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The Change in Shock-Tunnel Tailoring Mach Number Due to Driver Gas Mixtures of Helium and Nitrogen

By L. PENNELEGION, Ph.D. and P. J. GOUGH, Dip.Tech.(Eng).

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* Replaces N.P.L. Aero. Report No. 1103—A.R.C. 25 102. Published with the permission of the Director, National Physical Laboratory.

1. *Introduction.*

The undoubted advantage of using a reflected-shock tunnel in the tailored condition[1] is the gain in the duration of the steady stagnation and test-section pressures. The resulting increase in testing time of perhaps five times has enabled measurements to be made with force balances and pressure transducers in wind-tunnel models, which have an inherently slow response when considered in terms of 'straight-through' shock-tube testing times.

If the shock-tunnel driver and channel gases are initially at room temperature, then the ideal tailoring Mach number is unique to a particular driver-driven gas combination. Because of the wind-tunnel testing requirements, it is common to use only nitrogen or air as the channel gas.

With only hydrogen, helium, air and nitrogen available separately as driver gases, the specific tailoring Mach numbers are 6·02[2], 3·42[1, 7] and 1·0 respectively.

Examination of the pressure recovery of a shock tunnel (i.e. the ratio of the reflected-shock pressure to the driver-gas pressure at instant of diaphragm burst) shows that P_{54} varies from 1·0 with hydrogen driver and $M_T = 6\cdot0$, to 0·6 with helium driver and $M_T = 3\cdot4$. At lower Mach numbers the pressure recovery has a maximum of 2·1 and 1·5 for hydrogen and helium drivers respectively. The variation of P_{54} with Mach number for three driver gases is plotted in Fig. 2.

In general the available testing time of a reflected-shock tunnel when used at low shock Mach numbers is limited by the arrival at the nozzle of the head of the expansion wave propagated from the diaphragm station into the driver chamber.

The advantage of an increase in pressure recovery by using a high sound-speed driver gas such as hydrogen or helium is often offset by a short test time due to an inadequately long driver tube, and the rapid motion of the expansion wave through the shock tube. If the sound speed of the driver gas is lowered then an increase in available test time will usually occur. With helium as the driver gas the expansion-wave head arrives at the nozzle entrance about 4mS after the shock wave, with nitrogen as driver gas it arrives about 16mS later (Fig. 3). A combination of these gases will provide a test time between these limits. It is with some pleasure that one realises that a mixture of helium and nitrogen as a driver gas will not only give an increase of testing time but will increase the pressure-recovery factor over that of a nitrogen driver gas.

The use of driver-gas mixtures for modifying the performance of a shock tube has been earlier considered[3, 4, 5], but the intention then was to produce a wave-free stagnation region for studies of gaseous-reaction kinetics.

In this study the accent is on improving the conditions in the expanded flow in the working section of the shock tunnel to enable test-section measurements to be made.

2. *The Use of Different Driver Gases in a Shock Tunnel.*

2.1. *Pressure Recovery at Nozzle Entrance.*

The eventual requirement of measurements being made in the hypersonic stream of the working section is generally eased if the nozzle stagnation pressure is large. At $M_\infty = 8\cdot0$ the working-section static pressure is approximately 10^{-4} of the stagnation pressure and imposes severe difficulties of measurement in short-duration facilities.

The limitation of a short-duration flow is that the quasi-steady-state values (of pressure for example) may not be obtained during the available testing time and thus give rise to uncertainties in the measurement.

Considerations of shock-tunnel performance at low shock Mach numbers indicate that quite appreciable running times and quasi-steady stagnation-pressure levels can be obtained that will generate a most suitable testing flow for the assessment of force and pressure-measuring techniques.

Because of the difficulty of measuring small model surface pressures ($\sim 10^{-2}$ lb/in^2 abs.), tunnel operating conditions have been studied to give the highest pressure recovery. It can be seen in Fig. 2, that for all shock-tube driver gases, the value of P_{54} increases as the shock Mach number is reduced, until some maximum value is reached. It is interesting to note that at $M_T = 6 \cdot 0$, using room-temperature hydrogen driving nitrogen, the value of $P_{54} = 1$, and that at $M_S = 2 \cdot 6$, the ideal value has increased to $P_{54} = 2 \cdot 1$. This feature has been utilised in the new 30 000 lb/in^2 stagnation-pressure AVCO shock tunnel, which has a maximum driver pressure of 15 000 lb/in^2.*

Subject to adequate test time being available, the operating conditions of the shock tunnel can be chosen for maximum pressure recovery, consistent with sufficient stagnation temperature (*see* Section 2.3) to avoid liquefaction at the required flow Mach number. Measurements at the Arnold Engineering Development Center$_6$ have shown that pressure distributions and forces on simple bodies are only slightly affected by the presence of liquefaction in the test section. It seems opportune therefore to operate at as low a stagnation temperature as possible in order to have the advantage of higher working-section pressures and densities.

