
Factors Limiting the Maximum Stagnation Temperature in a Gun Tunnel

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SUMMARY

The problems of piston development and the limitations these impose on gun tunnel operation are discussed. However, even when it is possible to operate at higher pressure ratios than hitherto, the expected improvement in performance is not achieved. Measured temperatures do not exceed 2200°K at a pressure ratio of 1000 without preheating. Factors limiting the maximum stagnation temperature include inefficient heating during the piston acceleration phase and heat losses to the barrel walls. Departures from normal operation, including the use of an evacuated acceleration section and a double piston/double compression technique, aimed at reaching temperatures in excess of 3000°K , are described.

1. INTRODUCTION

The first gun tunnel was that built at the NASA Ames Laboratory. A powder charge was employed to drive a light piston at high velocity along a barrel, heating the enclosed gas by means of the shock generated by the piston and by successive shock reflections between the end of the barrel and the piston. Stagnation temperatures at the end of the shock compression process, when the piston came to rest, were about 1200°K . Efforts to reach even higher temperatures were abandoned, according to Eggers⁽¹⁾, due to difficulties in containing the peak pressure generated by the piston as it overshot its equilibrium position. This led to damage of the nozzle and the end of the barrel and contamination of the working gas.

In 1955 Cox at A.R.D.E. took up the development of the gun tunnel, replacing the powder charge by a high pressure air or helium driver. Nearly

all gun tunnels currently in use have been built on this principle. By 1959 Cox was able to report stagnation temperatures of 1500°K in air at a pressure ratio of 250 using air as a driver, and 2000°K at a pressure ratio of 100 using helium as a driver⁽¹⁾. He also expressed the opinion that temperatures between 5000°K and 6000°K could be expected, provided suitable pistons could be developed to withstand the peak pressures that would be generated at the high pressure ratios necessary to achieve these temperatures.

Thus it seemed that the gun tunnel offered several advantages over the shock tunnel. Among these, effective separation of driven and driver gases, longer running times (~ 50 msec), high stagnation pressures (~ 250 atm), higher Reynolds numbers ($\sim 10^6$ per cm) and higher stagnation temperatures for the same driver, should be mentioned.

However, although the gun tunnel has proved itself as a versatile and cheap facility for high Reynolds number studies and even as a low density facility where the long running times reduce instrumentation problems⁽²⁾, most workers now accept that it has failed as a high temperature facility. Consequently most tunnels are operated 'cold', i.e. at temperatures around 1000°K , sufficient to avoid condensation at $M=8$ to 10. In this way there are less severe demands on the piston and the maximum running time is obtained, since the gun is operated at low pressure ratios (~ 100).

At F.F.A. in 1959 there was a requirement for a hypersonic tunnel capable of producing temperatures up to 3500°K and a gun tunnel seemed the logical choice. It was realised that special emphasis would have to be placed on improving the then current piston designs. Many different designs and materials were tried before Lemcke in 1962 was able to announce the development of a very light Makrolon piston, weighing 8 gm, suitable for pressure ratios up to 1400⁽³⁾. Temperatures calculated from the measured shock strengths and final pressure rise at the end of the barrel indicated that temperatures of 3000°K had been reached at this pressure ratio.

However, later measurements by Edney, using stagnation-point heat transfer methods, indicated that the temperature was in fact much lower, $\sim 2200^{\circ}\text{K}$ ⁽⁴⁾. Subsequent measurements by Brown-Edwards, using a sodium-line reversal method, confirmed this⁽⁵⁾. Moreover, recent work by Bowman at R.A.R.D.E., based on flow velocity measurements to measure stagnation temperatures, has indicated that the maximum temperature obtainable in the R.A.R.D.E. facility is 2000°K at a pressure ratio of 1000, but this could be increased to 2700°K by preheating the barrel to 550°K ⁽⁶⁾.

The purpose of this paper is to examine the problems of achieving high temperatures in gun tunnels, to explain the apparent discrepancy between predicted and actual performance and to outline some novel methods which might be used to improve gun tunnel performance.

