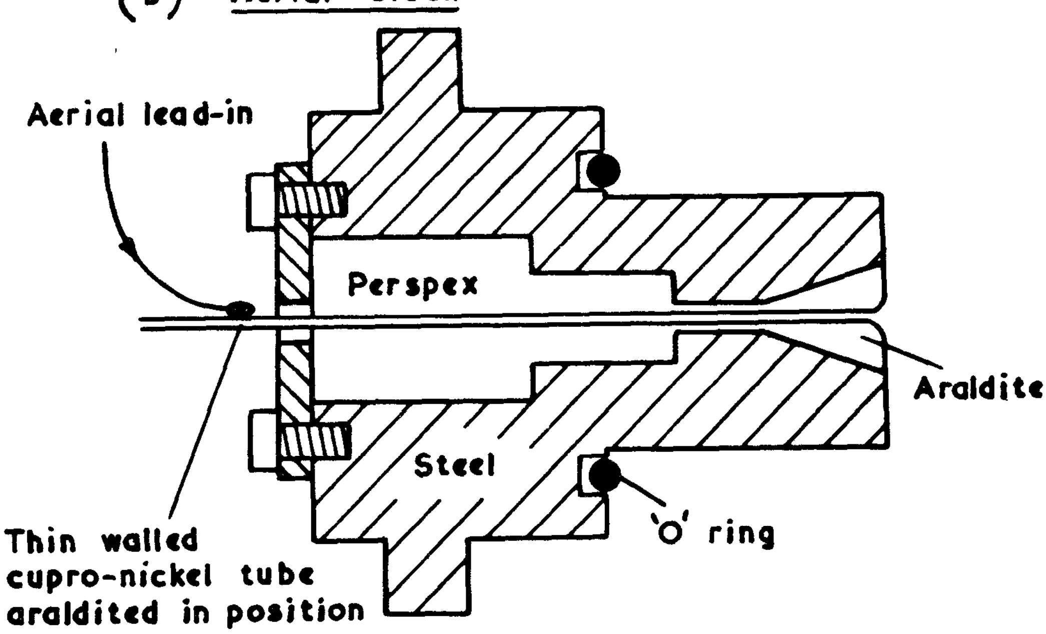
Variation of equilibrium pressure with diaphragm pressure ratio p_{41}

FIG. 4

(a) Electronic equipment connections.



