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By

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September, 1963

SUMMARY

It has been found necessary to increase the overall pressure level of shock tunnels owing to the emphasis and need, especially in the U.S.A., to have flight simulation of re-entry and hypersonic cruise conditions. Helium and hydrogen as driver gases are to be used at pressures up to 20 000 lb/in.^{2} in facilities currently under construction.

Subject to overcoming the mechanical engineering difficulties associated with high pressure containment, it has been generally assumed that the capability of the shock tunnel would be increased proportionally in pressure and density by the ratio of the change in driver pressure.

Experiments at the N.P.L. using helium and nitrogen at steady driving pressures up to 10 000 p.s.i. have supported theoretical considerations of the bulk properties of gases at high pressure, and shown that the available testing time is markedly reduced.

Working section conditions of the shock tunnel are normally defined by the ratio of pressures upstream and downstream of the hypersonic nozzle. The influence of compressibility in the reflected shock region, on the shocked-gas parameters has been studied, and it is shown that though the magnitude of reflected shock pressure is close to ideal, the density and temperature may differ significantly from the ideal value. It is clear that the measurement of stagnation pressure alone will not adequately define the flow parameters in the working section.

List/

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Notation

A_T	area of nozzle throat
a	sound velocity, real gas
a_o	sound velocity, ideal gas
a^*	sound velocity at nozzle throat
B	second virial coefficient in $1/V$ series, a function of temperature, cm^3 $mole^{-1}$
$B^{(o)}(\tau)$	second virial coefficient function, B/b_o
B_1	coefficient of P in pressure series for PV/RT, atm^{-1}
B_1^1	TdB_1/dT_1 atm^{-1}
b_o	characteristic parameter of Lennard-Jones interaction potential cm^3, $mole^{-1}$

b_2/

b_2 — b_o for pairs alone as distinct from pairs in larger clusters, 63 cm^3 $mole^{-1}$

b_3 — b_o for pairs within a cluster of three, 61·7 cm^3 $mole^{-1}$

C — third virial coefficient in 1/V series, a function of temperature, $(cm^3\ mole^{-1})^2$

$C^{(0)}(\tau)$ — third virial coefficient function, C/b_o^2 in simple theory

C_1 — coefficient of p^2 in pressure series for PV/RT, atm^{-2}

C_1^1 — TdC_1/dT_1 atm^{-2}

D — fourth virial coefficient in 1/V series, a function of temperature, $(cm^3\ mole^{-1})^3$

D_1 — coefficient of P^3 in pressure series for PV/RT_1 atm^{-3}

D_1^1 — TdD_1/dT_1 atm^{-3}

E_o^o — internal energy for 1 mole of gas in ideal-gas state at 0°K; equal to H_o^o, enthalpy for same conditions.

F^o — free energy per mole in standard static (ideal gas at 1 atmosphere for gaseous substances)

H — enthalpy per mole

H^o — enthalpy per mole in standard state (ideal gas at 1 atmosphere for gaseous substances)

H_o^o — enthalpy per mole in standard state at $0°K_1$

κ — thermal conductivity, cal^{-1} sec^{-1} $°C^{-1}$ also Boltzmann's constant for proportionality of energy to temperature $1{\cdot}38048 \times 10^{-16}$ $erg°K^{-1}$

K — (P_6/P_2)

$\dot{m}$ — mass flow rate

P — pressure

P_{ij} — p_i/p_j

p^* — pressure in nozzle throat

R — universal gas constant

S — entropy for 1 mole

T — absolute temperature, °K

T_o — temperature at standard conditions, 273°K

u/

u	velocity
V	volume per mole
w_2	reflected shock velocity
Z	bulk compressibility factor $(P/\rho RT)$
Γ_{ij}	ρ_i/ρ_j
γ	ratio of specific heats. c_p/c_v
ϵ	maximum energy of binding between molecules with a Lennard-Jones potential, ergs
ϵ/K	characteristic parameter of Lennard-Jones interaction potential
ϵ_2/K	ϵ/K for pairs alone, 95·42°K
ϵ_3/K	ϵ/K for pairs within a cluster of three, 97·7°K
ρ	density
ρ^*	density at nozzle throat
τ	a reduced temperature, KT/ϵ
τ_H	time interval between arrival of primary shock wave and arrival of head of expansion at nozzle entrance.

Subscripts of p, ρ, T, u and Z

1	initial conditions in low pressure section
2	conditions behind the primary shock
4	initial conditions in high pressure section
5	conditions behind reflected shock.

1. Introduction

The available testing time in a reflected shock tunnel running under tailored conditions is determined by the arrival of the head of the expansion wave which has reflected from the end of the high pressure chamber. Using simple shock tube theory this time is independent of absolute pressure values in the chamber and channel. Techniques designed to increase the testing time include lengthening the chamber, the use of a driver-reservoir arrangement[1] which is a means of simulating an increase in driver length, and the use of driver gas mixtures[2]. With a simple shock tunnel the use of high driving pressures necessitates a determination of bulk compressibility effects on the motion of the head of the expansion wave originating from the diaphragm station.

The performance of a shock tunnel is usually defined by the measurement of two pressures, upstream and downstream of the nozzle. The use

of/

of high driving pressures is of course in order to raise the overall working pressures of the wind-tunnel nozzle, thereby entering the working range of existing pressure transducers and higher Reynolds number flows. Mindful that the expanded flow is invariably defined by the ratio of the pitot pressure and reflected shock wave pressure, and that at the high driving pressures the reflected shock-heated gas may exhibit bulk compressibility effects, the relationship of p_5, ρ_5 and T_5 is not necessarily that of an ideal gas. Thus the value of p_5 used in conjunction with the pitot pressure and ideal gas relations will not necessarily define the flow conditions in the working section and will therefore lead to errors in determination of static pressure, density and temperature.

The results of a theoretical and experimental investigation into the flow in a reflected shock tunnel, when bulk compressibility effects are taken into consideration, are described below.

2. Theoretical Considerations

2.1 Compressibility in gases at high pressures

For a perfect gas $pV = nRT$, and a plot of pV vs p at a given temperature will give a horizontal straight line. A plot of pV/nRT for a perfect gas gives a line which has unit value for all temperatures and pressures. Let us define a compressibility factor Z (say) by

$$Z \equiv \frac{pV}{nRT}. \qquad \ldots(1)$$

Then Z, which is unity for a perfect gas, varies with pressure and temperature giving a series of curves of Z vs p at different temperatures which meet at unity for low pressures (see Fig. 2).

For low temperatures, Z becomes less than unity as the pressure increases, returns to unity and then increases in value with increasing pressure. When Z is less than unity then the volume is less than the perfect gas volume and vice versa for $Z > 1$.

Values of Z at different pressures and temperatures are obtained using the simple equation

$$Z = 1 + B_1 p + C_1 p^2 + D_1 p^3. \qquad \ldots(2)$$

The coefficients B_1, C_1, D_1 are functions of temperature. These are related to the virial coefficients in the analogous equation in powers of reciprocal volume.

Following the method used by Woolley[3], the coefficients B_1 and C_1 in terms of the virial coefficients for 6-12 Lennard-Jones potentials, as tabulated in the dimensionless form $B^{(0)}(\tau)$ and $C^{(0)}(\tau)$ by Hirschfelder[4], are represented by

$$B_1 = b_2 B^{(0)}(\tau_2)/RT$$

and $$C_1 = b_3^2\{C^{(0)}(\tau_3) - 4[B^{(0)}(\tau_3)]^2\}/(RT)^2 + 3B_1^2$$

where $\tau_2 = KT/\epsilon_2$, $\tau_3 = KT/\epsilon_3$

$\epsilon_2/K/$

$$\epsilon_2/K = 95 \cdot 42^\circ K, \quad b_2 = 63 \text{ cm}^3 \text{ mole}^{-1}$$

$$\epsilon_3/K = 97 \cdot 7^\circ K, \quad b_3 = 61 \cdot 7 \text{ cm}^3 \text{ mole}^{-1}.$$

Empirically D_1 is given by Woolley as

$$D_1 = 0 \cdot 091442\, T^{-3} - 297 \cdot 4\, T^{-4} + 111\,984\, T^{-5}$$
$$- 6 \cdot 9819 \times 10^{6}\, T^{-6} - 2 \cdot 4526 \times 10^{-5}\, T^{-3}\, e^{1600/T}.$$

Enthalpy values at the pressures and temperatures required were calculated using the equation

$$\frac{H - E_o^\circ}{RT_o} = \frac{H^\circ - E_o^\circ}{RT_o} - \frac{T}{T_o} \times B_1^1\, P - \frac{T}{T_o}\,\frac{C_1^1\, p^2}{2} - \frac{T}{T_o}\,\frac{D_1^1\, p^3}{3} \qquad \ldots(3)$$

and values of $\dfrac{H^\circ - E_o^\circ}{RT_o}$, B_1^1, C_1^1, and D_1^1 tabulated by the above author.