When assessing the dynamic performance of pressure-plotting models or force balances, it is an advantage to use a step-function force or pressure input to simplify the analysis of resonant frequencies and system response time. To this end, the term the 'steady-pressure time' used in Fig. 4, means the longest time of the pressure history of the run for which the pressure level was constant. Thus in the case of nitrogen driver gas and $M_S = 2 \cdot 0$, though Fig. 3 shows that the expansion-wave head does not arrive until 16mS after the shock at the nozzle entrance, Fig. 4 shows that only $1 \cdot 7$ mS of this is at constant pressure. The initial step associated with the p_5 level is in the opinion of the authors the only suitable testing time, since the subsequent pressure rise gives no clear indication of the continuing wave interactions (as in Fig. 5a).

In Fig. 4, the variation of steady-pressure time for helium driver requires some explanation. The reduction in the range $M_S = 2 \cdot 0$ to $2 \cdot 45$ is the usual reduction associated with the duration of the p_5 level as the shock Mach number is increased. The head of the expansion wave arrives before a p_8 level is formed (*see* Fig. 5c). Above $M_S = 2 \cdot 45$ and up to $M_T = 3 \cdot 4$ there is a steady-pressure time, where $p_8 < p_5$ but which has a time duration greater than the p_5 level. The pressure variation shown in Fig. 8a represents a similar situation. The steady-pressure time of Fig. 4 has an abrupt maximum duration at the tailoring Mach number ($M_T = 3 \cdot 4$) when $p_5 = p_8$, and both level-pressure times add together. When $M_S > 3 \cdot 4$ the steady pressure which exists before the arrival of the disturbances from the contact-surface interactions continues to decrease.

2.2. *Expansion Waves from Diaphragm.*

The limitation to the running time of a shock tunnel is generally imposed by the arrival at the nozzle entrance of either the head or the tail of the expansion wave which originated when the diaphragm burst.

The head of the expansion wave moves into the driver chamber with velocity a_4 and is reflected from the closed end of the driving chamber, and travels through the shock tube to the nozzle. The tail of the wave moves directly into the channel at a velocity of $(u_3 - a_3)$.

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* At the N.P.L., the close proximity of public buildings precludes the routine use of hydrogen as a shock-tunnel driver gas and operation is confined to helium and nitrogen at driver pressures up to 10 000 lb/in^2.

At high shock Mach numbers the tail usually arrives first and the head at low shock Mach numbers.

An improvement in testing time at low shock Mach numbers can usually be effected by either increasing the length of the driver chamber, or by lowering the sound speed (a_4) of the driver gas.

2.3. *Advantage of Using a Driver Gas Composed of Helium and Nitrogen.*

The immediate advantage of using a driver gas composed of helium and nitrogen is that the Mach number at which the reflected shock can be 'tailored' can be varied between $M_S = 1\cdot0$ and $M_S = 3\cdot4$. This means that the choice of stagnation temperature can be between 290°K and 1 557°K, and the range of flow Mach number that can be expanded to without liquefaction is respectively $4\cdot9 \leqslant M_\infty \leqslant 12\cdot3$.

If we suppose that a stagnation temperature of 700°K is required to satisfactorily expand to $M_\infty = 8\cdot0$, then the incident shock Mach number should not be less than $M_S = 2\cdot0$.

Using pure helium or nitrogen to drive this shock Mach number would give a theoretical pressure recovery of $1\cdot5$ and $0\cdot44$ respectively with a steady-pressure time of 4 to 2mS respectively. With a helium fraction of $0\cdot8$ as the driver gas, then the *theoretical* tailored Mach number is $M_T = 2\cdot0$ and the calculated pressure recovery $= 1\cdot02$. The expected steady-pressure time = 5mS. Thus in theory the advantage of using a mixture of helium and nitrogen as the driver gas is that the pressure recovery and testing time is greater by approximately $2\cdot5$ times that using nitrogen only.

3. *The Calculation of Tailoring Mach Number.*

The tailored interface technique refers to the conditions under which the reflected primary shock wave passes through the contact surface without giving rise to additional disturbances. The condition for no disturbances to be reflected from the contact surface requires that

$$\frac{a_2}{a_3} = \frac{\gamma_1}{\gamma_4}\left[\frac{1+\left(\dfrac{\gamma_1+1}{2\gamma_1}\right)(P_{52}-1)}{1+\left(\dfrac{\gamma_4+1}{2\gamma_4}\right)(P_{52}-1)}\right]^{1/2} \tag{1}$$

be satisfied, which has a unique solution of Mach number for a particular combination of driver and driven gases.

If we use bar-notation to denote the value of any gas-mixture parameter, in terms of helium fraction 'x' we have

$$\bar{p}_4 = p_{\text{helium}} + p_{\text{nitrogen}}$$

$$p_{\text{helium}} = x p_4$$

$$p_{\text{nitrogen}} = (1-x)p_4$$

$$\overline{m}_4 = 4x + 28(1-x)$$

$$\bar{\gamma}_4 = \frac{\overline{C}_p}{\overline{C}_v} = \frac{xC_p(\text{helium}) + (1-x)C_p(\text{nitrogen})}{xC_v(\text{helium}) + (1-x)C_v(\text{nitrogen})}$$

$$\bar{a}_4 = \left[\frac{\bar{\gamma}_4}{\overline{m}_4} RT_0\right]^{1/2}.$$

The value of each of these parameters for different helium fractions is given in Table 1.

