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The Development at Cranfield of a Free Piston Compression Shock Tube

By

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CRANFIELD

The Development at Cranfield of a Free Piston Compression Shock Tube

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M.J. Pratt, M.A., D.C.Ae.

SUMMARY

The free piston compression shock tube provides a simple means of obtaining shock Mach numbers of the order of 30. This paper concerns the design and development at Cranfield of such a shock tube. The problems encountered in evolving a piston capable of withstanding heavy impacts at the completion of its stroke are outlined, and some preliminary shock tube performance data given.

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*Replaces CoA Report Aero No.194 - A.R.C.29 360

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1.0 INTRODUCTION

Essentially, a shock tube consists of a long tube divided by a diaphragm into two unequal sections. The longer section contains a test gas at a low pressure, while the shorter section is charged with gas at a high pressure. Upon the rupture of the diaphragm separating the two sections, which may be effected either by some mechanical means or simply by increasing the pressure in the shorter section sufficiently, the interface between the expanding high-pressure driver gas and the low-pressure test gas acts as a piston, driving a shock wave down the longer section of the tube. The test gas is raised to a high temperature by the passage of the shock wave, and may then be used for experiments in diverse fields of high-temperature research.

The degree of heating experienced by the test gas is dependent upon the velocity of the shock wave, which in turn is governed by the velocity of the contact surface, or interface between the driver and the test gas. In order to obtain the maximum possible heating of the test gas, therefore, two conditions must be fulfilled, firstly, the initial pressure of the driver gas should be as high as possible, and secondly, the density of the driver gas should be as low as possible. This latter condition ensures that the pressure drop arising from the acceleration of the flow of driver gas into the test section is kept to a minimum, and it has led to the widespread use of the light gases hydrogen and helium as driver gases in shock tubes. The fact that at a given pressure the density of a gas decreases as its temperature is raised has given rise to developments in which the driver gas is preheated, with the object of still further increasing the attainable shock wave velocity. Combustion heating, achieved by initiating a reaction between hydrogen and oxygen in the driver gas, has extended the available range of shock Mach numbers, but is of limited advantage since the heavy combustion products increase the density of the driver. Electrical heating is also possible, either by using conventional methods of heat exchange or by employing an electric discharge to heat the driver gas directly. The former method is limited by the properties of available materials and, whilst extremely high shock Mach numbers have been obtained by discharge heating, the nature of the flow behind the shock wave appears to be extremely non-uniform, which fact renders shock tubes employing this device of little use for many research purposes. Shock tubes in which the gas is first ionized and then accelerated by magnetogasdynamic means suffer from a similar disadvantage.

The present paper concerns the development of a type of shock tube first described by Stalker (1961), in which the driver gas is raised to a high pressure by the action of a free piston moving in a tube containing the gas. The compression process is approximately isentropic, and consequently raises the temperature of the driver gas to a level depending upon the degree of compression. The theory given by Stalker indicates that, in the absence of losses, the sole limitation upon the peak pressures attainable using this technique is the structural strength of the compression tube. The free piston shock tube, therefore, embodies its own simple means of raising the driver gas to a high pressure and temperature without the use of bulky and expensive compressors or of auxiliary heating devices.

2.0 DESCRIPTION OF THE SHOCK TUBE

A schematic diagram of the free piston compression shock tube is given in Figure 1. The apparatus is seen to comprise four main components:

(i) the pressure reservoir, which is charged with compressed air and which supplies the force driving the piston,

(ii) the compression tube, in which the piston moves to compress the driver gas,

(iii) the test section, separated from the compression tube by a diaphragm,

(iv) the dump chamber, for the occupation of spent gases after the shock tube has been operated.

2.1 The Pressure Reservoir

The cylindrical stainless steel reservoir is 6.5 feet in length and 5.34 in. in internal diameter, giving a volume of approximately 1 cu. ft. Some advantage would be gained by having a larger reservoir but, as will be shown later, the resulting increase in performance of the compression section would be marginal, and the present dimensions were chosen on grounds of cost. Connection to the compression tube is by a 2 in. internal diameter stainless steel pipe and a ball valve of similar internal diameter, which can be used to isolate the reservoir from the remainder of the system. The reservoir can be charged with compressed air at a pressure of up to 1,000 p.s.i.

2.2 The Compression Tube

The compression tube is 6 feet long, 2.548 in. in internal diameter, and machined out of stainless steel. The piston in present use will be described fully in Section 4.1, it is 15 in. in length, weighs 6lb. 13 oz., and has a 0.002 in. radial clearance in the compression tube.

A double diaphragm system is used for the initiation of the compression cycle. The two aluminium diaphragms are installed one inch apart at the end of the compression tube nearest the reservoir, their bursting pressure is chosen to be about three-quarters of the difference between the reservoir air pressure (generally several hundred p.s.i.) and the initial pressure of the driver gas in the compression tube (usually less than 100 p.s.i.). The space between the two diaphragms is charged with air at a pressure midway between these two pressures. Both diaphragms are therefore ruptured on venting this space to atmosphere, and the piston, which initially is stationary adjacent to the double diaphragm station, is accelerated down the compression tube.

At the other end of the compression tube is a further diaphragm, whose bursting pressure is chosen to be slightly below the peak pressure which would occur in the driver gas were this end of the compression tube to be blanked off. When this diaphragm bursts, the piston has expended most of its kinetic energy in compressing the driver gas, and is almost stationary.

2.3 The Test Section

The test section, down which the shock wave propagates, is 1.03 in. square internally, 9.5 ft. in length, and composed of stainless steel. Two quartz windows, 0.75 in. thick and 1.75 in. in diameter, are positioned 4 in. from the downstream end of this section.

2.4 The Dump Chamber

The dump chamber is connected to the end of the test section, and takes the form of a cylinder 4 ft. long and 9 in. in diameter.

2.5 Ancillary Equipment

Compressed air is supplied to the reservoir by a four-stage Hofer compressor. Before reaching the reservoir, the air is passed through a carbon filter to remove traces of oil from the compressor, and then through two silica gel driers. The test section and dump chamber are evacuated using an oil diffusion pump and rotary backing pump, prior to being filled with the test gas to the required pressure. The compression tube is not pumped out before being charged with the driver gas, but is merely flushed through with this gas for a short period. The pipework associated with the shock tube is necessarily fairly complex, and is shown diagrammatically in Figure 2.