Values of Z obtained using this data are plotted in Fig. 2.

2.2 The effect of high pressures on the sound speed in the driver gas

The testing time of a reflected shock tunnel is generally terminated by the arrival at the nozzle entrance of the head or tail of the expansion wave originating at the diaphragm station. The head of the expansion wave moves into the undisturbed driver gas at the local speed of sound (a_o).

It is necessary to define $a^2 = \gamma \left(\dfrac{\partial p}{\partial \rho} \right)_T$ since both γ and Z are functions of pressure (Figs. 2 and 3). The effect of variation in these parameters at high pressures is a profound increase in the sound speed of the static high pressure gas. Thus the head of the expansion wave travels considerably faster than at lower driving pressures, and arrives at the nozzle entrance earlier than is predicted by ideal gas theory thereby reducing the available testing time. Calculation shows that the sound speed of nitrogen at 10 000 lb/in.^{2} (290°K) has increased by a factor of 1·79. This will have an effect, too, on the pressure ratio required across the diaphragm to produce a given shock Mach number. The variation of sound speed for nitrogen and helium is presented in Fig. 4.

2.3 Variation in value of ρ_5/ρ_2 due to compressibility effects

It was pointed out in Section 1 that compressibility effects may be observed in the region behind the reflected shock at high p_5 values. An examination of this region has been carried out as outlined below.

The conservation equations for one-dimensional isentropic flow in a constant area duct are:-

ρ_5/

$$\rho_5 w_2 = \rho_2(u_2 + w_2) \qquad \ldots(4)$$

$$p_5 + \rho_5 w_2^2 = p_2 + \rho_2(u_2 + w_2)^2 \qquad \ldots(5)$$

$$h_5 + \tfrac{1}{2} w_2^2 = h_2 + \tfrac{1}{2}(u_2 + w_2)^2. \qquad \ldots(6)$$

Also

$$\frac{p_5}{p_2} = \frac{Z_5}{Z_2} \cdot \frac{\rho_5}{\rho_2} \cdot \frac{T_5}{T_2}. \qquad \ldots(7)$$

Values of u_2, ρ_2, T_2, p_2 are assumed and a guess is made of the value of $K = \rho_5/\rho_2$.

From (1)

$$w_2 = \frac{1}{K}(u_2 + w_2)$$

$$w_2 = \frac{u_2}{(K - 1)}.$$

From (2)

$$p_5 = p_2 + \rho_2 u_2^2 \frac{K}{K - 1}. \qquad \ldots(8)$$

From (3)

$$h_5 = h_2 + \tfrac{1}{2}u_2^2 \left[\frac{K + 1}{K - 1}\right]. \qquad \ldots(9)$$

Values of T_5 are obtained from h_5 using equation (3). Using T_5 and p_5 a value is obtained for Z from equation (2).

Finally these calculated values are put into equation (7) from which another value of K is derived. The exact value of K is obtained by a re-iteration process[5,6,7,8].

The results of a calculation for He/N_2 at $M_S = 3{\cdot}6$ are presented in Fig. 8b.

At $p_1 = 100$ lb/in.^{2} which for $M_S = 3{\cdot}6$ requires $p_4 = 10\,000$ lb/in.^{2}, the value of K is found to fall to 3. This will have an effect on the mass flow through the nozzle. p_5 and T_5 however vary very little and have almost ideal values (comparing with calculations by Bernstein[9]). This has been verified experimentally for p_5, as is described later.

2.4 The effect on flow through the nozzle

The rate of mass flow through the nozzle is given by $\dot{m} = \rho^* a^* A_T$ where ρ^*, a^* and A_T are the density, local sound speed and area of the throat, respectively.

The critical ratios for nozzle flow are defined for an ideal gas as

$$\frac{p^*}{p_5} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}}, \quad \frac{\rho^*}{\rho_5} = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma-1}}, \quad \frac{T^*}{T_5} = \frac{2}{\gamma + 1}. \qquad \ldots(10)$$

The/

The mass flow rate through the nozzle is proportional to the density and sound speed in the throat, i.e., $\dot{m} \sim \rho^* a^*$ and from equation (10) $\dot{m}$ is proportional to $\rho_5 a_5$. If the change in specific heat ratio from the reservoir to the throat is not large and if Z differs but little from unity the error in assuming the relationship -

$$\frac{\dot{m}_B}{\dot{m}_I} \sim \left(\frac{T_{5_B}}{T_{5_I}}\right)^{\frac{1}{2}} \cdot \frac{\rho_{5_B}}{\rho_{5_I}} \qquad \ldots(11)$$

where suffices

B = bulk compressibility

I = ideal gas values

- is small.

For 1 000 lb/in.^{2} nitrogen driver and $M_s = 2{\cdot}0$ then a decrease of 4% is obtained on the right hand side of equation (11), whereas for 10 000 lb/in.^{2} helium driver and $M_s = 3{\cdot}6$, the decrease is 10%. From this estimate it is considered that a significant deviation from ideal should obtain in the mass flow rate through the nozzle affecting the conditions in the working section proportionally.

When variable specific heats and bulk compressibility are considered, these equations are no longer applicable. In order to calculate the conditions at the throat, the enthalpy must be defined as a function of two of the thermodynamic variables, e.g., $h = h(p,T)$ and the change in this function from the reservoir into the nozzle can be followed.

Because stagnation pressure is insensitive to bulk compressibility effects and does not easily show when perfect gas relations are inapplicable, the use of its measured value in the real gas equations will impair the accuracy of the predicted test section conditions.

It is proposed therefore to define the stagnation enthalpy from the more accurately known initial channel pressure and shock velocity, through the derived real gas equations, and to define the equilibrium flow conditions from one further measurement in the test section; such as pitot pressure, which will not exhibit bulk compressibility effects.

Calculations incorporating these real gas departures are being done and will be presented at a later date in a form which predicts a hypothetical stagnation condition which may be used with perfect gas nozzle tables to define the actual flow parameters.

3./

3. Experimentation

3.1 Apparatus

The experimental work described herein was carried out in the N.P.L. 2 in. shock tunnel. This consists of a 10 ft driving section (or high pressure chamber) which is divided into two sections 7 ft and 3 ft long. In the present work there is no diaphragm between these two sections, the 10 ft length is used. The high pressure chamber has the same internal diameter as the low pressure channel, viz. 2 in. A photograph of the apparatus is shown in Fig. 1.

Between the chamber and the channel is a double diaphragm block 2 in. thick. In the work described in this report both the single and double diaphragm techniques were used. For chamber pressures up to 5 000 lb/in.^{2} nickel diaphragms were used. These were unscribed. For the higher pressures, (p_4 > 5 000 lb/in.^{2}) treated steel diaphragms 0·1 in. thick scribed to a depth of 0·030 in. were used. This thickness of diaphragm was necessary owing to vacuum sealing requirements. The steel diaphragms burst at an overpressure of 5 500 lb/in.^{2}. The diaphragm section and nozzle section are secured by a hydraulic clamping force of 30 tons.

The low pressure channel is 12 ft long terminated by a nozzle section which allows the hot quiescent gas behind the reflected shock to expand through a small throat area nozzle to an 8 in. internal diameter working section, i.e., a typical reflected shock tunnel. The nozzle was blocked off in this series of experiments and the tunnel was used as a simple shock tube using nitrogen as the working gas and driving with nitrogen for M_s = 2 and helium for M_s = 3·6.

