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A PERFORMANCE STUDY OF A PISTON COMPRESSION SHOCK TUNNEL

G. P. Rouel and B. E. Richards
von Kármán Institute for Fluid Dynamics
72 Chaussée de Waterloo,
1640 Rhode-Saint-Genèse, Belgium

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Elton R. Thompson

Robert O. Dietz

ELTON R. THOMPSON
Research and Development
Division
Directorate of Technology

ROBERT O. DIETZ
Director of Technology

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A theoretical study of a high performance piston compression tailored mode reflected shock tunnel, designed to achieve re-entry flow simulation, has been carried out. The designed tunnel supply conditions were pressures varying from 2000 to 5000 atm at temperatures from 6000 to 12,000°K. The pressures and temperatures involved in the study were high enough that imperfections in the equation of state covering both dense gas effects and

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) internal energy modes were required to be assumed. Similar running times as in conventional shock tunnels have been shown to be achieved at the design performance with relatively lowly stressed tube extensions. Helium is shown to be a more efficient driver gas than hydrogen in piston compression operation in terms of both performance and running time. An analysis applied to the geometry of the HIRHO facility currently being developed at AEDC shows that its predicted performance can be achieved using the free piston driver using helium as a driver gas.

PREFACE

The work reported was sponsored by the Arnold Engineering Development Center (AEDC), Directorate of Technology, under Program Element 65802F. The monitor for this project was Mr. Elton Thompson, AEDC/DYR. The report covers work conducted during the period February 1972 through February 1973.

The authors would like to acknowledge the useful discussions at the beginning of the study with Dr. Michael Lewis, then Assistant Professor at the von Kármán Institute, now at the Institut Fédéral de Recherches en Matière de Réacteurs in Würenlingen, Switzerland. The support given by Major R. M. Bowman, Project Officer, Directorate of Engineering and Life Sciences, Department of the Air Force, European Office of Aerospace Research, London, W. 1 was greatly appreciated. Mme Rigaux typed the manuscript.

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

The performance of a shock tunnel is mainly controlled by the driver gas composition, the diaphragm pressure ratio, and the initial temperature of the driver gas. With hydrogen as the driver gas, at a particular temperature, the maximum performance is limited to that achieved with an infinite diaphragm pressure ratio. Better performance may only be obtained by increasing the temperature of the driver gas. Several methods are available for accomplishing this, for example, resistance heaters, arc heating, combustion and compression heating. Experience at the von Kármán Institute in the use of piston-driven facilities (Longshot described in Ref. 1 and the Piston-Driven Shock Tube described in Ref. 2) has shown that compression heating has many advantages over more conventional methods. In particular, uniform heating of the driver gas to very high temperatures (>3000°K) may be obtained without a complex electrical power supply. Furthermore, the high pressure, high temperature gas is confined to the driver tube for such brief intervals of time (order of milliseconds (msec)) that the wall temperature does not increase much above room temperature. This has advantages both in the design of the very high pressure vessels required and in minimizing the risk of a dangerous explosion from gas leakage or vessel rupture. It has been shown that, at very high shock speeds, helium becomes a more efficient driver gas than hydrogen (Ref. 3). By using helium any probability of an exothermic explosion is removed.

The piston-driven shock tunnel in tailored-mode has been developed and appraised by Stalker (Ref. 4) and Stalker and Hornung (Ref. 5). An initial appraisal of the presently configured AEDC HIHRO facility has been carried out by Stalker and Pate (Ref. 6). This present study involves an analytical study of an uprated version of HIRHO to achieve combinations of high temperature and high pressure in air behind the reflected shock wave in a useable running time (greater than 1 msec) using the piston compression method of heating the driver gas.

The HIRHO facility, as currently planned, has an internal-resistance-heated driver and will use hydrogen as the driver gas. The driver is 6.25 m (20.5 ft) in length with an 18-cm internal diameter. The driven tube is 12.5 m in length with an 18-cm internal driver. The downstream end of the driven tube will have provisions for interchangeable nozzle throats. Nozzle throat diameters of 12.7, 25.4, and 38.1 mm were used in the current calculations to determine tunnel run times.

The predicted performance of the unmodified HIRHO facility using hydrogen driver gas is given on the following page. The performance figures are for the pressures and temperatures in the reflected shock region of the driven tube, i.e., immediately upstream of the nozzle throat.

Tunnel Performance with a 1000°K Heater

Pressure, atm	Temperature, °K
5000	6000
4000	7000
3000	8000
2000	9000

Tunnel Performance with a 1600°K Heater

Pressure, atm	Temperature, °K
5000	10300
4000	10900
3000	11600
2000	12300

Tunnel run times of 1 to 3 msec were predicted for the conditions given above.

From the performance figures it is deduced that the driver tube can withstand pressures of the order of 10,000 atm. It is assumed that for the purposes of this study, the driver can be increased in length with an extension tube of the same internal diameter and with a pressure rating of no more than 2000 atm. Also a reservoir vessel of a diameter three times that of the driver, with approximately the same length of driver and with a pressure rating of 1500 atm, is required to drive the piston. These extensions could be added for a relatively small expense. In this study, it was assumed that the piston weight was 300 kg and that the petals of the broken diaphragm would fold into recesses in the tube allowing the piston to pass and come to rest at the nozzle end wall under the cushioning effect of the mixture of driver and test gases. Such a method has been used by Hovstadius (Ref. 7).

Preliminary calculations showed that the densities of the piston driver gas, the shock tube driver gas, and the test gas of the piston-driven shock tunnel under investigation were so high that intermolecular forces have to be taken into account. High temperature imperfections also have to be included in the shock tube driver and test gases. The thermodynamic information of the likely gases (hydrogen, helium, nitrogen, and air) considered to be presently the most accurate at combined high temperature and high density conditions are usually in the form of tabulated data derived from theories based on statistical mechanics (Refs. 8 and 9). At extreme conditions, such tables remain unverified experimentally. Furthermore, for numerical performance studies of the piston-driven shock tunnel in which multiple calculations of the Riemann function and Rankine-Hugoniot equations of real gases have to be made, simplifications of the equations of state are required to make a reasonable parametric study.

Section 2.0 of this report presents a review of the equation of state models for dense high temperature gases used in this study. Section 3.0 describes briefly the four main computer programs devised. The results are presented and discussed in Sections 4.0 and 5.0, respectively.

2.0 REVIEW OF EQUATION OF STATE MODELS FOR DENSE, HIGH TEMPERATURE GASES

Calculations of performance of shock tunnels and piston-driven facilities often use simplified equations of state. For example, Enkenhus (Ref. 2) used the Lewis and Burgess model (Ref. 10) to calculate the properties of air through a normal shock; Siegel (Ref. 11) used Abel-Noble and Van der Waals models for dense helium and nitrogen. The advanced piston-driven shock tunnel under study requires more sophisticated equations to take into account the combined intermolecular force and internal energy terms. The computer (IBM 1130) limitations at the Institute meant that only analytical equations of state could be used, similar to that developed by Enkenhus and Culotta (Ref. 12) for nitrogen. The following equations of state were selected for the study.

Air: The conditions expected to be encountered in the air test gas are up to 5000 atm pressure at 10,000°K temperature. Dense gas models for this mixture of two main gases with different species at high temperatures is particularly difficult to describe analytically. A gross assumption was made that the molecular separation at these high temperatures was so large that dense gas effects could be ignored. The Hansen model (Ref. 13) was thus selected.

Helium: The virial form of the equation of state by Miller and Wilder (Ref. 14), considered by these authors to be accurate over the range up to 3600 atm and 15,000°K partially covers the expected range of conditions needed by a helium shock tunnel driver of 2000°K and 10,000 atm.

Hydrogen: The equation of state of Woolley (Ref. 15) considered by this author to be accurate over the range up to 20,000 atm and 3500°K, and agreeing with the calculation of Reggiani (Ref. 10) which are based on the "6-12" Lennard-Jones potential covers the expected range of conditions needed by a hydrogen shock tunnel driver of 2000°K and 11,000 atm.

Algorithms to solve the Rankine-Hugoniot relations for the flow across a normal shock and to compute the Riemann function for calculating the flow across expansion waves, were developed for the gas models mentioned above. These and their application to the performance study of the shock tunnel, the results of which are explained in Section 4.0, will be reported in a forthcoming VKI publication (Ref. 17).

3.0 CALCULATION METHOD

The calculations were carried out in four stages using separate computer programs. Reference to Figs. 1 and 2, illustrating the operation of the facility and the wave processes of the shock tube part, respectively, will aid understanding the programs, which will be described more fully in a forthcoming publication (Ref. 17). Typical outputs from the programs are given in Tables 1 to 4, respectively.

3.1 TAILORED-MODE REFLECTED SHOCK TUBE PERFORMANCE CALCULATION

Using the usual shock tube equations the computer program calculates the temperature behind the reflected shock, T_5, in the test gas originally at room temperature, and the driver gas pressure, P_4, required to generate pressures behind the reflected shock, P_5, from 2000 to 5000 atm using driver gas temperatures between 1000°K and 2000°K. The assumptions of Wittliff et al. (Ref. 18) to determine the tailored conditions were used. This occurs when the gas behind the positive going wave (KL", caused by the interaction of the reflected shock wave with the contact surface) has zero velocity and a pressure equal to that behind the reflected shock wave. Another way of putting this is that

$$u_5 = u_6 = 0$$

$$p_5 = p_6$$

In this region it is assumed that the gas is homogeneous. The shock is thus transmitted without creating additional waves. The method of calculation is then as follows:

I - guess initial shock Mach number and compute, from initial temperature and pressure in the test gas (air), the conditions behind the incident shock (Region 2) and behind the reflected shock (Region 5).

II - Knowing the reflected shock Mach number calculate the velocity and pressure change in the driver gas (Region 3) after shock passed through the interface (tailoring conditions).

III - Calculate conditions in the driver gas at the beginning (Region 4) by using the Riemann variable (expansion fan).

IV - If temperature in Region 4 is not correct, change initial shock Mach number and repeat steps I to IV.

The method of calculation will be described with more details in Ref. 17.

3.2 TAILORED-MODE REFLECTED SHOCK TUBE RUNNING TIME CALCULATION

For the cases examined in Section 3.1 this program calculates the length of driver tube necessary to generate a given running time defined as the time from the arrival of the incident shock wave to the arrival of the reflected rarefaction wave. The usual shock tube equations and expressions for the flow of gas through an orifice are used and real gas effects are assumed to calculate all the events, J, K, 4, 3, N, M, L, L', L", and I, given in the wave diagram of Fig. 2.

The following main assumptions are made:

i. The diaphragm bursts when the piston is momentarily at rest (or more precisely, when uniform conditions exist throughout the driver).

ii. Viscous effects are ignored such that there is no shock wave attenuation.

iii. Heat-transfer losses to the walls are ignored in Region 5.

iv. The effect of the flow through the nozzle is felt immediately in the region behind the reflected shock wave.

3.3 ISENTROPIC COMPRESSION CALCULATION

This program calculates, assuming an isentropic compression of the gas with a given initial temperature (this assumption was verified for a helium driver gas by the tests described in Ref. 19 for the range of driver gas considered, i.e., up to 2000°K), the initial pressure that would be required to achieve the driver conditions of the shock tunnel in program (a) and the compression tube length to provide the driver tube length of calculation (b).

3.4 PISTON CYCLE CALCULATION

This program calculates the basic conditions required to drive the 300-kg piston, thus generating the shock tube driver conditions calculated in program (c) with a driver tube length estimated by program (b). As shown in Section 4.0, it was found that to obtain realistic driver tube lengths the gas used to drive the piston was required to be room temperature helium. It was assumed that the piston speed was so low that an assumption of infinite speed of sound of the gas both upstream and downstream could be used. This assumption was satisfactorily checked out by comparing several cases with calculations using the full characteristics solution.

4.0 PRESENTATION OF RESULTS

The main numerical results of the parametric study of the piston-driven shock tunnel are given in Tables 5 to 8*. Table 5 reviews the values of input conditions T_4, P_5, T_{4_i}, T_1, T_{0_i}, piston weight, testing time, shock tube length, and constituent gases chosen to be studied. Table 6 gives the calculated values of the parameter M_s (i.e., shock Mach number), T_5, P_4 required to obtain tailoring conditions in the shock tube and P_{4_i} and λ (compression ratio) for two values of T_{4_i} (293°K and 500°K) to achieve the necessary driver conditions. Table 7 gives l_p (distance between the shock tube diaphragm and the position at which the piston comes to rest), L_c (compression tube length) required to give a running time of 2 msec, ignoring viscous effects, terminated by the arrival of the head of the reflected expansion wave for a shock tube length of 64 ft. The values of P_{0_i} (initial piston driver gas pressure) and V_p (piston velocity) are also given. Table 8 gives the same parameters as given in Table 7 but with values for shorter shock tube lengths considered to be optimum to obtain a running time of 2 msec. These results are illustrated graphically in Figs. 4 to 11 in order to assist the ensuing discussion of the results. The final driver gas temperature, T_4, is used as the primary variable.

*Copies of the complete computer readouts are available from VKI.

5.0 DISCUSSION

5.1 CHOICE OF RESERVOIR GAS

The following physical reasoning, based on calculations made early in the study, was used to select helium at room temperature as the optimum reservoir gas to drive the piston.

i. Unsteady one-dimensional flow solutions (e.g., Ref. 20) of shockless piston compression of gases show that a heavy piston is most efficient for extracting energy from a reservoir gas. This is because a large piston travels more slowly than a light one; hence, the strength of the expansion wave is lower and the pressure acting on the back of the piston is higher. For a 7-in. internal diameter tube, the weight of a steel piston with the largest practical length is estimated to be 300 kg.

ii. Helium is more powerful than nitrogen or air as a piston driver because it not only has a much higher sound velocity, but also its high value of the ratio of specific heats allows smaller driving pressure loss. Furthermore, the compressibility factor at the high pressure conditions anticipated is smaller than air or nitrogen at the same pressure and temperature conditions. Some alleviation of the adverse effect of compressibility could be made by preheating the reservoir gas. Although it is found in calculations that considerably better performance using nitrogen could be achieved by heating to 500°K than operating at room temperature, only slightly better performance (about 2 percent) could be achieved by heating the helium gas. Hence, room temperature helium was selected as the reservoir gas.

iii. At these selected conditions, it was shown that it is satisfactory to assume that the reservoir gas (and driver gas) has infinite sound speed in order to calculate the compression cycle. This was verified by carrying out check cases of the cycle using the complete characteristics solution.

5.2 FACTORS CONTROLLING THE TESTING TIME

The running time of the reflected shock tube may be terminated by four possible events dictated by the arrival at the end wall of the following waves:

i. The reflected wave generated from the interaction of the reflected shock wave, JK (see Fig. 2 for explanation of symbols and Fig. 3 which gives a typical computed wave diagram) and the contact surface OK, (point L'').

ii. The head of the reflected rarefaction wave (L).

iii. The reflection from the diaphragm station or piston face of the reflected shock wave (L').

iv. The contact surface (I).

The use of tailoring is assumed to eliminate (i) as a criterion for terminating the run time, and until further estimation of the possibilities of cancelling the expansion wave by means of the piston forward motion, it is apparent from Fig. 3 that (ii) will provide the practical termination of the testing time since events (iii) and (iv) will occur later.

The most practical approach considered by the authors to carrying out the parametric study was to calculate for a known shock tube length the distance from the diaphragm station to the piston face, L_p, to achieve a useful running time considered to be 2 msec. The values of L_p obtained are discussed later. Values of the running time denoted by JL'', JL', and JI for a typical value of L_p are on the order of 2 msec, 10 msec, and 300 msec, respectively, thus justifying the selection of criterion (ii). Running times of 1 msec and 3 msec were also considered.

It has been checked also that the diameter of the nozzle throat does not significantly change these values. Therefore the 0.5-in. throat diameter was used in all the calculations (see Ref. 21).