2.6 The Complete Assembly

As has already been explained, the diaphragm separating the driver gas from the test gas bursts as the compression stroke nears its completion, the piston then being almost stationary. After the diaphragm has burst, however, the force previously exerted by the compressed driver gas in opposing the motion of the piston vanishes, and the piston is once more accelerated by the reservoir pressure until it finally strikes the end of the compression tube. The shock tube as a whole has therefore been designed to permit a certain degree of axial movement in order to absorb the energy of this impact. With the exception of the pressure reservoir and the dump chamber, each separate component of the shock tube is suspended by means of one or more steel rods 0.5 in. in diameter from a framework of steel girders. At the lower end of each rod is a rubber shock-absorber, while at the upper end is a small bogey carrying four nylon wheels running in tracks supported by the upper members of the framework. The various parts of the shock tube can therefore be disconnected and moved apart for the insertion of the diaphragms or for purposes of maintenance. The suspension rods are adjustable in length to enable each component to be properly aligned with its neighbours. The pressure reservoir and the dump chambers are mounted on shock absorbers on trolleys so that they too can move with the rest of the assembly. Two views of the complete shock tube are shown in Figures 3 and 4.

3.0 SOME THEORETICAL CONSIDERATIONS

3.1 Compression Tube Performance

It is assumed in the following calculations that the compression tube is blanked off at its high-pressure end by a solid wall. The piston velocity is taken to be sufficiently small to permit the use of the isentropic relation PV^{γ} = constant for both the expansion of the reservoir air and the compression of the driver gas during the compression stroke. The peak pressure occurs when the piston comes instantaneously to rest, the work done by the reservoir gas is then equal to the work done in compressing the driver gas, the following relation being obtained

$$\frac{P_D V_D}{\gamma_D - 1}\left(1 - \left\{\frac{V_D}{V_D + v}\right\}^{\gamma_D - 1}\right) = \frac{P_A V_A}{\gamma_A - 1}\left(\left\{\frac{V_A}{V_A - v}\right\}^{\gamma_A - 1} - 1\right). \qquad (1)$$

The subscript D refers to initial conditions in the reservoir, and A to initial conditions in the compression tube. The volume swept by the piston is denoted by v, since this volume is small compared with V_D, the left hand side of Eq.(1) may be expanded to yield

$$P_D v\left(1 - \tfrac{1}{2}\gamma_D \frac{v}{V_D} + 0\left(\frac{v}{V_D}\right)^2\right) = \frac{P_A V_A}{\gamma_A - 1}\left(\left\{\frac{V_A}{V_A - v}\right\}^{\gamma_A - 1} - 1\right). \qquad (2)$$

In the present case $^{v}/V_D$ is roughly 0.2, and terms of order $(^{v}/V_D)^2$ and smaller will be neglected. If the volume of the driver gas at the instant of peak pressure is denoted by V_B, then $v = V_A - V_B$; in normal operation of the shock tube $^{V}B/V_A \ll 1$. Substitution for v in Eq.(2) leads to

$$P_D\left(1 - \frac{V_B}{V_A} - \tfrac{1}{2}\gamma_D \frac{V_A}{V_D}\left\{1 - 2\frac{V_B}{V_A}\right\}\right) = \frac{P_A}{\gamma_A - 1}\left(\left\{\frac{V_A}{V_B}\right\}^{\gamma_A - 1} - 1\right). \qquad (3)$$

where a term in $(^{V}B/V_A)^2$ has been neglected. In his analysis, Stalker (1961, 1966) has regarded the reservoir volume V_D as being effectively infinite, and has retained only the first two terms on the left of Eq.(3). In the present instance, $^{V}A/V_D = 0.166$, and the value of γ_D (for air at a pressure of about 30 atmospheres) may be taken as 1.5. Then $\gamma_D(^{V}A/V_D) = 0.25$ and Eq.(3) becomes

$$\frac{P_D}{P_A} = \frac{1}{\gamma_A - 1}\left(\left\{\frac{P_B}{P_A}\right\}^{\frac{\gamma_A - 1}{\gamma_A}} - 1\right) \Big/ \left(7/8 - \tfrac{3}{4}\left\{\frac{P_A}{P_B}\right\}^{\frac{1}{\gamma_A}}\right). \qquad (4)$$

Stalker's neglect of the increase in reservoir volume leads to the replacement of $\left(7/8 - \frac{1}{8}\left(\frac{P_A}{P_B}\right)^{\frac{1}{\gamma_A}}\right)$ in the above equation by $\left(1 - \left(\frac{P_A}{P_B}\right)^{\frac{1}{\gamma_A}}\right)$; under most operating conditions $\frac{P_A}{P_B}$ is very small, so that the increase in the value of $\frac{P_D}{P_A}$ required to obtain a given value of $\frac{P_B}{P_A}$ is of the order of 12½% for the present shock tube.

Using Eq.(4), $\frac{P_B}{P_A}$ is plotted as a function of $\frac{P_D}{P_A}$ for hydrogen in Figure 5. Clearly, very high values of P_B may be reached with only moderate pressures P_A and P_D. The peak temperature attained in the driver gas may be found from the relation

$$\frac{T_B}{T_A} = \left(\frac{P_B}{P_A}\right)^{\frac{\gamma_A - 1}{\gamma_A}}$$

Taking T_A as 300°K, values of T_B are also given as a function of $\frac{P_D}{P_A}$ in Figure 5.

The above analysis assumes that the compression is performed under ideal conditions, in practice, however, losses are of course present. The main factors which affect the efficiency of the process are (i) gas leakage past the piston, (ii) heat transfer from the hot driver gas to the tube walls, (iii) real gas effects in the driver gas, which have the effect of increasing γ_A in the course of the compression stroke, and (iv) piston friction (probably the least important).

3.2 Piston Velocity

It is a simple matter to show that for a given shock tube the kinetic energy of the piston at any point during the compression stroke is a function of P_D and P_A alone, and hence independent of the piston mass. Under the present range of operating conditions, with a piston weighing approximately 7lbs, maximum velocities attained should be in the range 50 - 70 ft./sec.

3.3 Operation in the Tailored Mode

One valuable aerodynamic application of shock tubes is in the generation of high stagnation temperature nozzle flows. If the shock wave is reflected by a plane wall at the end of the shock tube, a region of stationary test gas results which has been twice processed by the passage of the shock wave, and which is consequently at an extremely high temperature. This hot gas can now be used to supply a nozzle, through which it is expanded to generate a high Mach number flow.