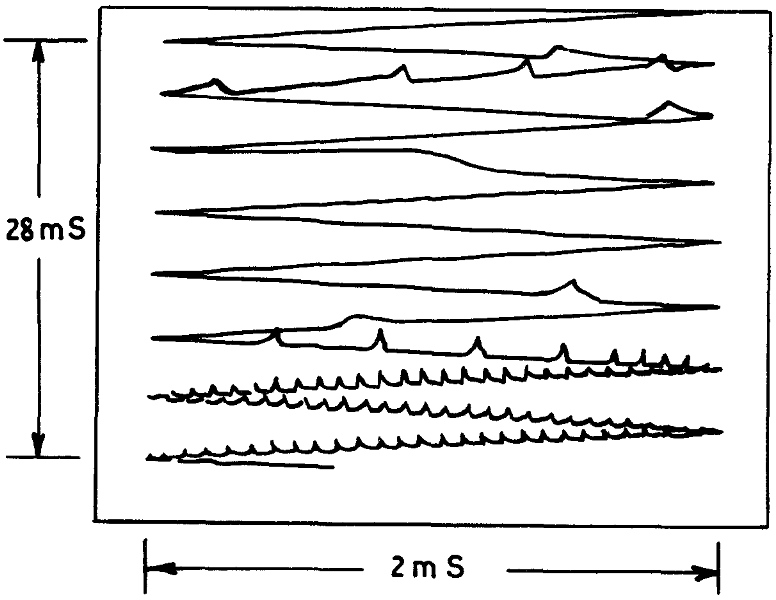
(b) Aerial block



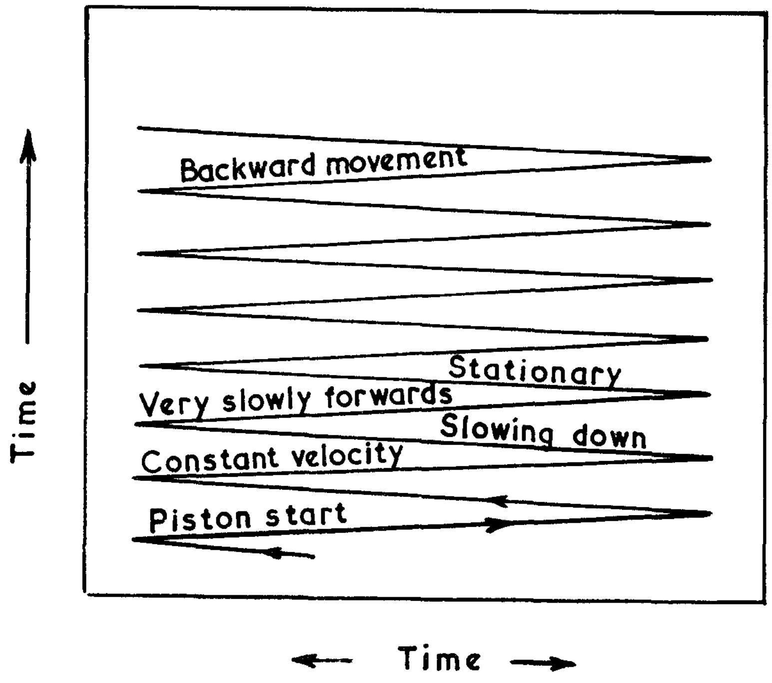
Arrangement of electronic equipment.

FIG.5

OSCILLOGRAM



EXPLANATION



Recorded piston motion trace.