Using the present configuration which features a constant diameter section from the compression tube to the shock tube, it is obvious that cancellation of the rarefaction wave will be very difficult, since the piston would have to be moving with a velocity on the order of that of the contact surface (equal to the flow velocity behind the shock). The velocity involved a large fraction of a kilometer per second. Further comments about cancellation of the expansion wave will be given later.

The use of constriction in order to achieve wave cancellation was not considered in this study, because of the degradation it would cause on the design performance as described in Ref. 6. It will be seen that to achieve such performance, the designer will already be hard-pressed to overcome structural difficulties of containing very high pressures without having to consider features that will increase tube pressures even further.

Using the arbitrary choice of 2 msec, it is found that L_p can be reduced by decreasing the length of the shock tube. The minimum shock tube length required to attain this running time is found to be approximately 54 ft for hydrogen and 34 ft for helium. These shock tube lengths were also used in the parametric study. Viewed in a different way, longer running times can be achieved for the same shock tube length using helium as a driver gas instead of hydrogen. This is caused by the slower speed with which the reflected head of the rarefaction wave catches up the contact surface and the position at which it bisects the tail of the rarefaction wave (point 3 in Fig. 2). Some conclusions given later indicate that if the level of shock tube driver temperature is not a main consideration, then helium can be as powerful a gas as hydrogen. It would be of value to examine the effect of using driver gases of even higher molecular weight to check whether equivalent performance can be achieved but with even larger running times (meaning a shorter facility for a chosen running time). An appropriate gas to study would be argon, or a mixture of helium and argon.

5.3 PARAMETRIC STUDY

The superior performance of a hydrogen driver over helium in conventional tailored-mode reflected shock tunnels is illustrated in Figs. 4 and 5. If the driver gas is heated to the same temperature, T_4, then much stronger shock waves and hence higher temperatures, T_5, are generated in air for the same pressure, P_5. In a piston-driven facility, the value of the driver gas temperature no longer becomes an important structural problem, since the gas is at that temperature for such a short period of time that the tube walls do not become further heated by an important amount. As T_4 is not an important consideration then it can be seen that for P_5 = 5000 atm, for instance, then an equivalent performance of T_5 = 12,000°K can be achieved using either a helium driver gas at 2000°K or hydrogen at 1000°K. In the following examination of other variables of the piston-driven shock tunnel cycle, we shall call the above-mentioned equivalent performance cases, Case A (helium driver at 2000°K) and Case B (hydrogen at 1000°K), respectively, to facilitate the comparison of the efficacy of the two gases. These parameters are reviewed in Table 9.

The first advantage of using a helium driver instead of hydrogen is illustrated in Fig. 6. The helium driver Case A requires 8720 atm driver pressure, 20 percent less than that required for the hydrogen driver Case B, i.e. 10,900 atm. The incident shock Mach numbers, M_s, and initial test gas pressure, p_1, for cases A and B are 12.07 and

2.57 atm and 15.48 and 1.45 atm, respectively, as shown in Figs. 4 and 7.

The driver tube length, L_p, after compression required to obtain a running time of 2 msec for helium and hydrogen is illustrated in Figs. 8a and b. Shock tube lengths of 16.3 m (34 ft) and 19.5 m (64 ft) for the former case and 16.4 m (54 ft) and 19.5 m (64 ft) for the latter are shown. It can be seen that the minimum length of L_p for Case A is 3.45 m (11 ft) and for Case B is 5.39 m (17.7 ft). Both of these values are lower than the projected length of the projected HIRHO facility (6.1 m, 20 ft), and it is clear that a smaller length of tubing at which the very high pressures, P_4 (order of 10,000 atm) have to be contained is required for helium than hydrogen. It is pointed out that the tubing, a little upstream of the position at which the piston comes to rest (defined by L_p), need be stressed only for pressures on the order of 1,000 atm.

The compression tube lengths necessary to achieve the design conditions are plotted in Figs. 9a and b for helium and hydrogen. A slight advantage of the hydrogen Case B over the helium Case A is that a shorter compression tube is required. It can also be seen that in order to keep to a realistic value of the length of the compression tube (i.e., below 30 m) then the driver gas will have to be preheated by, for example, a resistance heater to 500°K in both cases.

Figures 8 and 9 also demonstrate that there is a penalty in either running time (for a fixed geometry) or length of compression tube (for a design running time) if higher temperatures than those used in Cases A and B are used. Figure 8b, for example, illustrates that for a fixed geometry, i.e., a shock tube length of 54 ft or 64 ft, then the maximum driving temperature for hydrogen that can be used to obtain 2 msec is less than 1600°K and 2000°K. Figures 9a and b also illustrate that at these high temperatures then the compression tube becomes increasingly longer. This penalty offsets the advantages in terms of performance of running with high T_4.

Finally, Figs. 10 and 11 illustrate the important parameters of the compression cycle. Again the helium Case A has an advantage over hydrogen Case B in that both P_{0_i} and P_{4_i} are lower in the former case (1620 and 248 atm against 3480 and 884 atm).

CONCLUSIONS

The following conclusions are made on the results of this parametric study of piston-driven shock tunnels.

1. It has been shown that helium is a better driver gas than hydrogen in terms of performance and running time on all counts except one. That is that the compression tube required is longer for helium than hydrogen, an unimportant feature since the tube is relatively lowly stressed over most of its length. This conclusion arises from the realistic assumption, different from that required for a conventional shock tunnel, that the level of driving temperature T_4 is unimportant. Further calculations may reveal that an even higher molecular weight gas may be more efficient than helium for the piston-driven mode of operation.

2. It was found at an early stage of the calculations that to achieve the running conditions planned for the AEDC HIRHO facility, that imperfections, associated with both high temperatures and high densities, in gas properties would have to be accounted for in the flows in all three chambers of the piston-driven facility.

3. The running time of the conventional tailored-mode reflected shock tunnel, with the dimensions and performance planned for HIHRO, appears to be terminated by the reflected rarefaction wave, rather than by the re-reflected shock wave from the diaphragm station or the contact surface reaching the end wall (due to flow of the shocked test gas through the nozzle throat).

4. The calculations show that generally the compression tube lengths calculated are always more than that planned for HIRHO (6.25 m) to achieve planned running times on the order of 2 msec; however, the expense in providing an extension tube may not be considerable. This is because the high pressures are only generated in the last 3 to 4 meters. Only low pressure rated tube (1000 atm) is necessary upstream of this.

5. The values of the temperature behind the reflected shock wave (T_5 in Table 2) for a hydrogen-driven tunnel are higher than those values calculated by AEDC and have an opposite trend with increasing pressure, P_5. It is thought that this is caused primarily by the different thermodynamic models of the air test gas used, and perhaps also in the model for the hydrogen driver gas.

6. Shock tube driver temperatures, T_4, of 2000°K for helium and 1000°K for hydrogen appear to be optimum from the point of view that for lower T_4 the overall pressure levels become higher and for higher T_4 the compression tube lengths become larger for a specified running time. An initial driven temperature of 500°K was required to reduce compression tube lengths

to a reasonable value, which, however, were still greater than planned for HIRHO.

7. Although the calculation has not been carried out, if it is assumed that the reflected rarefaction wave is not cancelled, then similar running times may be achieved by not using tailoring conditions. If this is so, then the operation of the tunnel can be made much more flexible.

8. Calculations were made to check whether it was feasible to cancel the rarefaction waves by forward piston motion. For the constant diameter tube considered here, it was found that the piston was required to be so fast as to be impractical. A constriction was not considered as a means of cancelling the rarefaction wave because of its detrimental effect on the performance. Studies are required for the case of a larger diameter compression tube as a means of achieving wave cancellation.

9. Allowing the diaphragm petals to fold into recesses such that the piston passes through the diaphragm station to come to rest at the nozzle end is suggested as a means to overcome the problem of removing the piston energy in this case of equal diameter compression tube and shock tube. Some calculations are necessary to ensure that unrealistic pressures are not built up at the nozzle end of the tube.

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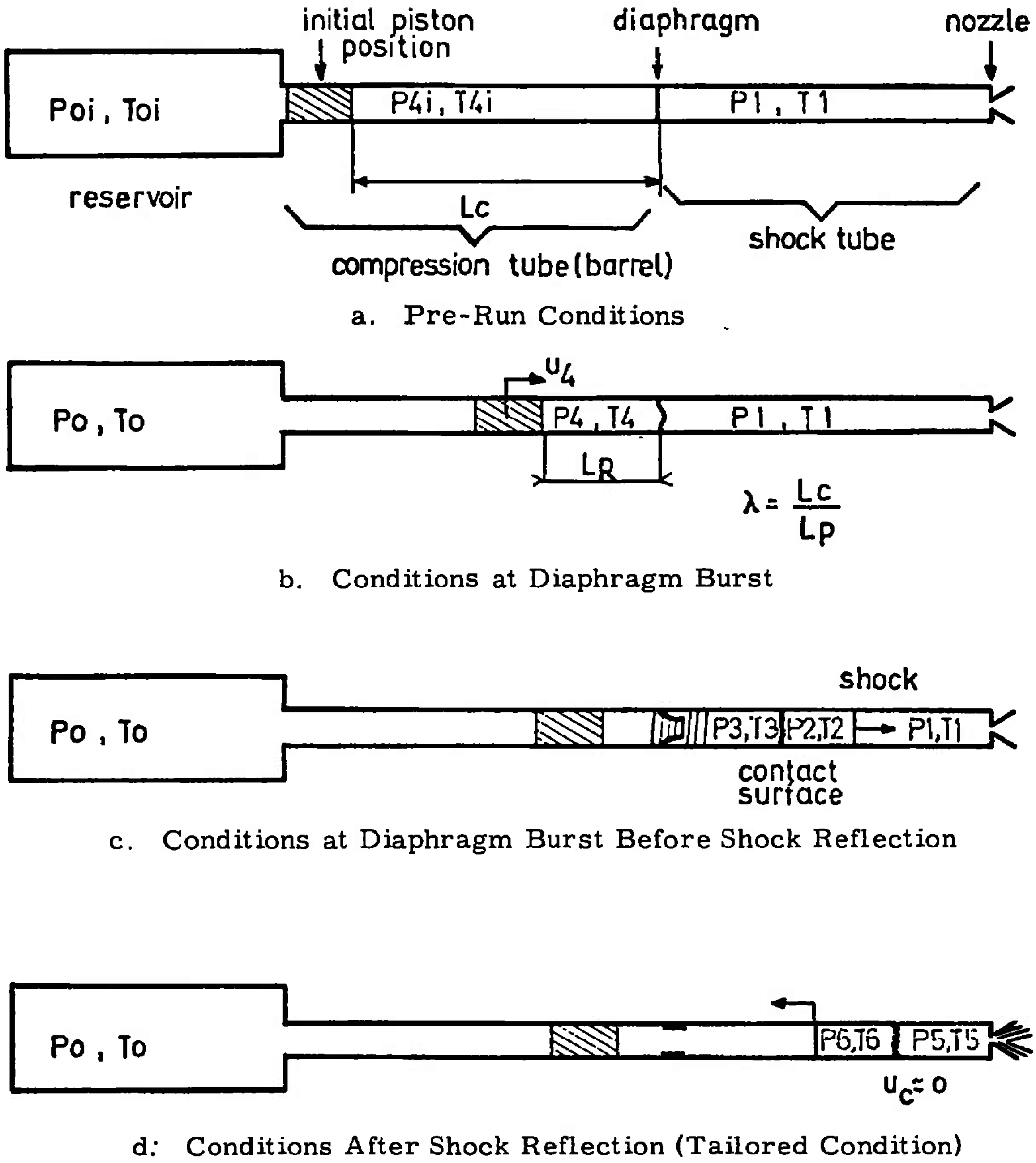
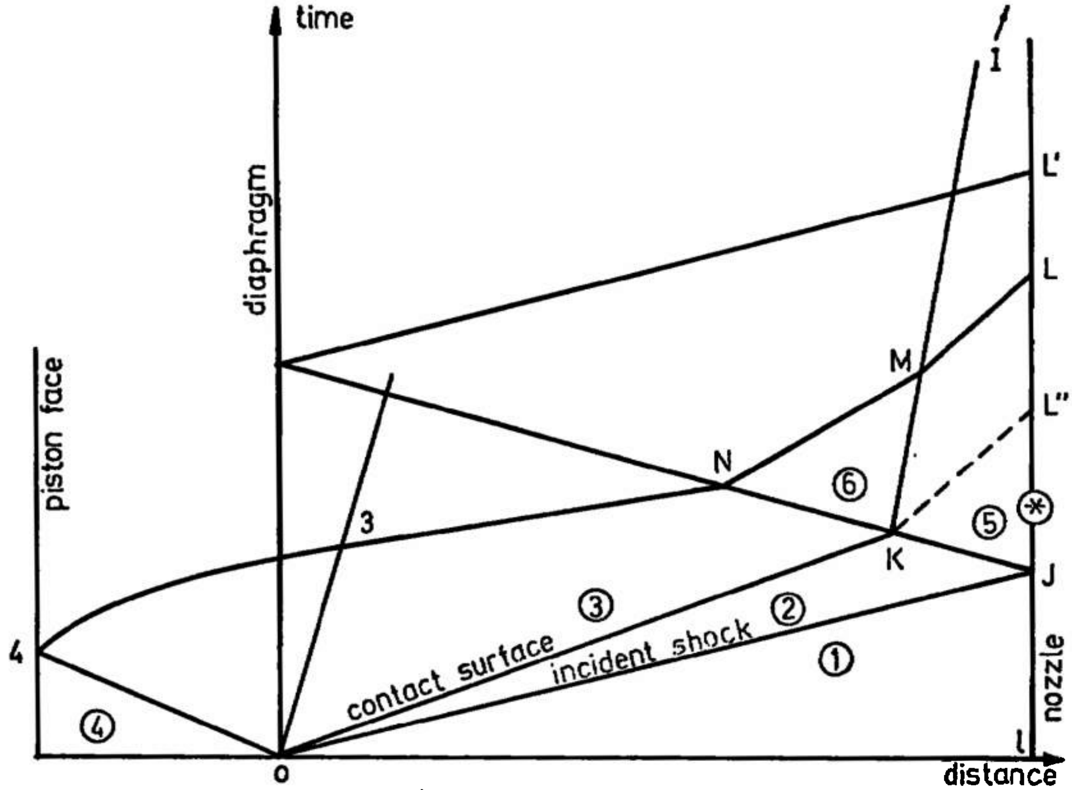


Figure 1. Schematic of Piston-Driven Shock Tunnel Operation



x-t diagram

Key

Numbers in circle : index of the different regions

* devotes conditions at the throat

J : intersection incident shock with end wall

K : intersection reflected shock with contact surface

4 : reflection of head of rarefaction wave on the piston face

3 : intersection reflected head rarefaction wave with tail of rarefaction wave

N : intersection reflected head rarefaction wave with reflected shock

M : intersection reflected head rarefaction wave with contact surface (nearly at rest).

