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A Progress Report on the University of Southampton Hypersonic Gun Tunnel

by

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SUMMARY

This note is intended as a brief report on progress made with the Southampton University hypersonic gun tunnel during the first six months since it became operational. It includes a description of the mechanical construction of the tunnel and the instrumentation that has been developed for it, together with some preliminary measurements designed to test the steadiness and uniformity of the flow. Specialised reports dealing with these subjects in detail will be issued at a later date.

1. Introduction

The "light gas hypersonic gun tunnel" is a development of the conventional shock tube giving a comparatively long running time for aerodynamic testing purposes. Its mode of operation has been fully described by other authors (Ref.1) and will only be outlined here. Fig.1 shows the principal components. A vessel (1) containing gas at high pressure is initially separated from the main tube or gun barrel (2) at a lower pressure by a metal diaphragm (3) and a light piston (4). When the diaphragm is ruptured the piston is driven down the barrel and a strong shock wave forms ahead of it. The shock wave is reflected several times between the end of the barrel and the piston before the latter is finally brought to rest, and so the slug of air ahead of it is heated and compressed in a non-isentropic manner. This heated air breaks a second diaphragm (5) and accelerates from rest through a convergent-divergent nozzle (6) into the test section (7) and finally passes into a large evacuated vessel (9) via a diffuser (8).

Calculations of the performance of a typical gun tunnel have been reported in Ref.2, in which allowance for real gas effects has been made. These calculations show that hypersonic flows with durations of several tenths of a second and with stagnation temperatures reaching several thousand degrees Kelvin may be expected.

The reason why the running time of the gun tunnel may be many times greater than that of the shock tube is simply that the use of a piston enables the processes of shock compression and expansion through the nozzle to be effectively separated. The piston, backed by the gas in the high pressure vessel, drives all the heated air out through the nozzle and the running time may be increased simply by reducing the throat size, until a limit is set by the melting of the throat. In the conventional shock tube, on the other hand, the running time cannot be greater than the time between the arrival of the shock wave and the arrival of the contact surface at the nozzle entrance, however small the nozzle is made.

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2. Mechanical Construction

The general arrangement of the tunnel and associated equipment is shown in Fig.2. The high pressure vessel and barrel run on a light railway for ease of dismantling to replace the piston and diaphragms. The railway rests on a concrete plinth which also supports the working section and the schlieren equipment, while the vacuum vessel is set in a hole in the floor.

2.1 High pressure vessel (Fig.3)

This is a 5 ft long section of a 3.7 in. gun barrel. One end is closed with a screwed blanking plug, and the other contains an adaptor which reduces the bore to 1.25 in. and also grips the diaphragm. The diaphragm is burst by means of an electrically operated "pricker".

2.2 Barrel (Fig.4)

A 10 ft long gun forging with a smooth bore 1.25 in. in diameter, the barrel is coupled to the diaphragm end of the high pressure vessel by means of a large nut. A section at the other end of the barrel is detachable and contains various entry ports for instrumentation. Another nut joins this section to the nozzle.

2.3 Nozzle (Fig.4)

Made in three sections, this has a conical contraction, a cylindrical throat 0.040 in. in diameter, a conical expansion with an over-all expansion angle of $7\frac{1}{2}$ degrees, and an exit diameter of 2 in. The throat section is made from copper and the other two parts are steel.

2.4 Test section

The nozzle exhausts into a 14 in. x 8 in. x $8\frac{1}{2}$ in. box of welded construction from U-section steel. The removable side plates contain 6 in. diameter schlieren windows. A diffuser is fitted at the downstream end of the test section through which the hypersonic jet enters the vacuum vessel.

2.5 Vacuum vessel

A 6 in. diameter pipe from the test section leads into a steel vessel of 70 cu ft capacity, which is evacuated by an Edwards rotary pump (Type GKS 27, displacement 27 cu ft/min).

2.6 Gas supply

The tunnel is at present being run from bottles of commercial compressed air. A 3500 p.s.i. air compressor is being set up for this purpose, and it is planned also to run the tunnel from bottled helium or hydrogen.

3. Measurements Required to Determine the State of the Test Gas

Three cases may be considered:

(i) Isentropic flow, gas in thermodynamic equilibrium.- Here two measurements are sufficient to determine the state of the gas, and a third suitable measurement can give its velocity. As the expansion process is isentropic the two state measurements may be made either upstream of the nozzle or in the test section.

If the additional assumption is made that the flow properties are constant throughout the run, then the following measurements suffice to determine the flow:

(a) reservoir pressure (in the end section of the barrel ahead of the nozzle);

(b) pitot pressure (in the test section);

(c) running time (from pitot pressure).

Knowing the reservoir pressure and the mass of gas heated, the running time gives a mean reservoir (stagnation) temperature. The pitot pressure and the shock wave equations then determine the flow Mach number and the isentropic relations give an effective nozzle area ratio, so that the state of the gas in the test section may be determined.

If one other measurement can be made, either in the reservoir ahead of the nozzle or in the test section, then the rather suspect running time calculation may be checked. This may be done, for example, either by direct measurement of the reservoir temperature or by observation of the gas velocity.

The above conclusions are not, of course, altered by equilibrium real gas effects. Calculations will be much more tedious if tabulated gas properties are used instead of the ideal gas equation of state with γ = constant, but the number of measurements required to solve the problem will be the same.

(ii) Non-adiabatic flow, gas in thermodynamic equilibrium.- In this case measurements in the reservoir are no help as they cannot be related to test conditions, so all three required quantities must be measured in the test section. For example, the pitot pressure, static pressure and gas velocity are sufficient.

(iii) Non-equilibrium flow. - This may occur either as a result of rapid expansion of the gas through the nozzle, or from rapid compression through a strong shock wave in front of a body. In either case one additional measurement is required in the region of interest for each molecular degree of freedom that is out of equilibrium. It appears extremely difficult to make sufficiently accurate measurements to deduce the state of equilibrium of the gas from thermodynamic quantities. A more hopeful approach seems to be to use an absorbtion technique as a direct measure of the density of the particles in question.

Work is under way or planned to measure the following quantities:

(a) reservoir pressure;

(b) reservoir temperature;

(c) piston velocity (giving reservoir density);

(d) pitot pressure;

(e) static pressure;

(f) gas velocity.

These measurements should be sufficient to check whether the flow through the nozzle is isentropic, but they will probably not be accurate enough to determine the equilibrium state of the gas as well.

4. Instrumentation for the Tunnel

The policy of instrumentation has been to investigate the main parameters in the gun tunnel and to record them simultaneously where possible.

We have therefore been mainly concerned with measuring static levels and low frequency variations, consistent with the frequency response of the multi-channel photographic recorder*.

Certain parameters have also been studied individually for high frequency behaviour and the results displayed on a large bandwidth oscilloscope.

It was envisaged at the outset that it would be better to investigate several parameters simultaneously in a simple manner rather than to devote a large amount of research time to measuring one parameter accurately. This has enabled us to gain experience in several techniques which can later be extended for more detailed studies.

4.1 Pressure transducers

All pressure measurements have been made with the S.L.M. quartz crystal pressure gauges. They have been found to be satisfactory. Because of their high insulation resistance (10^{14} ohms) it is possible to measure static pressure levels; this, however, can only be done if an electrometer valve is used to isolate the gauge charge from the display instrument. The S.L.M. Piezo-Calibrator Unit serves this function and delivers an output voltage of order 0.5 volts at 10^5 ohms impedance for connection to other equipment. It further provides a convenient pressure sensitivity control, simply by selection of input capacitor to the electrometer valve.

We have used the following types of S.L.M. piezo gauge:-

Type	Pressure Range p.s.i. gauge	Natural Frequency cycles/sec.	Sensitivity p.Cb./p.s.i.	Dimensions (ins.)	
				Diam.	Length
PZ 6S	1.4 - 4,000	500×10^3	0.46	0.25	0.56
PZ 14	1.4 - 2,100	48×10^3	4.0	0.625	2.25
PZ 60	0.05 - 85	7×10^3	128	2.35	2.42

The miniature PZ 6S gauge has been fitted behind a pitot tube in the working section to measure pitot pressure. In the most sensitive condition of the Piezo Calibrator unit, the voltage output is ≈ 0.5 m.V. for 1 p.s.i. pitot pressure. This is fed into a D.C. amplifier having a voltage gain of 400 and an output impedance of 200 Ω to feed the moving coil galvanometers of the photographic recorder. The P.Z. 60 has also been used for measurement of pitot pressures and provides 60 m.V. for 1 p.s.i. pitot pressure. Unfortunately it is large and can only be

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* Type - Heiland 708 - 24.
Brief description - 16 channel photographic recorder (8 - 450 cycle/sec. galvanometers).
Kindly lent by - R.A.E., Farnborough, Hants.

connected to the pitot tube by a length of capillary tubing. Thus a higher voltage output is gained at the expense of frequency response, which, with the capillary tubing, is approximately 200 cycles/sec.

The P.Z. 14 gauge has been used for barrel pressures.

4.2 Piston displacement and velocity measurement by microwaves

We wished to study the effect of piston mass and shape upon the flow steadiness and length of running time of the gun tunnel. For this purpose a microwave technique is being developed. This technique regards the gun barrel as a resonant microwave cavity, and the travelling piston as a tuning plunger moving in the cavity. A brass face is fixed to the nylon piston for the purposes of these measurements (see Fig.6). The standing wave field is monitored by a crystal diode detector, and it is observed that whenever the piston passes through a half-wavelength station the standing wave field is disturbed in a cyclic manner (Fig.7). The crystal diode output voltage is a varying D.C. level, the time between successive crests corresponding to the time taken for the piston to travel through $\lambda_g/2$ (where λ_g is the wave-length of the wave system set up in the barrel). Thus not only displacements can be measured, but also the average velocity of the piston between any $\lambda_g/2$ stations.

In the Southampton University gun tunnel the barrel is energised by a low power reflector klystron* operating in the 3 cm. commercial band (see Appendix I).

A simple $\lambda_g/4$ aerial is used at the nozzle end of the barrel, consisting of a copper ring or cross supported in a nylon plug. Because of the high pressure involved, coupling the microwave energy into the gun barrel is very difficult and involves a considerable loss of power. We have now developed a satisfactory coupling which has been tested to 4,500 p.s.i.

The output voltage from the silicon crystal diode is normally displayed on a Solartron C.D. 513 oscilloscope and photographed on 35 mm. film.

An oscillogram is shown (Fig.7) of the variation in crystal diode voltage during a typical run, taken 4.0 mSecs after the diaphragm was ruptured. Analysis of this (Fig.8) indicates that the piston is increasing in velocity from 1,445 ft/sec to 1,490 ft/sec over a barrel length of 3.02 in. during a time interval of 170μ Secs. This requires an acceleration of order 265,000 ft/sec^2. The maximum piston velocity so far observed has been 1,700 ft/sec. Velocities and displacements have been measured throughout the entire period of the piston motion.

The Tektronix Oscilloscope used in this instance was kindly lent by Aerodynamics Division, N.P.L.

Since the primary measurement is one of piston displacement along the barrel from starting position, it should be possible to calculate the stagnation density of the gas at any time during the flow. This may be done by estimation of the rate of mass flow through the throat, since the initial mass contained in the barrel is known.

We are developing a "raster" type of C.R.T. display which will enable the whole run to be recorded, yet have an individual time-base sufficiently short in duration to enable accurate piston velocity variations to be determined.

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* Kindly loaned by A.S.R.E., Cosham, Hants.

4.3 Temperature measurement

It is intended to measure the temperature of the heated gas in the barrel by an optical method. The method used is the sodium line reversal technique as applied to the shock tube by Gaydon and Glass (Ref.3).