The calculation of tailoring Mach number is carried out as follows:
Obtain

$$P_{41} = P_{21}\left[1 - (P_{21}-1)a_{14}\left(\frac{\beta}{\alpha_1 P_{21}+1}\right)^{1/2}\right]^{-1/\beta} \tag{2}$$

for a given M_S and helium-fraction parameters. Substitute into

$$a_{32} = a_{41}(P_{14}\,P_{21})^{\beta_4}\left[\frac{\alpha_1 P_{21}+1}{P_{21}(P_{21}+\alpha_1)}\right]^{1/2}. \tag{3}$$

Substitute the same M_S and helium-fraction parameters into equation (1), and use a graphical solution to interpolate for the unique tailoring Mach number.

The values of some pertinent parameters are listed in Table 2, and the numbers showing the appropriate steps as an example are here given for a helium fraction of 0·8 and $M_S = 2\cdot0$.

Example

Helium fraction = 0·8
$\bar{\gamma}_4 = 1\cdot646$
$a_{41} = 1\cdot952$
$\alpha_1 = 6$
$\beta_4 = 0\cdot1962.$

At $M_S = 2\cdot0$, $P_{21} = 4\cdot51$, $P_{51} = 15\cdot0$. Substitution into equation (2) gives $P_{41} = 14\cdot71$ and therefore $P_{54} = P_{51}/P_{41} = 1\cdot02$. Substitute known values into equation (3) and obtain $a_{32} = 1\cdot19$, i.e. $a_{23} = 0\cdot84$. Substitute the appropriate Mach number and helium-fraction parameters into equation (1) and calculate

$$a_{23} = 0\cdot87.$$

Thus a match has not been exactly achieved, so the same procedure is followed for $M_S = 2\cdot1$, say, and the subsequent results used for a graphical solution of the tailored condition.

4. *Experimentation.*

4.1. *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 are used. These are 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. are used. This thickness of diaphragm is 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 and helium gases.

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/in² and 5 000 lb/in², respectively. These gauges are backed by Sangamo-Weston servo-potentiometers which feed 0 to 10 m.a. milliameters scaled in lb/in². The pressure in the channel is measured on a Wallace-Tiernan gauge which measures 0 to 100 lb/in² 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/in², 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§.

4.2. *Details of the Experiment.*

The high-pressure chamber is fed from a manifold having nitrogen and helium gases separately controlled, at line pressures up to 15 000 lb/in².

For this investigation the initial driver chamber pressure was 1 000 lb/in², and the shock Mach number was altered by variation of the initial channel pressure.

From a consideration of diffusion processes, the time of contact of the helium and nitrogen gases would have affected the homogeneity of the driver gas. Comparative tests showed that the nitrogen or helium could be introduced in either order and that the time of residence in the driver chamber before firing the tunnel (up to 2 hours), made negligible difference to the shock Mach number obtained.

The procedure standardised upon was to initially pressurise with the nitrogen component (i.e. $1-x$) and to complete the pressurising to 1 000 lb/in² with the helium. The computed theoretical value of channel pressure was used for tailoring. An examination of the subsequent stagnation-pressure record indicated whether the run had been 'below' or 'above' tailoring (*see* Fig. 8 as an example), and the channel pressure was lowered or raised until the desired condition was obtained, keeping the driver mixture constant.

4.3. *Discussion of the Results.*

Analysis has been made of the reflected-shock profiles for 6 driver-gas compositions over a wide range of shock Mach numbers. For the purpose of presenting a clear comparison of theory and experiment the results of only one mixture are presented graphically with those of the pure gases. Some of the analysed data from the other cases is in Table 3.

4.3.1. *Tailored Mach number.*—Experimental agreement with the simple one-dimensional shock-tube theory, and the assumption of a homogenous driver gas is surprisingly good. At Mach numbers of 1·4 and 3·4 it agrees completely, and has its greatest under-estimate near $M_T = 2\cdot 2$

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* These are made by J. Langham Thompson.

† Supplied by Edwards High Vacuum.

‡ A 4 C 1 000.

§ Solenoid valve—supplied by S. E. Laboratories, Feltham, rated up to 3 600 lb/in², tested in the N.P.L. up to 8 000 lb/in².

where the disagreement is 20%. Since the experimental tailoring condition is adjusted from observation of the stagnation-pressure record, the lack of complete agreement with theory might very well be associated with imperfect performance of the shock tunnel. Fig. 8 shows the change in pressure profile obtained by varying the channel pressure, with a fixed composition driver gas at constant pressure.

Because of slight experimental scatter, the deduction of tailored conditions was made by calculating the magnitude of P_{85} and plotting against Mach number as in Fig. 9. The condition for tailoring is that the reflected disturbance from the contact surface should be a Mach wave, i.e. $P_{85} = 1$.

All the results were plotted in this way and the value of M_T obtained.

The diaphragm pressure ratio (Fig. 7) is found to be about 15% higher than theory which means that for a fixed driver pressure the channel pressure must be correspondingly reduced.

4.3.2. *Pressure recovery.*—Comparison has been made of the ratio of P_{51} with theory and reasonable agreement found. Because the channel pressure requires to be 15% lower than theory for a fixed driver pressure to drive a specific shock Mach number, it is not unexpected that the pressure recovery P_{54} is less than theory as is depicted in Fig. 6.