The pressures in the chamber and in the double diaphragm block are measured by means of B.P.6 strain gauge transducers* having pressure ranges up to 15 000 lb/in.^{2} and 5 000 lb/in.^{2}, respectively. These gauges are backed by Sangamo-Weston servo-potentiometers which feed 0 - 10 m.a. milliameters scaled in lb/in.^{2}. The pressure in the channel is measured on a Wallace-Tiernan gauge which measures 0 - 100 lb/in.^{2} in two revolutions.

The system is evacuated using an ISC 3 000 'Speedivac' high vacuum pump**. The working gas is supplied from cylinders charged to 2 200 lb/in.^{2}, and the high pressure section is pressurised from a 1·2 cu ft vessel which has been charged by a Corblin*** diaphragm compressor.

No means other than high pressure are used to rupture the diaphragms. Both single and double diaphragm techniques are employed. Diaphragm rupture in the second case is initiated by venting the space between the diaphragms via a solenoid valve****.

Three/

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*These are made by J. Langham Thompson.

**Supplied by Edwards High Vacuum.

***A 4 C 1000.

****Solenoid valve - supplied by S.E. Laboratories, Feltham, rated up to 3 600 lb/in.^{2}, tested in the N.P.L. up to 8 000 lb/in.^{2}.

Three platinum resistance thermometers at distances of 1, 2 and 3 ft from the nozzle section measure the velocity of the shock wave by starting and stopping two Racal microsecond chronometers. The resistance thermometers have, individually, a constant 2 volts across them. Any one of the three can be used to supply a voltage pulse to initiate the sweep of a Techtrorix 502 cathode ray oscilloscope.

The reflection pressure is measured with a S.L.M. PZ 14 piezo electric pressure transducer mounted in the channel at a distance of $\frac{1}{2}$ in. upstream of nozzle entrance. The gauge output is fed through a S.L.M. PV 17 electrometer amplifier (voltage gain unity) from whence the signal goes to the input of the oscilloscope.

Gauge calibration is carried out on a hydraulic dead weight tester and the PZ 14's used have been calibrated up to 10 000 lb/in.^{2}. The calibration trace over this range is non-linear and deviates as much as 5% from a straight line approximation. Pressures are measured to better than 3%.

Pressure-time traces are recorded on Polaroid 3 000 film using a Hewlett-Packard 196A camera.

3.2 Experimental results for nitrogen-nitrogen

The effects of bulk compressibility on the testing time are considerable when the driving gas is nitrogen (Fig. 5(a)). At 1 000 lb/in.^{2} the available testing time is 16 milliseconds, whereas at 10 000 lb/in.^{2} this value has fallen to 9·8 milliseconds. The decrease is monotonic with increasing pressure. This effect is considered to be a result of the increasing values of γ and Z and the subsequent change in sound speed.

With increasing driving pressure the ratio p_5/p_4 falls to an almost constant value for values of p_4 in excess of 7 000 lb/in.^{2} (Fig. 7).

3.3 Experimental results for helium-nitrogen

A decrease in available testing time of approximately 20% is obtained at 10 000 lb/in.^{2} when helium is used as the driver gas (Fig. 5(b)). The decrease is again monotonic with pressure.

The values of P_{41} required for given Mach numbers using helium as the driver gas are not very different (2-5%) from the ideal gas values (Fig. 6) when single or double diaphragms are used.

Values of P_{54} are about 20% below the ideal gas values (Fig. 7) at the higher driver pressures.

In both the nitrogen-nitrogen and helium-nitrogen cases the values of P_{51} agree closely with ideal gas theory. This supports the theory described in Section 2 where it is suggested that the measurement of stagnation pressure will not indicate the true state of the hot quiescent gas behind the reflected shock wave.

4. Conclusions

Realistic values of the flow Reynolds number are obtained in the working section of the N.P.L. 2 in. shock tunnel when driving pressures up to

10 000 lb/in.^{2} are used. At these high driving pressures the bulk compressibility factor and variation in specific heat ratio in the high pressure section combine to give a higher sound speed and therefore faster rarefaction head velocity than is predicted by ideal gas considerations.

Measurements have been made confirming a decrease in the available testing time owing to the early arrival of the reflected rarefaction head at the nozzle.

It follows therefore that the difficult problem of measuring low pressures in shock tunnel test sections will not necessarily be improved by simply raising the overall tunnel pressures, since the possibility arises that there will be inadequate time for the pressures in the model transducer cavities to reach a steady value.

The effect of bulk compressibility and variable specific heat ratio has been considered in evaluating the reflected shock parameters. At the preferred operating shock Mach numbers of the N.P.L. tunnel, using helium or nitrogen driver gas at 15 000 lb/in.^{2} there is negligible change in reflected shock pressure, only 1-2% in temperature, but 4-10% decrease in density. The deviation is increased by using the shock tunnel in the "under-tailored" mode, for, even though a lower driver pressure can be used to obtain the same high stagnation pressure, the stagnation density especially will decrease substantially.

The effect of these parameter changes on the mass flow rate through the nozzle has been estimated and decreases of 4-10% will be experienced for driver pressures of only 10 000 lb/in.^{2}. It is concluded that at these high stagnation pressures and temperatures the measurement of stagnation pressure and pitot pressure is not sufficient to define the flow parameters.

Acknowledgements

Miss B. Redston and Mr. M. J. Beere (vacation student) assisted with the computations and shock tunnel data reduction. Messrs. J. Godwin and J. Darcy of Aero. Division, N.P.L. were responsible for the design, construction and assembly of the high-pressure shock-gun tunnel.

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APPENDIX I/

APPENDIX I

The Importance of the Compressibility Factor in Computing Thermodynamic Data

When real gas effects are considered, the equation of state in the form $p = Z\rho RT$ is used. Z is known as the compressibility factor. This is an ambiguous term since it can mean the effects due to dissociation and ionization of the gas at high temperatures, i.e.,

$$Z = (1 + \alpha)(1 + \chi)$$

where α = fraction of original number of molecules which has dissociated and χ = fraction of original number of molecules which has ionized, or alternatively it may represent the effect due to Van der Waals forces.

In the calculation of the thermodynamic properties of say nitrogen, the choice of Z is extremely important at certain pressures and temperatures.

At room temperature in nitrogen at 1, 10, 100, 1000 atmospheres pressure, the value of Z due to dissociation and ionization is unity, whereas the bulk compressibility values are

p (Atm)	Z (bulk compressibility)
1	0·99973
10	0·99804
100	0·99935
1000	2·0142

The dimensionless form of the internal energy is

$$\frac{E}{RT} = \frac{H}{RT} - Z.$$

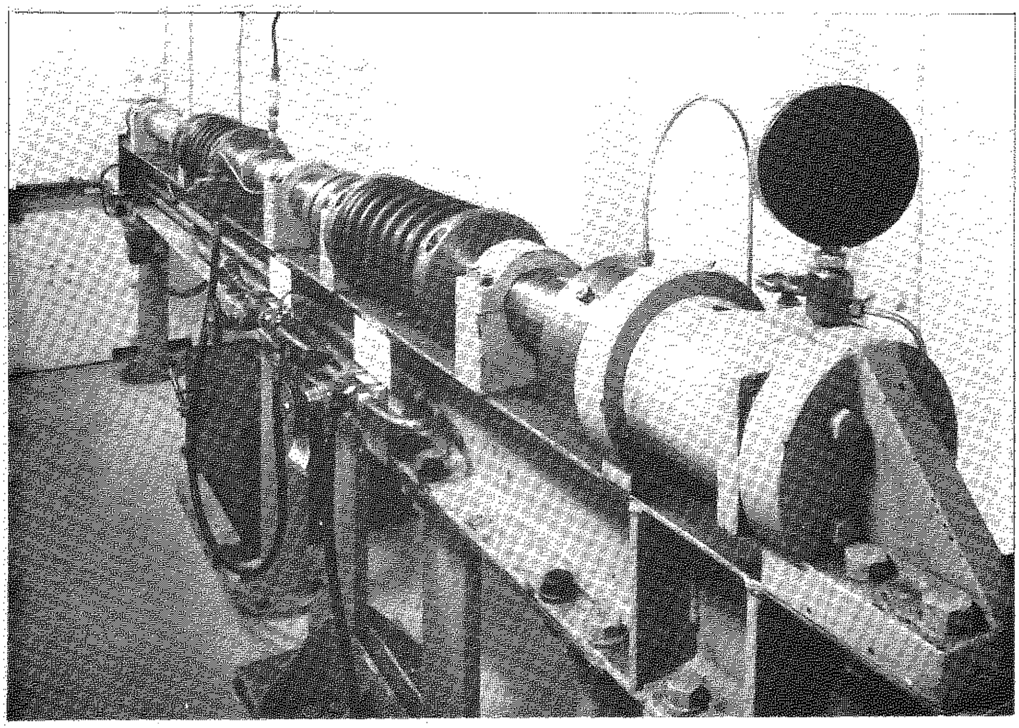
From this equation the table below has been prepared. Z_D refers to dissociation and ionization effects and Z_B to bulk compressibility. $T = 293°K$.