Two quartz windows have been installed in the detachable section of the barrel (see Fig.4). A 13-stage photomultiplier tube (type E.M.I. 9502 B) has been tested in conjunction with a Tungsten "Point-o-lite" lamp and transmission filters to isolate a bandwidth of 80 A° in the region of the sodium D lines. Absorbtion effects have been readily observable through the flame of a Meca burner.

The method is a null-point one, and as such means that the measurement obtained is that of the time during the run at which the temperature of the heated gas is equal to the temperature of the background source used. In order to obtain a temperature-time history of the heated gas a series of runs using constant initial conditions must be performed.

Preliminary runs have indicated that the method is suitable for reservoir temperature measurements in the hypersonic gun. At present the sodium is introduced into the working gas by depositing sodium chloride crystals in the barrel before a run.

4.4 Schlieren system

The schlieren system used to date has been a conventional single pass, twin mirror installation, using a spark discharge light source. Owing to limitations of space, the optical axis has been "bent" on either side of the working section. This has necessitated the use of two optically flat plane mirrors, which has reduced the amount of light available for photography.

The concave mirrors are of 6 ft focal length, and the image lens 17" focal length, giving an image approximately 3.5 times smaller than the object under examination. The image of the spark gap is focussed onto a rectangular slit approximately 0.75 mm. by 5 mm. The spark gap utilises steel electrodes and is triggered by a third electrode as described in Section 4,§4.5. It is partially constrained by means of a paxolin channel surrounding the electrodes. The duration of the spark is approximately 2µ secs.

It has been found from preliminary photographs that the system has inadequate sensitivity for the low densities under consideration. Only severe density gradients, i.e. through a shock, have been noticed. The edges of the hypersonic jet have not been observed.

It is intended to use a longer focal length mirror and an improved light source of shorter duration and increased brightness in order to improve the overall sensitivity of the system.

4.5 Delay generator for schlieren spark

This permits photography of the flow by means of the spark at any time during the run.

The delay generator is a conventional phantastron square wave generator utilising a variable duration square wave. This wave is differentiated sharply, and the trailing edge "pip" arranged to fire a thyratron. This discharges a 4µFd condenser (charged at 250 V) through the primary of a car ignition coil, the high voltage output of which is connected to the trigger electrode of the spark gap system.

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The discharge pulse of the spark is too rapid to be monitored on the recorder, so the phantastron pulse is brought out to the recorder for this purpose, enabling the duration of the delay to be observed. (See Fig.13). The actual moment of spark firing is coincident in time with the trailing edge of the phantastron square wave. At present the phantastron is triggered from a voltage step caused by a breaking wire in the mouth of the jet exit in the working section.

4.6 High voltage supply for spark

A 10 K.V. r.m.s. transformer secondary feeds a conventional half-wave rectifier circuit. The mains input to the transformer is controlled by a Variac, this providing a convenient fine adjustment to the high voltage output and hence to the brightness of the schlieren spark.

4.7 Diaphragm "pricker"

Because of the need to make several simultaneous measurements on a multichannel photorecorder, it was considered impracticable and wasteful of film to start the recorder running and then rely on natural bursting pressure.

A spring loaded "pricker" has therefore been developed (see Fig.3). The spring is compressed manually, prior to inserting the first diaphragm, and retained in compression by a light pawl. This pawl is then released by a solenoid.

The pricker has been deliberately made long so that the spring and solenoid assembly can be mounted as far back from the constriction as possible, thereby avoiding blockage. It was found that a conically pointed pricker tended to seal itself in its puncture hole. However, since using a wedge-shaped profile, diaphragm sealing has not occurred.

Early tests made at atmospheric pressure in the breech indicated that the pricker had sufficient force to puncture diaphragms suitable for 1000 p.s.i., yet when the breech was pressurised to 1000 p.s.i. the diaphragms failed to burst. It was concluded that this was because of the increased air density slowing down the ram and accordingly the bolt-ram casing was liberally vented with holes. Since this was done the diaphragms have burst cleanly every time and it has been found possible to pressurise at 20% below the natural bursting pressure and still adequately burst the diaphragm with the pricker. However, in order to obtain good petalling, it was found necessary to burst at 5% below the natural bursting pressure.

4.8 "Pricker" trigger

It was realised that this electro-mechanical pricker would be inherently irregular in time of operation. This ruled out using the pricker firing voltage step as a master trigger. Clearly the best trigger would be that occurring at the instant of diaphragm burst.

The pricker has therefore been electrically insulated from the gun (the gun being at earth potential) and placed at +24 volts. The only reason for this potential is that the solenoid operating voltage is 24 volts and comes into the breech via a pressure-tight connection and hence is immediately available. When the released pricker impinges on the metal diaphragm there is a momentary short circuit which disappears as the diaphragm petals open. To safeguard the accumulator supply a 24 volt, 36 watt bulb is included in the circuit, which, when cold, has negligible resistance.

The pricker voltage has been monitored on the multi-channel recorder (see Fig.13) and some interesting events may be observed:-

(i) It provides a measure of the operational time of the pricker system and shows that at a breech pressure of 1010 lb/in^2 it varies from 50 to 80 milliseconds for individual runs.

(ii) The actual shorting pulse may be seen on the record, and appears to be of the order of 1 millisecond duration, though this may conceivably be a result of the galvanometer frequency response. However, no matter what the duration of this pulse is, its leading edge may be utilised to operate a fast speed trigger valve, this then serving as a master trigger.

(iii) That the petalling of the diaphragm can oscillate to and fro due to the reflected wave system and in sweeping past the pricker completes the circuit. An oscillation at a frequency of about 30 cycles/sec may be discerned corresponding to the acoustic resonance in the barrel (see Section 5,§5.2).

4.9 Future measurements

Gas velocity:- by photographing a spark disturbance propagated downstream. We plan to develop this in a small shock tube.

Temperature:- in high pressure vessel, barrel and working section by means of resistance thermometers and thermocouples.

Shock speed:- by inserting a pair of resistance film thermometers in the barrel at the nozzle end, we hope to detect and measure the shock speed for its several reflections.

Piston velocity check:- Two foil strain gauges "Araldited" onto the barrel, wired into a D.C. bridge circuit and detecting change in circumferential strain due to passage of piston past that point.

Aerodynamic forces:- For various bodies we plan to measure the aerodynamic lift and drag forces. We will try to do this by means of strain gauges mounted on the sting support.

5. Experimental Results

The results reported in this paper are preliminary findings from the first few months of operation of the gun tunnel. All measurements have been made using air at a driving pressure of 1010 lb/in^2 and barrel pressure of 1 atmosphere. Hence the stagnation temperature has been only of the order of 1000°K. The dump chamber has been evacuated to 1/10 m.m. of Hg.

The area ratio of the conical nozzle was designed to produce a Mach number of approximately 10 at its exit, allowance being made for the finite wall boundary layer.

5.1 Diaphragms

The high pressure vessel of the gun is separated from the barrel by a metal diaphragm. Both annealed copper and pure aluminium have been used. Tests have been carried out to determine the bursting pressures and mode of rupture of various thicknesses of material, and to test the suitability of the spring loaded pricker as a means of initiating rupture.

A simple theory was used to predict bursting pressure (see Appendix II) and checked against experimental data. The results of diaphragm bursting rests are shown in Fig.9.

In order to fire the gun, diaphragms are ruptured by means of a spring loaded steel pricker (see Fig.3). It has been found that good petalling has been obtained with diaphragms ruptured by this method, if they have been subjected to pressures 5% below the natural bursting pressure prior to rupturing. 5% is the minimum allowance that can be made since this must cover the expected scatter due to slight variations in material properties. Examples of diaphragms burst naturally and with the spring loaded pricker are shown in Fig.10.

The second diaphragm separating the barrel from the dump chamber was originally placed at the nozzle exit. Its purpose was to delay flow establishment in the nozzle until steady conditions had been achieved in the barrel. The delay between the gun firing and flow establishment could be varied by changing the thickness of the diaphragm. This sheme was abandoned since the temperature decay in reservoir conditions is appreciable during the delay and the hottest portion of the running time is lost. At present the barrel is separated from the dump chamber by a piece of "Sellotape" at the contraction end of the nozzle. This has been found to withstand a pressure differential of 1 atmosphere. Using this system the flow is established soon after the piston reaches the nozzle end of the barrel on its first excursion. It has been found that the "Sellotape" is vaporized by the high temperature working gas and the nozzle therefore remains unobstructed during the run.

5.2 Pressure measurements in barrel

The pressure in the barrel during the run has been measured using an S.L.M. P.Z. 14, 0-2000 p.s.i. pressure transducer. The gauge is screwed into a hole in the barrel situated 3" from the nozzle end, the sensing element of the gauge being recessed 1/16 in. from the inner wall. The output is recorded on the Heiland recorder. The natural frequency of the recorder galvanometers is 500 cycles/sec. so that only fluctuations up to this frequency may be linearly observed. A typical barrel pressure record is shown in Fig.11.

It is noted that during the run the barrel pressure trace consists of approximately a square waveform on which is imposed a decay. This waveform can be attributed to an acoustic oscillation set up behind the piston. Every time a wave is propagated in the barrel towards the diaphragm station it is reflected by the area discontinuity as a wave of opposite sign. The pressure transducer thus responds to a series of steps of alternate sign, thereby producing the square waveform. The oscillation attenuates to 10% of the mean pressure level after 0.1 secs. The square waveform is modulated by further disturbances of smaller amplitude which probably arise from a secondary wave system reflected from the rear of the breech. The measured frequency of the square waveform (30 cycles/sec) is in close agreement with the predicted frequency of an acoustic wave travelling in a pipe 10 feet long. The frequency in a pipe closed at one end is given by

$$f = \frac{a_\omega}{4\ell}$$

where a_ω is the wave velocity and ℓ is the length of the pipe.

It would appear from these measurements that the flow quantities in the working section will be subject to similar oscillations. However, the magnitude attentuates so that after 0.1 second (for present conditions) the oscillation in the working section pitot pressure, for example, will be not greater than 10% of the mean level.

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A preliminary investigation has been made into the shock reflection process by means of the P.Z.14 pressure transducer, the result being recorded on a C.R.O. Results have shown that two shock reflections occur, i.e. one reflection from the closed end of the barrel and one from the face of the piston. The incident shock pressure ratio has been found to be smaller than theoretically predicted from shock tube theory. This is probably due to excessive piston friction. However, successive reflected shock pressure ratios agree closely with a theoretical estimate obtained from the measured value of the incident shock pressure ratio. It is intended to study the shock reflection process in more detail for a series of diaphragm pressure ratios and to measure the peak pressures acting on the barrel.

5.3 Pressure measurements in the jet

Pressure measurements in the open jet working section have been restricted to pitot pressure. Hypodermic tubes (0.065" O.D., 0.043" I.D.) are attached to a double wedge section support positioned across the jet. Each tube in turn is connected via flexible tubing to the S.L.M. P.Z. 60, 0-80 p.s.i. pressure transducer. The length of tubing is kept to a minimum in order to keep the response time of the pressure measuring system as short as possible. The natural frequency of the present system is of the order of 200 cycles/sec.

In order to record higher frequency components, the centre hypodermic tube is connected to an S.L.M. P.Z. 6 miniature pressure transducer mounted in the wedge support. The tube length in front of the gauge is thus much reduced and the frequency response of the system improved. However, the transducer is working at the lowest end of its range, and together with the fact that it was found to be very temperature sensitive, results so far obtained from this system have been unreliable. The outputs from both gauges are amplified and recorded for the duration of the run on the Heiland recorder. The systems are statically calibrated against a mercury manometer.