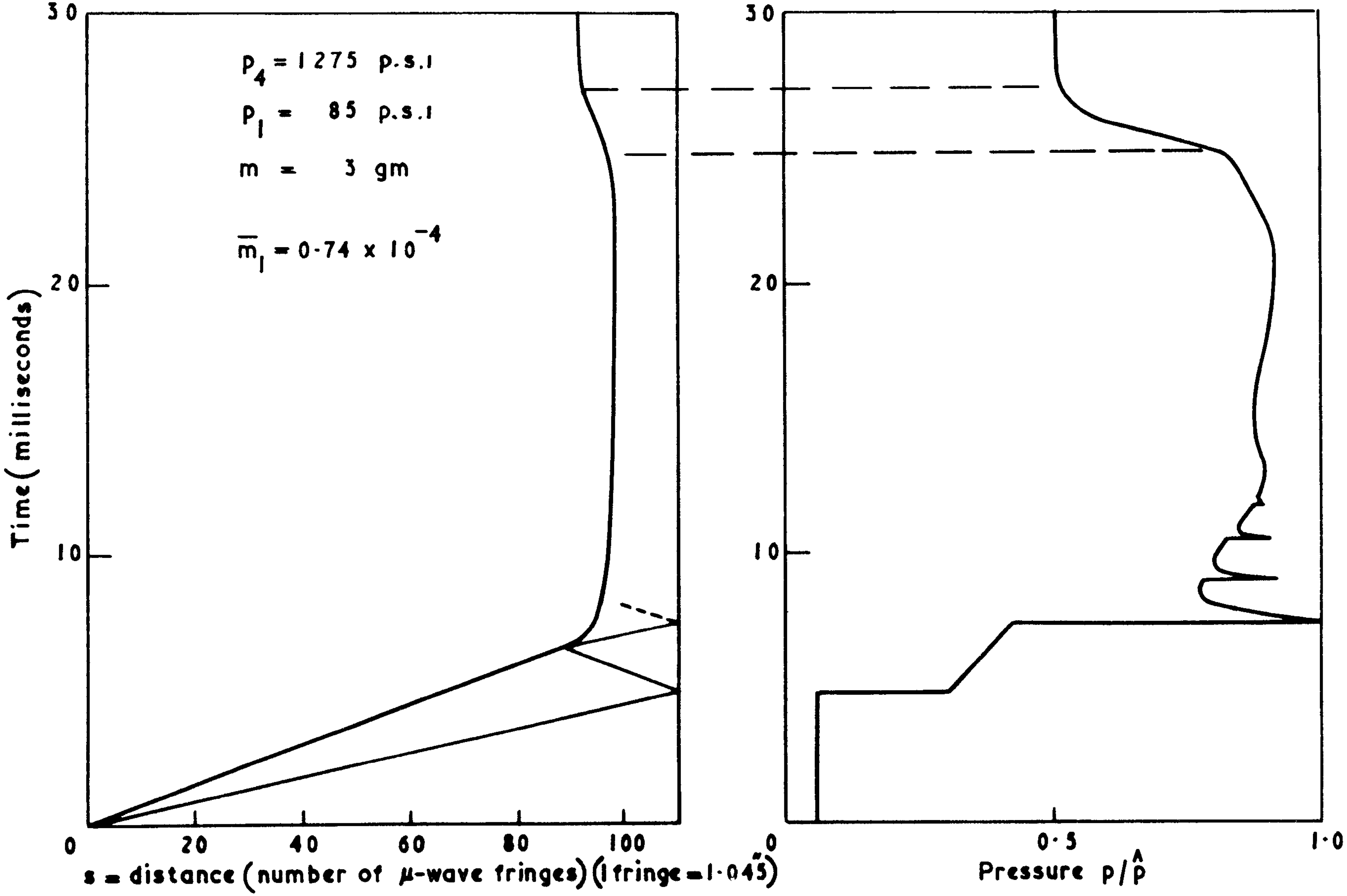
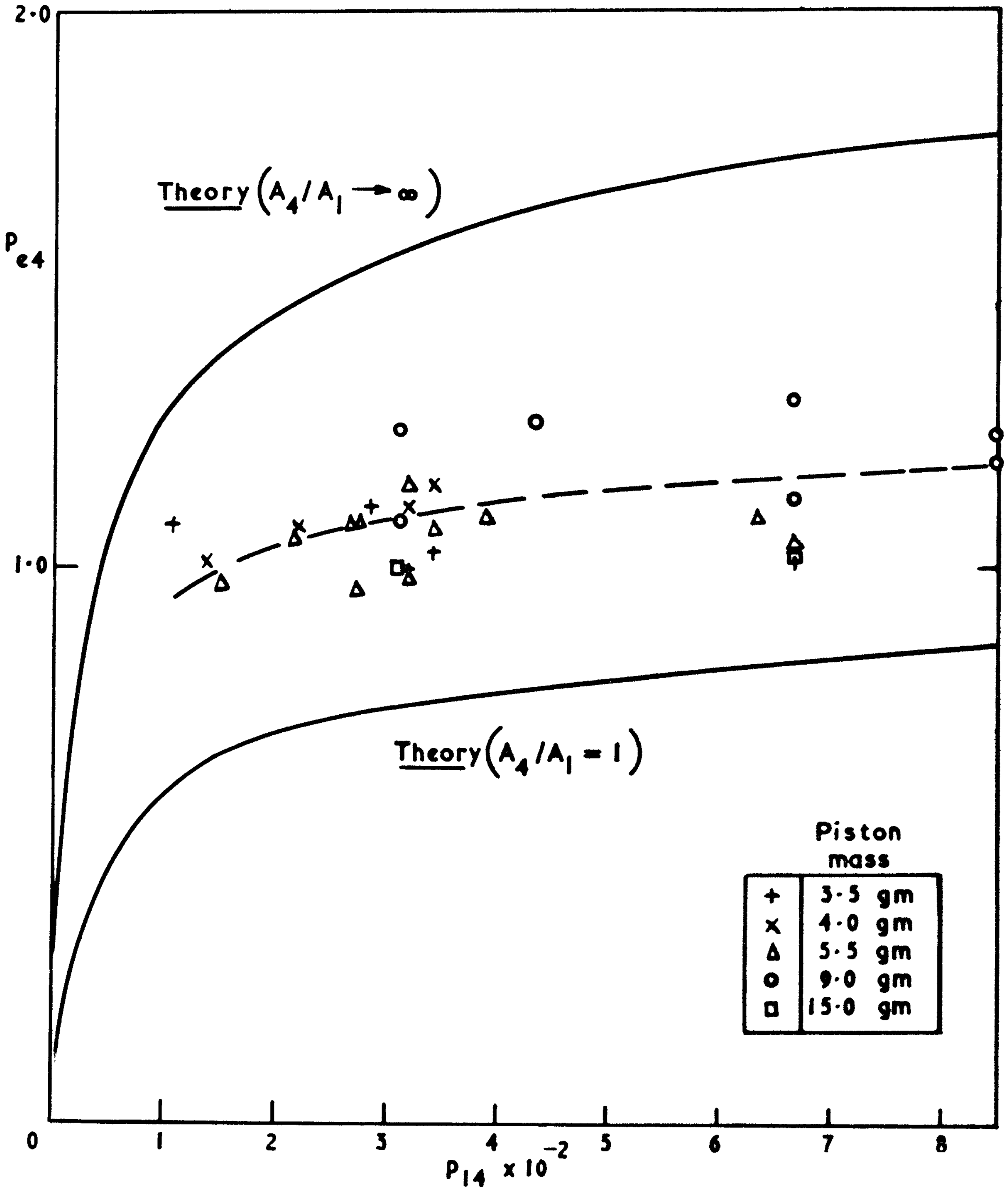