LIST OF SYMBOLS

a	speed of sound
A	cross-sectional area of barrel
b	distance between shock and piston
C_p	specific heat at constant pressure
f	time between passage of initial shock and piston
ΔH_2	heat lost
h	specific enthalpy
I	integral defined by equation (14)
k	constant defined by equation (8)
L	barrel length
m	piston mass
M	mass of gas in barrel
P	pressure
Pr	Prandtl number
q	heat flux to barrel wall
r	barrel radius
Re	Reynolds number
St	Stanton number
t	time
T_s	final stagnation temperature
T_2	temperature behind the initial shock
U_p	piston velocity
U_s	shock velocity
x	distance behind initial shock
α	constant in equation (16)
β	constant in equation (15)
ρ	density
μ	viscosity
τ	time for initial shock to reach end of barrel

Suffixes

0	ideal condition
1	initial condition in barrel
2	behind initial shock
4	in driver
5	behind first reflected shock
r	recovery
w	wall

2. TEMPERATURE MEASUREMENTS IN GUN TUNNELS

Before discussing the factors limiting the stagnation temperatures in gun tunnels, it is relevant to say something about how such temperatures are measured, since this is in itself a formidable problem and one which has not been satisfactorily solved. In shock tunnels the temperature, at the beginning of the run at least, may be calculated from the strength of the reflected shock measured at the end of the barrel. Similar calculations based on the measured pressure rise at the end of the barrel in a gun tunnel, however, where several reflected shocks followed by an isentropic compression to some steady pressure level must be considered, predict higher temperatures than actually realised. This discrepancy is very large at high pressure ratios.

Up to the present time it has been necessary to rely on some previous calibration carried out in the test section and to check the guns repeatability of operation by monitoring, say, the pressure at the end of the barrel.

Probably the most accurate temperature measurements so far are those based on flow velocity measurements in the test section. This technique enables variations during the run to be studied. Other indirect methods include measurement of the blowing time, which gives a temperature averaged over the entire run, and measurement of the heat transfer rate at the stagnation point of a hemisphere, which is more accurate and capable of following variations during a run, especially if thin-film gauges are used. There is also a more direct method using the sodium-line reversal technique, which in a modified two-beam form can be used to measure accurately the variation in temperature during a run.

The earliest measurements made by Lemcke in the F.F.A. gun tunnel, before the present working section had been added, were based on measurements of the pressure history at the end of the barrel and of the blowing time⁽³⁾. The upper curve in Fig. 1 is that calculated by Lemcke from pressure measurements and represents the temperature of the gas nearest the end of the barrel, assuming no heat losses to the barrel walls and no mixing. The lower curve represents the temperature of the gas farthest from the end of the barrel, just ahead of the piston. The average temperature depends on the piston acceleration, but for the very light pistons used in the F.F.A. facility would lie nearer the upper curve.

Following the construction of a working section it was possible to check these predictions using alternative methods. Two main lines of investigation were pursued. One concentrated on heat transfer measurements at the stagnation point of a hemisphere, using both thin-film gauges and thin-shell copper calorimeters⁽⁴⁾. Data reduction was based on Fay and Riddell's theory for stagnation point heat transfer. These measurements yielded an

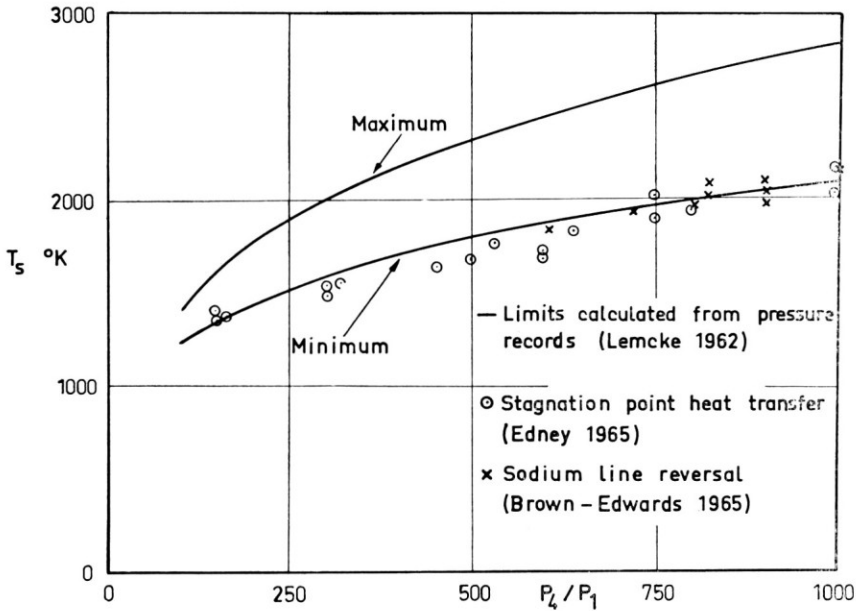


FIG. 1 — Comparison of temperature measurements made in F.F.A. gun tunnel using various techniques

average temperature for the first 5 millisecc of the run, when a steady pressure level in the stagnation chamber had been reached. The accuracy of the thin-film measurements was impaired due to erosion from piston material in the test gas and only the results obtained using the calorimeters are presented here.