Initial measurements were taken with the jet entering the dump chamber through a large hole. Only one pressure channel could be obtained from each run owing to the fact that only one set of ancillary equipment was available. By selecting different channels for separate runs the pitot pressure distribution across the jet was obtained and the variation of the distribution with time noted. A typical record is shown in Fig.12. An oscillation of approximately 30 cycles/sec. is apparent in the record and was found to be in phase with the oscillation in barrel pressure. Thus, as would be expected, the fluctuations in reservoir conditions are transmitted through the nozzle to the working section.

In general, pitot pressure records obtained showed considerable unsteadiness of flow throughout the run. Variations in total head of the order of 30% have been recorded. The scatter in this quantity between consecutive runs was approximately 10%.

In order to overcome the problem of unsteadiness of flow a diffuser has been fitted at the entrance of the working section to the dump chamber (see Fig.1). The series of pitot pressure measurements previously discussed was repeated. These showed that the flow steadiness had been improved; variations in pitot pressure were no greater than 10% over the duration and measurements from consecutive runs were repeatable. Typical pitot pressure records for this condition are shown in Fig.13.

Typical profiles of pitot pressure across the jet are shown in Fig.14, corresponding to the two working section conditions discussed previously. The profile was measured at a distance of 1.15" from the 2" diameter exit of the nozzle and 0.10 seconds from the commencement of flow establishment. They show that for the diffused condition there is a region of uniform flow of approximately 0.3" diameter, while for the undiffused state there is a considerable variation across the whole of the jet.

Pitot pressure measurements have been repeated for two other axial positions along the jet and have shown that there is a Mach number gradient along the axis. The axial variation is shown in Fig.15.

From the measured values of pitot pressure and reservoir pressure it is theoretically possible to calculate the flow Mach number using the Rayleigh supersonic pitot formula. However, this assumes an ideal gas with constant ratio of specific heats (γ). The calculation of Mach number using this method is very sensitive to small changes in γ and hence the reservoir temperature of the gas must be known. At present the only means of estimating the temperatures is to calculate the mean reservoir temperature using the measured running time as outlined in Ref.1. Assuming constant conditions during the run the reservoir temperature (T_R) is given by

$$\frac{T_R}{T_0} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}} \cdot \frac{a_0^2}{\ell^2} \cdot \left(\frac{d_T}{d}\right)^4 \cdot \left(\frac{p_D}{p_0}\right)^2 \cdot t^2$$

where T_0 is the initial temperature of the gas in the barrel;

a_0 is the velocity of sound of the gas in the barrel before firing;

p_D is the mean driving pressure in the barrel during the run;

p_0 is the initial barrel pressure;

d_T is the throat diameter;

d is the barrel diameter;

ℓ is the barrel length;

and t is the tunnel running time.

Hence the reservoir temperature depends on the square of the running time, and also critically upon the value of γ . It is thus necessary to determine t accurately.

The temperatures calculated in this way so far have been lower than those predicted from adiabatic compression of the working gas. It is suspected that some of the gas in the high pressure region ahead of the piston is leaking past the piston and thereby reducing the amount of working gas which is available for expansion through the nozzle. This will appear as a decrease in running time. Consequently, measurements of temperature obtained by this method are incorrect, and the test section Mach number cannot be predicted with certainty until the reservoir temperature has been measured as outlined in Section 4,§4.5.

5.4 Microphone records

These have been useful in determining the tunnel running time and in assessing the steadiness of the flow.

The microphone used is a balanced armature type with frequency response up to 5000 cycles/sec., mounted on sponge rubber in the working section out of the high speed flow. The output is connected directly to the Heiland Recorder.

Records have shown the noise caused by the starting shock and then a period of steady, small amplitude oscillations corresponding to the steady flow. The end of the hypersonic flow is indicated by a definite large response. The running time obtained from this measurement is the same as that obtained from pitot pressure measurements.

The change in times of flow establishment, steady flow and breakdown caused by fitting the diffuser at the entrance of the dump chamber was noticed from the microphone records. In the undiffused state the jet emitted considerable noise of unsteady character which lasted until the end of the run. Fitting the diffuser decreased the amplitude of the microphone output and the end of the run was better defined.

From the records it was possible to note that fitting the diffuser enabled a steady flow to be established. Examples of flow noise output, with and without diffuser, are shown in Figs.12 and 13.

5.5 Flow visualization

Preliminary photographs have been taken of the flow over a flat plate with square leading edge and of that over a flat plate with hemicylindrical leading edge. A typical result is shown in Fig.16. The photograph was taken with a spark of duration of approximately 2 microseconds. The shock profile at the leading edge is apparent but no further details of the flow are visible. This is due to the present schlieren system being inadequate for the low density in the working section (approximately 1/100 atmospheric density). It is intended to increase the mirror focal length and use an improved light source to improve the sensitivity of the system.

It was hoped to use the system to visualize the edges and regions of the hypersonic jet and to correlate the flow photographs with pressure measurements discussed in Section 5,§5.3: with the poor sensitivity of the system this has proved difficult. In order to overcome this difficulty a model has been constructed consisting of several thin flat plates with blunt leading edges mounted parallel to each other in the jet. By observing the plates over which the bow shock is symmetrical it is possible to estimate the extent of the uniform flow region. Estimates so far obtained have shown close agreement to the uniform flow region outlined in Section 5,§5.3.

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No.	Author(s)	Title, etc.
1	R. N. Cox and D. F. T. Winter	The Light Gas Hypersonic Gun Tunnel at A.R.D.E., Fort Halstead. A.G.A.R.D. Report No.139, July 1957.
2	D. J. Maull	The performance of a Hypersonic Gun Tunnel for real and perfect gases,(unpublished). Department of Aeronautics, Imperial College, London.
3	A. G. Gayden, I. I. Glass and J. G. Clouston	Temperature measurements of shock waves by the spectrum line reversal method. "Nature" <u>181</u>, p.1325, May 10th 1958.

APPENDIX I/

APPENDIX I

Notes on the Use of Microwaves to Measure Piston Displacement and Velocity

The microwave frequency chosen should be such as to

(i) sustain a simple mode within the gun barrel;

(ii) for the mode to have radial symmetry.

Condition (i) ensures minimum attenuation along the barrel whilst (ii) obviates amplitude variations arising from rotation of the polarising field caused by change of dielectric constant with pressure and temperature.

For the diameter of the University of Southampton gun tunnel (1.25") the most suitable mode satisfying the necessary conditions is the TM_{01}, which falls within the '3 cm' commercial microwave equipment range (8.6 Gc/s - 9.8 Gc/s).

The steel gun barrel was found to be highly selective in frequency and the best transmission frequency was found by inserting simple probe aerials axially into each end of the barrel, feeding the Klystron oscillator into one and detecting the signal through a crystal detector at the other. The D.C. output voltage was then plotted against Klystron frequency. A very distinct peak was obtained at 9.225 Gc/s and this frequency has since been used.

The microwave power to the gun barrel is passed through a directional coupler to the aerial system. This permits the simultaneous monitoring of the reflected or transmitted wave system with a single aerial.

A "20dB" directional coupler used with a CV2304 Reflector Klystron gives a crystal diode (CV1044) current of order 1.0 mA. We have found that positioning of the aerial is very important and can make an improvement of 40 dB. Unfortunately coaxial cable heavily attenuates the microwave signal before entering the barrel. A flexible coupler must, however, be used since not only does the barrel nut require unclamping, but also the direct vibration from the gun "explosion" can result in frequency jumping of the Klystron and a decrease in sensitivity of the crystal diode. If the measured signal is made asymmetric (by alteration of matching), then it is possible to observe a change of signal phase whenever the piston reverses its direction. This effect has been clearly seen during actual runs.

Detection of the nylon piston is greatly aided if a disc of "shim" metal (brass, copper or aluminium) is fixed to its front surface (Fig.6), though it is possible to detect reflections from the nylon alone.

APPENDIX II/

APPENDIX II

Bursting Pressure of Pure Aluminium Diaphragms

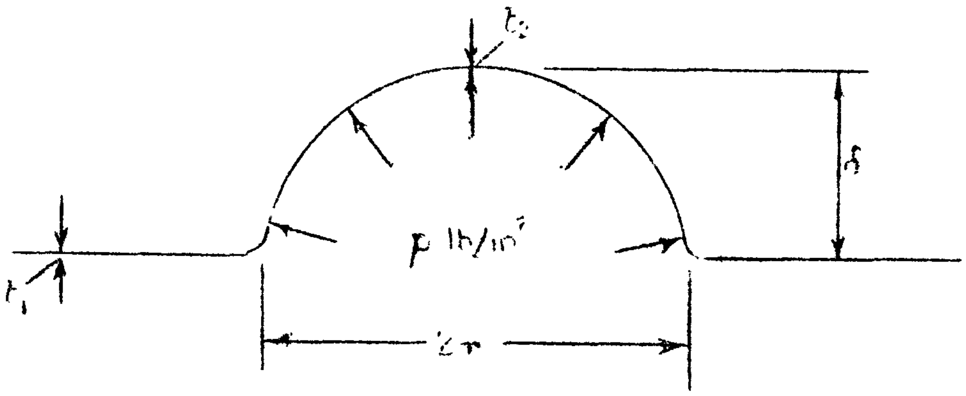
A simple theoretical estimate of the bursting pressure can be made by considering the diaphragm in its stretched condition to be a thin membrane. This implies a uniform stress distribution. It is assumed that bursting occurs when the indentation becomes hemispherical (this has been found to be almost the case experimentally).

Using the notation of the figure, the deformed thickness is

$$t_2 = \frac{r^2}{\delta^2 + r^2} t_1$$

where t_1 is the undeformed thickness and δ is the depth of indentation.

As $\delta \longrightarrow r$ then $t_2 \longrightarrow \frac{1}{2} t_1$.



Let the stress in the material be σ lb/in². By considering the balance of forces around the rim of the hemispherical bowl we have

$$2\pi r\,(\sigma\, t_2) = p.\pi r^2$$

$$\therefore\ p = \frac{2\,\sigma\, t_2}{r}.$$

At/

At burst $p = p_{rupture}$

and $\sigma = \sigma_{ult} =$ ultimate tensile strength

i.e.

$$p_{rupture} = \frac{2\sigma_{ult.} t_2}{r} = \frac{2\sigma_{ult.} t_1}{2r}$$

i.e.