L : intersection reflected head rarefaction wave with end wall

I : intersection contact surface with end wall

JL" : minimum running time in tailored-mode (KL" is parallel to ML)

JL' : maximum running time

Figure 2. Schematic Wave Diagram of Shock Tunnel

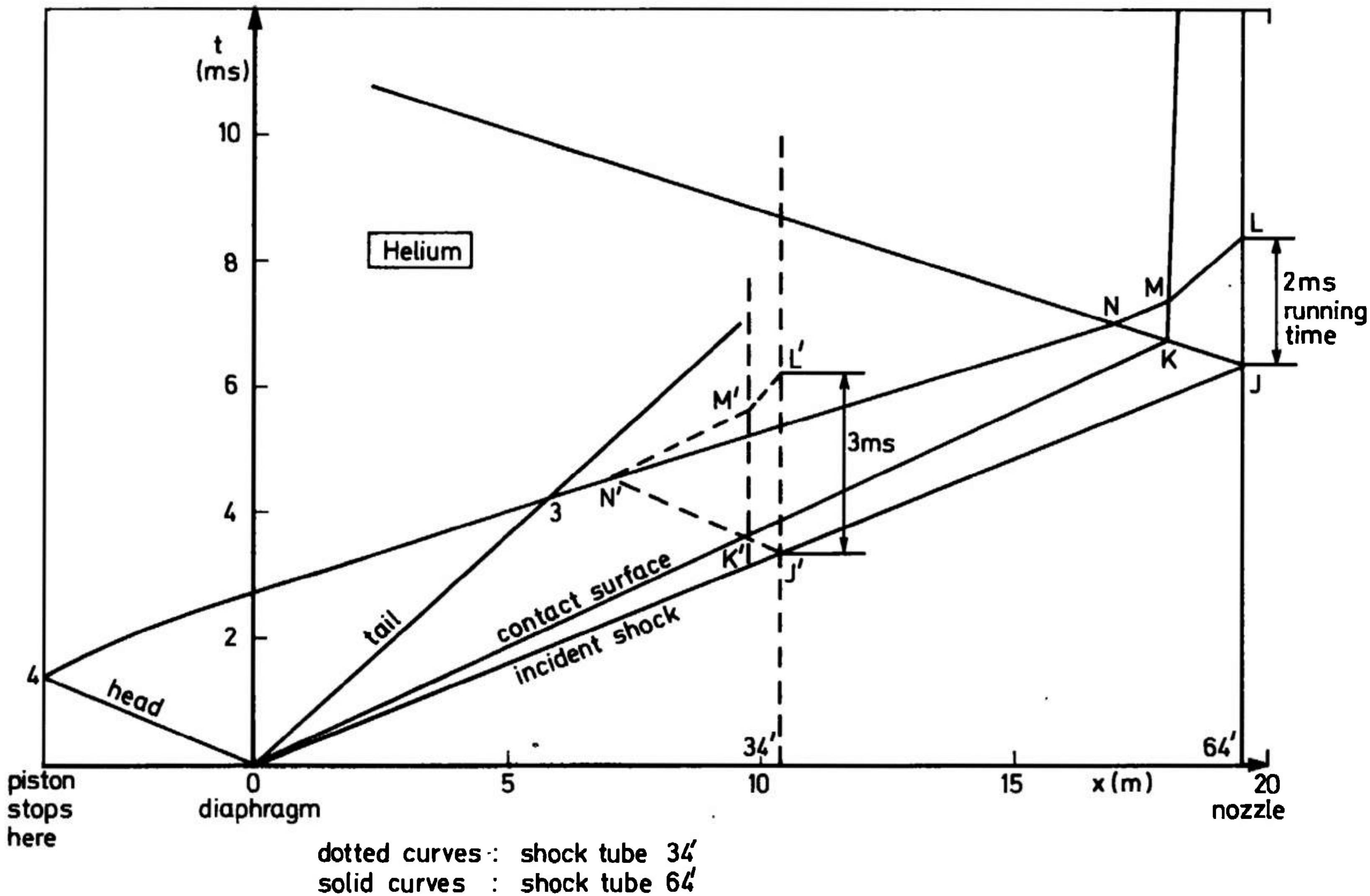


Figure 3. A Typical x-t Diagram Obtained from Computer Programs

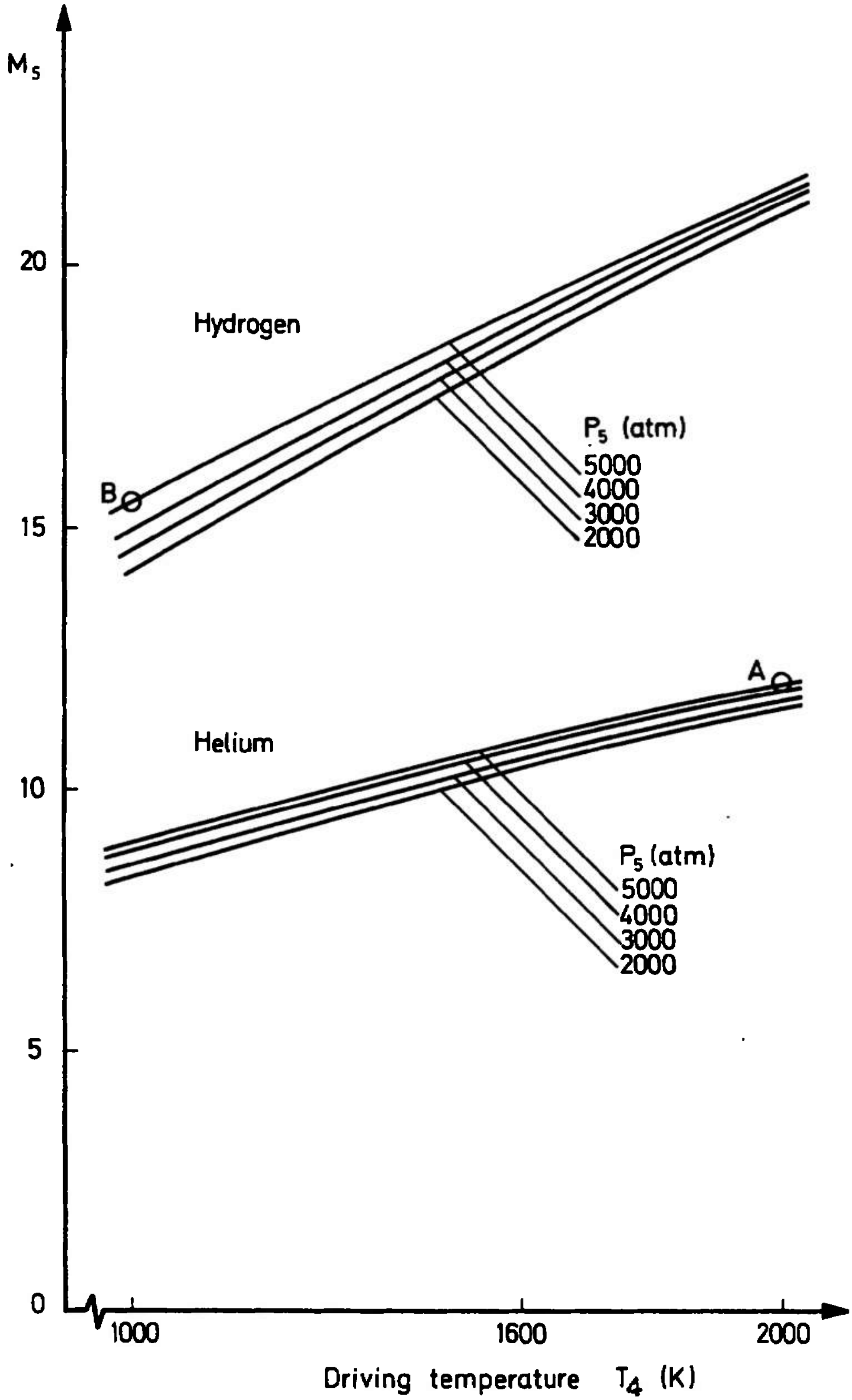


Figure 4. Shock Mach Number, M_s, for Tailored Configuration

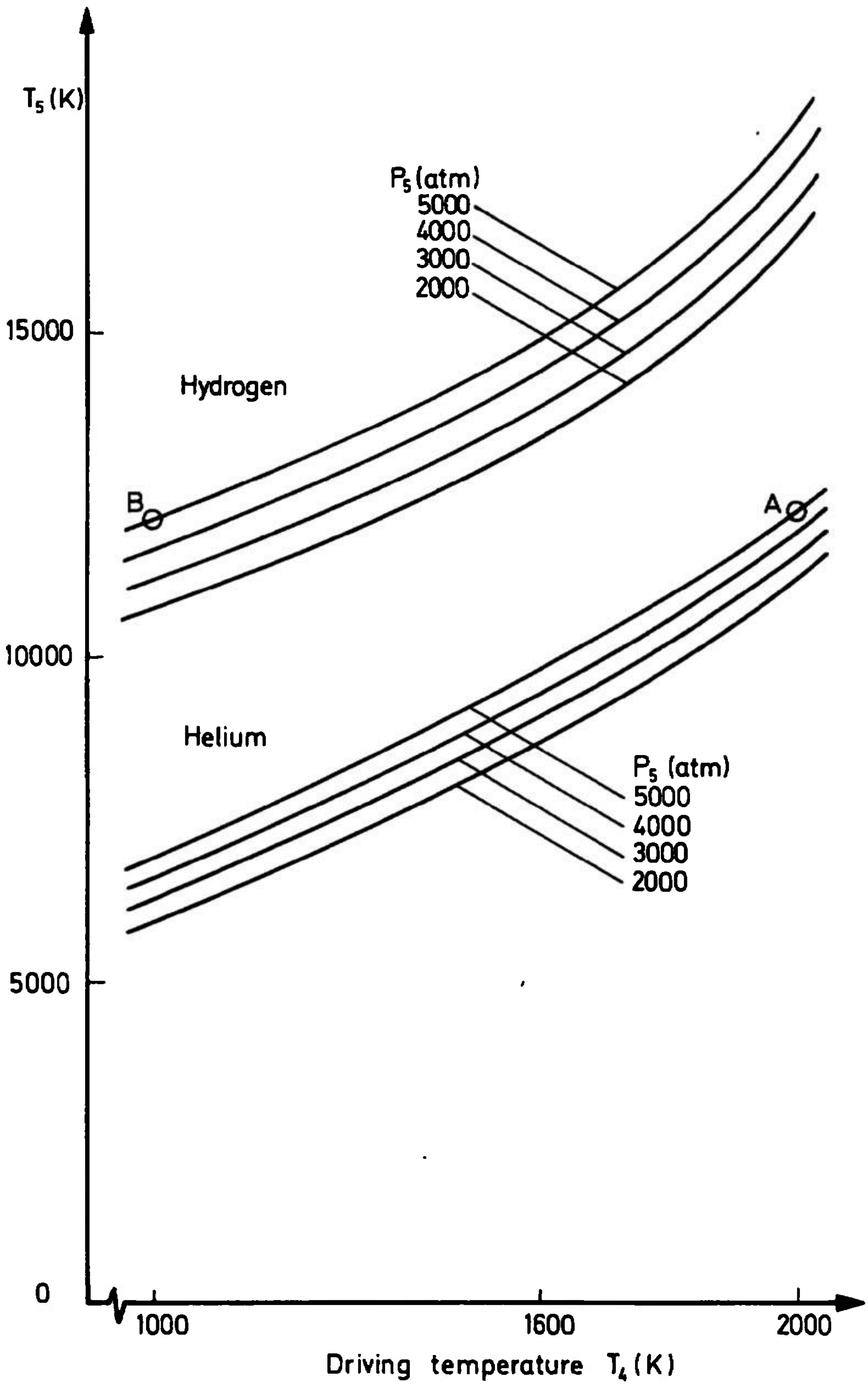