p_1 (Atm)	$\left(\frac{E}{RT}\right)_{Z_D}$ (Ref. 14)	$\left(\frac{E}{RT}\right)_{Z_B}$ (Refs. 11,15)	$\left(\frac{E}{RT}\right)_{Z_B} \Big/ \left(\frac{E}{RT}\right)_{Z_D}$
1	2·5	2·497	0·998
10	2·5	2·4746	0·99
100	2·5	2·25	0·9
1000	2·5	1·3316	0·5325

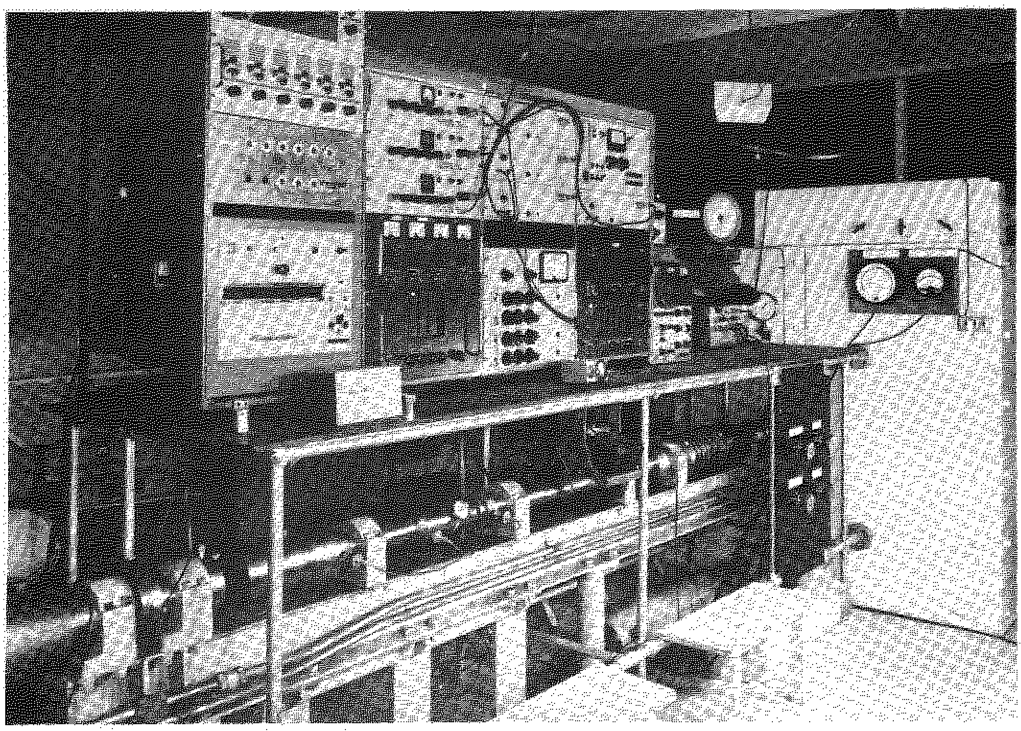
Similar variations in other thermodynamic parameters occur showing that serious errors may result if bulk compressibility is ignored.