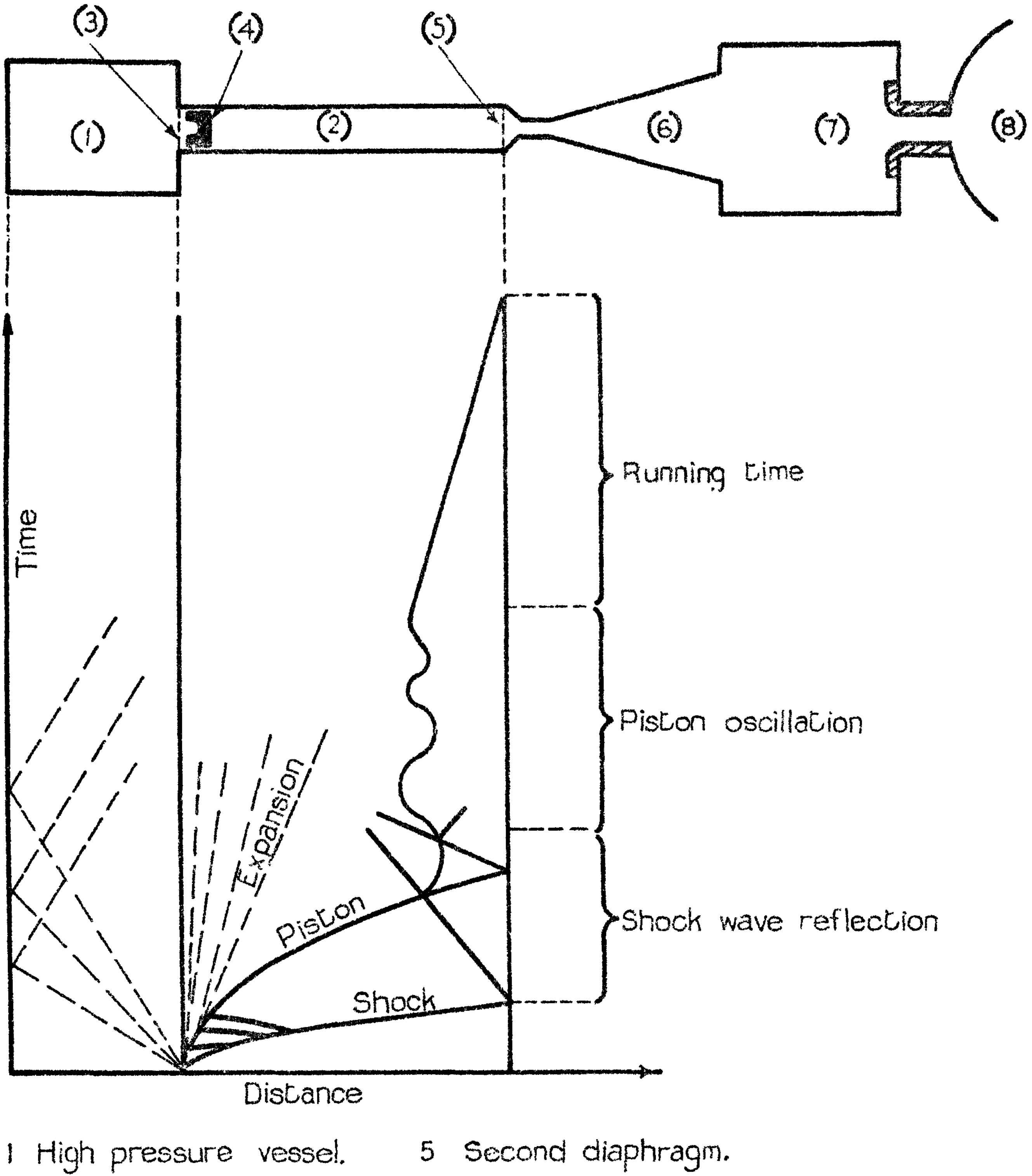
$$p_{rupture} = \sigma_{ult.} \frac{t_1}{r}.$$

Since the material has been greatly deformed the ultimate tensile strength to be considered should be that of the cold worked material. For aluminium this is 9 tons/in^2 which gives

$$p_{rupture} = 2.02 \times 10^4 \times \frac{t_1}{r} \text{ lb/in}^2.$$

This expression shows a good agreement with experimental results obtained from the University of Southampton gun tunnel and is plotted on Fig.9.

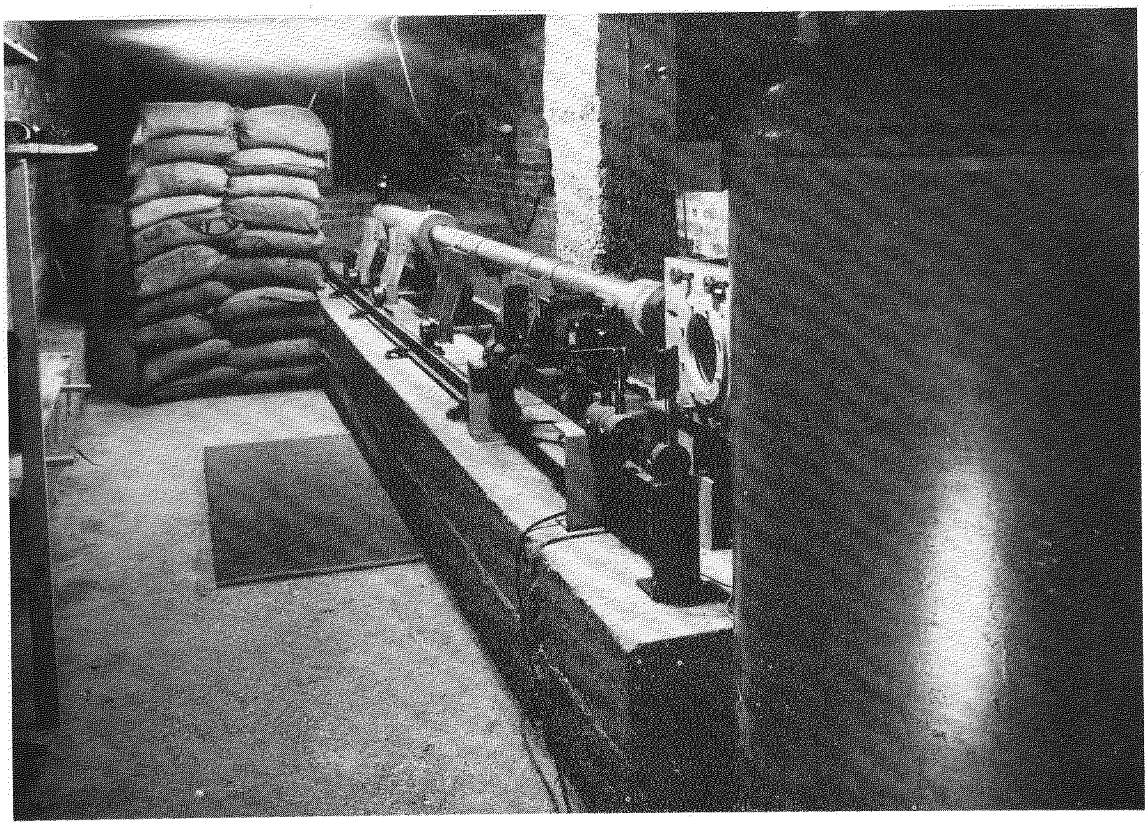
FIG. 1.



1 High pressure vessel.
2 Barrel.
3 First diaphragm.
4 Piston.
5 Second diaphragm.
6 Nozzle.
7 Test section
8 Dump chamber

General layout of gun tunnel and simple x-t diagram

FIG. 2.



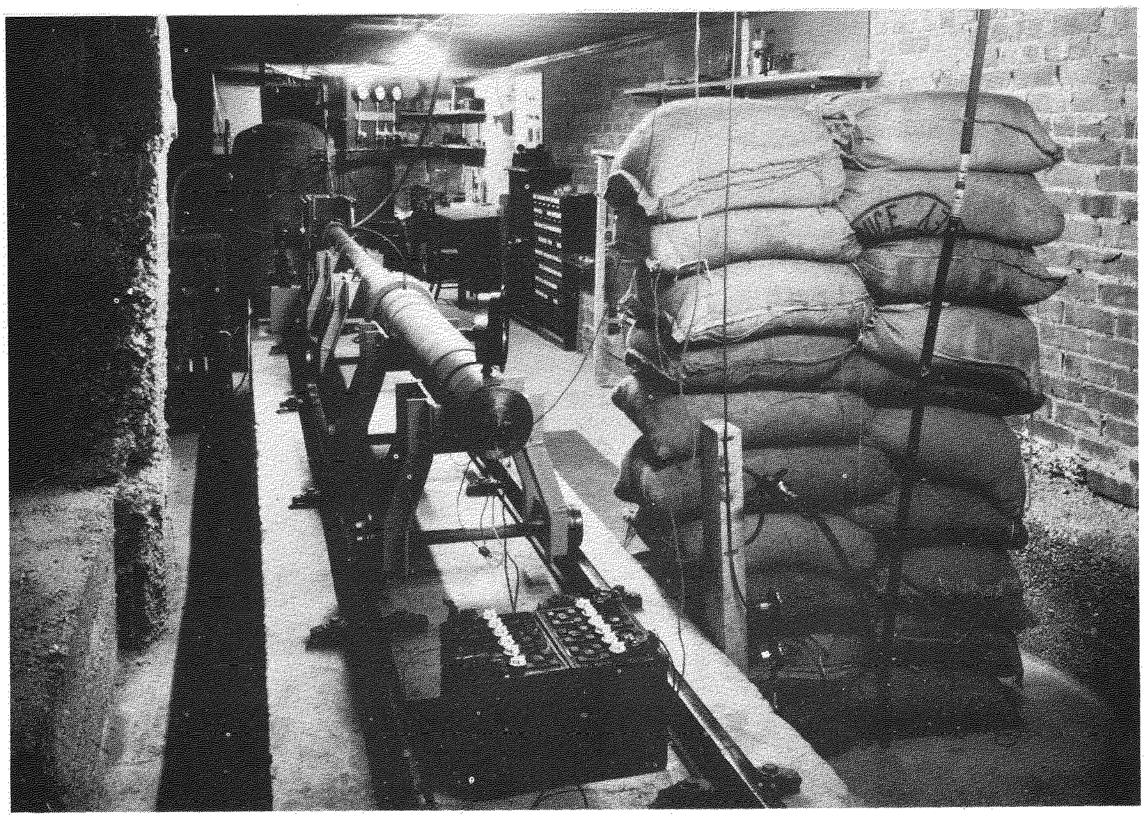


FIG. 2 GENERAL ARRANGEMENT PHOTOGRAPHS OF GUN TUNNEL.

FIG. 3.

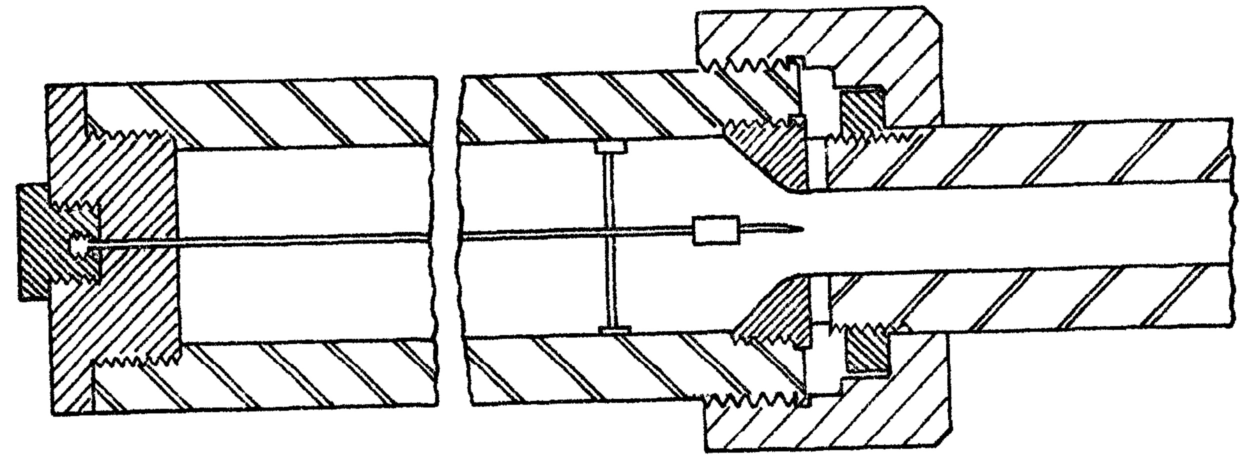
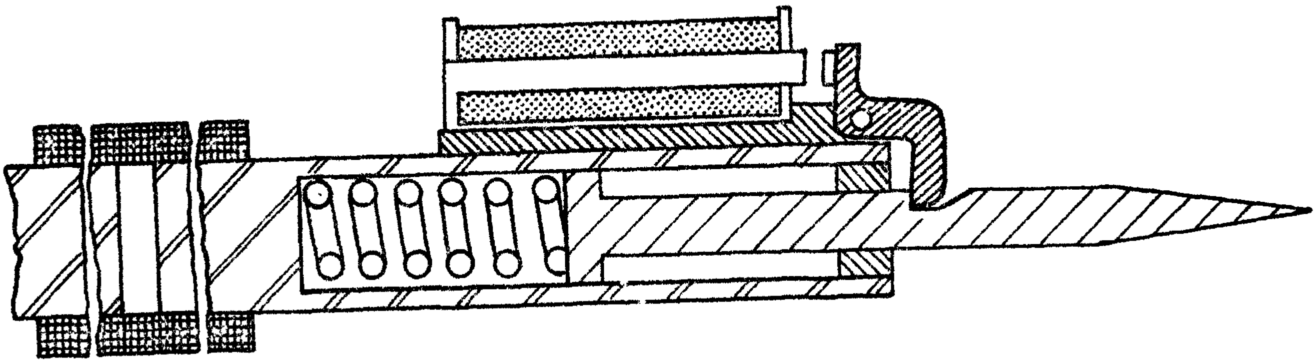


Diagram of high pressure vessel including pricker assembly



Enlargement pricker assembly

FIG. 4.