The duration of useful flow in the nozzle is determined by the length of time that conditions remain steady in the gas supplying the nozzle. Ideally this would correspond to the time interval between the arrivals of the shock wave and the contact surface, although multiple reflection of the shock wave between the end of the tube and the contact surface usually severely reduces the duration of these steady conditions in practice. This difficulty may be overcome, however, by preheating the shock tube driver gas to such a temperature that the reflected shock wave passes through the contact surface without reflection of a return disturbance. This technique is generally known as 'tailored interface' operation, and Stalker has pointed out in Ref. 1 that since the free piston compression process not only compresses but also heats the driver gas, the type of shock tube at present under discussion may well prove suitable for operation in the tailored mode by judicious choice of operating conditions.

In order to achieve the desired heating of the driver gas, high values of the pressure ratio $\frac{P_B}{P_A}$ must be reached, which implies that at the time of diaphragm rupture the effective length of the driver section (i.e. the distance between the front face of the piston and the diaphragm station) must be small. A problem then arises in that the expansion wave which propagates back into the driver section upon the bursting of the diaphragm now has but a short distance to travel before it is reflected from the piston face; after reflection it is travelling faster than the contact surface, which it tends to overhaul. If this occurs, the steady conditions in the hot gas supplying the nozzle will now be terminated by the expansion wave before the arrival of the contact surface, curtailing the running time of the nozzle. In order to remove this limitation, Stalker has proposed in Ref. 1 that the shock tube flow should be initiated whilst the piston is still in motion at such a velocity that the pressure in the driver section remains effectively constant for a few milliseconds after the diaphragm bursts. The expansion wave is thereby eliminated, and the full running time available in the nozzle.

To summarize, successful operation in the tailored mode requires a choice of initial conditions such that (a) tailoring occurs, and (b) the expansion wave is eliminated. Stalker has carried out a heuristic theoretical analysis of this problem in Ref. 1, where he also refers to an experimental test of the feasibility of operation under the above conditions. Although this test appeared to give encouraging results, he makes no further mention of tailored operation in his later article, Ref. 2. Except for the purpose of this one trial, Stalker has used a shock tube configuration having a stop near the end of the compression tube. The initial conditions are chosen so that when the diaphragm bursts the piston is very close to this stop and almost stationary. Under such circumstances the piston impact energy will be small, but the possibility of tailored operation as described above will be precluded.

It seems inevitable that for operation under the conditions outlined in this Section, provision must be made to absorb the energy of piston impacts of no mean order at the end of the compression tube. The College of

Aeronautics free piston shock tube was designed with the possibility of tailored operation in mind, and the problems encountered in developing a suitable piston are described in the following Section.

4.0 DEVELOPMENT PROBLEMS

4.1 The Piston

Two possible approaches were available to the problem of absorbing the kinetic energy of the piston on impact. The first was to design the shock tube to incorporate some form of shock-absorbing mechanism at the end of the compression tube, and the second was to design the piston itself as a shock absorbing device. The latter approach was decided upon as probably giving rise to fewer mechanical complications.

Numerous major and minor variations of piston design were tested. It was found at an early stage that operating under only moderate conditions (400 p.s.i. reservoir pressure, 80 p.s.i. initial driver pressure and using a diaphragm bursting at 2,400 p.s.i.), simple pistons incorporating no shock-absorbing means expanded on impact with the transition block at the end of the compression tube, jammed, and had to be extracted by mechanical means. These pistons had masses ranging from 1 lb. (aluminium alloy) to 8 lbs. (steel).

A $\frac{1}{4}$ in. thick copper pad on the front of the heavy steel piston was found to prevent deformation of the main piston body at first, though the pad became so work-hardened after two or three impacts as to be virtually ineffective. Nevertheless, the use of disposable copper pads offered a solution to the problem if all else failed. Deformable hollow lead pellets were also tried as a means of absorbing the energy of impact. These were confined behind a light alloy cap on the front of the piston in order that the deforming lead should not escape into the compression tube. The cap had to be as light as possible to minimise its own kinetic energy, that of the main piston body being absorbed by the lead. It was found, however, that if the cap were made sufficiently robust to withstand the internal pressure exerted by the deforming lead, it was not only too heavy, but did not provide sufficient volume for the lead to deform into. Consequently, the piston became effectively solid before all its energy had been absorbed.

A hydraulically damped piston was also tested. Although this device appeared satisfactory under static compression, it proved to leak hydraulic oil under the severe dynamic conditions encountered during the operation of the shock tube. As a result, distinct signs of combustion were evident at the end of the compression tube and on the front face of the piston, decarbonisation being necessary.

The most satisfactory pistons which have so far been developed are of a composite nature. The philosophy behind these designs is based on the fact, already mentioned in Section 3, that the kinetic energy of the piston at any point in its travel is a function only of the initial conditions, and not of the piston mass. A heavy piston therefore travels comparatively slowly, and if it is composed of several elements, each of whose mass is a small fraction of the total, each element has little energy of motion on its own account. Then each separate element may be provided with its own shock absorber, which has to cope with but a small proportion of the total impact energy.

The standard element employed in these composite pistons is a light alloy cylinder one inch long and with 0.002 in. radial clearance in the compression tube. On its front face it carries a spigot 1.75 in. in diameter and 0.2 in. in length, which locates the shock absorber, a silicone rubber 'o'-ring 0.375 in. in cross-sectional diameter. The piston consists of an assembly of these units, the number employed at present being ten. On the deceleration of the piston the 'o'-rings are compressed longitudinally and expand radially, to prevent their coming into contact with the bore of the compression tube and depositing rubber, some material has been machined from the outside of these rings, leaving their cross-section roughly in the form of a D with the flat face outwards. The front face of the piston, preceding the first standard unit, is simply a $\frac{1}{4}$ in. thick circular plate of aluminium alloy, and therefore carries a very small proportion of the total kinetic energy of the piston.

The problems arising with this design have largely been concerned with the means of holding the assembly together. An axial mild steel bolt was first employed, with its head at the rear and a nut at the front of the piston. On the first trial the head of the bolt was sheared off, the shank proceeding with considerable velocity under its own momentum into the dump chamber, fortunately causing no more damage than an impressive dent. Two standard cold-forged high-tensile steel bolts showed visible signs of necking near the head after two trials. Attempts were then made to hold the piston together by means of an elastic cord passing through the axis of the assembly, and maintained in tension by a clamp at either end. However, no satisfactory method of securing the leading end of the cord was found, the clamps having a tendency to detach themselves on impact. The elastic cord was also found to be subject to a good deal of wear and tear. Finally a 15 in. long bolt 0.375 in. in diameter and having a large head was machined from solid high tensile steel, and this has so far withstood all the rigours imposed upon it. A $\frac{1}{2}$ in. thick hard rubber pad serving as a shock absorber is inserted between the head of the bolt and the rear face of the last piston section.