It is clear that at $M_T = 2\cdot0$, the use of $0\cdot7$ helium fraction (which is tailored at $M_T = 2\cdot0$) results in an experimental gain in stagnation pressure of $2\cdot7$ times that of the nitrogen driver-gas case. This is vividly demonstrated in the oscilloscope records of Fig. 5, where the vertical pressure scale is identical for all three cases.

Of particular interest is the fact that the pressure record Fig. 5b is repeated almost exactly for the other tailored helium mixtures. In Fig. 11 it can be seen that the magnitude of the reflected-pressure step (p_5-p_1) is almost constant with change of Mach number, unlike the pure driver-gas case which is strongly dependent upon Mach number.

This means that the effect of stagnation temperature (which is the main variable) can be more easily assessed simply by changing the helium fraction.

4.3.3. *Useful test time.*—Examination of Fig. 5 shows that the requirement of an increased-duration constant-pressure level at the nozzle entrance is achieved by using a driver-gas mixture and its appropriate tailored Mach number. In Fig. 4 it can be seen that the tailored mixtures always give a greater time of steady pressure than the pure gases alone. Specifically for example, at $M_S = 2\cdot0$ and therefore using $x = 0\cdot7$, the steady-pressure time has increased by nearly five times that of the pure nitrogen $(x = 0)$ case, to 8 mS.

This means that force and pressure measuring systems can have resonant frequencies as low as 300 c/s, and that a sufficient time exists for electrical filtering to be employed.

5. *Conclusion.*

Helium gas diluted with nitrogen gas can be used as a driver gas for a shock tunnel, and gives 'tailored' operation over the incident shock Mach number range $1\cdot25$ to $3\cdot4$. It has been experimentally determined that the pressure step throughout this Mach number range is normally constant for a given driver pressure, and that the usable duration of constant stagnation pressure is increased by a factor of 2 to 3 on that of the pure gas alone.

6. *Acknowledgements.*

Mr. K. Dolman assisted with the shock-tunnel tests, and Mrs. M. Marshall performed most of the data reduction and calculations.

LIST OF SYMBOLS

a		Speed of sound
a_{ij}	=	a_i/a_j
m		Molecular weight
mS		Millisecond
M_S		Shock Mach number
M_T		Tailored Mach number
M_∞		Free-stream Mach number
P_{ij}	=	p_i/p_j, where p = absolute pressure lb/in^2
R		Gas constant
T_0		Room temperature °K
u		Particle velocity
x		Fraction of helium present in driver gas
α	=	$(\gamma+1)/(\gamma-1)$
β	=	$(\gamma-1)/2\gamma$
γ	=	C_p/C_v

Notes

(i) Shock-tube notation is from Ref. 7.

(ii) Values of shock-wave relationships from Ref. 8.

(iii) Nitrogen was used as channel gas in all cases.

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TABLE 1

Driver-Gas Constants

Helium Fraction	$\bar{\gamma}_4$	$\bar{m}_4$	$\bar{a}_{41}$
0	1·40	28·0	1·0
0·2	1·538	23·2	1·162
0·4	1·594	18·4	1·328
0·5	1·612	16·0	1·432
0·6	1·626	13·6	1·561
0·7	1·637	11·2	1·725
0·8	1·646	8·8	1·952
0·9	1·654	6·4	2·294
1·0	1·667	4·0	2·913

TABLE 2

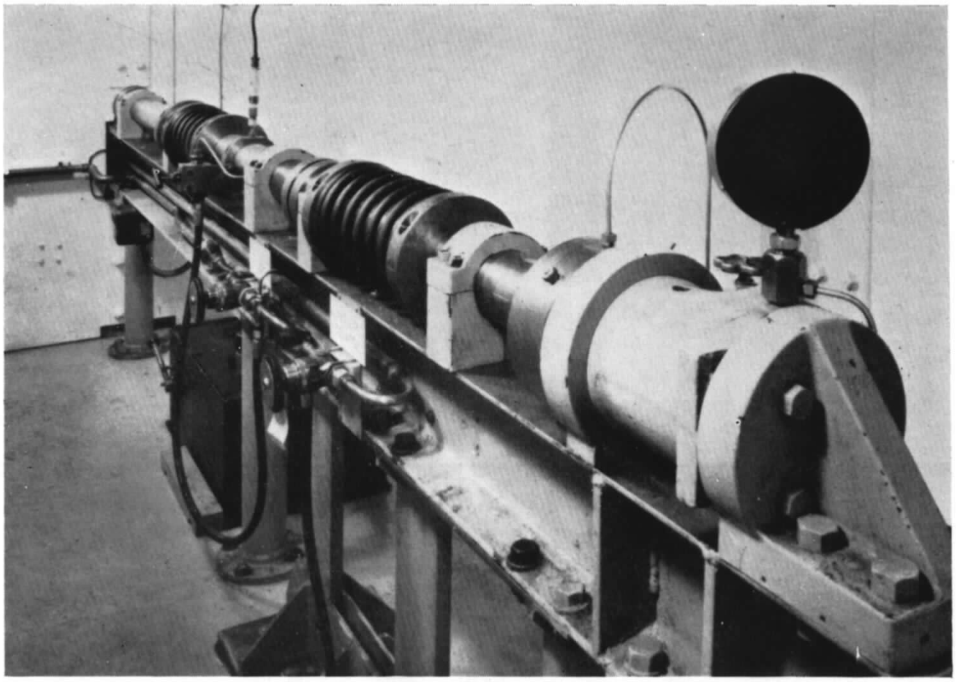
Experimental Tailored Mach Number Values