ES

FIG. 1



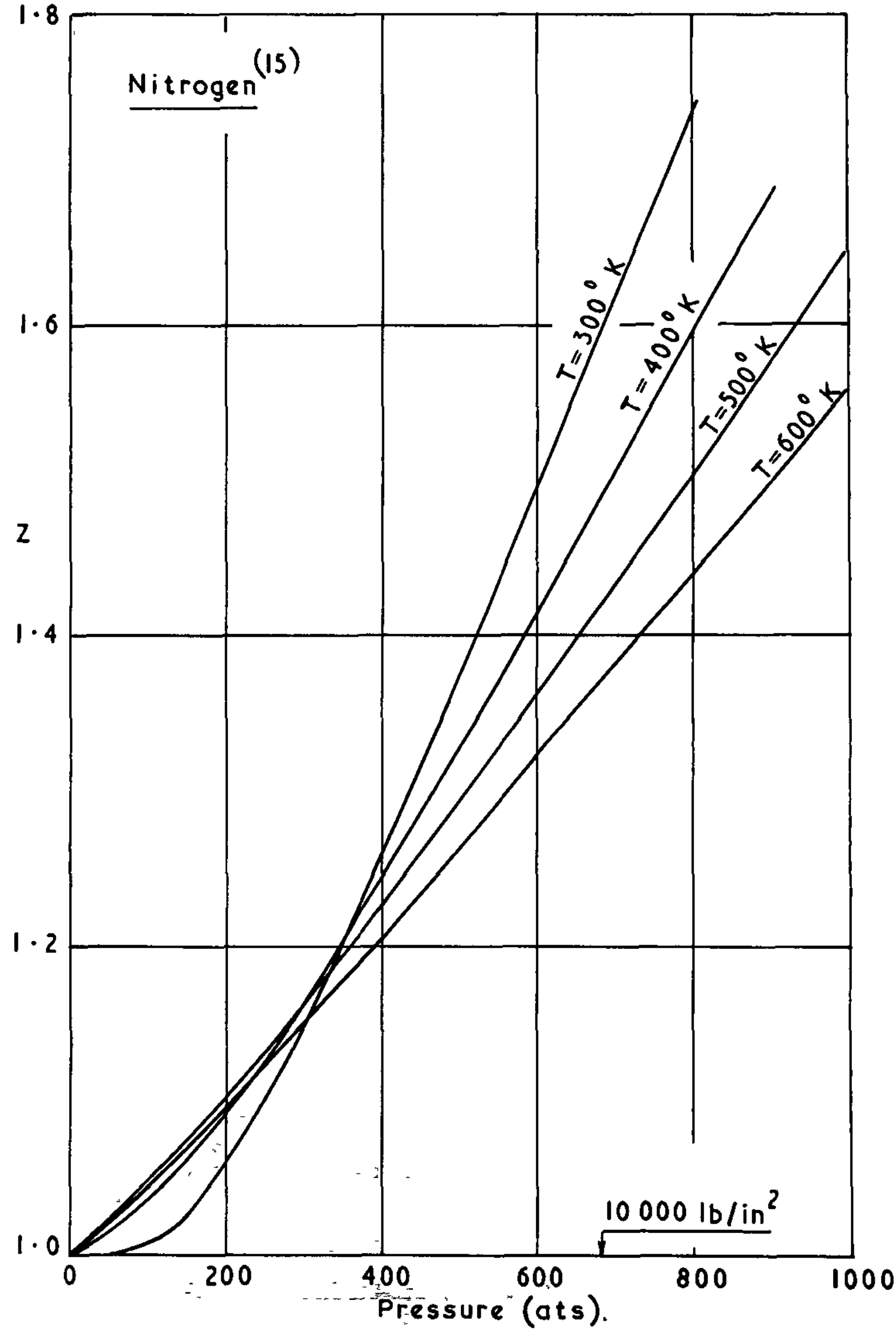
High pressure chamber



Low pressure channel

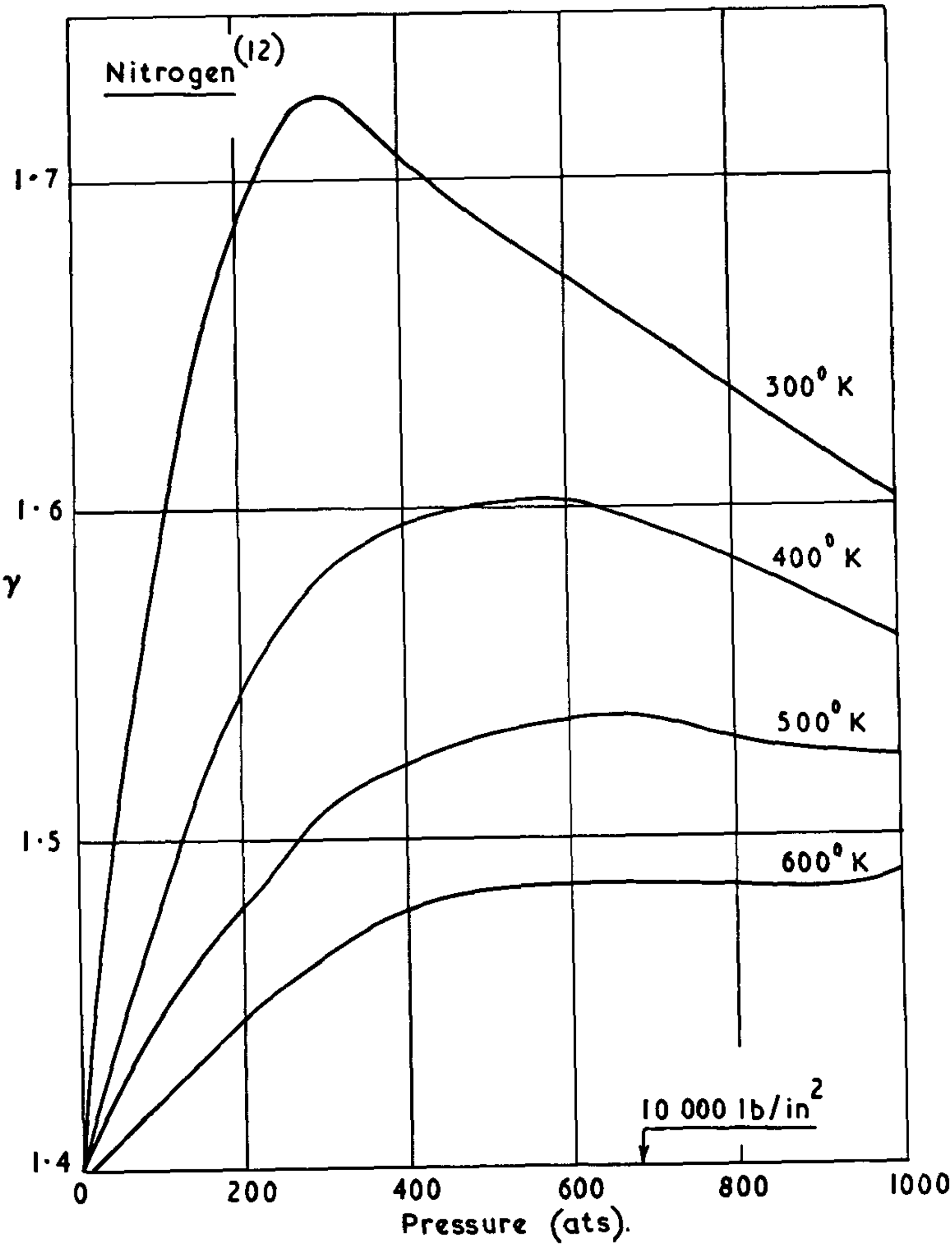
N.P. L. 2" Shock tunnel

FIG. 2