In its present version (see Figure 6), this piston has been subjected to more than one hundred trials over a range of conditions, and has performed very satisfactorily. It will eventually be replaced by an identical design constructed from stainless steel, a material which should be less subject to erosion by the hot compressed driver gas.

4.2 Other Development Aspects

With the exception of the piston problem, no major obstacles were encountered in bringing the shock tube to an operational state, and such minor modifications as have been effected were confined largely to the associated pipework. Initially a 3 in. i.d. steam valve was used as the main valve isolating the reservoir from the remainder of the system, but this proved so cumbersome to operate that it was replaced by the present 2 in. i.d. ball valve. An investigation was made into the possibility of dispensing with the double diaphragm method of firing the shock tube and operating simply by opening this ball valve manually. It was found that the peak driver pressures obtained depended very strongly on the rate of opening the valve, results were not repeatable, and in any case fell well below those obtained using the double diaphragm system.

5.0 INSTRUMENTATION

5.1 Measurement of Driver Gas Pressure

The pressure in the driver gas during the course of the compression cycle is measured by means of an Ether Ltd. Type BP 6 unbonded strain gauge pressure transducer with a range of 0-20,000 p.s.i. The transducer is used in conjunction with a Tektronix Type 551 oscilloscope and Type Q plug-in unit (transducer pre-amplifier). A typical pressure record is shown in Figure 7; the pressure is seen to reach a peak, falling rapidly after the diaphragm bursts. The impact of the piston on the transition block follows some 22 milliseconds later.

5.2 Measurement of Shock Velocity at the Working Section

Using hydrogen as the driver gas, shock wave velocities are readily obtainable in air or argon such that the shock-heated gas is luminous. At two stations 13.5 cm. apart, equidistantly spaced from the quartz windows in the working section, plugs are inserted in the shock tube wall which permit the egress of a 0.02 in. diameter beam of collimated radiation from the hot test gas; the radiation is conducted from both plugs via fibre optics to an E.M.I. 9526 S photomultiplier, whose output is displayed on a Tektronix Type 551 oscilloscope. As the region of luminous gas passes each plug the photomultiplier registers a pulse of radiation, and the shock velocity is inferred from the time interval between the two pulses. Figure 8 depicts a typical photomultiplier record.

5.3 Continuous Monitoring of Shock Wave Velocity

In order to study the variation of velocity of the shock wave as it travels the length of the shock tube, a microwave Doppler system is being developed, similar to that described by Dunn and Blum in Reference 3. A coaxial probe introduces the electromagnetic signal into the shock tube, which acts as a wave guide. The Doppler-modified signal reflected from the ionized gas behind the advancing shock wave is received by the same probe and mixed with part of the local oscillator signal to obtain the Doppler frequency f_D, which is related to the shock wave velocity by the equation

$$v = \tfrac{1}{2} f_D \lambda_g,$$

where λ_g is the guide wavelength of the microwaves in the shock tube.

A diagram of the present microwave system is shown in Figure 9. The klystron used operates at a frequency of 9.4 Gc/s. Part of its output is reflected by the variable stub tuner into the crystal mixer on one arm of the 10db directional coupler. In order to obtain linear mixer characteristics the reflected Doppler-modified signal is arranged to be about 20db less than the local oscillator signal by the imposition of a 10db padding attenuator between the stub tuner and the coaxial probe; part of this returning signal is also coupled into the mixer, whose output is the Doppler frequency.

This system is still in the course of development, and for the moment the mixer output is simply displayed upon an oscilloscope. Approximate values for the shock velocity can be determined from the resulting traces, but it is intended that the final version shall include a discriminator which converts frequency into voltage, permitting a direct velocity-time history to be recorded. The Doppler waveform being obtained at present is not perfectly sinusoidal, but this should be rectified by proper matching of the waveguide co-axial transition and by taking measures to suppress the TE_{11} mode, which may be propagating to a certain degree in the shock tube in addition to the required fundamental TE_{10} mode.

6.0 RESULTS

6.1 Compressor Performance

The compressor was tested by blanking off the end of the compression tube and observing the peak pressures obtained in the driver gas under a range of starting conditions. The results for one series of tests, using air in the compression tube, are shown in Figure 10. It is evident from these measurements that an increase in the reservoir pressure leads to a decrease in the compressor efficiency, which appears to indicate that the main source of loss in the system is gas leakage past the piston. Despite the drop in efficiency, very high peak driver pressures can nonetheless be obtained; the maximum recorded to date has been 13,000 p.s.i. (with P_D = 800 p.s.i., P_A = 80 p.s.i.), and there is no apparent bar to the attainment of higher pressures if required.

6.2 Shock Wave Velocity

Most of the measurements so far made of shock wave velocity have been obtained in air at pressures in the range 0.5 mm. - 3.0 mm. Hg, using nickel diaphragms bursting at about 5,200 p.s.i. The driver gas has been hydrogen. Shock Mach numbers ranging between 20 and 30 have been observed. Initial results from the microwave Doppler system indicate that the shock wave accelerates during the passage down the shock tube, which fact may possibly be explained by the finite time taken for the diaphragm to open fully as it bursts.

7.0 CONCLUSION

The development at The College of Aeronautics of a free piston compression shock tube is now virtually complete. It is intended to carry out a programme of research concerned with radiant heat transfer in shock-heated gases, and with shock precursor ionization.

8.0 ACKNOWLEDGEMENTS

The author would like to express his gratitude to all those who have assisted him in bringing this shock tube to an operational condition. In particular, thanks are due to Mr. J.R. Busing of the Department of Aerodynamics for much constructive discussion and advice. Mr. S.H. Lilley and Mr. J. Greenwood have rendered valuable assistance on the engineering side, and the guidance of Mr. R.G. Smerdon of the Department of Electrical and Control Engineering on microwave techniques has been greatly appreciated.

9.0 References

1. STALKER, R.J. National Research Council of Canada, Engineering Report MT-44, May, 1961.

2. STALKER, R.J. Aeronautical Quarterly 17, 4, 351 - 370, Nov. 1966.

3. DUNN, M.G. & BLUM, R.J. NASA CR-490 May 1966.

*4. STALKER, R.J. AIAA J. 5, 12, 2160-2165, December, 1967.