FIG. 6

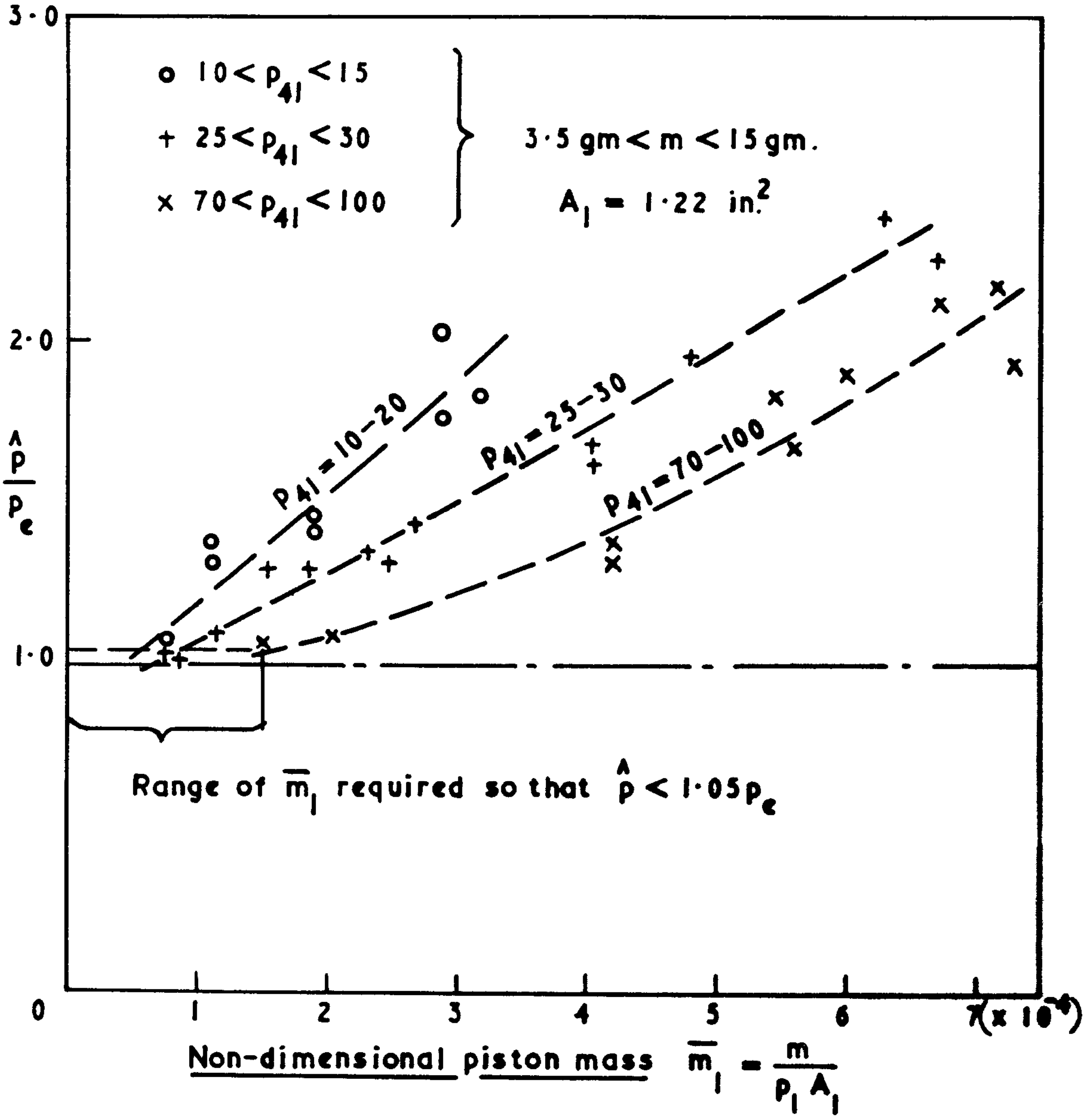
Complete piston trajectory and pressure-time diagram for equilibrium piston operation.