The other investigation concentrated on a modified sodium-line reversal method, using a two-beam optical pyrometer, developed at ONERA in France, which compares the emission from the hot gas alone with the emission from the hot gas seen against a calibrated background source⁽⁵⁾. With this method the temperature could be monitored throughout a run (~ 50 msec) with a response time less than 1 msec. Difficulties due to vibrational relaxation were overcome by means of a 'relaxation tube' — a flat-sided glass tube, with a restriction at the downstream end, mounted along the axis of the working section. A detached shock is formed at the mouth of the tube and the vibrational temperature of the gas in the tube can be measured at various distances, up to 10 cm, behind the shock. This is necessary since it is assumed the sodium atoms follow the vibrational temperature of the air which may differ considerably from the equilibrium temperature immediately behind the shock. Because of low emission at temperature below 1800°K measurements could not be carried out at pressure ratios below 600 in the F.F.A. gun tunnel.

The results of the heat transfer and sodium-line reversal measurements are also shown in Fig. 1 and are seen to be in good agreement, within the limits of experimental accuracy ($\pm 100^\circ\text{C}$). Both methods indicate stagnation temperatures far below those predicted from pressure measurements in the barrel. This discrepancy is approximately 800°C at a pressure ratio of 1000.

Direct measurements in the stagnation chamber using the sodium-line reversal technique are planned, providing windows capable of withstanding the peak pressures can be constructed.

3. LIMITATIONS IMPOSED BY PISTON DESIGN PROBLEMS

The development of a suitably light, yet strong, piston poses many problems. There are indeed more piston designs than gun tunnels yet none fulfils all the requirements for use in a high-performance gun tunnel at pressure ratios in excess of 500. At F.F.A. much work has gone into refining piston design and it is now possible to operate at pressure ratios up to 1400. The requirements for a suitable piston may be stated as follows:

(1) The piston must withstand high starting loads (up to 300 atm in the F.F.A. facility).

(2) It must seal against the barrel walls. Cold gas from the driver should not leak into the compressed working gas, lowering its temperature and altering its composition. Nor must the working gas leak into the driver gas since this results in a loss of running time.

(3) The piston must be stable against tipping. This means a piston length/diameter ratio about $1/4$. Fins are preferred to a long skirt since these give better mass distribution which is desirable because of the high initial acceleration (10^5 – 10^6g) and deceleration.

(4) The piston material should be chemically inert and not react with the working gas, altering its composition. Nylon, a commonly used material, is particularly bad in this respect.

(5) The mass should be low. This arises from two considerations. The first is that the piston shall accelerate to its maximum velocity in a small fraction of the barrel length if full advantage is to be taken of the initial shock heating. We shall discuss this in more detail later.

The second is that as the piston overswings at the end of the barrel a peak pressure, P_M , is generated which may be several times the driving pressure P_4 . P_M increases rapidly with increasing piston mass, m , according to the approximate relation

$$P_M \simeq P_5 \left(1 + 0.2 \frac{mU^2}{P_1 LA} \right)^{3.5} \quad (1)$$

where P_1 and P_5 are the initial pressure in the barrel and the pressure behind

the first reflected shock respectively, U is the maximum piston velocity, L the length of the barrel and A the cross-sectional area. For a given facility L , A and the maximum driving pressure, P_4 , are fixed. In addition P_1 must be as low as possible (high compression ratio) and U as high as possible (strong shock heating) if high temperatures are to be reached. Thus P_M can only be reduced by reducing m . If the piston is too heavy the peak pressure may not only destroy the piston but also the end of the barrel^(1, 7). Since the piston must be designed to withstand the starting load, P_4 , it is sufficient to reduce the mass to the point where the differential pressure $P_M - P_S = P_4$. P_S , the pressure behind the piston as it is brought to rest, is in theory $1.89P_4$ and in practice more like 1.1 to $1.5P_4$, depending on the dimensions of the barrel. Consequently we can accept a peak pressure of about $2.5P_4$ without damage to the piston. Lemcke, using a more refined theory, has calculated the optimum piston mass necessary to contain the peak pressure in the F.F.A. tunnel (Fig. 2). Figure 3 shows pistons made from Makrolon and aluminium.