Figure 5. Temperature, T_5, Achieved by Shock Tunnel

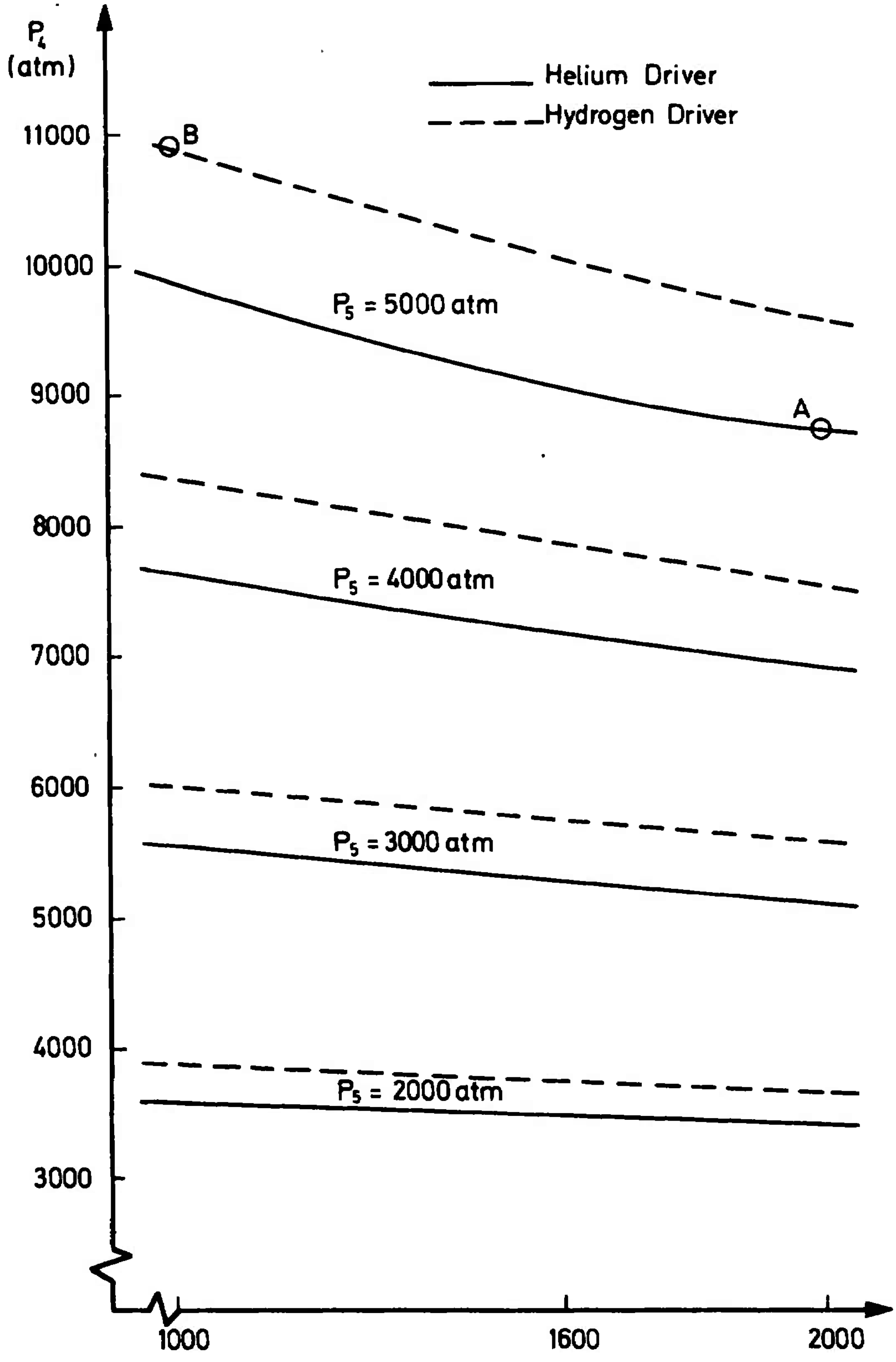


Figure 6. Driver Pressure, P_4, Required to Achieve Performance Aim

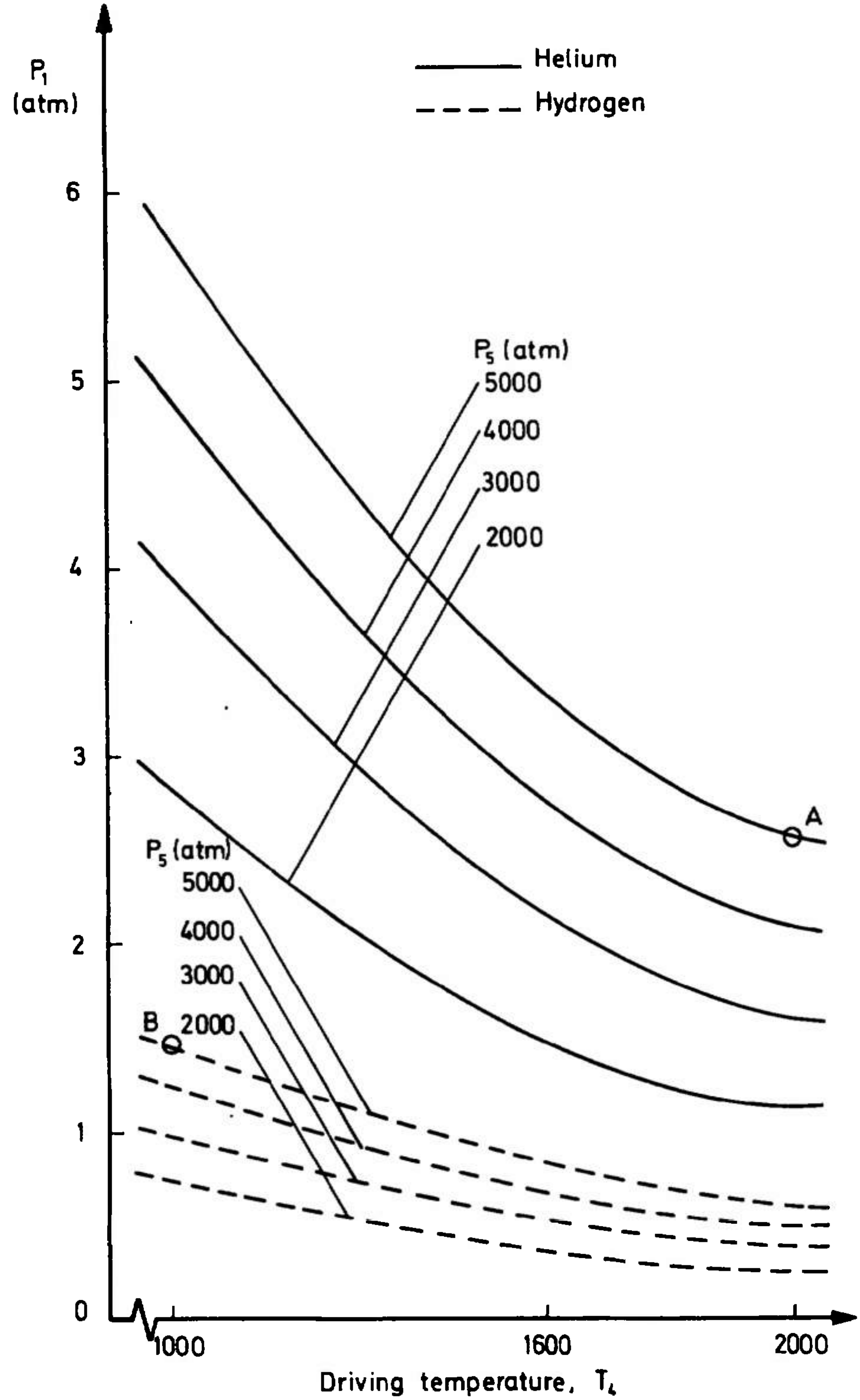
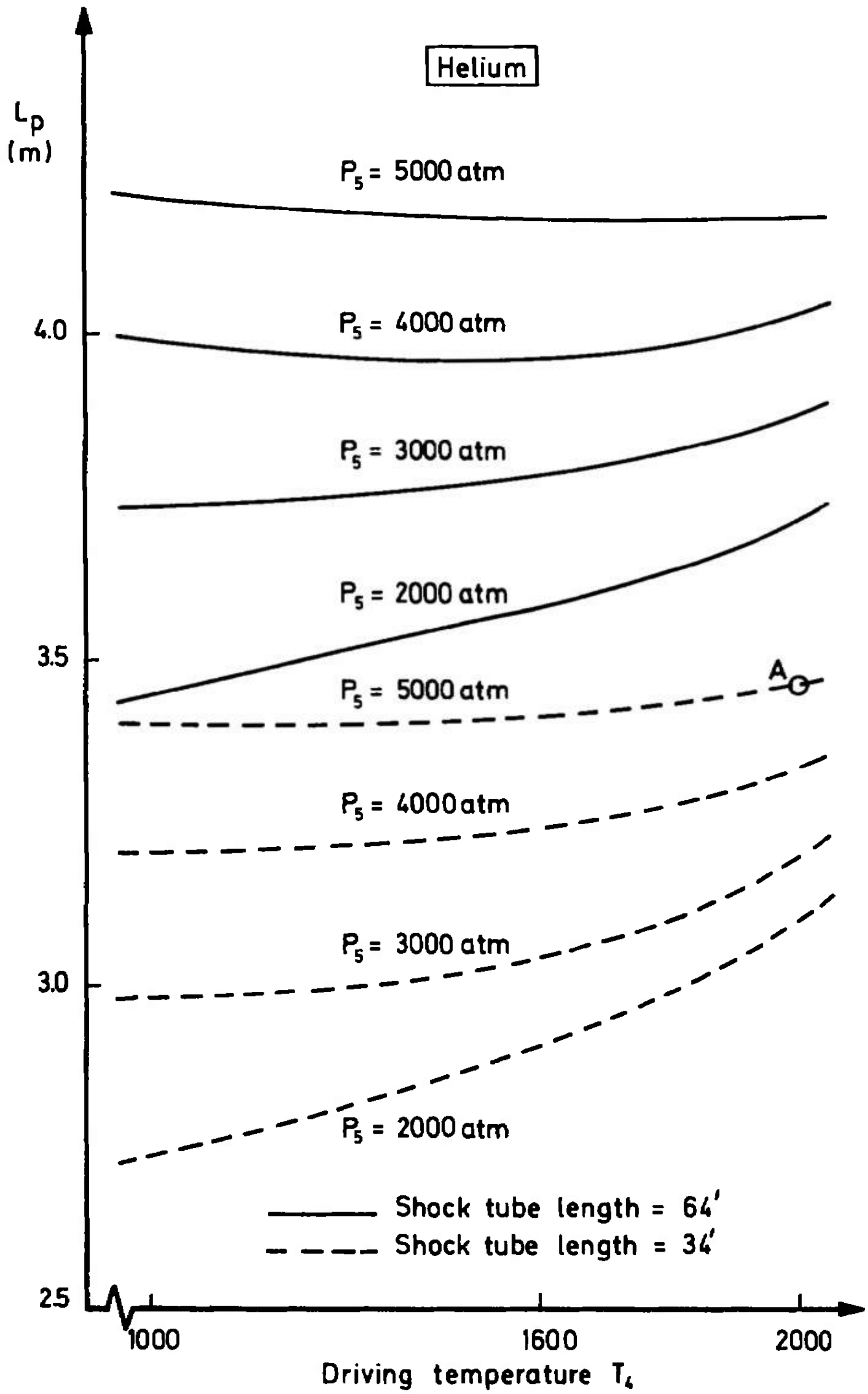
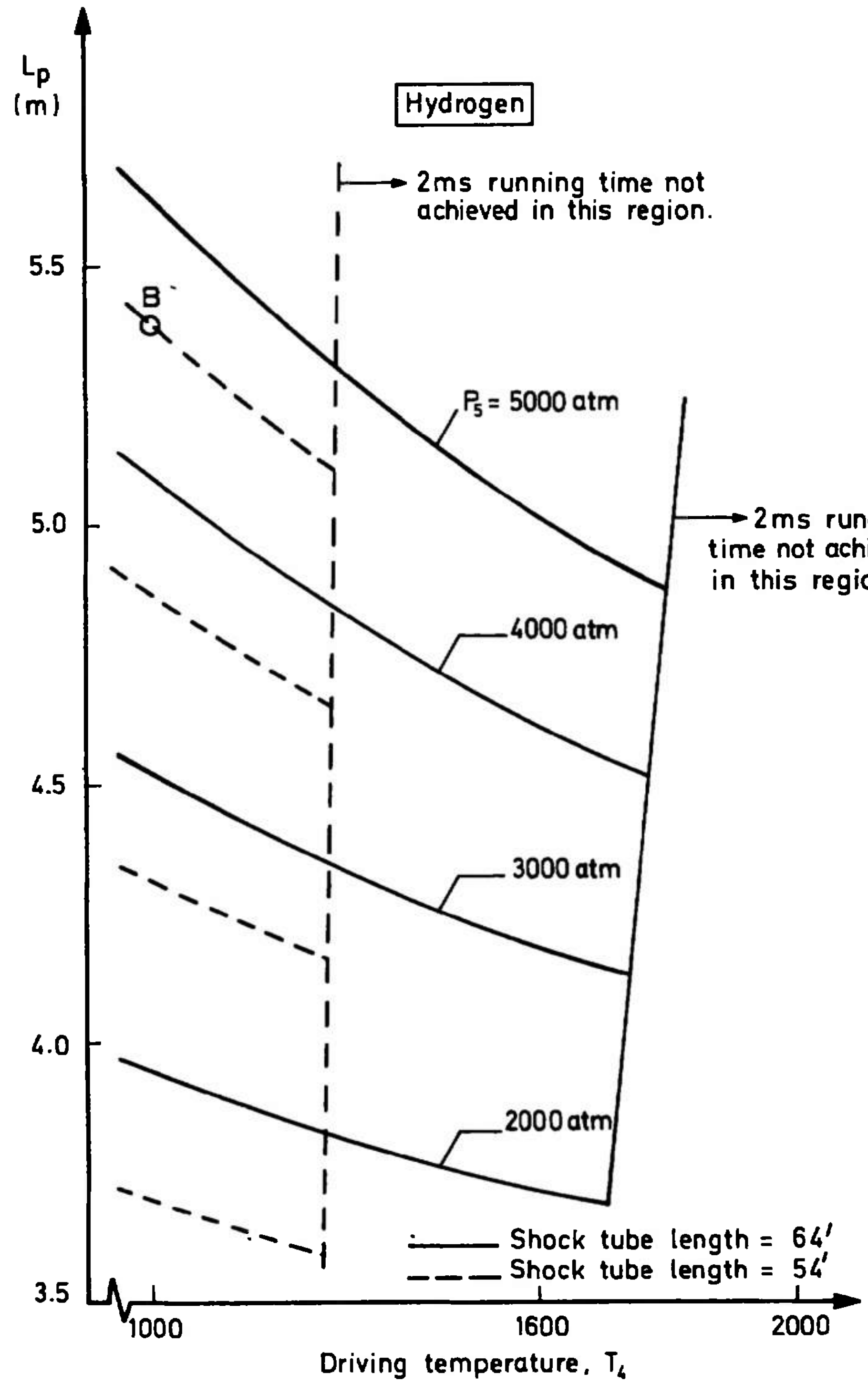


Figure 7. Test Gas Initial Pressure, P_1, Required to Achieve Performance Aim

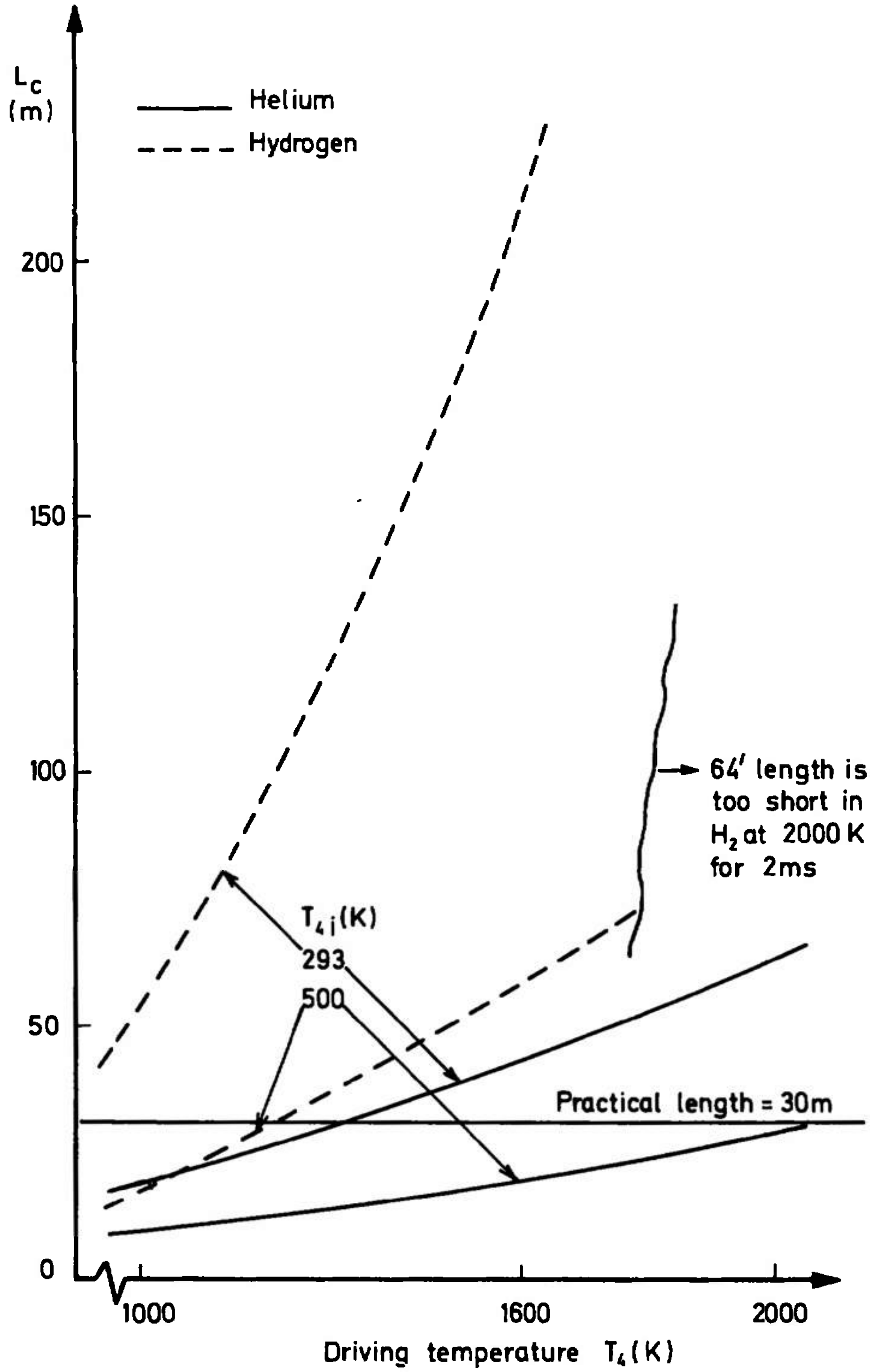


a. Helium

Figure 8. Length, L_p, of Compressed Gas in the Barrel Necessary to Achieve 2 msec Running Time in Tailored Configuration