Helium Fraction	M_T	P_{41}
0·4	1·25	—
0·5	1·38	—
0·6	1·60	9
0·7	2·0	24
0·8	2·7	60
0·9	2·8	70
1·0	3·4	124

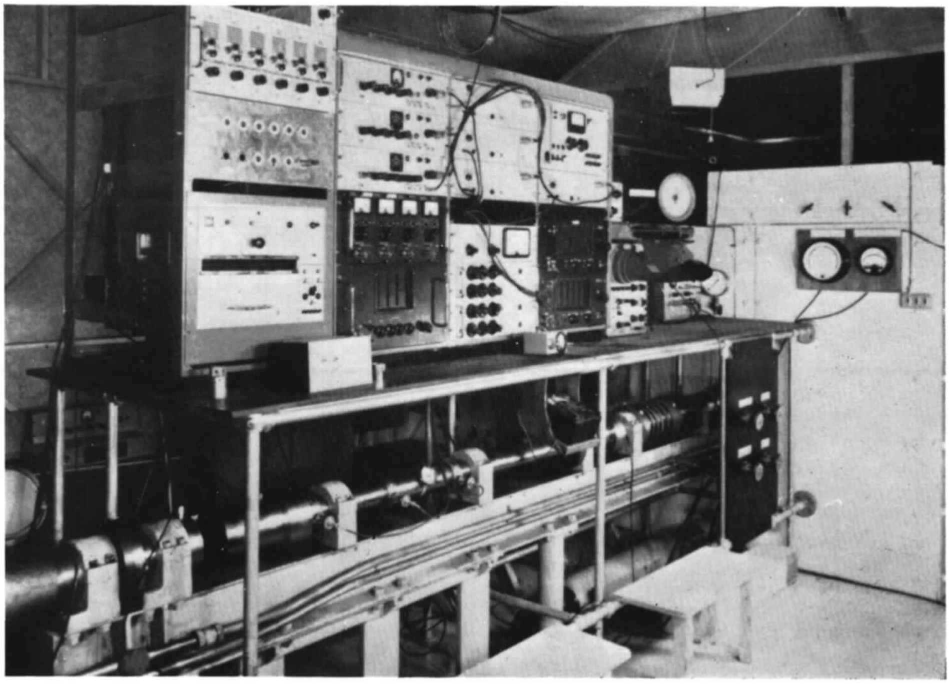
TABLE 3

Sample of Other Experimental Data

Helium Fraction	M_S	P_{41}	P_{54}	P_{85}
0·6	1·66	11·1	0·61	1·13
	2·05	25	0·61	1·17
	2·92	200	0·26	1·70
	3·69	1000	0·11	2·4
0·7	1·90	17·2	0·714	1·0
	2·59	83	0·43	1·36
	3·0	200	0·28	1·95
	3·44	500	0·177	2·36
0·8	1·90	15·4	0·84	0·94
	2·86	83	0·54	1·20
	3·65	500	0·19	2·45
	3·97	1000	0·13	3·0
0·9	2·01	16·7	0·88	0·77
	2·86	71	0·68	1·0
	3·55	250	0·39	1·75
	4·42	1000	0·17	2·5



High-pressure chamber.



Low-pressure channel

FIG. 1. N.P.L. 2 in. Shock Tunnel.

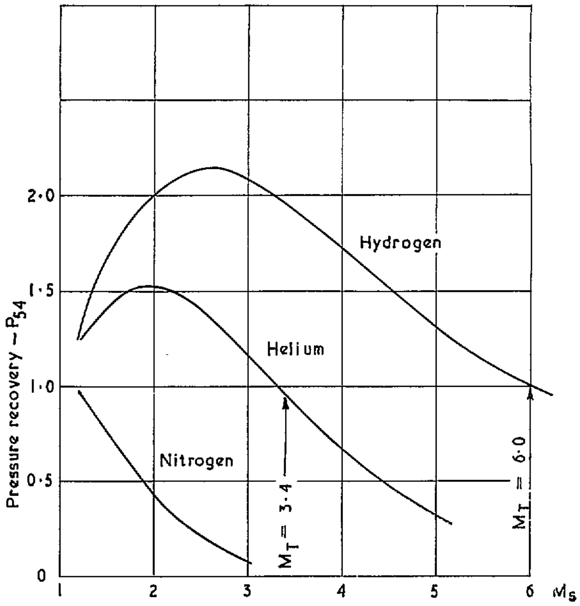


FIG. 2. Theoretical recovery for different driver gases.

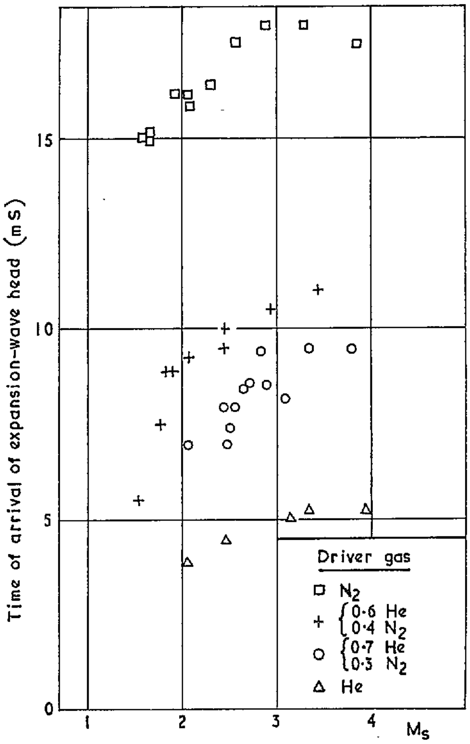


FIG. 3. Time between arrival of shock and expansion-wave head.