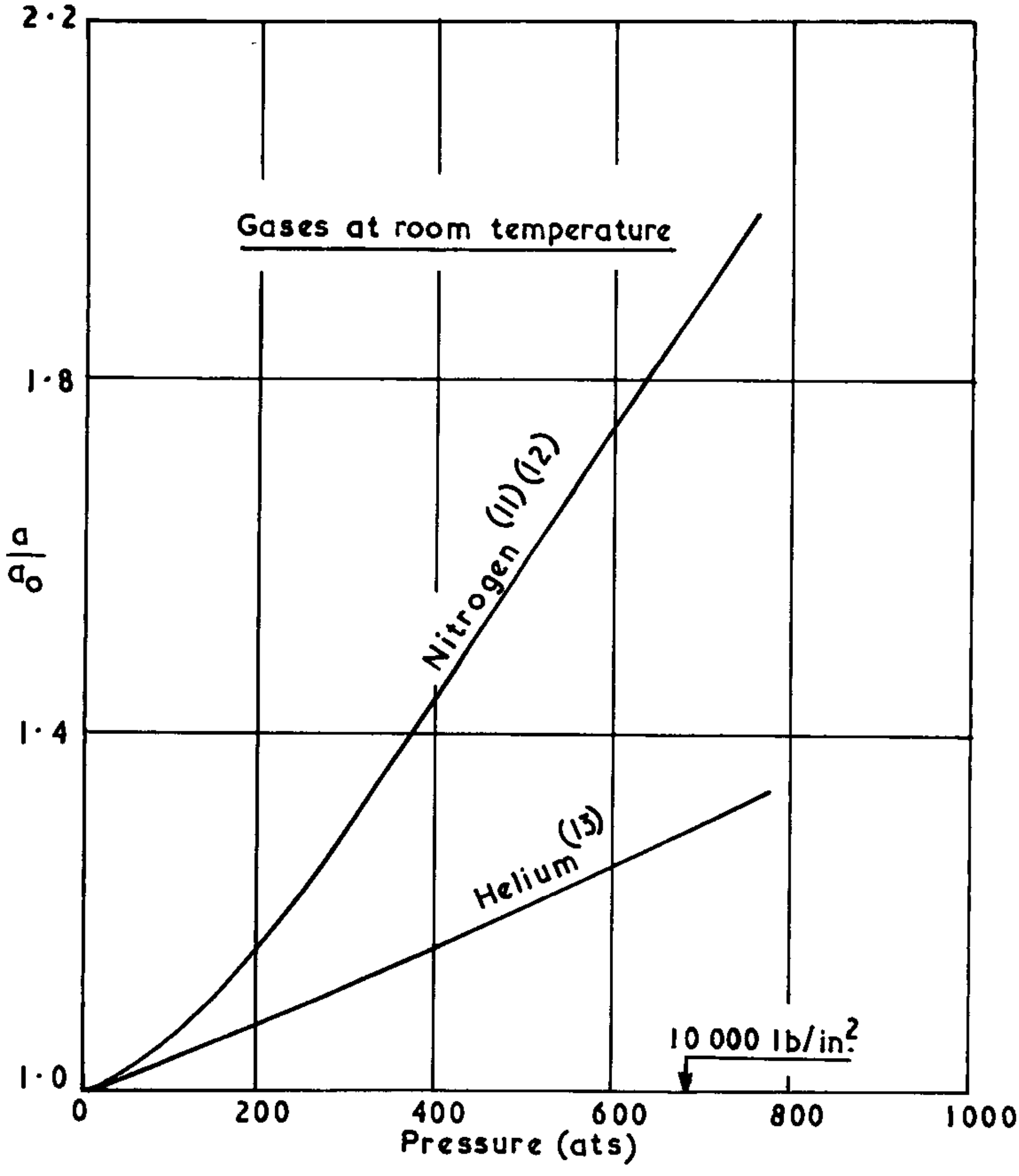
Compressibility factor

FIG. 3



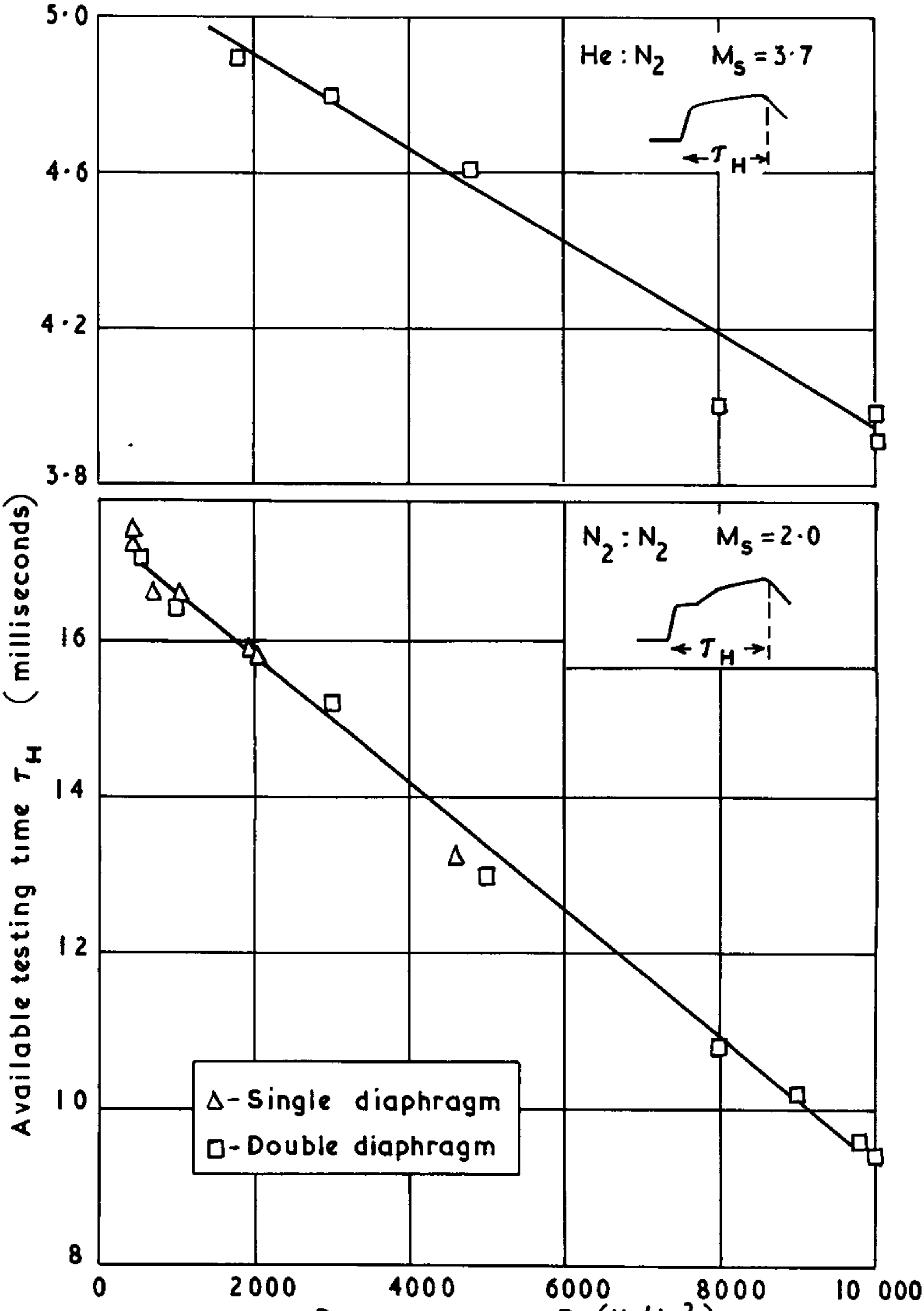
Specific heat ratio

FIG. 4



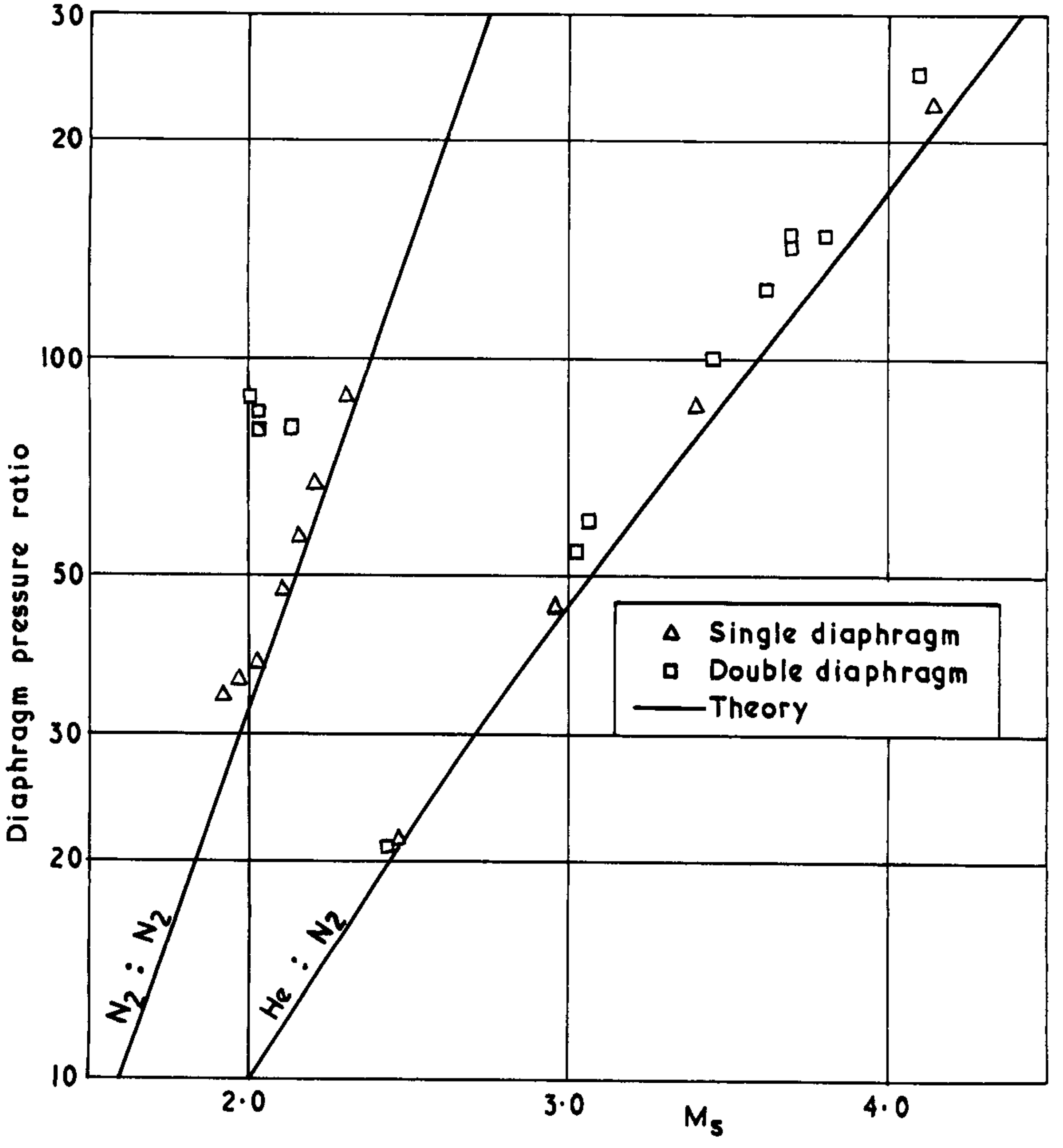