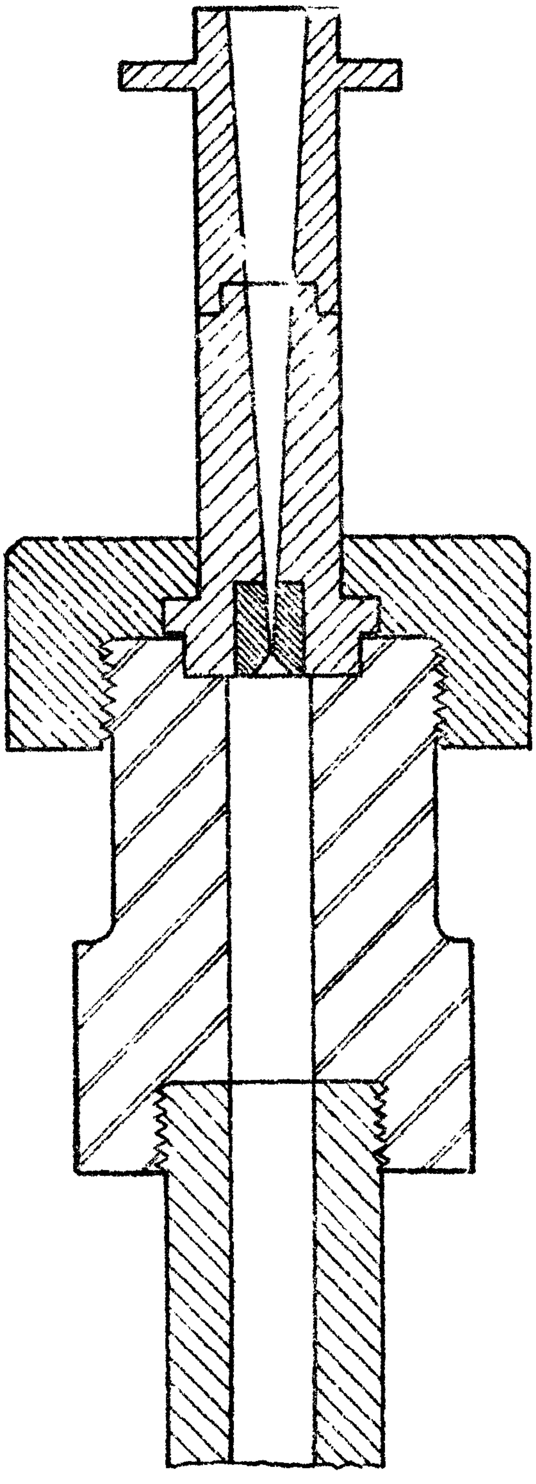


Diagram of barrel and nozzle.

FIGS.5. & 6

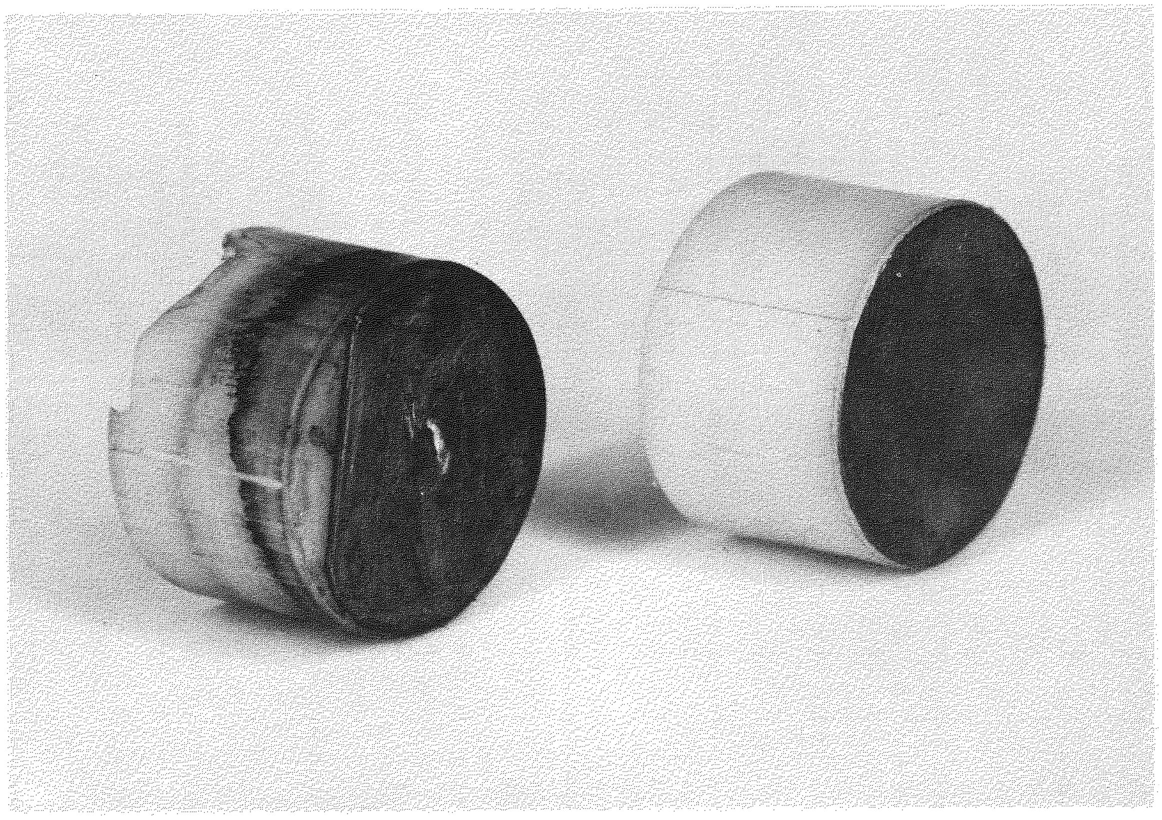


FIG. 6. PHOTOGRAPH OF NYLON PISTONS WITH METAL FACES.

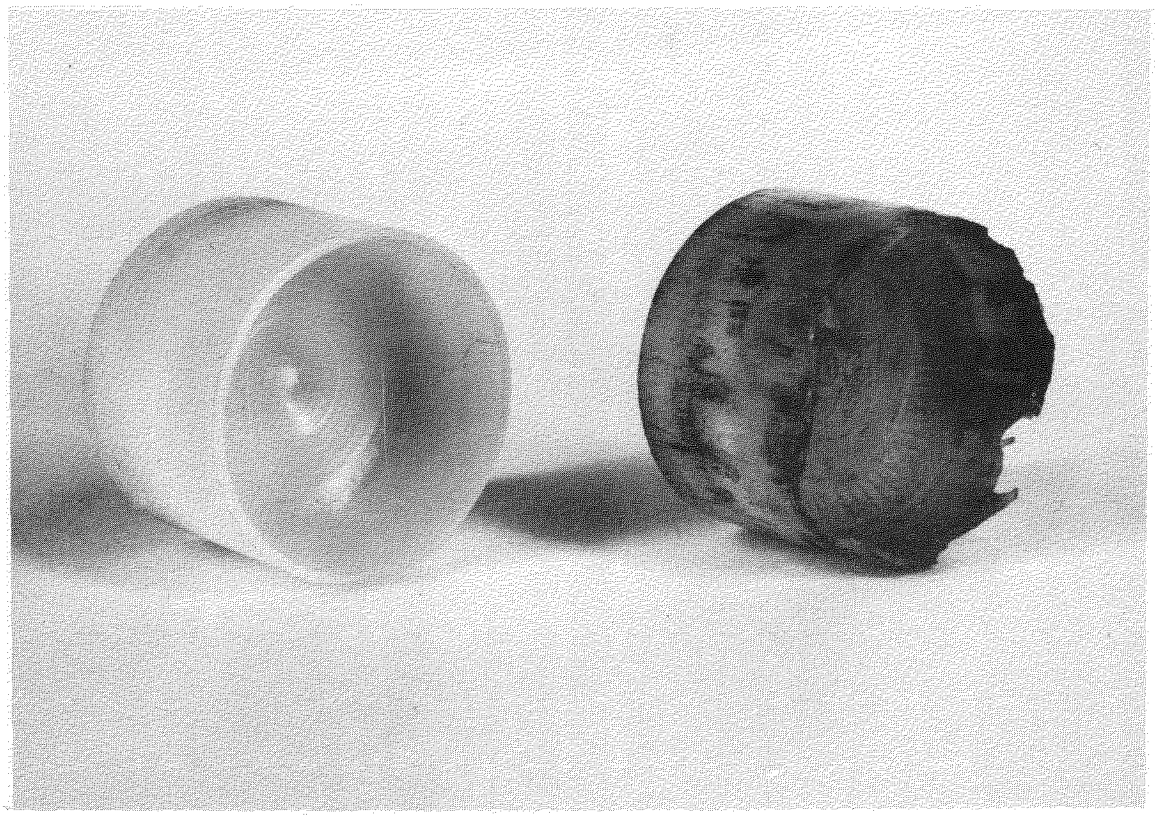
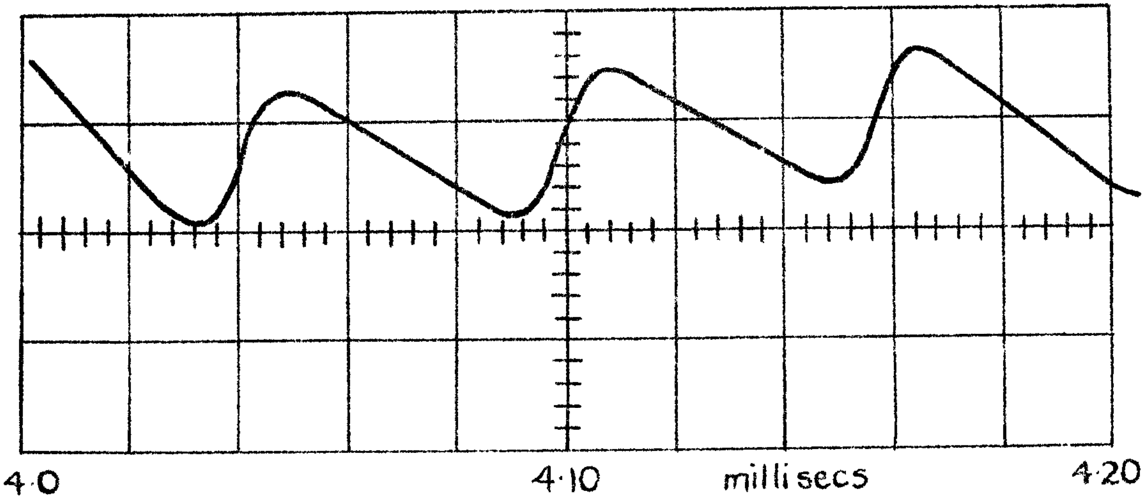