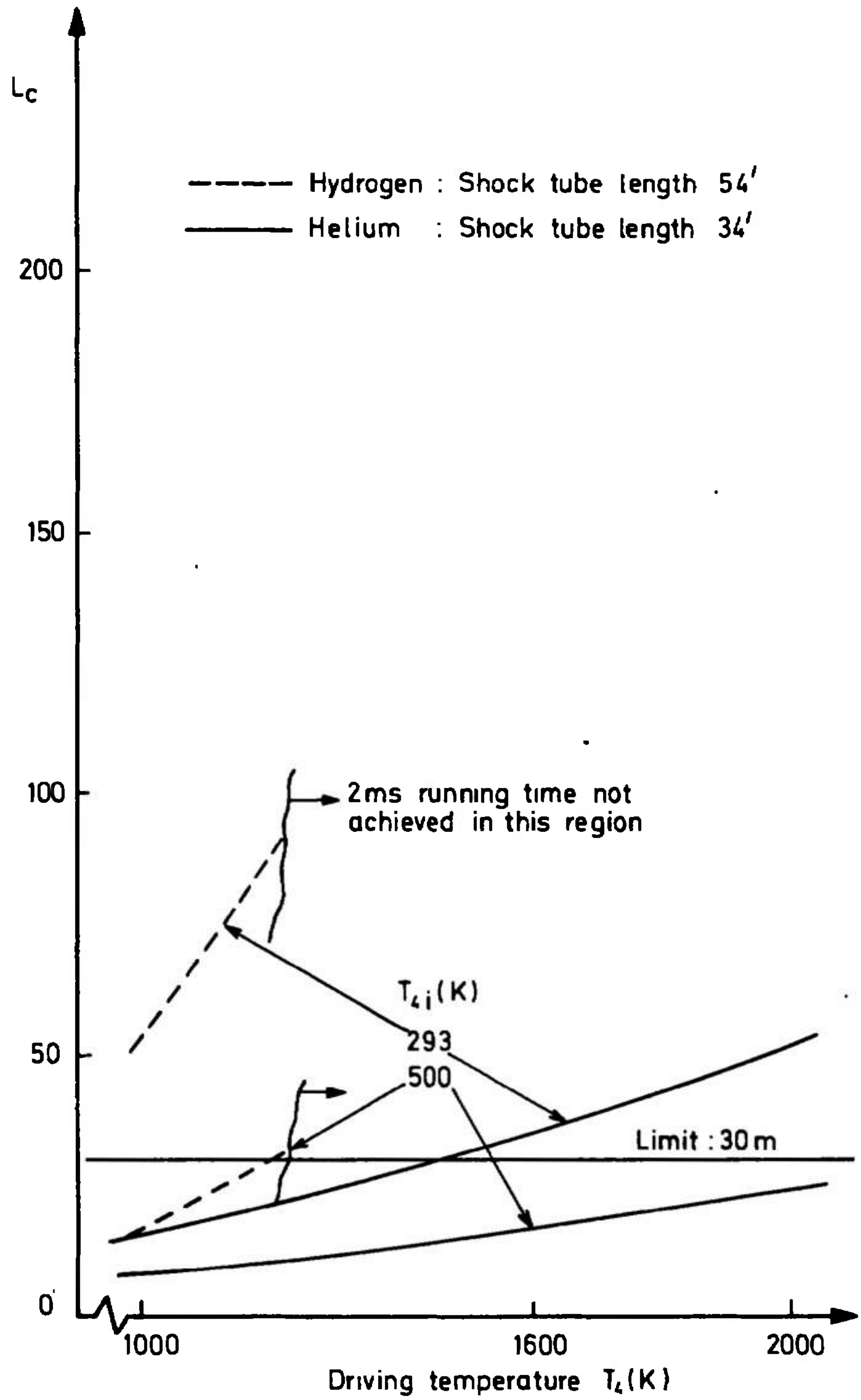


b. Hydrogen
Figure 8. Concluded

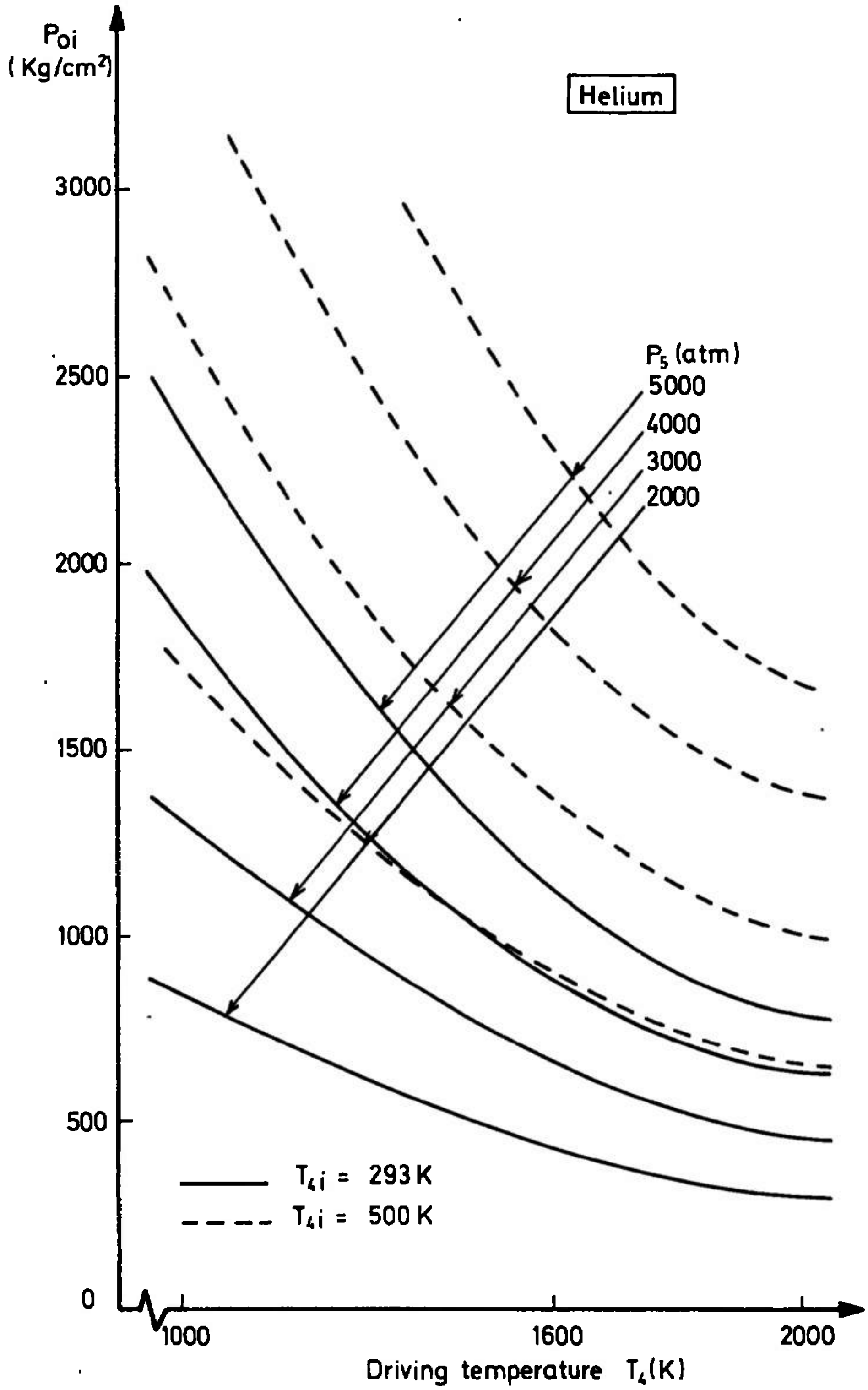


a. All Values of P_5 Between 5000 and 2000 atm, 64' Shock Tube Length

Figure 9. Compression Tube Length, L_c, Required to Achieve 2-msec Test Duration in Tailored Configuration

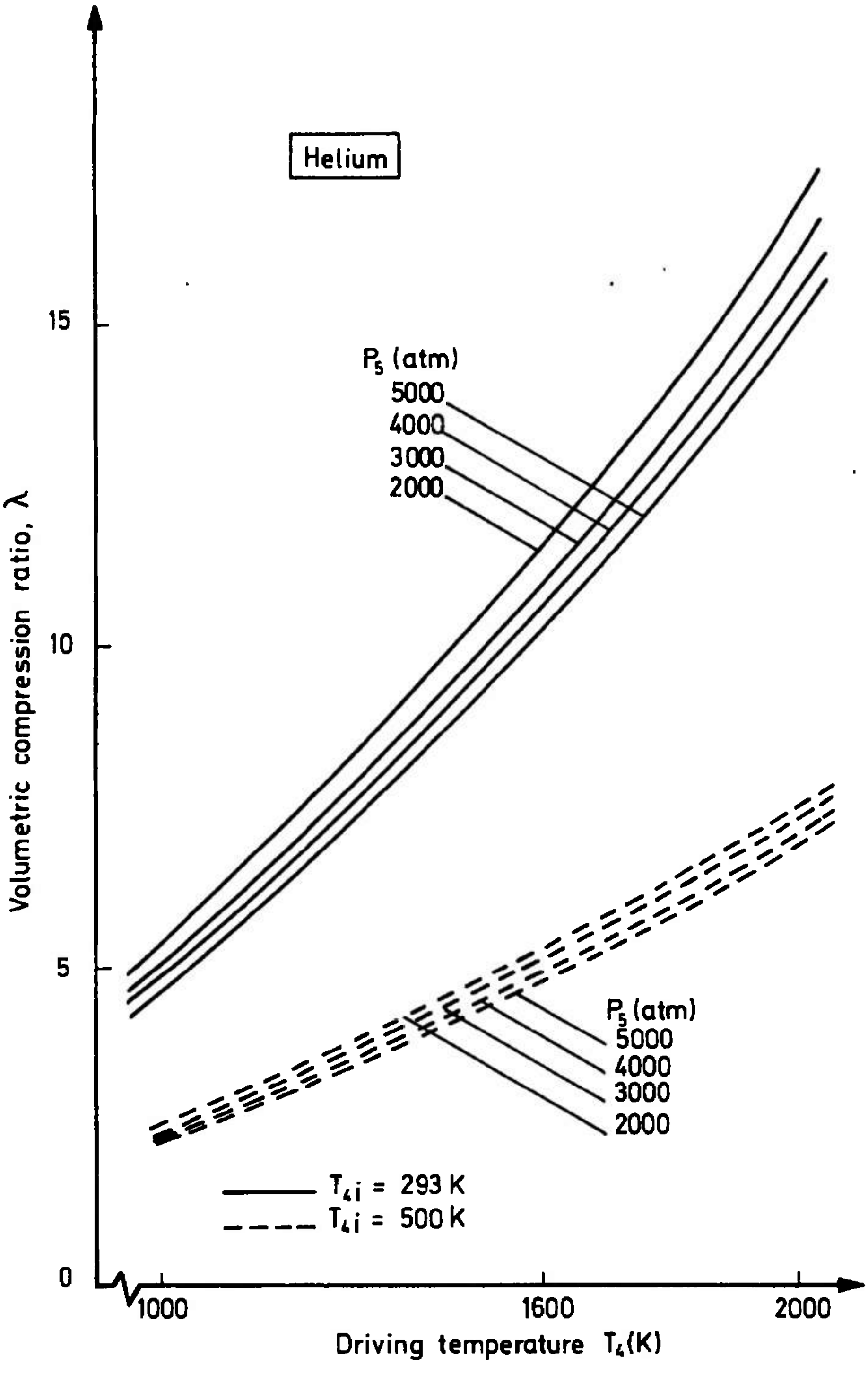


b. Reduced Shock Tube Lengths
Figure 9. Concluded



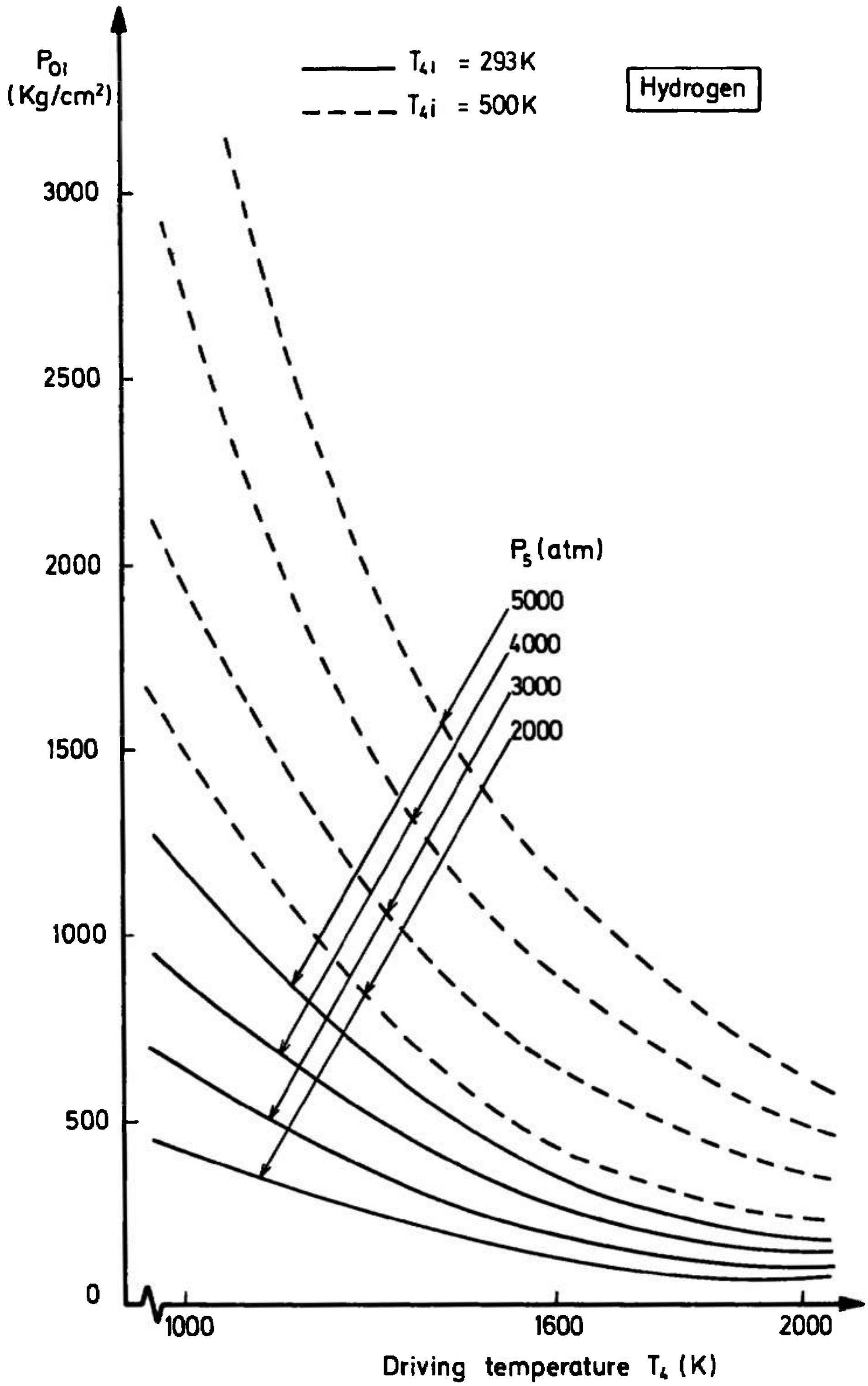
a. Helium

Figure 10. Reservoir Pressure, P_{0i}, (T_{0i} = 293 K) Required to Achieve Performance Aims



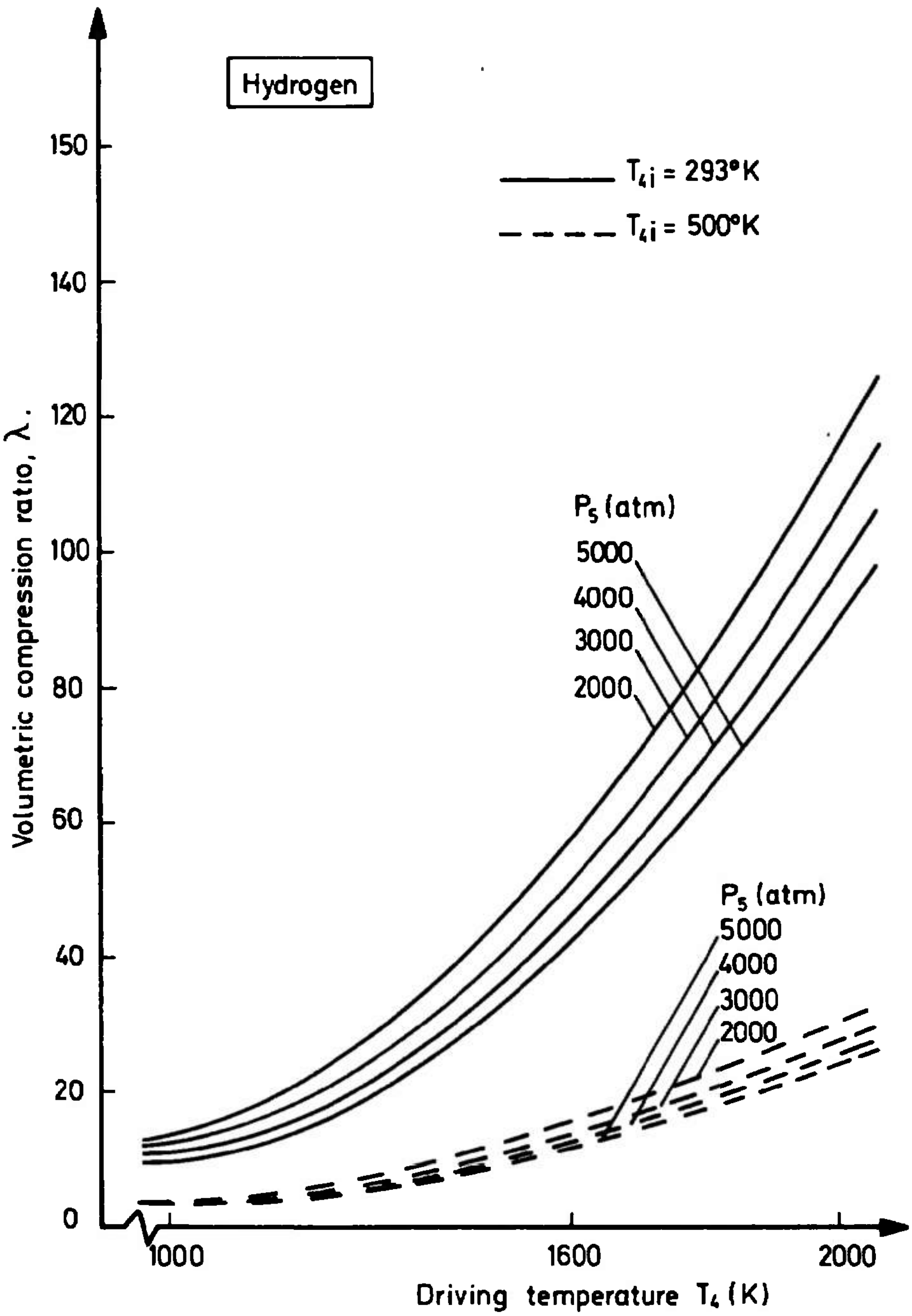
a. Concluded

Figure 10 (Cont). Volumetric Compression Ratio, λ, Required to Achieve Performance Aims