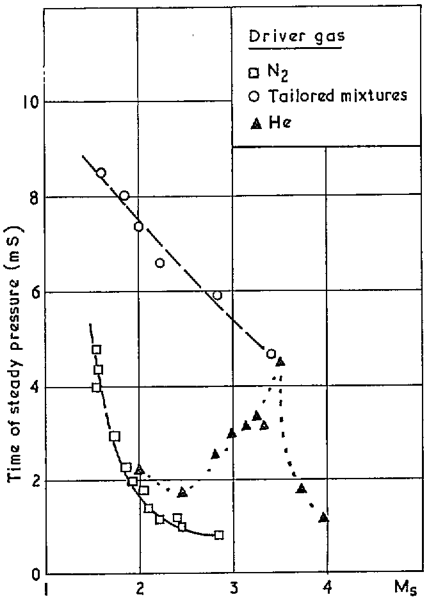


FIG. 4. Available steady-pressure time.

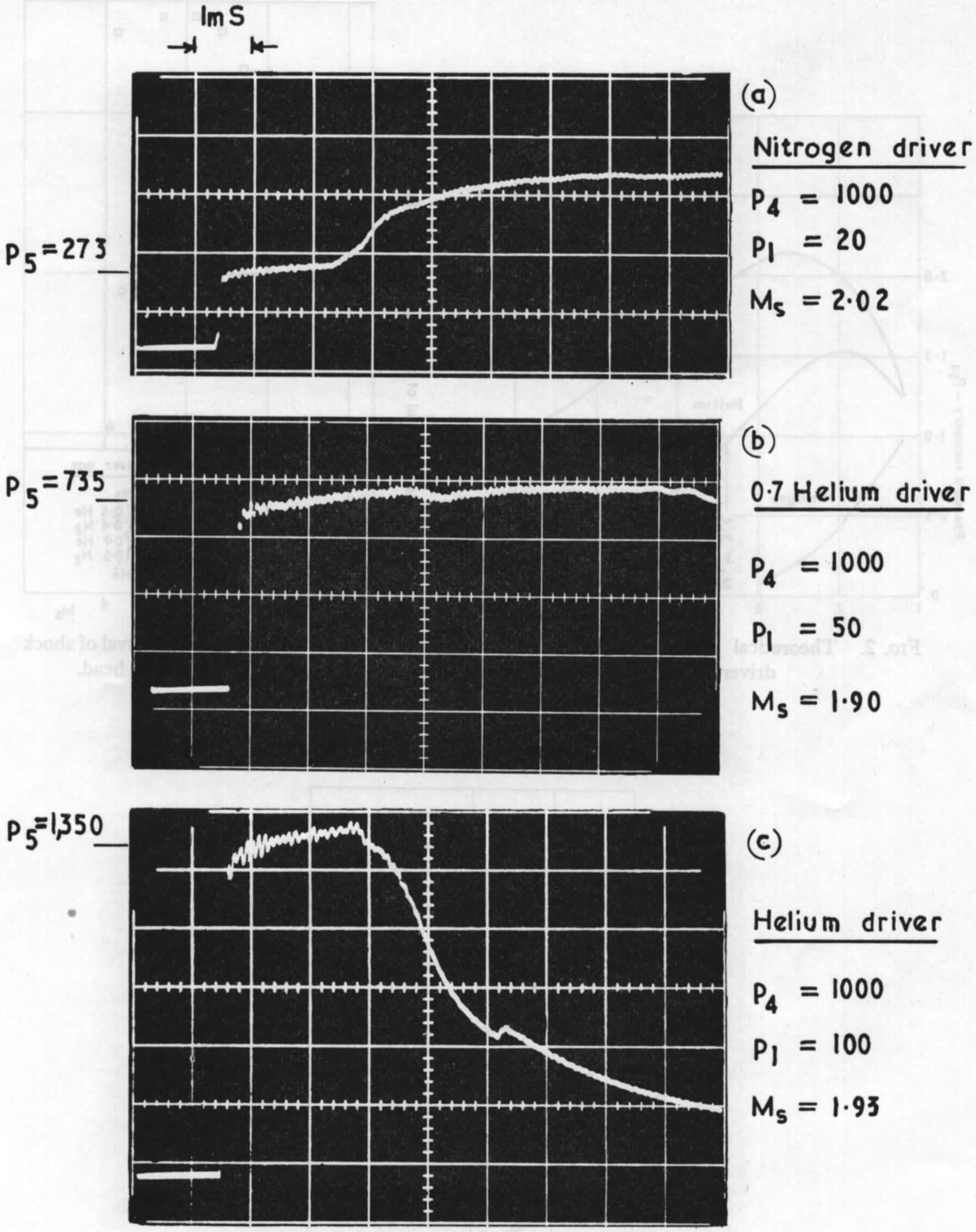


FIG. 5. The effect of driver-gas variation for constant Mach number.