FIG.5 PHOTOGRAPH OF NYLON PISTONS

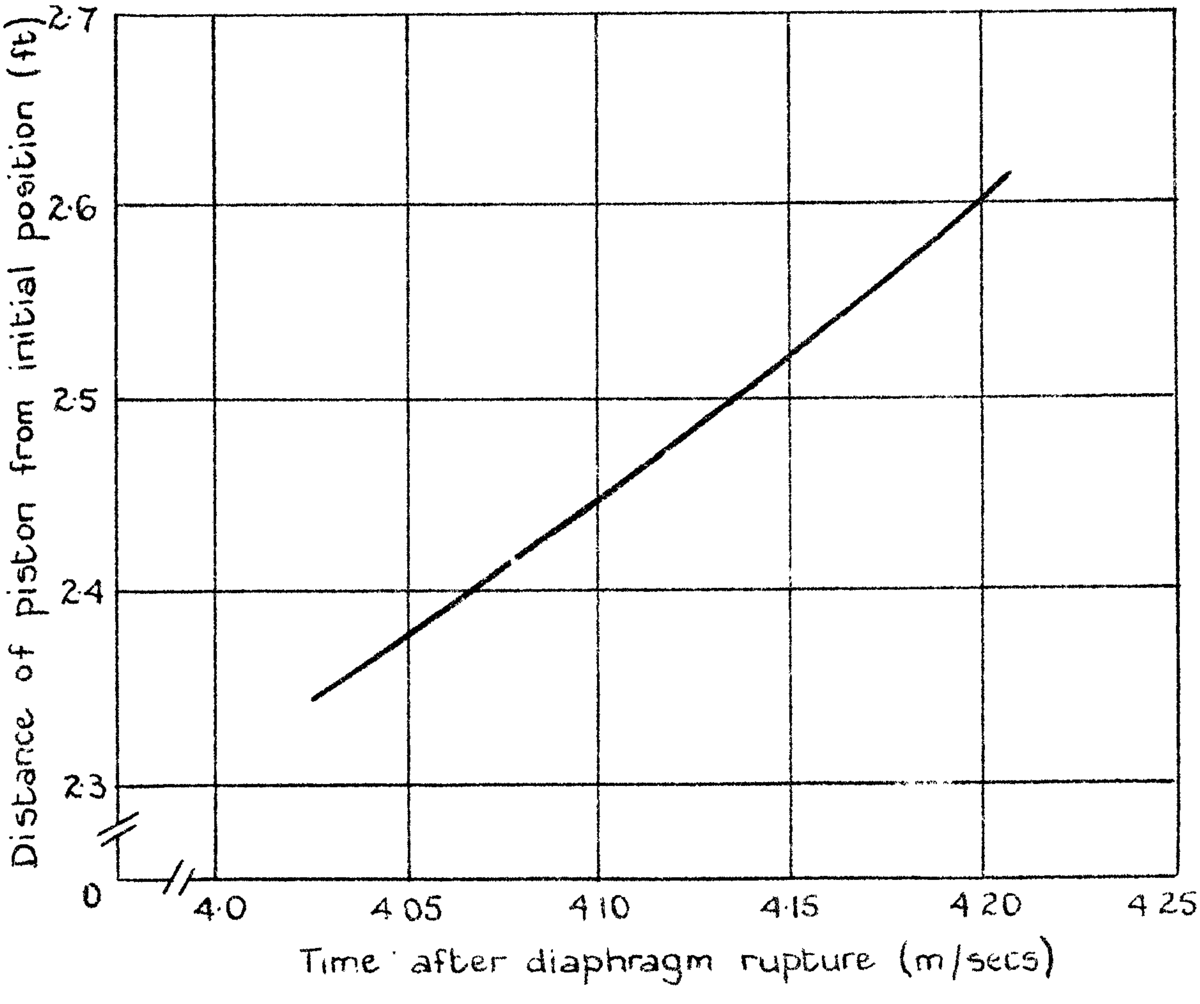
FIGS 7 & 8.

Fig. 7



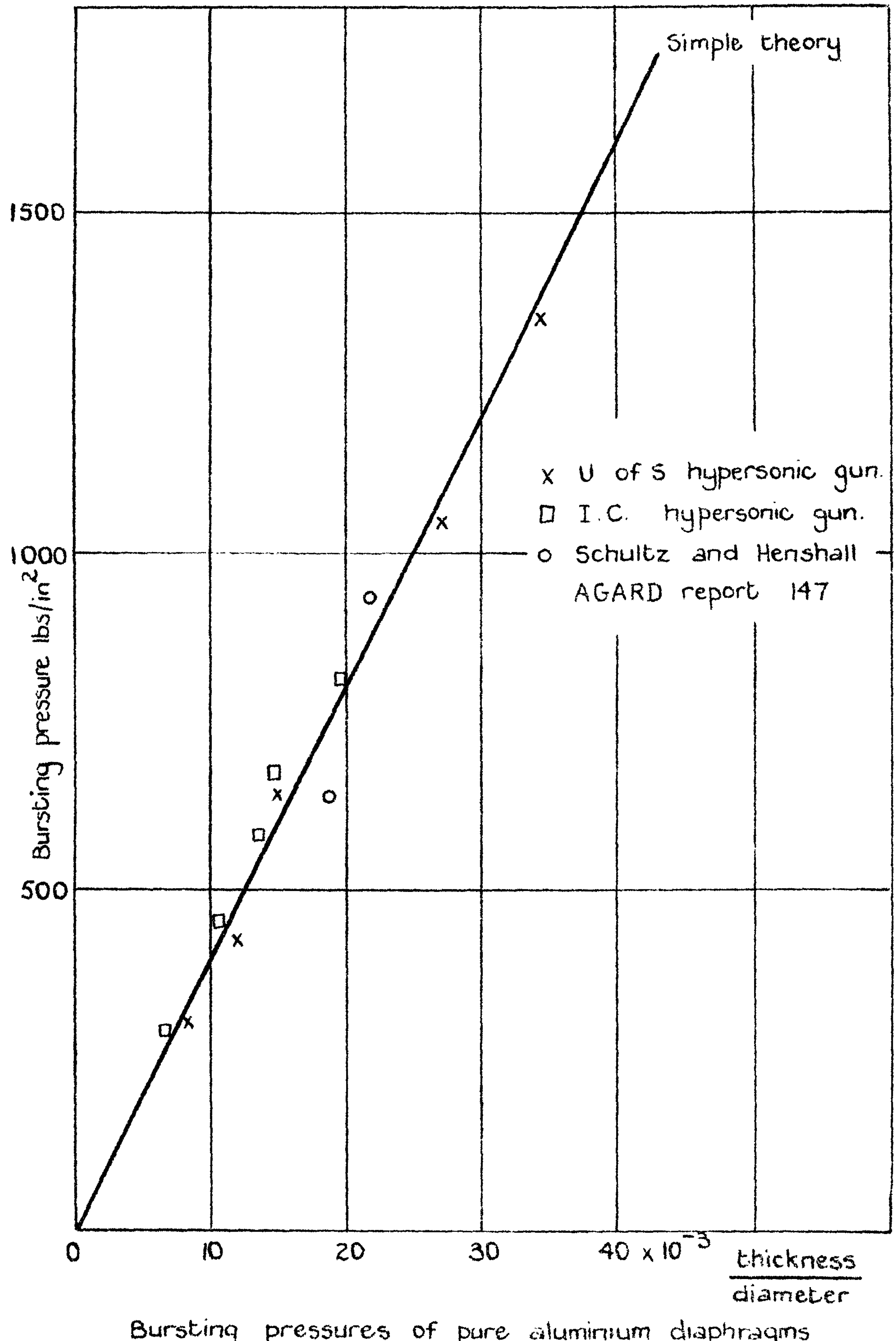
C.R.O. trace showing piston in motion.

Fig. 8



Piston displacement v time

FIG 9



Bursting pressures of pure aluminium diaphragms

FIG. 10.

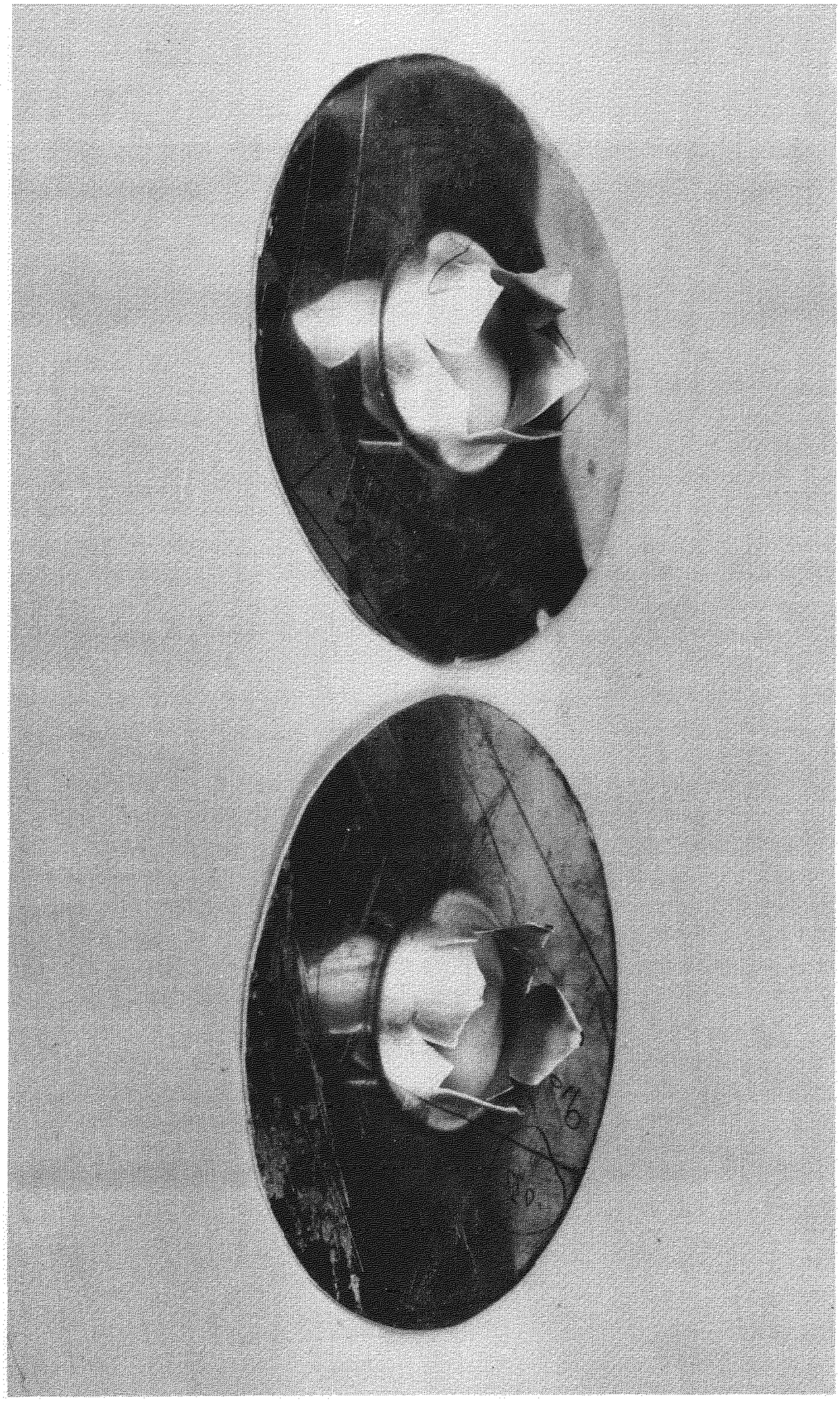
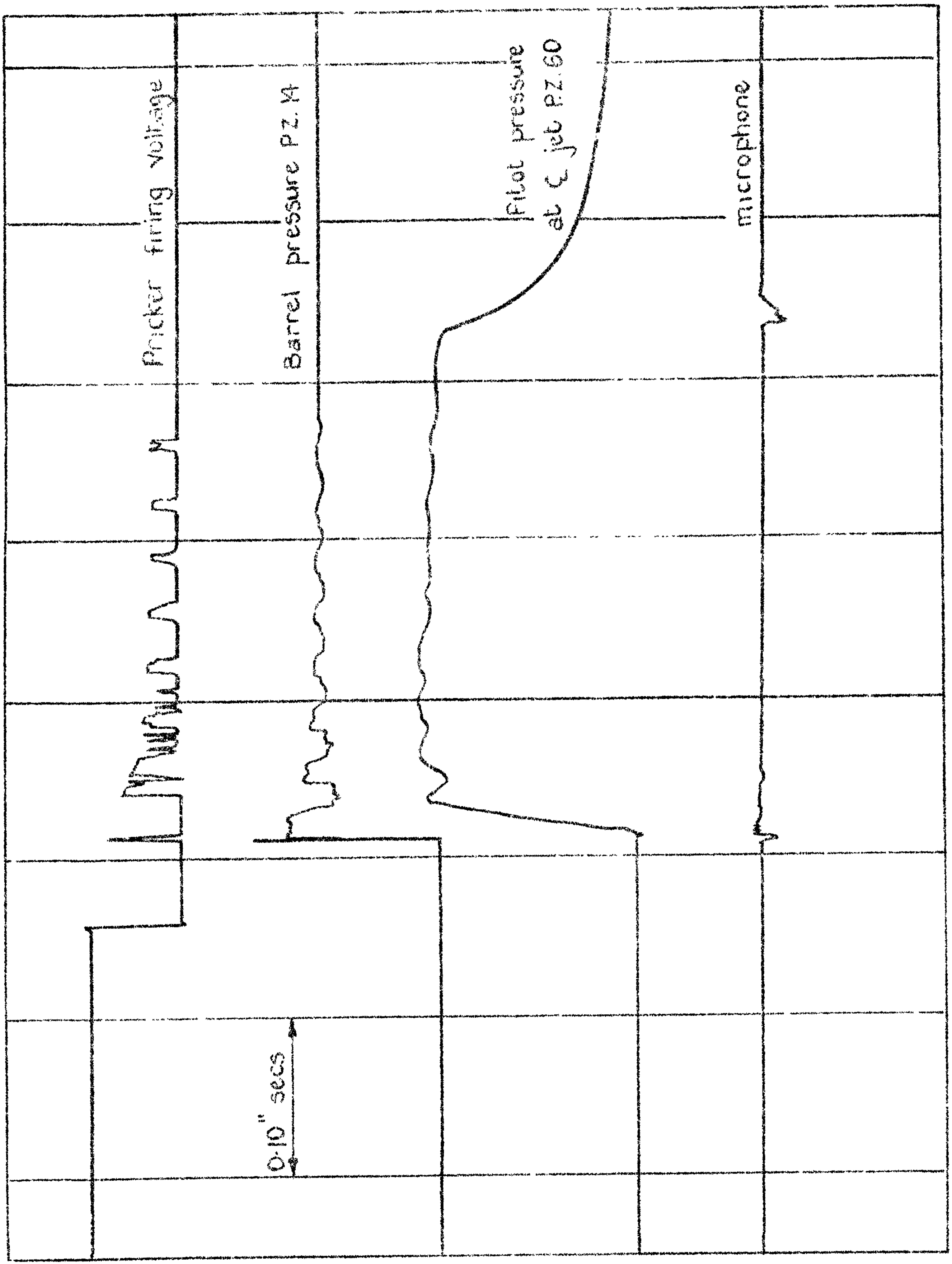