Sound speed ratio

FIG. 5



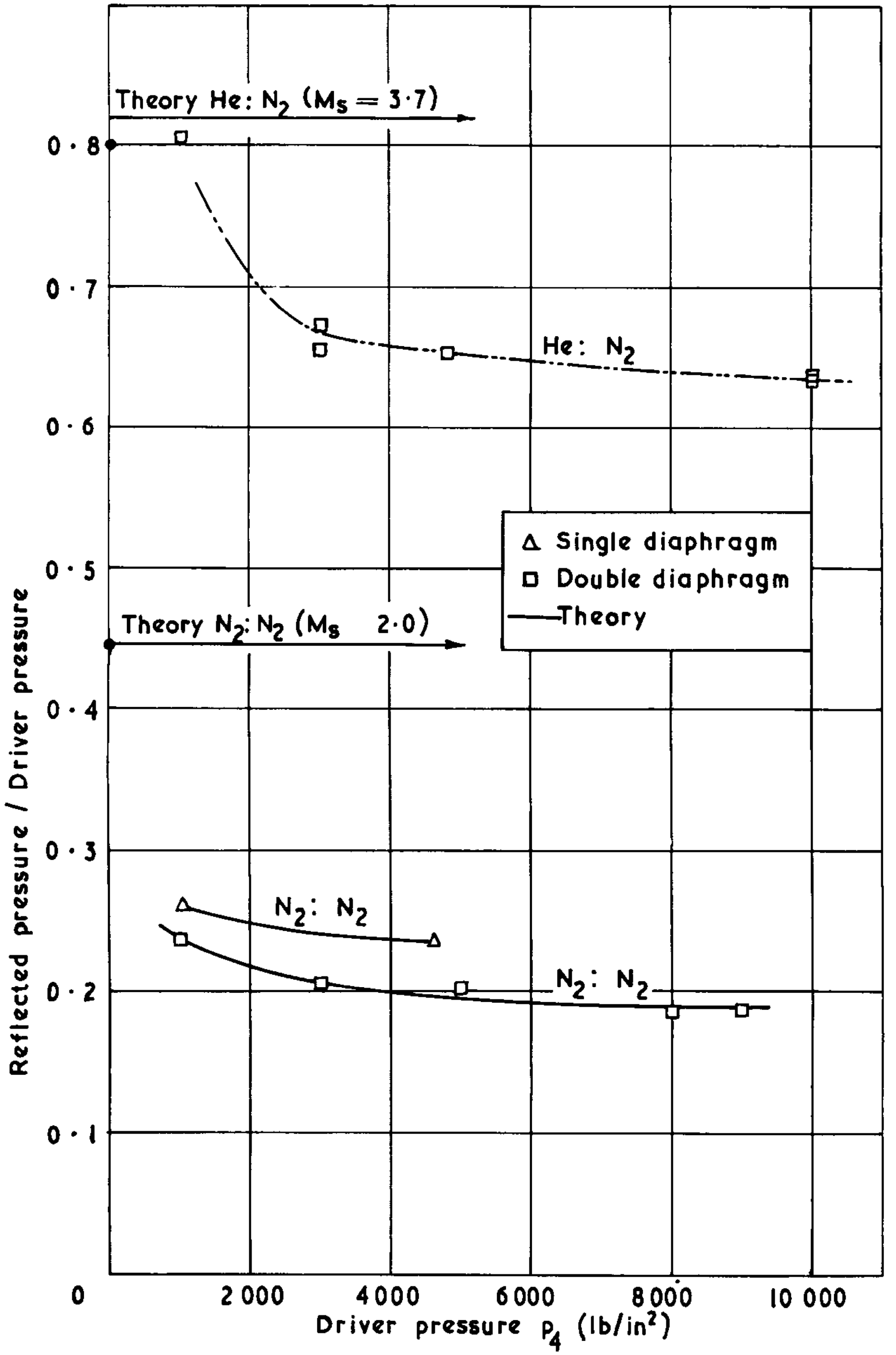
Available testing time

FIG. 6



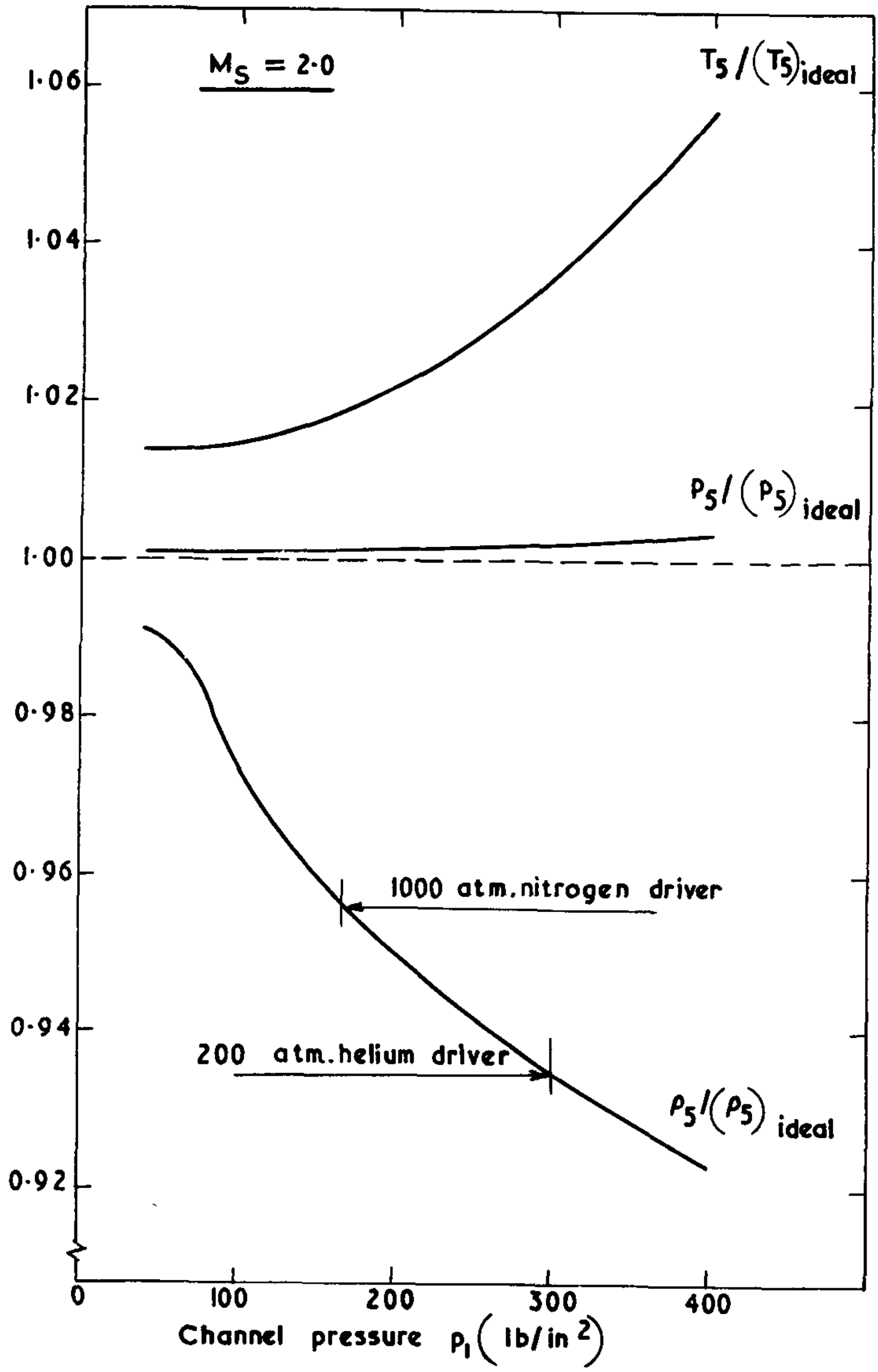
Diaphragm pressure ratio v. shock Mach number.