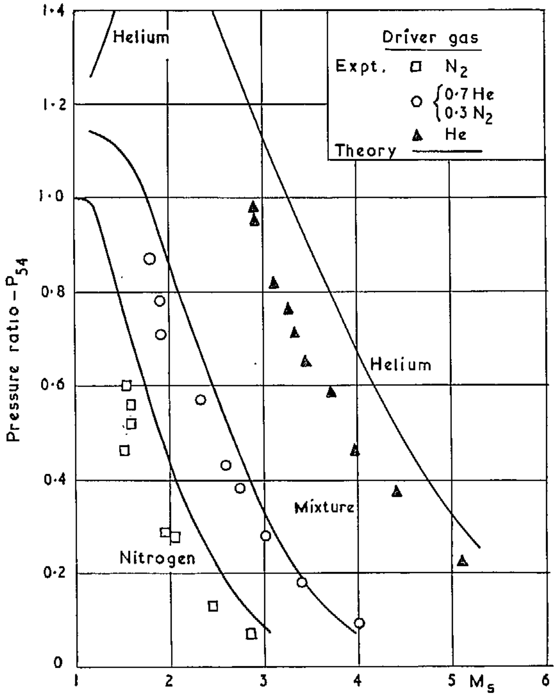


FIG. 6. Experimental pressure recovery for different driver gases.

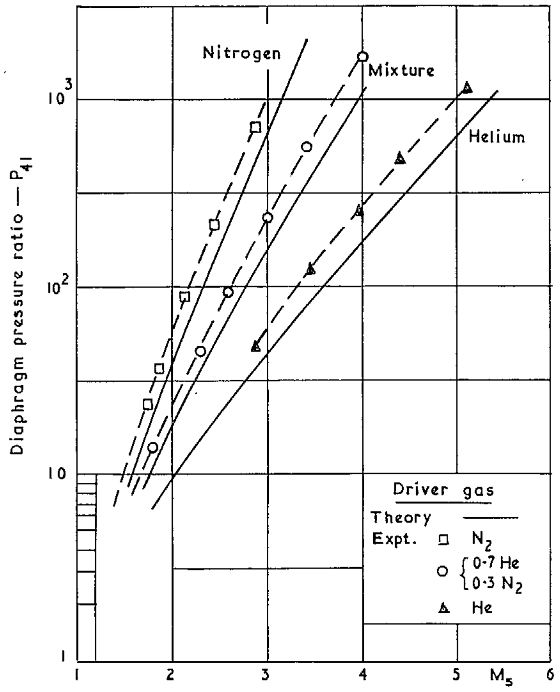


FIG. 7. Variation of diaphragm pressure ratio.