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*Further Reference

Since the original publication of this work as a College of Aeronautics Report, Stalker has given an account of further investigations into the possibility of tailored interface operation of this type of shock tube.

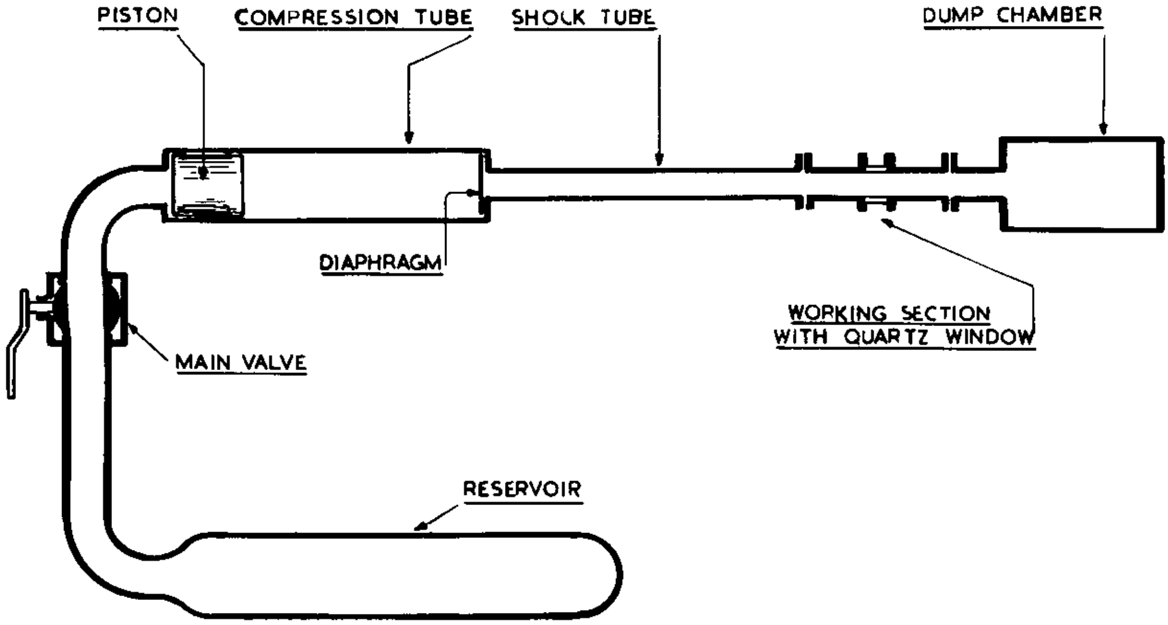


FIG 1 SCHEMATIC DIAGRAM OF THE SHOCK TUBE.

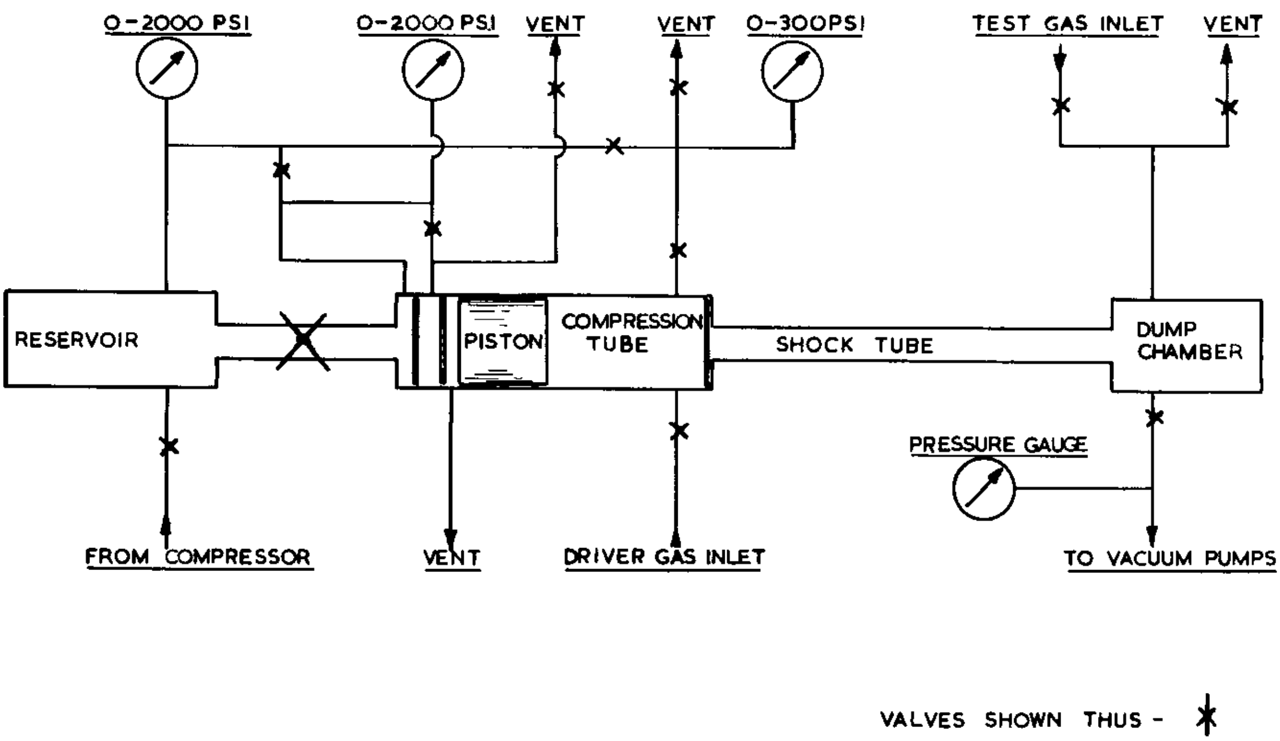


FIG 2 DIAGRAM OF PIPEWORK.