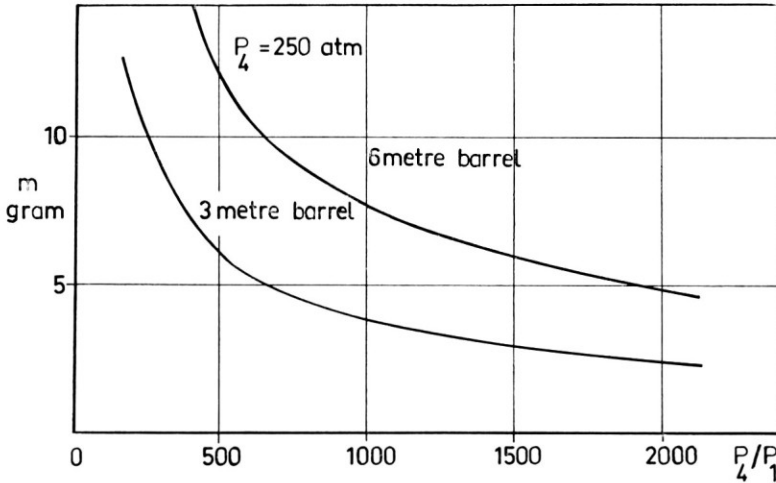


FIG. 2 — Optimum piston mass as function of P_4/P_1

The Makrolon pistons are injection moulded and holes drilled in the fins to reduce their mass to about 8 gm. These may be used up to pressure ratios of 1400 in the F.F.A. tunnel and driving pressures of 300 atm. (These same pistons are also supplied to Johns Hopkins University where they are run at driving pressures of 1000 atm). Makrolon was chosen because of its high strength to density ratio and good elasticity. Although mechanically very satisfactory, as the pressure ratio and consequently the temperature is increased pitting and burning of the Makrolon occurs. Figure 3 shows this clearly. Particles from the piston damage models, particularly thin film

gauges⁽⁴⁾, hinder optical measurements⁽⁵⁾ and use up oxygen from the air, totally changing its composition. Attempts have been made to add protective metal or ceramic coatings but these are either burnt or torn off during a run⁽⁵⁾. An alternative and more costly procedure was to machine pistons from high strength aluminium bolts. Pistons weighing about 10 gm and usable at pressure ratios up to 800 have been manufactured. These are also

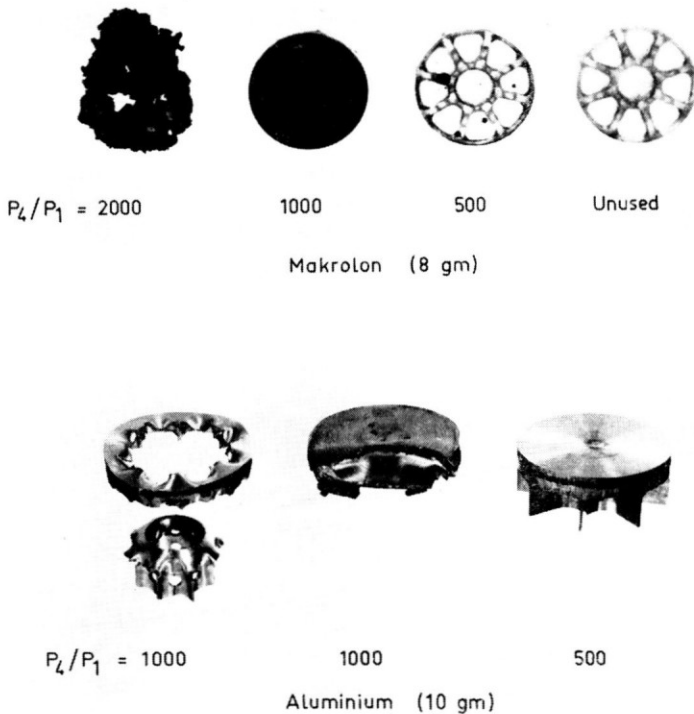


FIG. 3 — Examples of Makrolon and aluminium pistons used at various pressure ratios. Driving pressure 150 atm. Nitrogen driving air

shown in Fig. 3. These do not burn, but spalling on the steel barrel walls causes some difficulties with model erosion. A Teflon coating on the skirt of the piston has been tried but affords only a slight reduction in spalling.