FIG. 10 PHOTOGRAPH OF BURST DIAPHRAGMS.

FIG. 11



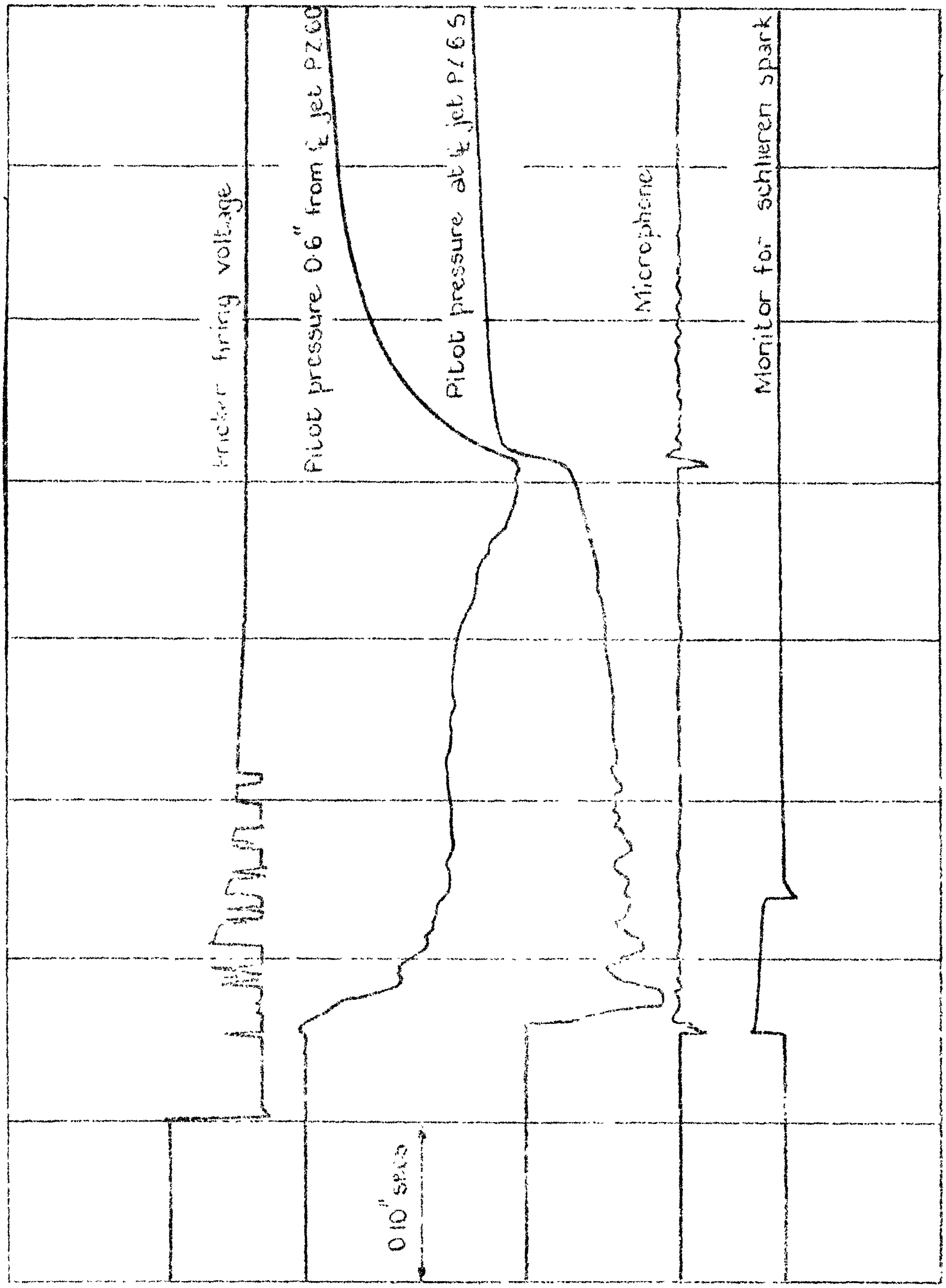
Copy of multi-channel recorder record

(Barrel pressure oscillation)

High pressure vessel 1010 p.s.i.g. Barrel pressure 14·7 psi

Dump chamber 0·1 mm Hg.

FIG 12.

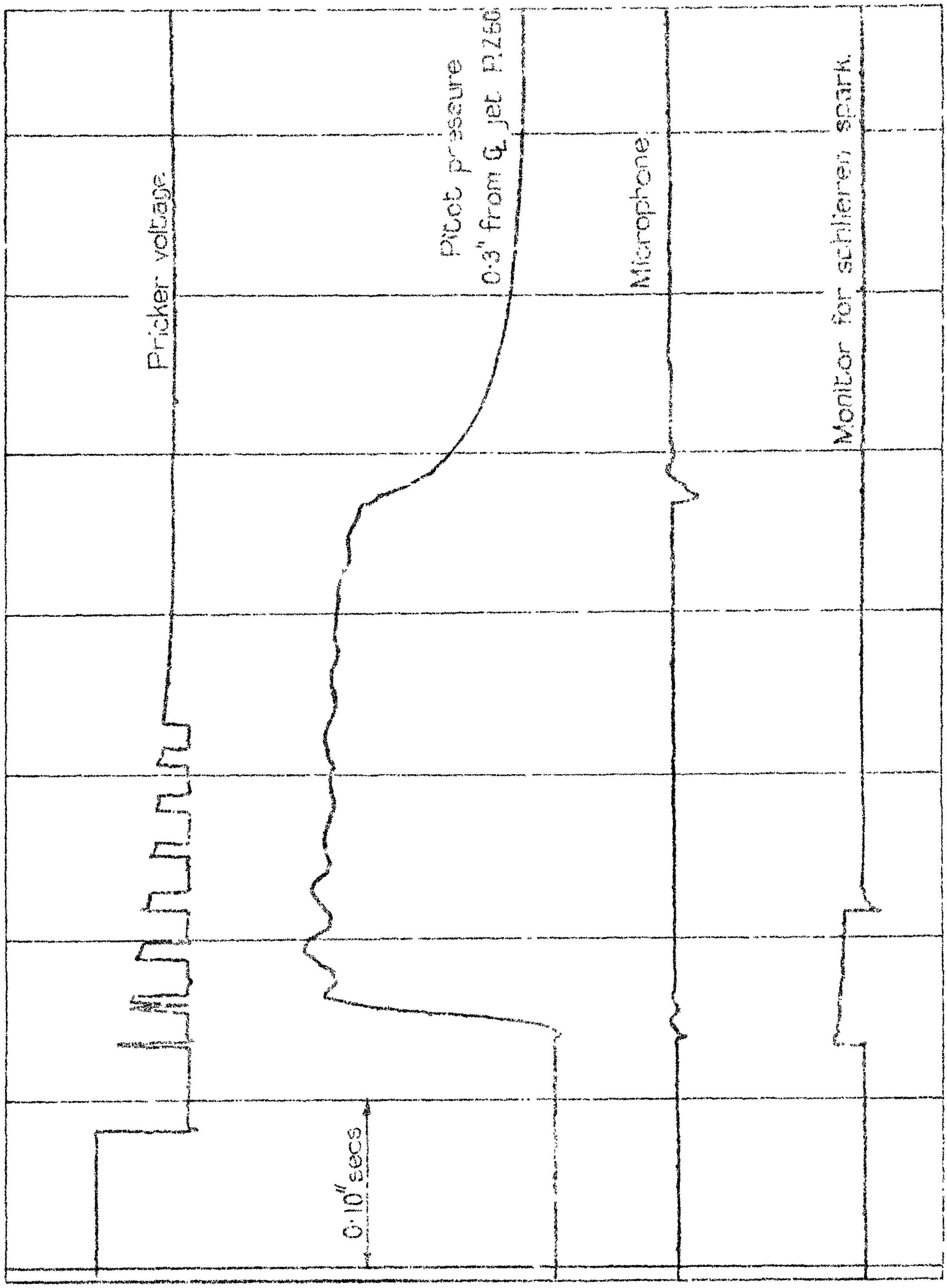


Copy of multi-channel recorder record

(Pitot pressures without diffuser not to same vertical scale)