FIG. 7



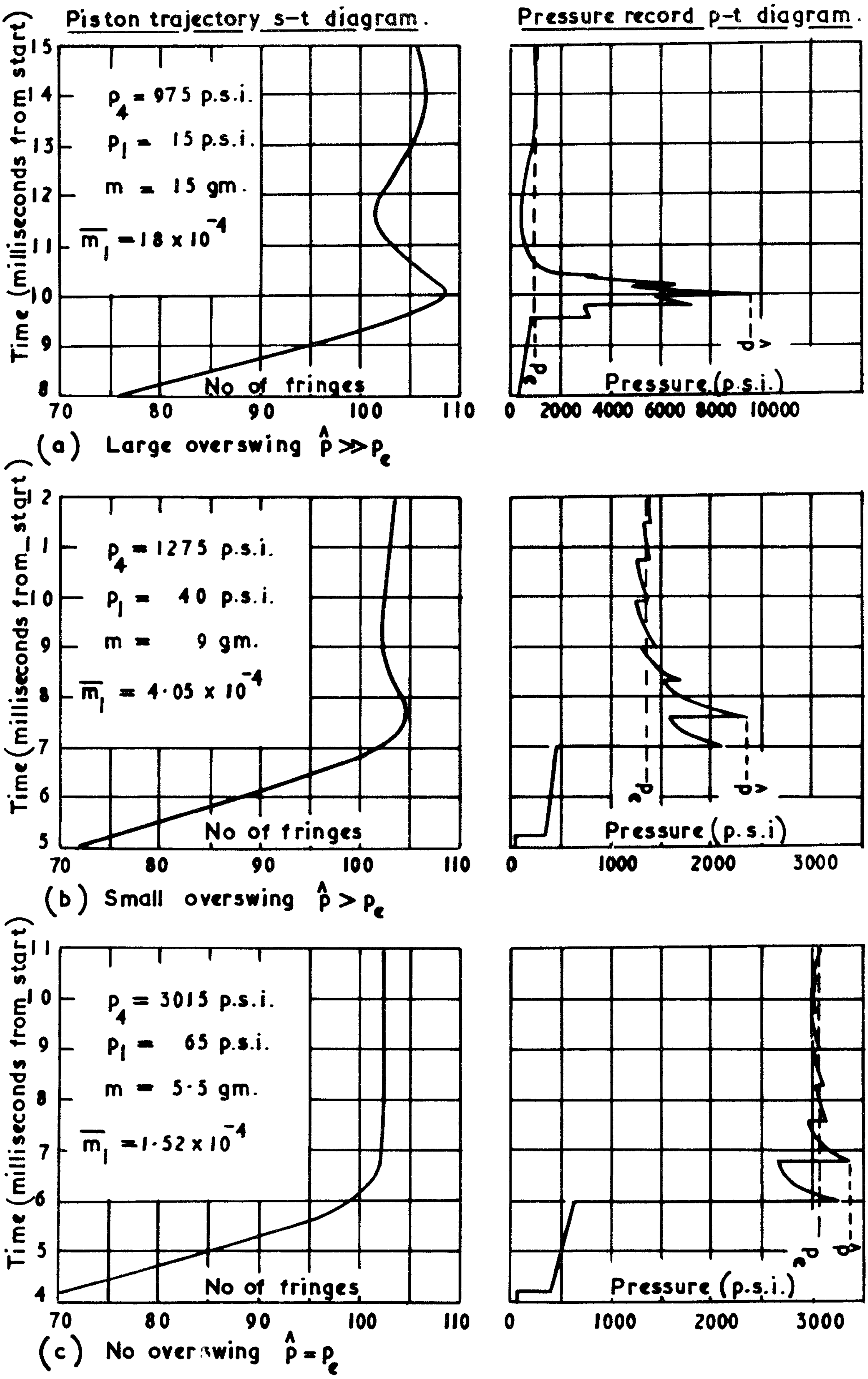
Variation of equilibrium pressure with diaphragm pressure ratio (experiment and theory)