Evidently the ideal piston material would be a plastic with similar or better mechanical properties than Makrolon but with better thermal properties. At present no material with markedly superior properties over Makrolon is available.

4. THE EFFECTS OF HEAT LOSSES TO THE BARREL WALL ON THE FINAL TEMPERATURE AND ITS SUBSEQUENT DECAY DURING A RUN

It is evident that heat lost by the working gas during the shock compression process, before a steady pressure level has been reached in the stagnation chamber and steady flow conditions established in the working section, will show up as a reduction in the maximum stagnation temperature. Subsequent heat losses will be observed as a decay in the stagnation temperature during the run. We shall consider these two effects in turn.

Estimation of the reduction in stagnation temperature

If the temperature, T_2 , of the gas between the initial shock and the piston is reduced by an amount ΔT_2 , due to heat losses from the boundary layer to the barrel wall, then the stagnation temperature, T_s , will be reduced by an amount ΔT_s where

$$\Delta T_s \simeq \left(\frac{\Delta T_2}{T_2} \right) T_s \quad (2)$$

assuming we can neglect any further losses. If strong mixing subsequently takes place we shall be interested only in the mean value of $\Delta T_2/T_2$. Let the heat transfer rate at some distance x behind the initial shock be $q(x)$ and let the distance separating the shock and the piston be $b(t)$ at time t . Then the total heat lost from the gas contained between the shock and the piston in the time, τ , taken by the initial shock to reach the end wall is given by

$$\Delta H_2 = 2\pi r \int_0^\tau \int_0^{b(t)} q(x) dx dt \quad (3)$$

where r is the radius of the barrel. Hence

$$\left. \frac{\Delta T_2}{T_2} \right|_{\text{mean}} = \frac{\Delta H_2}{M T_2 C_p} = \frac{2\pi r}{M T_2 C_p} \int_0^\tau \int_0^{b(t)} q(x) dx dt \quad (4)$$

where M is the total mass of gas and C_p the specific heat. If we assume that the piston velocity, U_p , and the shock velocity, U_s , are constant along the length of the barrel, L , then

$$b(t) = (U_s - U_p)t \quad (5)$$

$$\tau = L/U_s \quad (6)$$

and

$$M = \pi r^2 \rho_2 (U_s - U_p) L / U_s \quad (7)$$

where ρ_2 is the density behind the shock.

Hartunian, Russo and Marrone⁽⁸⁾ have made side wall heat transfer measurements in a shock tube, over a wide range of shock Mach numbers, and find that for a turbulent boundary layer

$$(St)(Re)^{1/5} = k = 3.7 \times 10^{-2} \quad (8)$$

in good agreement with the theory of Mirels⁽⁹⁾, where we define

$$(Re) = \frac{\rho_2 U_p x}{\mu_2} \quad (9)$$

μ_2 denoting the viscosity behind the shock,

$$(St) = \frac{q(x)}{\rho_2 U_p (h_r - h_w)} \quad (10)$$

and where the recovery enthalpy h , is defined by

$$h_r = h_2 + \frac{1}{2} U_p^2 (\text{Pr})^{[0.39 - 0.023 U_s / (U_s - U_p)]} \quad (11)$$

h_w denoting the enthalpy at the wall.

If we assume, therefore, that the same conditions hold in a gun tunnel, except for a small region ahead of the piston, where the boundary layer is swept up by the piston instead of continuing through the contact surface, as in the case of a shock tube, then combining equations (4), (5), (6), (7) and (8) we get

$$\left. \frac{\Delta T_2}{T_2} \right|_{\text{mean}} = \frac{25}{18} \left(\frac{k}{r} \right) \left[\frac{\mu_2}{\rho_2 (U_s - U_p)} \right]^{1/5} \left(\frac{U_p L}{U_s} \right)^{4/5} \frac{(h_r - h_w)}{T_2 C_p} \quad (12)$$

In Fig. 4 $\Delta T_2/T_2 \big|_{\text{mean}}$ has been evaluated as a function of shock Mach number U_s for various initial pressure levels p_1 , taking $r = 2$ cm and $L = 6$ m. We notice that $\Delta T_2/T_2$ increases almost linearly with shock speed. Also, to attain higher shock speeds and hence higher temperatures, for a fixed driving pressure P_4 , it is necessary to reduce P_1 , which increases still further $\Delta T_2/T_2$. The broken curve is that applicable to the F.F.A. gun tunnel based on measured P_1 and U_s . We should expect therefore, if this simple physical picture is true, a reduction in stagnation temperature varying from 21% at a pressure ratio of 150 rising to 42% at a pressure ratio of 1000. The observed values are 15% and 26% respectively.