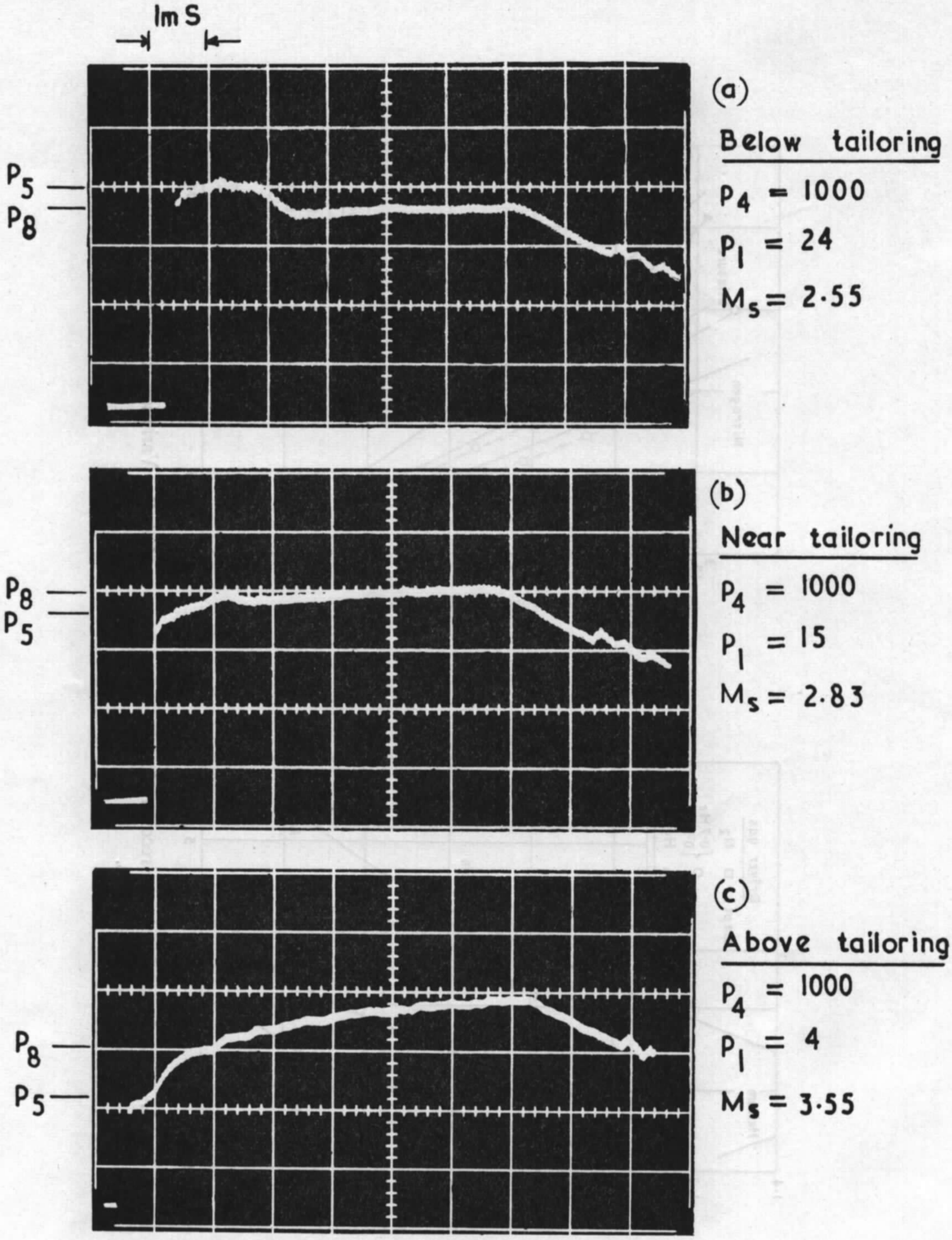


FIG. 8. The effect of shock Mach number for constant driver-gas mixture ($x = 0\cdot9$).

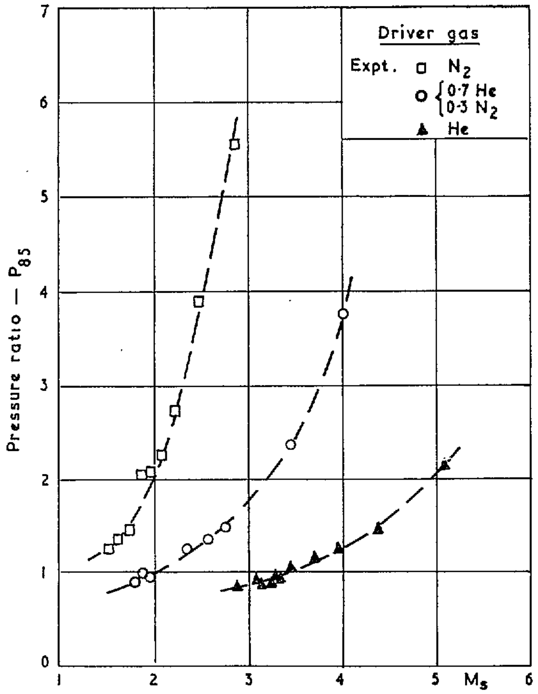


FIG. 9. Pressure ratio across 1st reflection from contact surface.

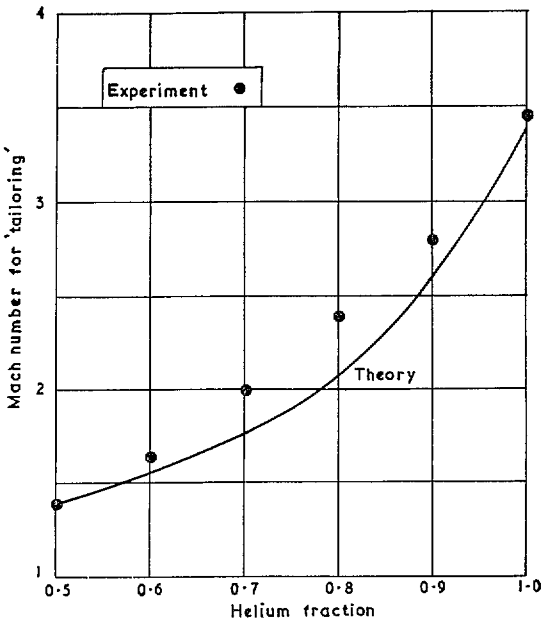


FIG. 10. Variation of tailored Mach number with helium fraction.

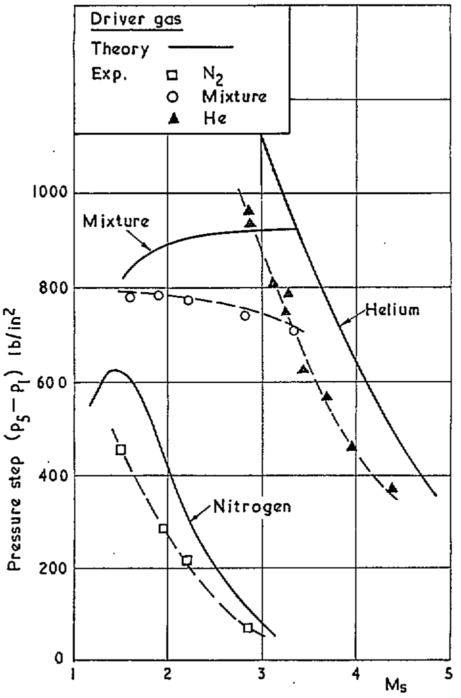


FIG. 11. Reflected-pressure step for constant driver pressure $= 1000$ lb/in^2.

(90903) Wt. 66/2301 K.5 2/65 Hw.

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