FIG. 8



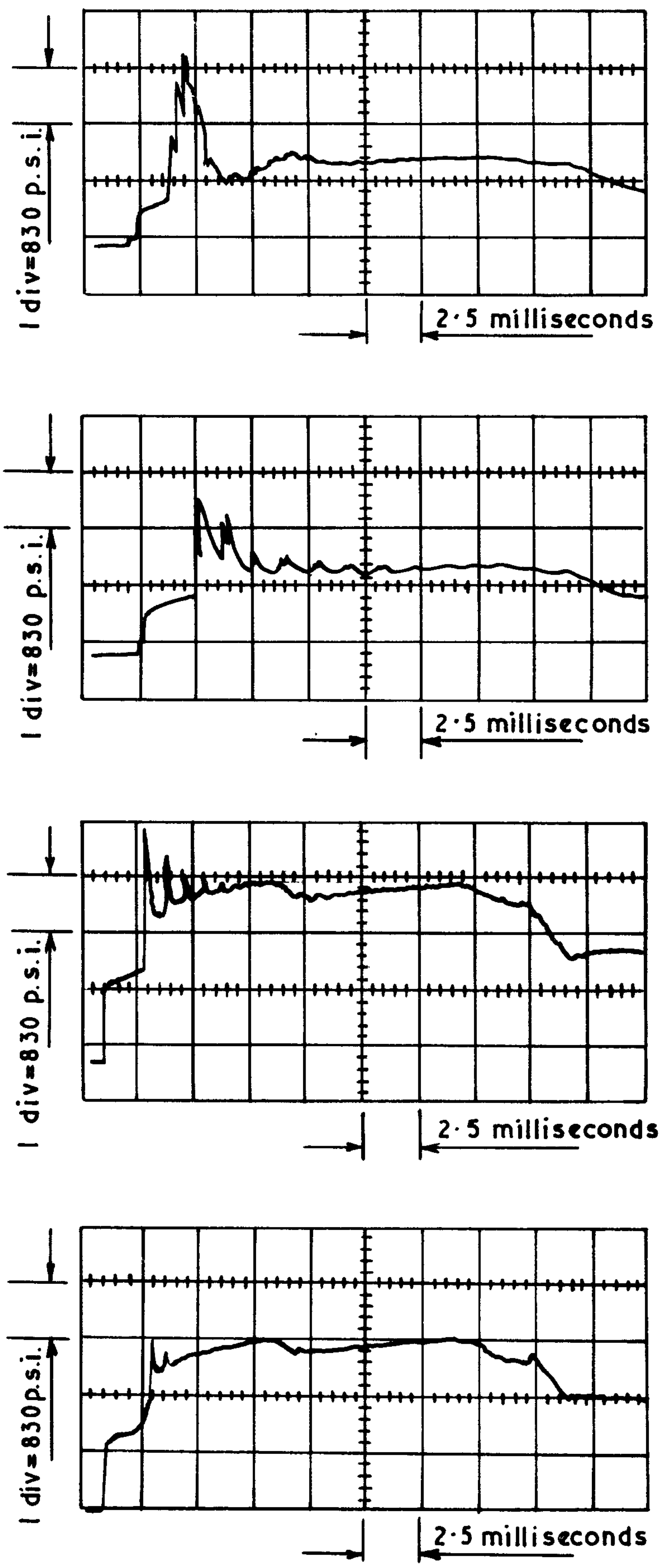
Ratio of peak pressure to equilibrium pressure (variation with non-dimensional piston mass $\overline{m}_1$ for several values of p_{41})

FIG. 9



Portions of s–t and p–t diagrams showing effect of $\overline{m}_1$ on the ratio $\hat{p}/p_e$ and piston overswing.

FIG. 10



(a)
$p_4 = 1275$ p.s.i
$p_1 = 40$ p.s.i.
$m = 15$ gm.
$\bar{m}_1 = 6{\cdot}75 \times 10^{-4}$

(b)
$p_4 = 1275$ p.s.i
$p_1 = 85$ p.s.i
$m = 15$ gm.
$\bar{m}_1 = 3{\cdot}18 \times 10^{-4}$

(c)
$p_4 = 2465$ p.s.i.
$p_1 = 85$ p.s.i.
$m = 5{\cdot}7$ gm.
$\bar{m}_1 = 1{\cdot}87 \times 10^{-4}$

(d)
$p_4 = 2465$ p.s.i.
$p_1 = 85$ p.s.i.
$m = 3{\cdot}5$ gm.
$\bar{m}_1 = 0{\cdot}74 \times 10^{-4}$

Typical barrel pressure records showing effect of $\bar{m}_1$ on the ratio $\hat{p}/p_e$

DS 67315/1/Wt.58 K.4 8/62 CL

A.R.C. C.P. No. 607. April, 1961
East, R. A., University of Southampton, and
Pennelegion, L., Nat. Phys. Lab.

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If the piston mass and initial barrel pressure are chosen correctly, then the peak pressures associated with the gun tunnel are avoided. A condition may be achieved where the piston has no overswing, and this has been confirmed experimentally. Calculations of stagnation pressure showing the effect of area change at the diaphragm station are given using air, helium and hydrogen as driving gases, and air as the driven gas.

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