An objection to the above analysis was raised by Stalker⁽¹⁰⁾ who maintained that the boundary layer would be re-activated by the piston and that the temperature of the gas would be restored to its original level. Resolving this objection is not straightforward. Certainly part of the boundary layer will be scooped up by the piston before the reflected shock passes back over it. Moreover, if the temperature and velocity are restored to the levels immediately behind the shock then an increase in the heat transfer rate immediately

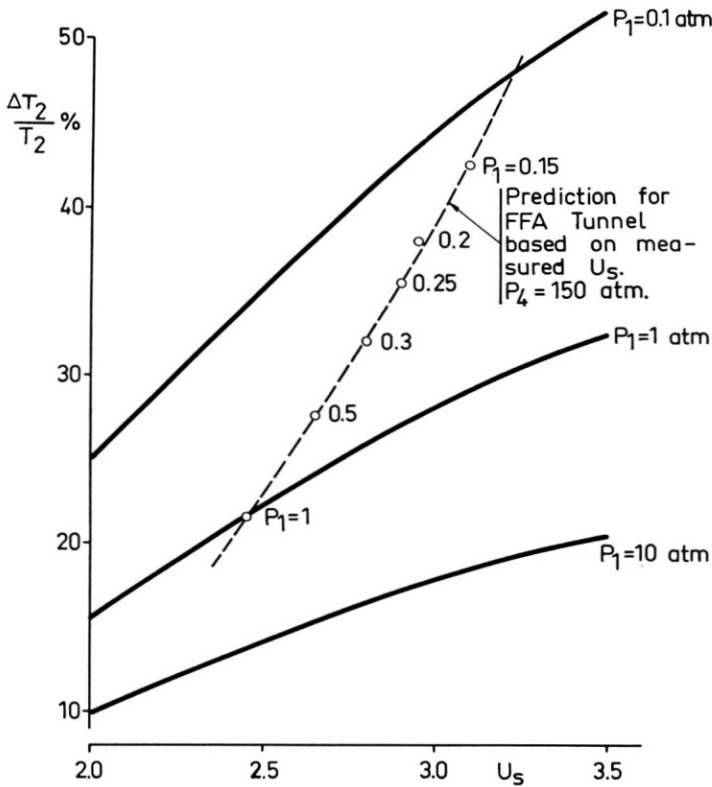


FIG. 4 — Relative temperature drop $\Delta T_2/T_2$ between initial shock and piston as function of shock speed U_s

ahead of the piston is to be expected, higher than in a shock tube, partially offsetting this energy gain. Since direct observations of the boundary layer are difficult in a gun tunnel little is known about the flow immediately ahead of the piston — except the possible existence of ring vortex⁽¹¹⁾ — on which to build a mathematical model and calculate the energy regained.

To resolve some of these points and check certain assumptions made in the simple analysis above, a series of tests to measure the heat losses to the wall was carried out. Thin film gauges, mounted flush with the walls of the barrel, were located 5, 25, 50 and 100 cm from the end of the barrel. Heat transfer rates were measured directly using T-section analogue networks. Pressure transducers were mounted opposite each gauge to measure the pressure variation between the shock and the piston simultaneously. Figure 5 shows a typical heat transfer record. Both the passage of the shock and the piston are clearly marked. The gun was also run without a piston, i.e. as a shock tube, for the purposes of comparison.