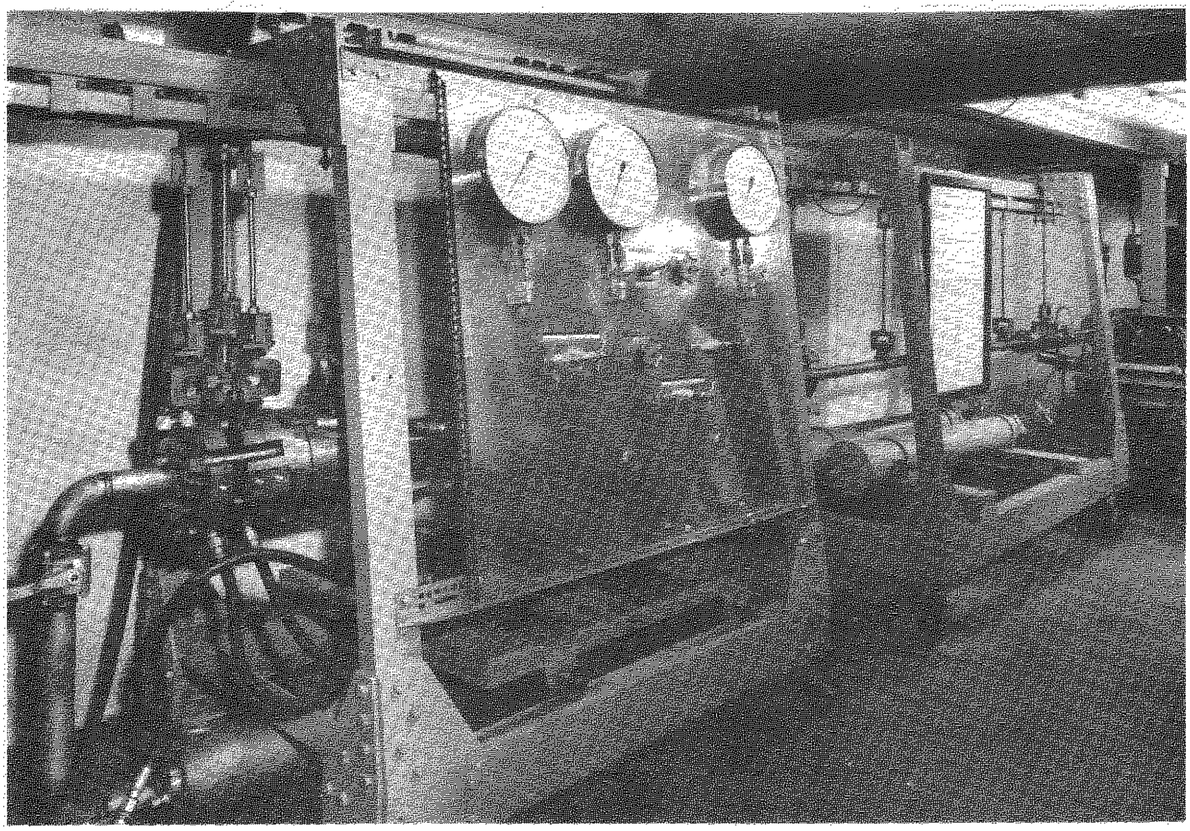


FIGURE 3 GENERAL VIEW OF THE SHOCK TUBE.

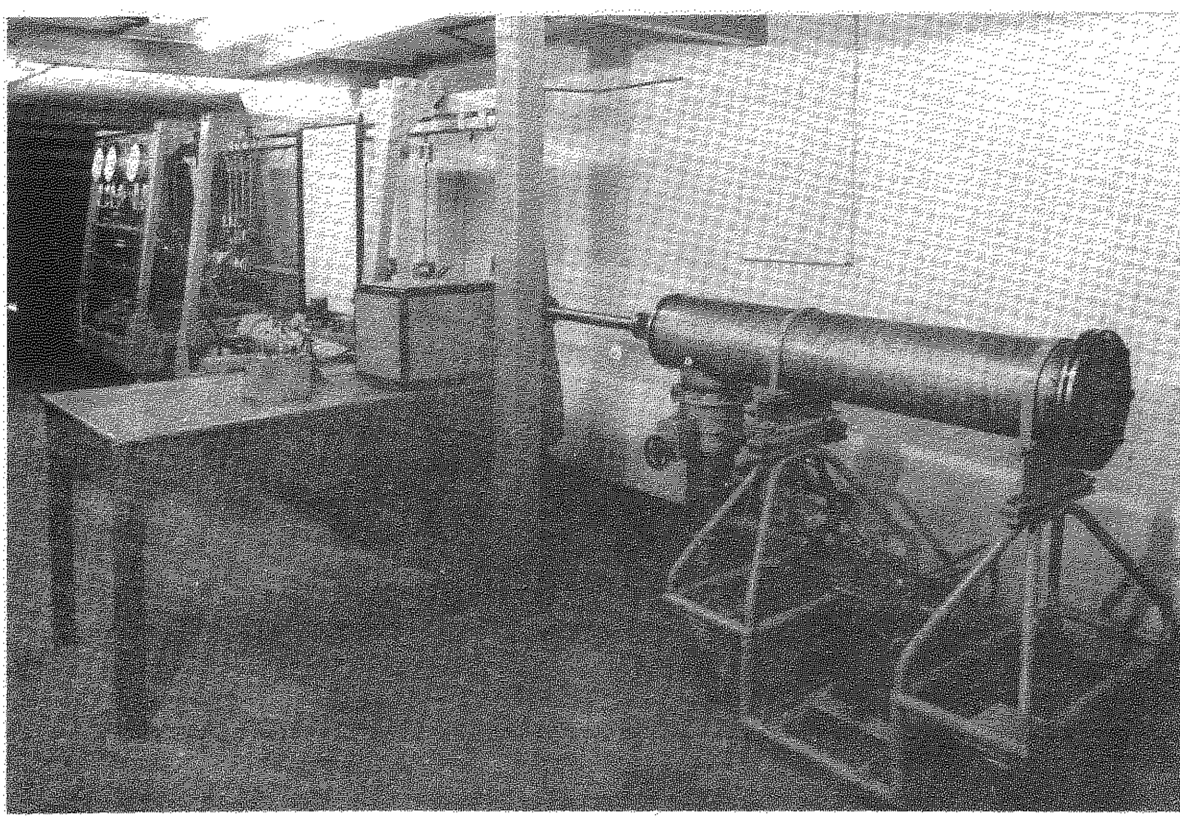


FIGURE 4 GENERAL VIEW OF THE SHOCK TUBE.