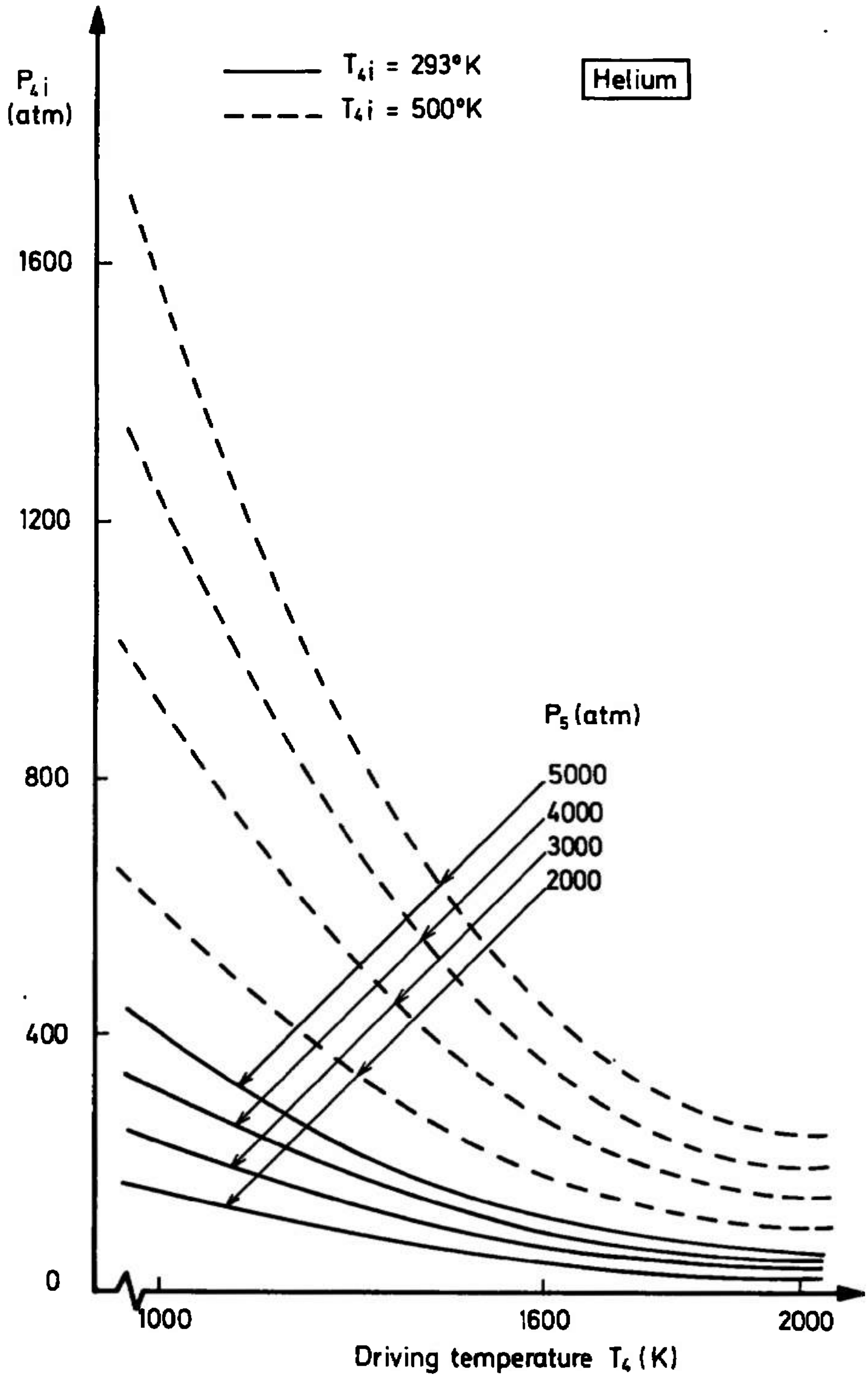
b. Hydrogen

Figure 10 (Cont). Reservoir Pressure, P_{01}, (T_{0i} = 293 K) Required to Achieve Performance Aims



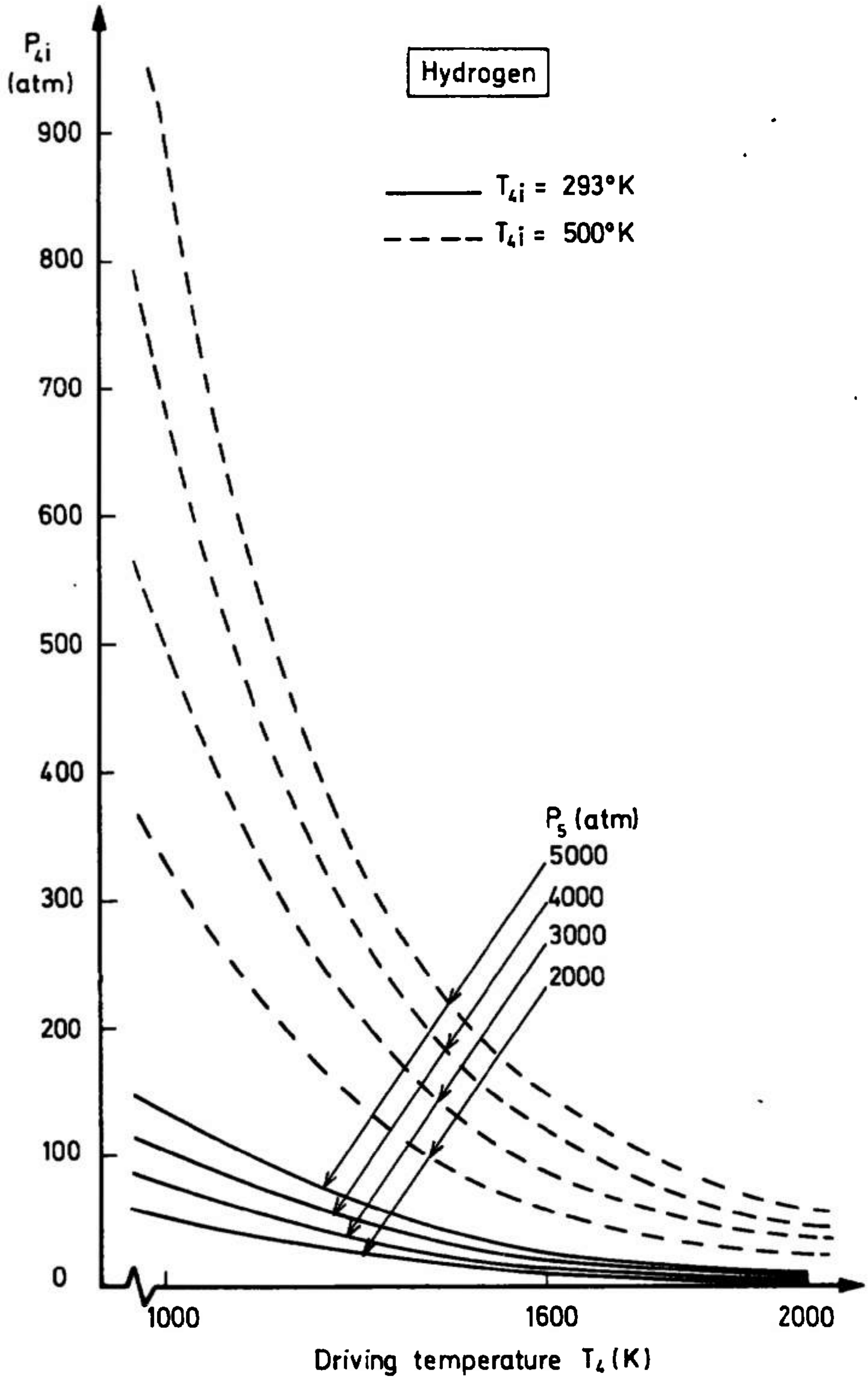
b. Concluded

Figure 10 (Concld). Volumetric Compression Ratio, λ, Required to Achieve Performance Aims



a. Helium

Figure 11. Initial Driver Gas Pressure, P_{4_i}, Required to Achieve Performance Aims



b. Hydrogen
Figure 11. Concluded

Table 1. Typical Computer Output of Tailored-Mode Reflected Shock Tube Performance Calculation

PERFECT GASES

DRIVER=HELIUM   TAILORING CONDITIONS   TEST=AIR

MS= 10.36   MR= 2.58

	1	2	3	4	5	6	
P	0.52394E 01	0.65562E 03	0.65562E 03	0.67232E 04	0.50000E 04	0.50000E 04	ATM
T	0.29300E 03	0.63951E 94	0.78824E 03	0.20000E 04	0.14213E 05	0.17969E 04	K
R	0.48844E 01	0.28003E 02	0.22719E 03	0.91823E 03	0.96090E 02	0.76004E 03	AMGT
A	0.34354E 03	0.16049E 04	0.16525E 04	0.26322E 04	0.23927E 04	0.24950E 04	M/S
V	0.00000E 00	0.29392E 04	0.29392E 04	0.00000E 00	0.00000E 00	0.00000E 00	M/S

CASE 9

REAL GASES

DRIVER=HELIUM   TAILORING CONDITIONS   TEST=AIR

MS= 12.07   MR= 3.17

	1	2	3	4	5	6	
P	0.25718E 01	0.46635E 03	0.46635E 03	0.87183E 04	0.50000E 04	0.50000E 04	ATM
T	0.29300E 03	0.55721E 04	0.64240E 03	0.20000E 04	0.12219E 05	0.22976E 04	K
R	0.23976E 01	0.20662E 02	0.18199E 03	0.87990E 03	0.93633E 02	0.50447E 03	AMGT
A	0.34341E 03	0.14836E 04	0.16078E 04	0.33361E 04	0.23705E 04	0.32150E 04	M/S
V	0.00000E 00	0.36662E 04	0.36662E 04	0.00000E 00	0.00000E 00	0.00000E 00	M/S

Table 1. Concluded

PERFECT GASES

DRIVER=HYDROGEN TAILORING CONDITIONS TEST=AIR

MS= 11.4285 MR= 2.5950

	1	2	3	4	5	6	
P	0.42714E 01	0.65017E 03	0.85017E 03	0.58382E 04	0.50000E 04	0.50000E 04	ATM
T	0.29300E 03	0.77176E 04	0.53412E 03	0.10000E 04	0.17235E 05	0.11928E 04	K
R	0.39820E 01	0.23011E 02	0.33249E 03	0.15947E 04	0.79238E 02	0.11449E 04	AMGT
A	0.34354E 03	0.17631E 04	0.17531E 04	0.24124E 04	0.26348E 04	0.25348E 04	M/S
V	0.00000E 00	0.32467E 04	0.32457E 04	0.00000E 00	0.00000E 00	0.00000E 00	M/S

CASE 1b

REAL GASES

DRIVER=HYDROGEN TAILORING CONDITIONS TEST=AIR

MS= 15.4574 MR= 3.2045

	1	2	3	4	5	6	
P	0.14614E 01	0.43964E 03	0.43964E 03	0.10881E 05	0.50000E 04	0.50000E 04	ATM
T	0.29300E 03	0.74046E 04	0.41062E 03	0.10000E 04	0.12099E 05	0.11502E 04	K
R	0.13624E 01	0.13099E 02	0.24167E 03	0.11244E 04	0.76043E 02	0.68711E 03	AMGT
A	0.34341E 03	0.17942E 04	0.18723E 04	0.54179E 04	0.25135E 04	0.41691E 04	M/S
V	0.00000E 00	0.47593E 04	0.47593E 04	0.00000E 00	0.00000E 00	0.00000E 00	M/S

Table 2. Typical Computer Output of Tailored-Mode Reflected Shock Tube Running Time Calculation

CASE 9

THROAT DIA.= 0.5 INCH RUN TIME G.T. 0.662 MS
POINT I X= 19.507 M TIME= 184.720 MS

RUN TIME= 2.0 MS

POINT L X= 19.507 M TIME= 6.706 MS
POINT M X= 18.249 M TIME= 6.177 MS
POINT N X= 15.948 M TIME= 5.463 MS
POINT 3 X= 8.234 M TIME= 4.000 MS

CURVE BETWEEN POINT 3 AND POINT 4

X M	T MS
8.234	4.000
6.919	3.746
5.805	3.523
4.848	3.337
4.017	3.170
3.289	3A20
2.645	2.886
2.073	2.766
1.560	2.656
1.098	2.556
0.680	2.464
0.300	2.380
-0.046	2.302
-0.364	2.229
-0.657	2.162
-0.926	2.099
-1.176	2.040
-1.408	1.985
-1.624	1.933
-1.824	1.884
-2.012	1.838
-2.188	1.794
-2.353	1.752
-2.508	1.713
-2.654	1.676
-2.791	1.640
-2.921	1.606
-3.043	1.573
-3.159	1.542
-3.269	1.513
-3.374	1.484
-3.473	1.457
-3.567	1.430
-3.657	1.405
-3.743	1.381
-3.824	1.358
-3.902	1.335
-3.976	1.313
-4.048	1.293
-4.116	1.272
-4.181	1.253

MINIMUM DRIVER LENGTH= 4.181 M

CASE 9

HELIUM DRIVING AIR

P5= 5000. ATM T4= 2000. K T1= 293. K

P5= 5000. ATM T5=12219. K R5= 93. AMGT
PS= 2696. ATM TS=10471. K RS= 59. AMGT

PS/P5= 0.5393 TS/T5= 0.8570 RS/R5= 0.6303

MAX.RUN.TIME= 8.295 MS

POINT J X= 19.507 M TIME= 4.706 MS
POINT K X= 18.241 M TIME= 4.375 MS

Table 2. Concluded

THROAT DIA.= 0.5 INCH RUN TIME G.T. 0.452 MS
POINT I X= 10.507 M TIME= 150.579 MS.