High pressure vessel 100 p.s.i.g (barrel pressure 14.7 p.s.i)
Dump chamber (1 mm Hg

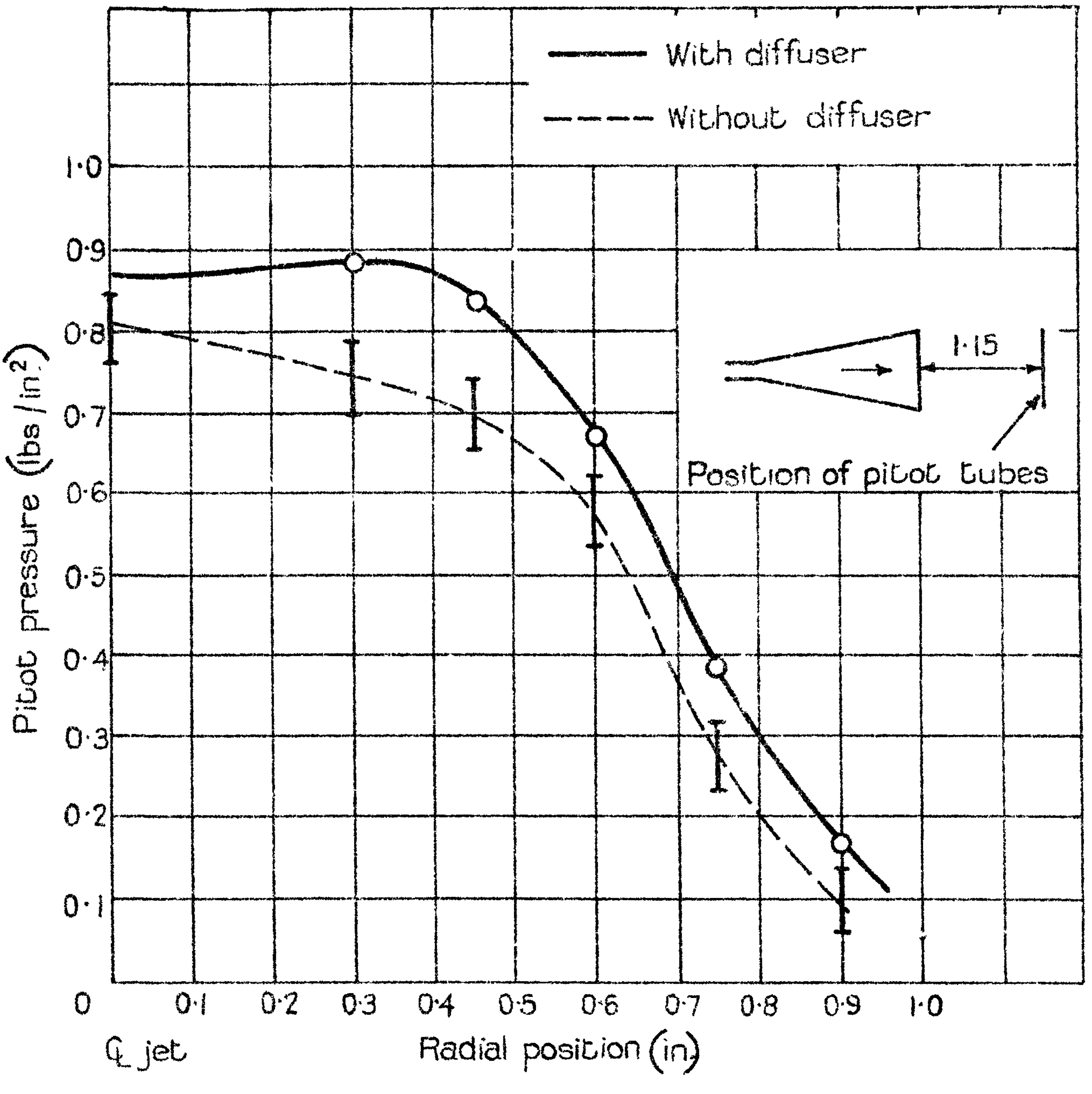
FIG. 13.



Copy of multi-channel recorder record (pitot pressure with diffuser)

High pressure vessel 1010 p.s.i.g. Barrel pressure 14·7 p.s.i.
Dump chamber 0·1 m.m. Hg.

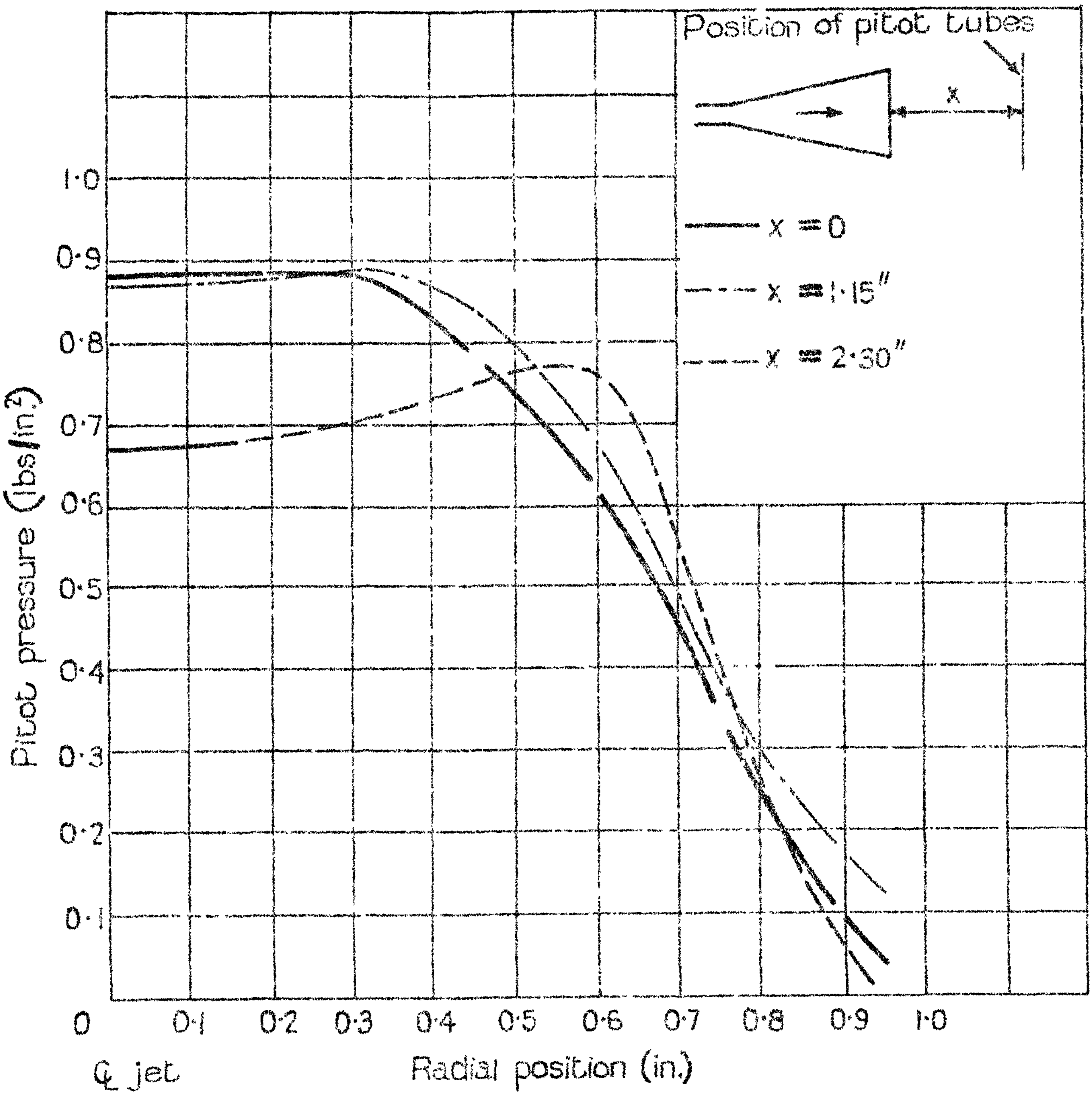
FIG. 14.



Variation of pitot pressure across the jet.

Reservoir pressure 760 lbs in.^{2} 0·10 secs from start of run.

FIG. 15.



Variation of pitot pressure profile with axial position in the jet.
with diffuser

Reservoir pressure 760 (lbs/in.²) 0·10 secs from start of run.

FIG 16.

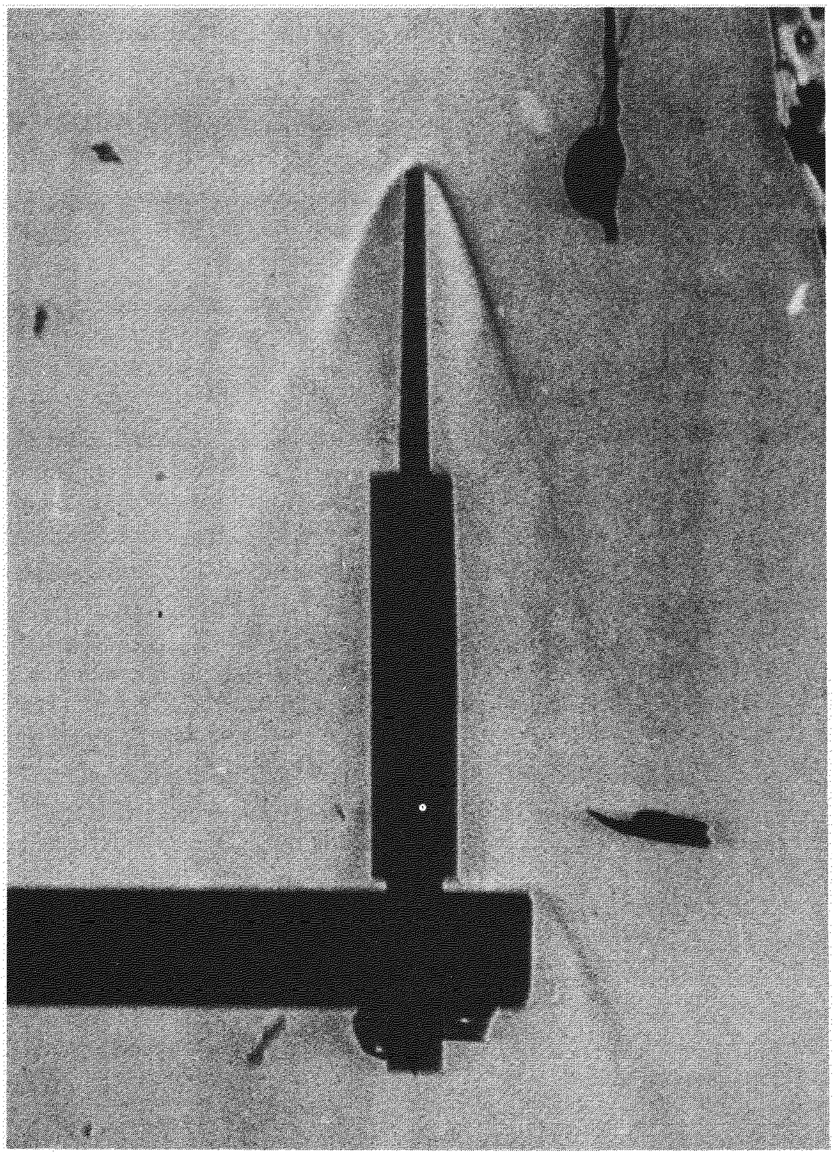


FIG 16, SCHLIEREN PHOTOGRAPH OF FLOW PAST A FLAT PLATE.

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