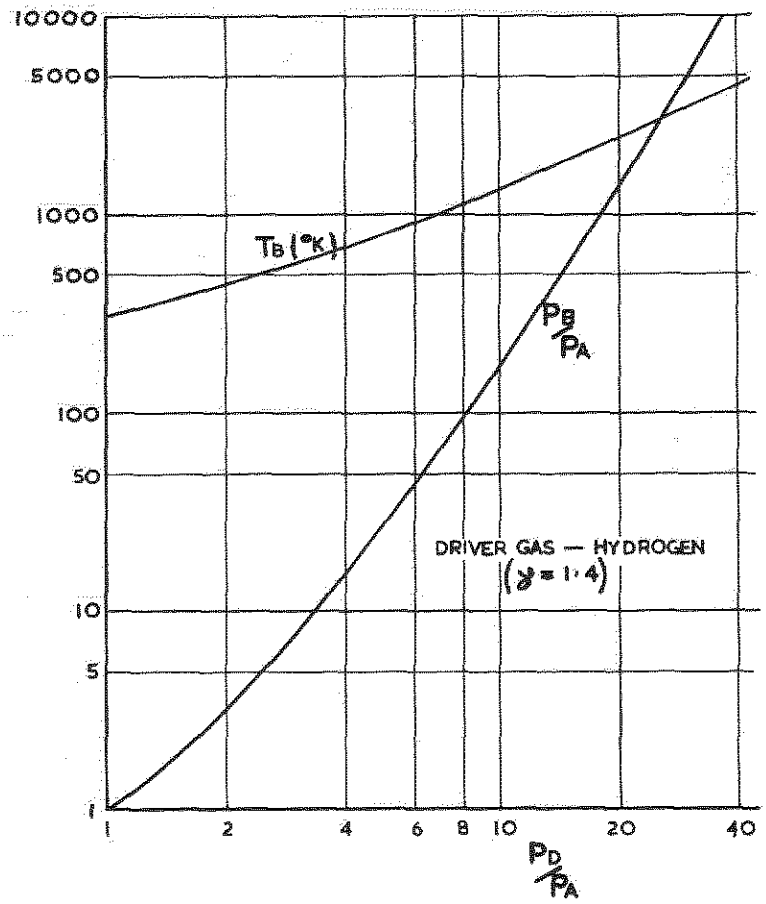


FIG 5. THEORETICAL COMPRESSOR PERFORMANCE.

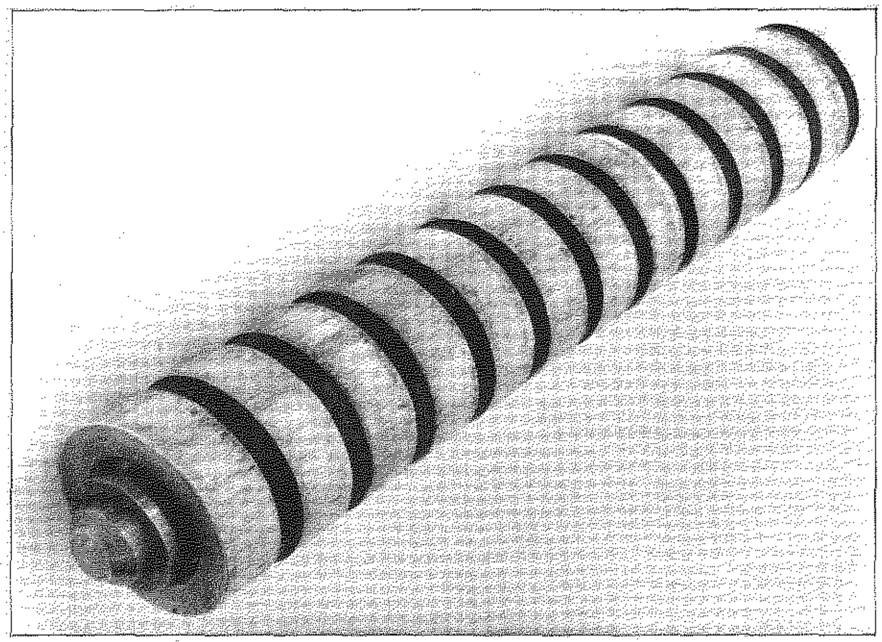
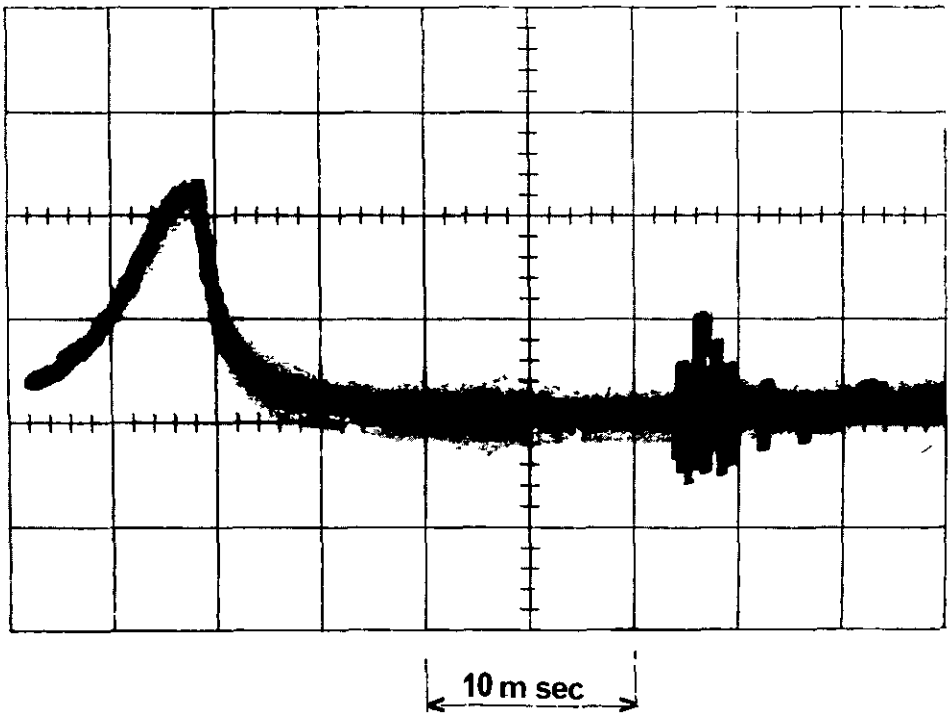
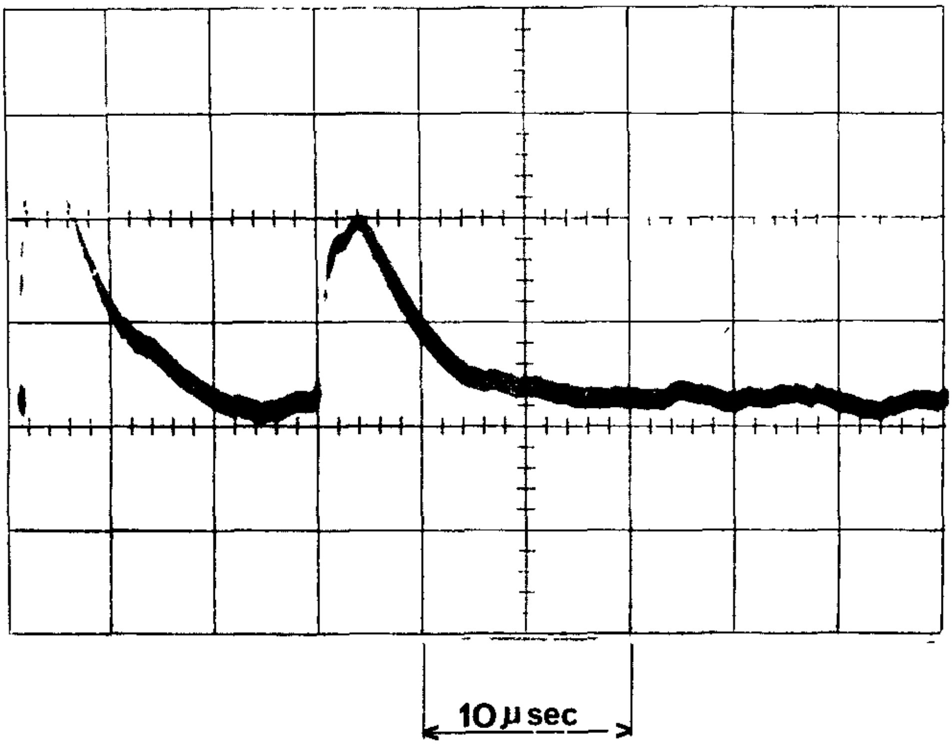