RUN TIME= 2.0 MS

POINT L X= 19.507 M TIME= 5.672 MS
POINT M X= 18.407 M TIME= 5.256 MS
POINT N X= 15.086 M TIME= 4.441 MS
POINT 3 X= 11.075 M TIME= 3.836 MS

CURVE BETWEEN POINT 3 AND POINT 4

X M	T MS
11.075	3.836
9.520	3.593
8.176	3.390
7.002	3.206
5.966	3.041
5.045	2.894
4.220	2.760
3.477	2.638
2.803	2.527
2.188	2.425
1.626	2.330
1.109	2.243
0.632	2.162
0.190	2.086
-0.219	2.015
-0.601	1.949
-0.957	1.886
-1.291	1.828
-1.605	1.772
-1.900	1.720
-2.178	1.671
-2.440	1.624
-2.688	1.579
-2.923	1.537
-3.146	1.496
-3.358	1.458
-3.560	1.421
-3.752	1.386
-3.936	1.352
-4.111	1.320
-4.279	1.289
-4.440	1.260
-4.594	1.231
-4.742	1.204
-4.884	1.178
-5.021	1.153
-5.153	1.128
-5.279	1.105
-5.402	1.082
-5.520	1.061
-5.634	1.039

MINIMUM DRIVER LENGTH= 5.634 M

CASE Ib HYDROGEN DRIVING AIR

P5= 5000. ATM T4= 1000. K T1= 293. K

P5= 5000. ATM T5=12099. K R5= 76. AMGT
PS= 2811. ATM TS=11191. K RS= 47. AMGT

PS/P5= 0.5622 TS/T5= 0.0249 RS/R5= 0.6231

MAX.RUN.TIME= 6.785 MS

POINT J X= 19.507 M TIME= 3.672 MS
POINT K X= 18.397 M TIME= 3.865 MS

Table 3. Typical Computer Output of Isentropic Compression Calculation

Case 1b

```
GAS...HYDROGEN

T4 = 1000.0 K    R4 = 1124.40 AMGT    P4 =11242.988 KG/CM2
T41=  293.0 K    R41=  115.61 AMGT    P41=  138.817 KG/CM2
S/R=  12.088    LAMBDA=   9.725

GAS...HYDROGEN

T4 = 1000.0 K    R4 = 1124.40 AMGT    P4 =11242.988 KG/CM2
T41=  500.0 K    R41=  359.11 AMGT    P41=  913.830 KG/CM2
S/R=  12.088    LAMBDA=   3.131
```

Case 2b

```
GAS...HYDROGEN

T4 = 1000.0 K    R4 =  987.65 AMGT    P4 = 8643.792 KG/CM2
T41=  293.0 K    R41=   91.78 AMGT    P41=  108.286 KG/CM2
S/R=  12.341    LAMBDA=  10.760

GAS...HYDROGEN

T4 = 1000.0 K    R4 =  987.65 AMGT    P4 = 8543.792 KG/CM2
T41=  500.0 K    R41=  295.34 AMGT    P41=  709.398 KG/CM2
S/R=  12.341    LAMBDA=   3.344
```

Case 3b

```
GAS...HYDROGEN

T4 = 1000.0 K    R4 =  625.20 AMGT    P4 = 6193.233 KG/CM2
T41=  293.0 K    R41=   67.94 AMGT    P41=   78.796 KG/CM2
S/R=  12.665    LAMBDA=  12.145

GAS...HYDROGEN

T4 = 1000.0 K    R4 =  825.20 AMGT    P4 = 6198.235 KG/CM2
T41=  500.0 K    R41=  227.12 AMGT    P41=  514.081 KG/CM2
S/R=  12.665    LAMBDA=   3.633
```

Case 5b

```
GAS...HYDROGEN

T4 = 1600.0 K    R4 =  879.34 AMGT    P4 =10394.408 KG/CM2
T41=  293.0 K    R41=   20.89 AMGT    P41=   23.463 KG/CM2
S/R=  13.888    LAMBDA=  42.095

GAS...HYDROGEN

T4 = 1600.0 K    R4 =  879.34 AMGT    P4 =10394.408 KG/CM2
T41=  500.0 K    R41=   76.08 AMGT    P41=  152.335 KG/CM2
S/R=  13.888    LAMBDA=  11.557
```

Table 3. Concluded

Case 9

```
GAS...HELIUM

T4  =  2000.0 K     R4  =   879.90 AMGT     P4  = 9008.041 KG/CM2
T41=    293.0 K     R41=     58.59 AMGT     P41=    66.940 KG/CM2
S/R=   14.430      LAMBDA=  15.017

GAS...HELIUM

T4  =  2000.0 K     R4  =   879.90 AMGT     P4  = 9008.041 KG/CM2
T41=    500.0 K     R41=    127.13 AMGT     P41=   255.887 KG/CM2
S/R=   14.430      LAMBDA=   6.921
```

case 10

```
GAS...HELIUM

T4  =  2000.0 K     R4  =   733.12 AMGT     P4  = 7132.395 KG/CM2
T41=    293.0 K     R41=     47.43 AMGT     P41=    53.372 KG/CM2
S/R=   14.656      LAMBDA=  15.456

GAS...HELIUM

T4  =  2000.0 K     R4  =   733.12 AMGT     P4  = 7132.395 KG/CM2
T41=    500.0 K     R41=    103.42 AMGT     P41=   205.752 KG/CM2
S/R=   14.656      LAMBDA=   7.088
```

case 11

```
GAS...HELIUM

T4  =  2000.0 K     R4  =   574.48 AMGT     P4  = 5290.748 KG/CM2
T41=    293.0 K     R41=     36.02 AMGT     P41=    40.678 KG/CM2
S/R=   14.936      LAMBDA=  15.944

GAS...HELIUM

T4  =  2000.0 K     R4  =   574.48 AMGT     P4  = 5290.748 KG/CM2
T41=    500.0 K     R41=     78.97 AMGT     P41=   155.217 KG/CM2
S/R=   14.936      LAMBDA=   7.274
```

Table 4. Typical Computer Output of Piston Cycle Calculation

CASE 9 PP7 PAGE 1

HELIUM DRIVING HELIUM M=300. KG L=24.0000 M LA=25M
P4I = 255.887 KG/CM2 T4I = 500.0 K
P0I =1677.200 KG/CM2 T0I = 293.0 K

T (SEC)	X (M)	DX/DT (M/SEC)	PO KG/CM2	TO (K)	P4 KG/CM2	R4 AMAGAT	T4 (K)
0.00000	24.0000	0.00	1677.19	293.0	255.886	127.13	500.0
0.00250	23.9652	27.50	1676.49	292.9	256.536	127.31	500.5
0.00500	23.8626	54.62	1674.41	292.8	258.475	127.86	502.0
0.00750	23.6922	81.64	1670.98	292.5	261.742	128.78	504.5
0.01000	23.4545	108.49	1666.20	292.2	266.411	130.08	508.0
0.01250	23.1499	135.13	1660.11	291.8	272.591	131.80	512.7
0.01500	22.7790	161.49	1652.74	291.2	280.429	133.94	518.5
0.01750	22.3427	187.52	1644.13	290.6	290.119	136.56	525.5
0.02000	21.8418	213.15	1634.33	290.0	301.916	139.69	533.9
0.02250	21.2773	238.31	1623.39	289.2	316.149	143.40	543.7
0.02500	20.6506	262.93	1611.37	288.3	333.240	147.75	555.2
0.02750	19.9631	286.93	1598.35	287.4	353.740	152.84	568.5
0.03000	19.2166	310.20	1584.38	286.4	378.365	158.77	583.8
0.03250	18.4128	332.63	1569.55	285.3	408.060	165.70	601.5
0.03500	17.5542	354.10	1553.94	284.2	444.084	173.81	622.0
0.03750	16.6433	374.44	1537.63	283.0	488.140	183.32	645.7
0.04000	15.6831	393.45	1520.72	281.8	542.573	194.55	673.1
0.04250	14.6773	410.87	1503.30	280.5	610.667	207.88	705.2
0.04500	13.6303	426.38	1485.49	279.2	697.125	223.85	742.9
0.04750	12.5474	439.52	1467.40	277.8	808.837	243.17	787.6
0.05000	11.4352	449.67	1449.17	276.5	956.157	266.82	840.9
0.05250	10.3022	455.95	1430.95	275.1	1155.077	296.16	905.4
0.05455	9.3655	457.31	1416.15	273.9	1374.041	325.78	968.8
0.05480	9.2512	457.19	1414.36	273.8	1405.205	329.81	977.3
0.05505	9.1369	457.00	1412.57	273.7	1437.488	333.93	986.0
0.05530	9.0227	456.75	1410.79	273.5	1470.943	338.16	994.9
0.05555	8.9085	456.42	1409.01	273.4	1505.621	342.49	1004.0
0.05580	8.7945	456.01	1407.24	273.3	1541.573	346.94	1013.2
0.05605	8.6806	455.52	1405.47	273.1	1578.864	351.49	1022.7
0.05630	8.5667	454.96	1403.71	273.0	1617.553	356.16	1032.4
0.05655	8.4531	454.31	1401.95	272.9	1657.705	360.95	1042.2
0.05680	8.3396	453.57	1400.20	272.7	1699.384	365.86	1052.3
0.05705	8.2263	452.74	1398.46	272.6	1742.667	370.90	1062.7
0.05730	8.1132	451.82	1396.72	272.4	1787.621	376.07	1073.2
0.05755	8.0004	450.80	1394.99	272.3	1834.330	381.37	1084.0
0.05780	7.8879	449.68	1393.27	272.2	1882.873	386.81	1095.1
0.05805	7.7756	448.45	1391.55	272.0	1933.340	392.40	1106.4
0.05830	7.6637	447.11	1389.84	271.9	1985.816	398.13	1117.9
0.05855	7.5521	445.67	1388.14	271.8	2040.401	404.01	1129.7
0.05880	7.4409	444.10	1386.46	271.7	2097.191	410.05	1141.8
0.05905	7.3301	442.41	1384.77	271.5	2156.293	416.25	1154.2
0.05930	7.2197	440.59	1383.10	271.4	2217.812	422.61	1166.8
0.05955	7.1098	438.65	1381.44	271.3	2281.862	429.15	1179.8
0.05980	7.0004	436.56	1379.79	271.1	2348.559	435.85	1193.0
0.06005	6.8915	434.33	1378.15	271.0	2418.025	442.74	1206.5
0.06030	6.7833	431.96	1376.53	270.9	2490.391	449.80	1220.4
0.06055	6.6756	429.42	1374.91	270.8	2565.791	457.06	1234.5
0.06080	6.5686	426.73	1373.31	270.6	2644.359	464.51	1249.0

Table 4. Continued

CASE 9 (CONT'D) PP7 PAGE 2

HELIUM DRIVING HELIUM M=300. KG L=24.0000 M LR=25 M
P4I = 255.887 KG/CM2 T4I = 500.0 K
P0I =1677.200 KG/CM2 T0I = 293.0 K

T (SEC)	X (M)	DX/DT (M/SEC)	P0 KG/CM2	T0 (K)	P4 KG/CM2	R4 AMAGAT	T4 (K)
0.06105	6.4623	423.87	1371.72	270.5	2726.229	472.15	1263.8
0.06130	6.3567	420.83	1370.14	270.4	2811.555	479.99	1279.0
0.06155	6.2519	417.62	1368.58	270.3	2900.480	488.04	1294.4
0.06180	6.1479	414.21	1367.04	270.1	2993.153	496.29	1310.2
0.06205	6.0448	410.60	1365.50	270.0	3089.731	504.75	1326.4
0.06230	5.9426	406.79	1363.99	269.9	3190.373	513.43	1342.9
0.06255	5.8414	402.77	1362.49	269.8	3295.228	522.33	1359.8
0.06280	5.7413	398.52	1361.01	269.7	3404.446	531.44	1377.0
0.06305	5.6422	394.04	1359.55	269.5	3518.176	540.77	1394.5
0.06330	5.5443	389.32	1358.11	269.4	3636.573	550.32	1412.4
0.06355	5.4476	384.35	1356.69	269.3	3759.768	560.09	1430.7
0.06380	5.3522	379.12	1355.29	269.2	3887.904	570.08	1449.2
0.06405	5.2581	373.62	1353.91	269.1	4021.078	580.28	1468.1
0.06430	5.1654	367.83	1352.55	269.0	4159.399	590.69	1487.4
0.06455	5.0742	361.76	1351.22	268.9	4302.933	601.30	1506.9
0.06480	4.9846	355.38	1349.91	268.8	4451.768	612.12	1526.7
0.06505	4.8966	348.68	1348.63	268.7	4605.899	623.12	1546.9
0.06530	4.8103	341.67	1347.37	268.6	4765.317	634.30	1567.2
0.06555	4.7258	334.31	1346.15	268.5	4929.967	645.64	1587.8
0.06580	4.6432	326.62	1344.95	268.4	5099.759	657.13	1608.6
0.06605	4.5625	318.56	1343.78	268.3	5274.503	668.74	1629.5
0.06630	4.4839	310.14	1342.64	268.2	5453.997	680.46	1650.6
0.06655	4.4075	301.34	1341.54	268.1	5637.936	692.26	1671.7
0.06679	4.3333	292.16	1340.47	268.0	5825.944	704.11	1692.9
0.06704	4.2615	282.59	1339.43	268.0	6017.545	715.98	1714.0
0.06729	4.1920	272.62	1338.43	267.9	6212.179	727.84	1735.0
0.06754	4.1252	262.24	1337.47	267.8	6409.149	739.63	1755.9
0.06779	4.0610	251.46	1336.55	267.7	6607.693	751.33	1776.6
0.06804	3.9995	240.26	1335.67	267.7	6806.911	762.88	1796.9
0.06829	3.9409	228.66	1334.83	267.6	7005.782	774.22	1816.8
0.06854	3.8852	216.65	1334.03	267.5	7203.187	785.32	1836.2
0.06879	3.8326	204.23	1333.28	267.5	7397.858	796.09	1855.0
0.06904	3.7832	191.41	1332.57	267.4	7588.463	806.50	1873.2
0.06929	3.7370	178.21	1331.91	267.4	7773.573	816.47	1890.5
0.06954	3.6941	164.63	1331.30	267.3	7951.626	825.94	1905.9
0.06979	3.6547	150.69	1330.74	267.3	8121.088	834.85	1922.4
0.07004	3.6188	136.42	1330.22	267.2	8280.357	843.13	1936.7
0.07029	3.5865	121.83	1329.76	267.2	8427.835	850.72	1949.8
0.07054	3.5579	106.95	1329.36	267.2	8561.888	857.56	1961.6
0.07079	3.5331	91.80	1329.00	267.1	8681.076	863.58	1971.9
0.07104	3.5121	76.43	1328.70	267.1	8784.009	868.76	1980.8
0.07129	3.4949	60.87	1328.46	267.1	8869.431	873.02	1988.2
0.07154	3.4317	45.14	1328.27	267.1	8936.263	876.34	1993.9
0.07179	3.4724	29.30	1328.14	267.1	8983.650	878.69	1997.9
0.07184	3.4710	26.13	1328.12	267.1	8990.732	879.04	1998.5
0.07189	3.4698	22.94	1328.10	267.1	8997.015	879.35	1999.0
0.07194	3.4687	19.76	1328.09	267.1	9002.478	879.62	1999.5
0.07199	3.4678	16.57	1328.07	267.1	9007.130	879.85	1999.9

Table 4. Continued

CASE 9 (CONT'D) PP7 PAGE 3

HELIUM DRIVING HELIUM M=300. KG L=24.0000 M LR=25 M
P4I = 255.887 KG/CM2 T4I = 500.0 K
P0I =1677.200 KG/CM2 T0I = 293.0 K

T (SEC)	X (M)	DX/DT (M/SEC)	P0 KG/CM2	T0 (K)	P4 KG/CM2	R4 AMAGAT	T4 (K)
0.07204	3.4670	13.39	1328.06	267.1	9010.980	880.04	2000.2
0.07209	3.4664	10.20	1328.05	267.1	9014.003	880.19	2000.5
0.07214	3.4660	7.01	1328.05	267.1	9016.205	880.30	2000.6
0.07219	3.4658	3.82	1328.04	267.1	9017.582	880.37	2000.8
0.07224	3.4656	0.62	1328.04	267.1	9018.142	880.39	2000.8
0.07229	3.4657	-2.56	1328.04	267.1	9017.880	880.38	2000.8
0.07234	3.4659	-5.61	1328.05	267.1	9016.828	880.33	2000.7
0.07239	3.4663	-8.66	1328.05	267.1	9014.988	880.24	2000.5