FIG. 7



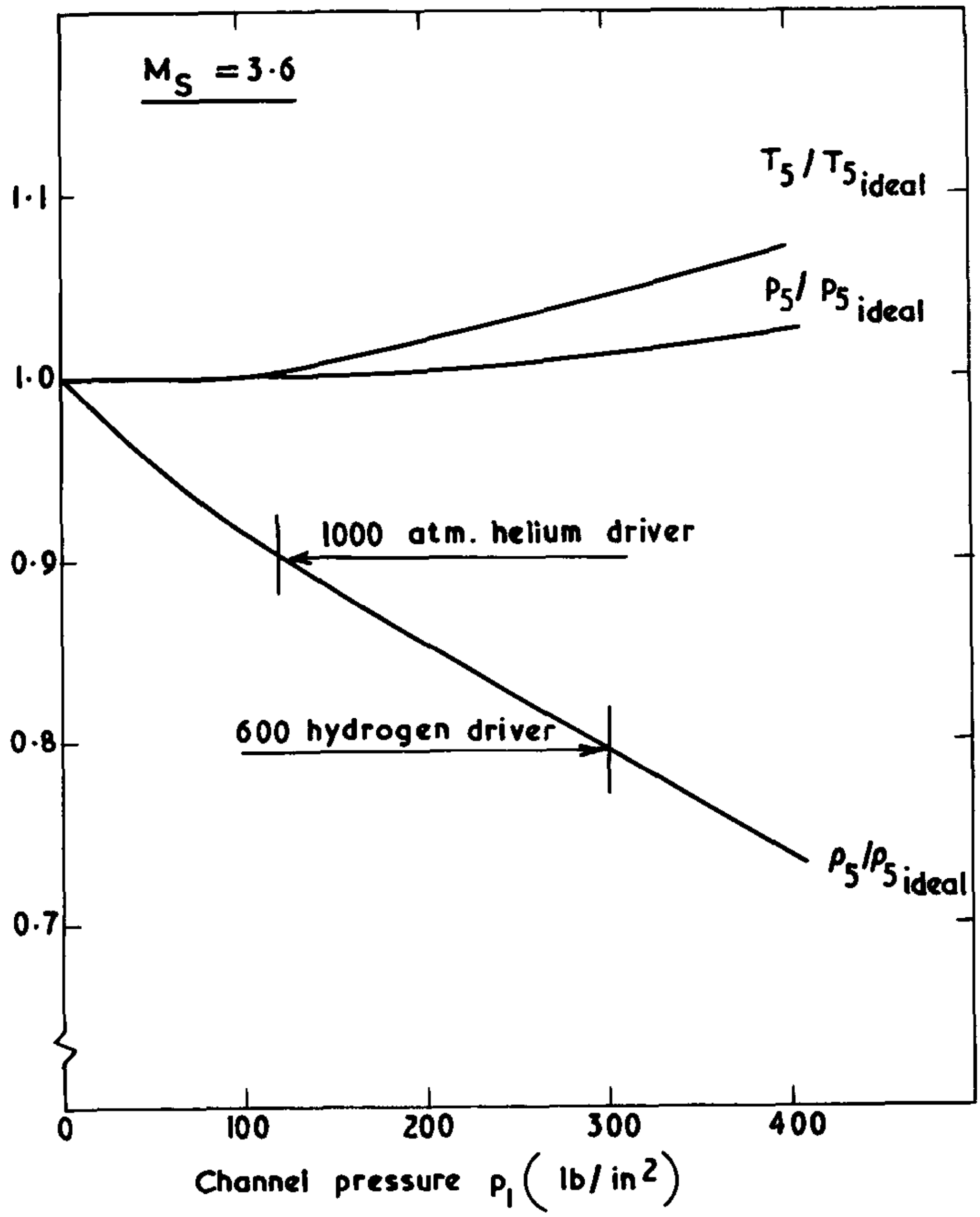
Reflected shock pressure ratio

FIG. 8 (a)



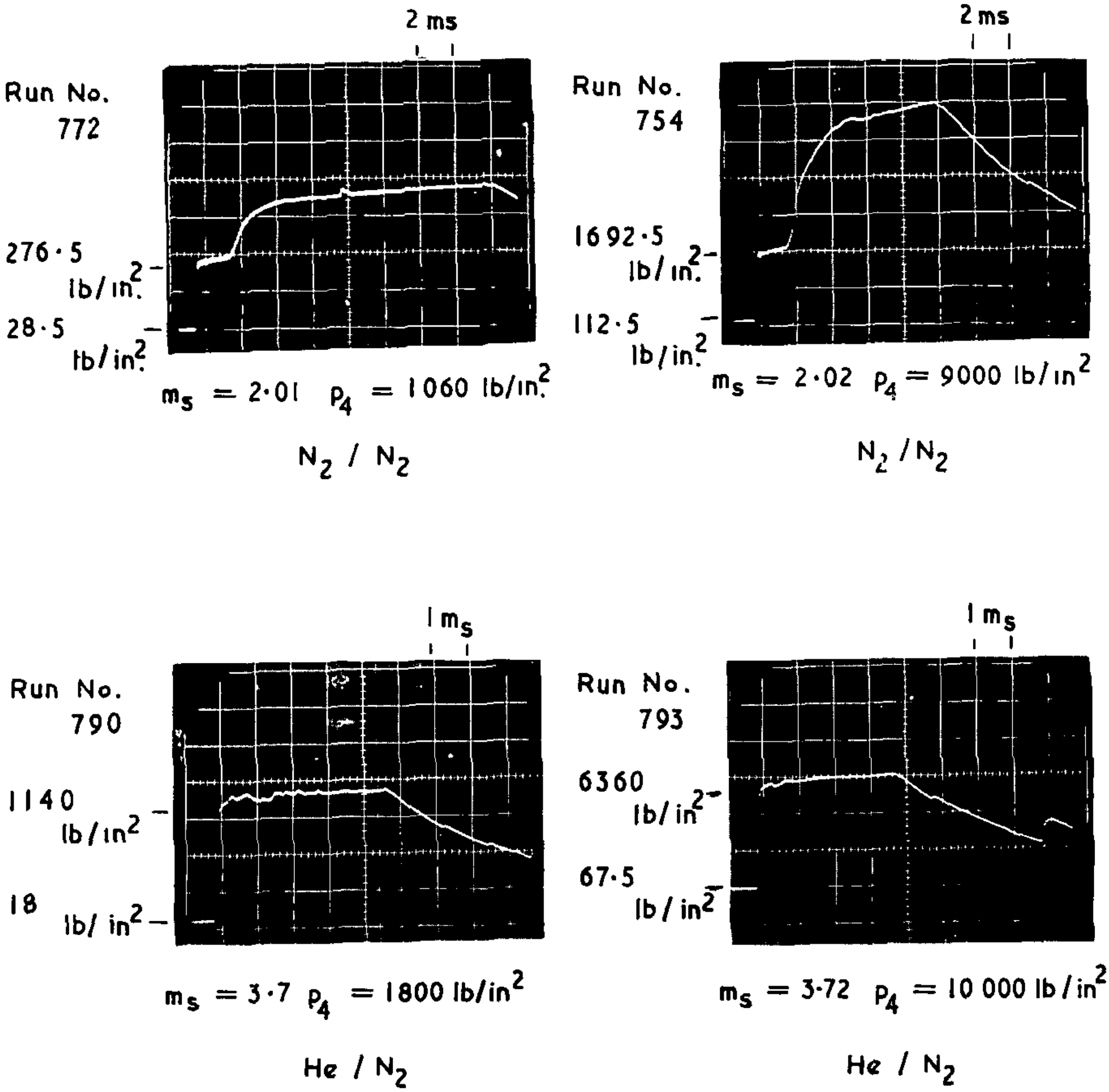
Effect of bulk compressibility on the reflected shock parameters in nitrogen ($M_S = 2{\cdot}0$)

FIG. 8 (b)



Effect of bulk compressibility on the reflected shock parameters in nitrogen ($M_S = 3.6$)

FIG. 9


2 ms
Run No. 772
276·5 lb/in²
28·5 lb/in²
ms = 2·01 P4 = 1060 lb/in²
N2 / N2
2 ms
Run No. 754
1692·5 lb/in²
112·5 lb/in²
ms = 2·02 P4 = 9000 lb/in²
N2 / N2
1 ms
Run No. 790
1140 lb/in²
18 lb/in²
ms = 3·7 P4 = 1800 lb/in²
He / N2
1 ms
Run No. 793
6360 lb/in²
67·5 lb/in²
ms = 3·72 P4 = 10 000 lb/in²
He / N2

A.R.C. C.P. No. 730
September, 1963
Davies, L., Pennelegion, L., Gough, P. and Dolman, K.

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