FIGURE 6 THE PISTON



Vertical scale 1000 p.s.i./cm.

FIGURE 7 COMPRESSION TUBE – PRESSURE RECORD.



Vertical scale 10 mV/cm

M_s = 28·4

FIGURE 8 PHOTOMULTIPLIER OUTPUT RECORD.

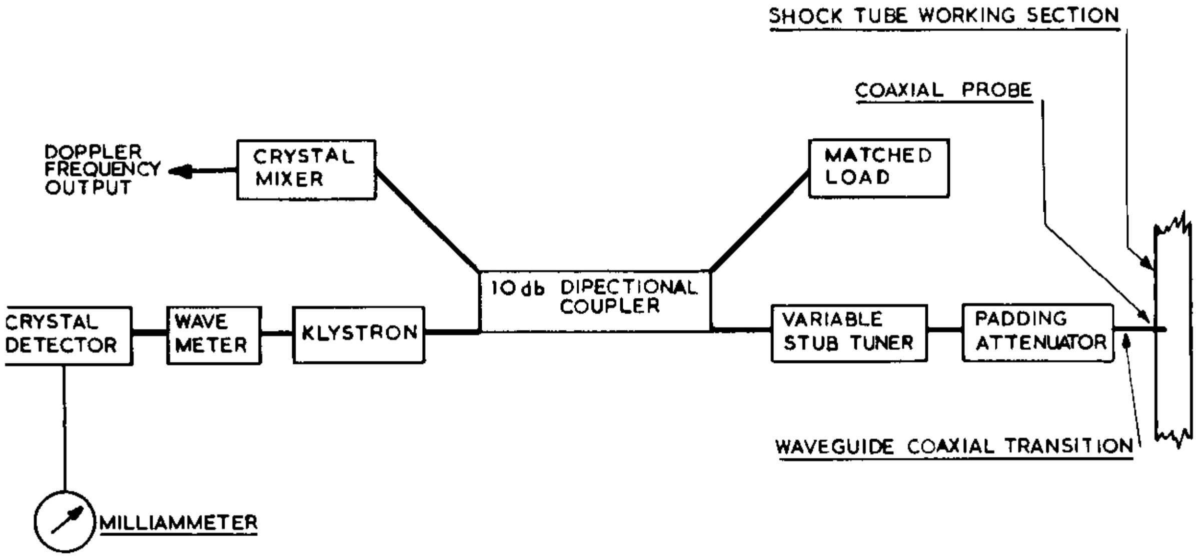


FIG 9 BLOCK DIAGRAM OF MICROWAVE SYSTEM.

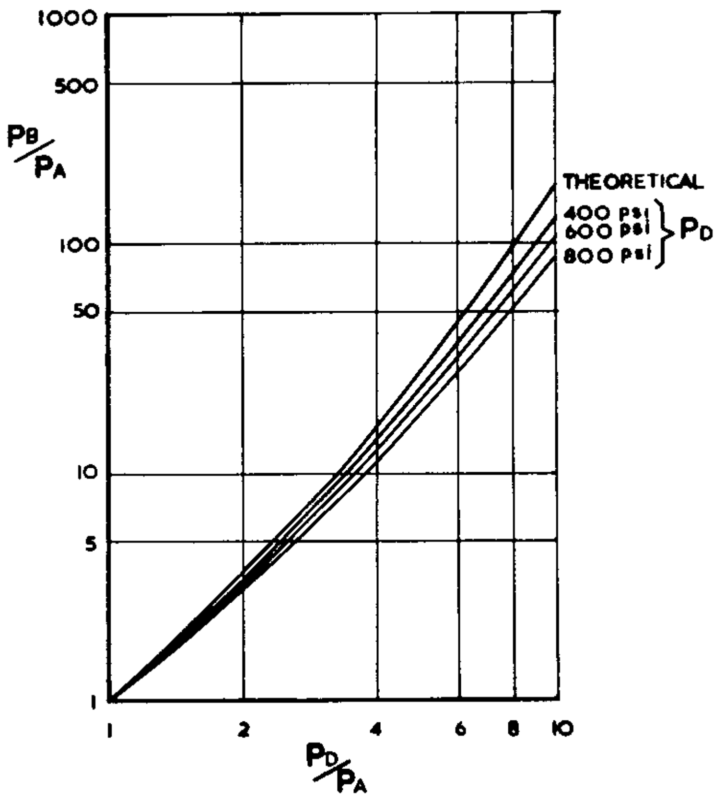


FIG 10 MEASURED COMPRESSOR PERFORMANCE

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