Table 4. Continued

CASE 16 PP7 PAGE 1

HELIUM DRIVING HYDROGEN M=300. KG L=16.9000 M LR=17.5 M
P41 = 913.838 KG/CM2 T41 = 500.0 K
P01 =3600.000 KG/CM2 T01 = 293.0 K

T (SEC)	X (M)	DX/DT (M/SEC)	PO KG/CM2	TO (K)	P4 KG/CM2	R4 AMAGAT	T4 (K)
0.00000	16.9000	0.00	3599.99	292.9	913.835	359.11	499.9
0.00250	16.8348	51.51	3595.29	292.8	920.368	360.50	500.9
0.00500	16.6429	101.85	3581.48	292.3	940.056	364.65	503.9
0.00750	16.3262	151.29	3558.85	291.6	974.135	371.72	509.0
0.01000	15.8876	199.35	3527.85	290.6	1024.871	381.99	516.3
0.01250	15.3311	245.48	3489.08	289.3	1095.886	395.85	526.0
0.01500	14.6622	289.09	3443.29	287.7	1192.725	413.91	538.7
0.01750	13.8883	329.42	3391.38	286.0	1323.834	436.98	554.6
0.02000	13.0186	365.55	3334.37	284.0	1502.217	466.17	574.5
0.02250	12.0651	396.21	3273.46	281.9	1748.254	503.01	599.2
0.02500	11.0435	419.66	3209.95	279.7	2094.675	549.54	630.1
0.02750	9.9749	433.29	3145.42	277.4	2594.972	608.41	668.6
0.02955	9.0837	434.39	3093.02	275.6	3180.019	668.11	707.3
0.02980	8.9752	433.75	3086.72	275.3	3265.654	676.18	712.5
0.03005	8.8669	432.92	3080.46	275.1	3354.896	684.45	717.8
0.03030	8.7588	431.88	3074.22	274.9	3447.909	692.89	723.3
0.03055	8.6509	430.64	3068.03	274.7	3544.860	701.53	728.8
0.03080	8.5435	429.18	3061.87	274.4	3645.920	710.35	734.5
0.03105	8.4364	427.50	3055.75	274.2	3751.267	719.37	740.3
0.03130	8.3297	425.59	3049.67	274.0	3861.084	728.58	746.2
0.03155	8.2236	423.43	3043.64	273.8	3975.560	737.98	752.2
0.03180	8.1181	421.03	3037.66	273.6	4094.865	747.58	758.4
0.03205	8.0131	418.36	3031.73	273.3	4219.200	757.37	764.6
0.03230	7.9089	415.42	3025.85	273.1	4348.740	767.35	771.0
0.03255	7.8055	412.19	3020.04	272.9	4483.674	777.52	777.5
0.03280	7.7028	408.68	3014.29	272.7	4624.181	787.88	784.2
0.03305	7.6012	404.85	3008.61	272.5	4770.434	798.42	790.9
0.03330	7.5005	400.71	3003.00	272.3	4922.572	809.14	797.8
0.03355	7.4008	396.24	2997.46	272.1	5080.774	820.03	804.7
0.03380	7.3024	391.43	2992.00	271.9	5245.130	831.09	811.8
0.03405	7.2051	386.26	2986.63	271.7	5415.762	842.30	819.0
0.03430	7.1093	380.73	2981.34	271.5	5592.757	853.66	826.2
0.03455	7.0148	374.81	2976.15	271.3	5776.124	865.15	833.6
0.03480	6.9219	368.51	2971.05	271.1	5965.898	876.77	841.0
0.03505	6.8306	361.79	2966.06	270.9	6162.010	888.48	848.5
0.03530	6.7410	354.66	2961.17	270.8	6364.374	900.29	856.0
0.03555	6.6533	347.10	2956.38	270.6	6572.806	912.16	863.6
0.03580	6.5675	339.09	2951.72	270.4	6787.070	924.07	871.3
0.03605	6.4838	330.63	2947.18	270.2	7006.861	936.01	878.9
0.03630	6.4023	321.70	2942.77	270.1	7231.739	947.93	886.5
0.03655	6.3230	312.30	2938.50	269.9	7461.222	959.81	894.1
0.03680	6.2462	302.41	2934.36	269.8	7694.644	971.62	901.7
0.03705	6.1719	292.03	2930.36	269.6	7931.303	983.32	909.2
0.03730	6.1002	281.16	2926.52	269.5	8170.303	994.87	916.6
0.03755	6.0313	269.79	2922.82	269.3	8410.669	1006.23	923.9
0.03780	5.9654	257.91	2919.30	269.2	8651.240	1017.36	931.0
0.03805	5.9024	245.54	2915.94	269.1	8890.767	1028.20	938.0
0.03830	5.8426	232.67	2912.76	269.0	9127.830	1038.72	944.8

Table 4. Concluded

CASE 1b (CONT'D) PP7 PAGE 2

HELIUM DRIVING HYDROGEN M=300. KG L=16.9000 M LR= 17.5 M
P4I = 913.838 KG/CM2 T4I = 500.0 K
P0I =3600.000 KG/CM2 T0I = 293.0 K

T (SEC)	X (M)	DX/DT (M/SEC)	PO KG/CM2	TO (K)	P4 KG/CM2	R4 AMAGAT	T4 (K)
0.03855	5.7861	219.31	2909.75	268.9	9360.925	1048.87	951.3
0.03880	5.7330	205.47	2906.93	268.7	9588.427	1058.58	957.5
0.03905	5.6834	191.16	2904.30	268.6	9808.584	1067.82	963.5
0.03930	5.6375	176.41	2901.86	268.6	10019.584	1076.52	969.1
0.03955	5.5953	161.23	2899.63	268.5	10219.576	1084.64	974.3
0.03980	5.5569	145.65	2897.60	268.4	10406.666	1092.13	979.1
0.04005	5.5225	129.70	2895.78	268.3	10579.015	1098.94	983.5
0.04030	5.4921	113.40	2894.18	268.3	10734.796	1105.02	987.4
0.04055	5.4658	96.80	2892.79	268.2	10872.355	1110.33	990.9
0.04080	5.4437	79.94	2891.63	268.2	10990.078	1114.84	993.8
0.04105	5.4259	62.85	2890.69	268.1	11086.621	1118.51	996.1
0.04130	5.4123	45.59	2889.98	268.1	11160.789	1121.31	998.0
0.04155	5.4031	28.19	2889.49	268.1	11211.675	1123.22	999.2
0.04160	5.4018	24.70	2889.42	268.1	11219.001	1123.50	999.4
0.04165	5.4006	21.21	2889.36	268.1	11225.361	1123.73	999.5
0.04170	5.3997	17.72	2889.31	268.1	11230.757	1123.94	999.7
0.04175	5.3989	14.22	2889.27	268.1	11235.187	1124.10	999.8
0.04180	5.3982	10.72	2889.23	268.1	11238.644	1124.23	999.8
0.04185	5.3978	7.22	2889.21	268.1	11241.134	1124.33	999.9
0.04190	5.3975	3.72	2889.20	268.1	11242.644	1124.38	999.9
0.04195	5.3974	0.22	2889.19	268.1	11243.189	1124.40	1000.0
0.04200	5.3975	-3.27	2889.20	268.1	11242.750	1124.39	999.9
0.04205	5.3978	-6.55	2889.21	268.1	11241.390	1124.34	999.9
0.04210	5.3982	-9.83	2889.23	268.1	11239.117	1124.25	999.9
0.04215	5.3987	-13.11	2889.26	268.1	11235.912	1124.13	999.8
0.04220	5.3995	-16.38	2889.30	268.1	11231.810	1123.98	999.7
0.04225	5.4004	-19.66	2889.34	268.1	11226.804	1123.79	999.6
0.04230	5.4014	-22.93	2889.40	268.1	11220.894	1123.57	999.4
0.04235	5.4027	-26.19	2889.47	268.1	11214.078	1123.31	999.2

Table 5. Parametric Study-Cases Examined

CASE N°		DRIVER GAS		T_5 (°K)	P_5 (atm.)
1	(1b)	He	(H_2)	1000	5000
2	(2b)	He	(H_2)	1000	4000
3	(3b)	He	(H_2)	1000	3000
4	(4b)	He	(H_2)	1000	2000
5	(5b)	He	(H_2)	1600	5000
6	(6b)	He	(H_2)	1600	4000
7	(7b)	He	(H_2)	1600	3000
8	(8b)	He	(H_2)	1600	2000
9	(9b)	He	(H_2)	2000	5000
10	(10b)	He	(H_2)	2000	4000
11	(11b)	He	(H_2)	2000	3000
12	(12b)	He	(H_2)	2000	2000

In all cases, test gas is air. T_{4_i} = 293°K, 500°K

Helium is used to drive 300 kg piston with T_{0_i} = 293°K

Shock tube length : 34 ft, 54 ft, 64 ft T_1 = 293°K

Test time : 2 msecs Tailored conditions

Table 6. Parametric Study-Tailoring Conditions for Shock Tube and Compression Conditions for Compression Tube

CASE No.	TAILORING CONDITIONS M_S	T_5 (°K)	P_4 (atm)	COMPRESSION CONDITIONS P_{4i} (atm) (T_{4i}=293°K)	P_{4i} (atm) (T_{4i}=500°K)	λ (T_{4i}=293°K)	λ (T_{4i}=500°K)	
1	8.99	6920	9840	403	1565	4.53	2.30	T_4 = 1000°K
(1b)	(15.47)*	(12 100)	(10880)	(134)	(884)	(9.72)	(3.13)	
2	8.76	6620	7660	318	123.3	4.74	2.36	
(2b)	(15.05)	(11660)	(8370)	(105)	(687)	(10.76)	(3.34)	
3	8.52	6300	5560	236	910	5.00	2.44	
(3b)	(14.65)	(11190)	(6000)	(76)	(498)	(12.14)	(3.63)	
4	(8.28)	5960	3580	155	596	5.32	2.53	
(4b)	(–)	(–)	(–)	(–)	(–)	(–)	(–)	
5	10.95	9760	9070	116	443	10.25	4.81	T_4 =1600°K
(5b)	(19.19)	(14860)	(10060)	(23)	(147)	(42.10)	(11.56)	
6	10.79	9410	7160	93	356	10.61	4.94	
(6b)	(18.93)	(14860)	(7880)	(18)	(116)	(46.01)	(12.52)	
7	10.62	9050	5290	70	268	11.03	5.09	
(7b)	(18.67)	(13860)	(5780)	(13.2)	(85.7)	(50.8)	(13.7)	
8	10.45	8670	3470	47	180	11.51	5.27	
(8b)	(18.42)	(13280)	(3770)	(8.7)	(56.3)	(56.95)	(15.23)	
9	12.07	12220	8720	65	248	15.02	6.92	T_4 =2000°K
(9b)	(21.49)	(18220)	(9510)	(9.04)	(58.7)	(89.8)	(24.0)	
10	11.94	11890	6900	52	199	15.46	7.09	
(10b)	(21.31)	(17630)	(7520)	(7.18)	(46.64)	(96.8)	(25.8)	
11	11.80	11570	5120	39	150	15.94	7.27	
(11b)	(21.13)	(17030)	(5570)	(5.35)	(34.8)	(105.2)	(27.9)	
12	—	—	—	—	—	—	—	
(12b)	(20.97)	(16430)	(3670)	(3.56)	(23.1)	(115.4)	(30.6)	

*Values in brackets : Hydrogen as barrel gas

Table 7. Parametric Study-Details of Compression Tube of a Piston-Driven Tailored-Mode Reflected Shock Tunnel

	"TAILORED" TUBE LENGTHS FOR 2 MS. RUN TIME WITH NO EXPANSION CANCELLATION			COMPRESSION TUBE CYCLE DETAILS FOR 293°K HELIUM RESERVOIR GAS AND 300 KG. PISTON			
				RESERVOIR PRESSURE		PISTON VELOCITY	
CASE No.	Lp (m.)	Lc (m.) (T_{4i} = 293°K)	Lc (m.) (T_{4i} = 500°K)	Poi (kg/cm²) (T_{4i} = 293°K)	Poi (kg/cm²) (T_{4i} = 500°K)	Vp (m/s) (T_{4i} = 293°K)	Vp (m/s) (T_{4i} = 500°K)
1 (1b)	4.21 (5.63)	19.1 (54.7)	9.69 (17.1)	2387 (1187)	4665 (3600)	445 (650)	293 (436)
2 (2b)	3.99 (5.10)	18.9 (55)	9.45 (17.1)	1844.5 (897.1)	3674 (2750)	391 (564)	263 (384)
3 (3b)	3.74 (4.52)	16.7 (55)	9.11 (16.45)	1332 (632.7)	2664 (1947)	330 (475)	221 (321)
4 (4b)	3.45 —	18.4 —	8.75 —	852 —	1717.2 —	266 —	176 —
5 (5b)	4.10 (5.02)	42.8 (212)	20.1 (58)	1131.9 (347.4)	2357.8 (1173.1)	556 (804)	445 (650)
6 (6b)	3.96 (4.61)	42.0 (212)	19.6 (57.7)	892 (269.2)	1860.8 (908.1)	491 (705)	388 (576)
7 (7b)	3.78 (4.18)	41.7 (212)	19.2 (57.4)	658.5 (195.7)	1374.9 (658.8)	421 (597)	334 (491)
8 (8b)	3.58 (3.71)	41.2 (211)	18.9 (56.5)	432.3 (126.8)	902.3 (425.6)	340 (485)	269 (393)
9 (9b)	4.18 (4.82)	62.8 (432)	29.0 (116)	793 (180.8)	1677.2 (626.2)	600 (855)	500 (739)
10 (10b)	4.03 (4.45)	62.3 (430)	28.6 (115)	627.8 (142)	1328 (491.2)	534 (760)	445 (654)
11 (11b)	3.88 (4.07)	62.0 (428)	28.3 (113.5)	465 (104.8)	984 (361.6)	457 (655)	382 (558)
12 (12b)	— (3.67)	— (424)	— (112)	— (69)	— (237.2)	— (528)	— (446)

COMPRESSION TUBE DETAILS FOR SHOCK TUBE LENGTH 34 FT. HELIUM DRIVER			
CASE N°	Lp(m)	Lc(m.) T_{4i}=293K	Lc(m) T_{4i}=500K
1	3.40	15.4	7.8
2	3.20	15.20	7.55
3	2.98	14.9	7.26
4	2.73	14.6	6.92
5	3.41	35.0	16.4
6	3.24	34.4	16
7	3.04	33.6	15.5
8	2.9	33.4	15.3
9	3.46	52	24
10	3.33	51.4	23.6
11	3.19	50.9	23.2
12	3.09	50.6	22.8

COMPRESSION TUBE DETAILS FOR SHOCK TUBE LENGTH 54 FT. HYDROGEN DRIVER			
CASE N°	L p(m.)	Lc(m.) T_{4i}=293K	Lc(m) T_{4i}=500K
1b	5.39	52.4	16.9
2b	4.87	52.4	16.3
3b	4.31	52.4	15.6
4b	14.15	52.4	15.1

Table 8. Parametric Study-Effect of Reduction of Shock Tube Length on Compression Tube Length for 2-msec Running Time

Table 9. Comparison of Performance of Helium and Hydrogen Driver Gases

CASE	A	B	
DRIVER GAS	HELIUM	HYDROGEN	
P_5, atm	5000	5000	
T_5, °K	12,200	12,100	
T_4, °K	2000	1000	
P_4, atm.	8720	10,880	
P_1, atm.	2.57	1.46	
T_1, °K.	293	293	
M_S	12.07	15.48	
L shock tube, m	10.35 (34')	16.46 (54')	
Lp, m	3.46	5.39	or
Lc, m	24	16.9	52.5
λ_4	6.92	3.13	9.72
T_4i, atm	500	500	293
P_4i, atm.	248	884	134
Toi, °k	293	293	293
Poi, atm.	1620	3480	1150