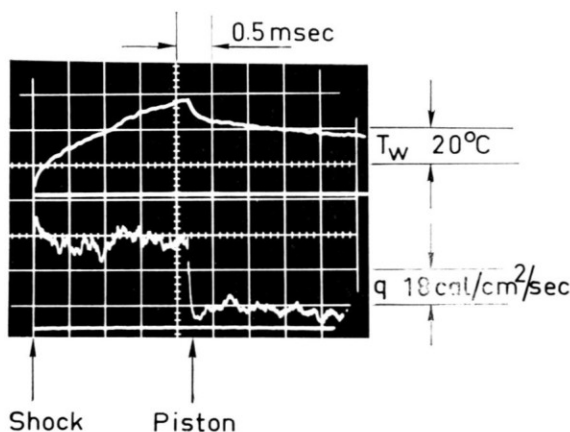


FIG. 5 — Heat transfer to side wall of barrel, $P_1 = 1$ atm. $U_s = 2.4$

The results of these tests may be summarised as follows:

(1) The measured piston speeds were in good agreement with those calculated from the measured shock speeds, using a simple shock tube model, and with piston speeds measured earlier using micro-wave techniques.

(2) Only slightly higher heat transfer rates were measured when a piston was used compared with when no piston was used (Fig. 6). The absolute heat transfer rates just behind the shock in both cases were some 20% higher than those measured by Hartunian⁽⁸⁾ and more in agreement with some measurements made by Martin⁽¹²⁾. This discrepancy is probably due to the fact that Martin's and the present measurements were made with plugs set in a steel wall, whereas Hartunian's measurements were made using gauges mounted on the inside of a smooth, glass section. The heat transfer rate decreased as $x^{-1/5}$, as predicted, for only a short distance but then increased roughly to its level behind the shock (Fig. 6).

(3) The pressure increased between the shock and the piston or contact surface. This is also shown in Fig. 6. Except at very low pressure ratio this increase was almost linear in x , i.e.

$$P_2(x) \approx P_{20} \left(1 + \alpha \frac{x}{b} \right) \quad (13)$$

where b is the shock/piston separation and α is a constant which varied between about 0.3 and 0.6, increasing with increasing pressure ratio.

(4) The time, f , between the arrival of the shock and the arrival of the piston was about 65% of the theoretical time, f_0 , decreasing slightly with increasing pressure ratio.

(5) The value of the integral

$$I(t) = \int_0^{b(t)} q(x) dx \quad (14)$$

which could be evaluated numerically, since $b(t) = U_p f$ and U_p , f and $q(x)$ were measured, was within 10% of the simple model's predictions. This is purely fortuitous and arises from the fact that although the measured heat transfer rate is higher than assumed, $b(t)$ is shorter. However, it does mean that the measured values are quite near the calculated values for the total heat lost.

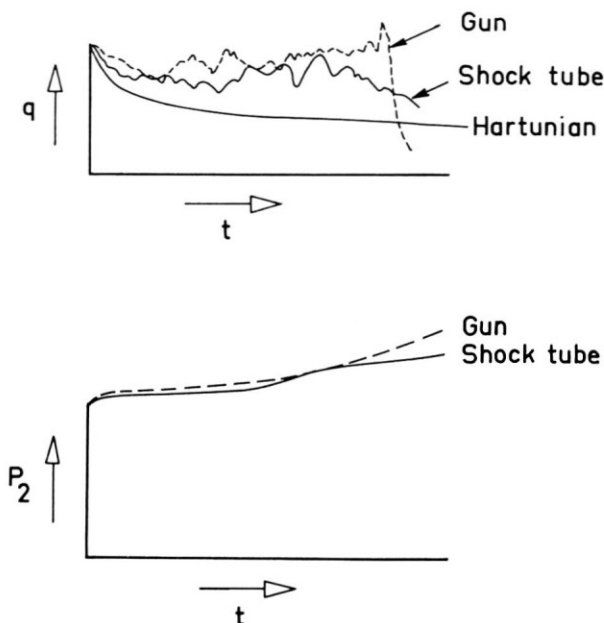


FIG. 6 — Heat transfer rate and side wall pressure measured between shock and piston compared with measurement in shock tube under identical conditions, $P_4/P_1 = 150$

A rough estimate of the average temperature drop behind the shock may also be made from the measured values of f/f_0 and $P_2(x)$. Thus if we assume that the temperature variation between the shock and the piston is of the form

$$T_2(x) = T_{20} \left(1 - \beta \frac{x}{b} \right) \quad \beta \text{ const} > 0 \quad (15)$$

and that

$$P_2(x) = P_{20} \left(1 + \alpha \frac{x}{b} \right) \quad \alpha \text{ const} > 0 \quad (16)$$

then the mass of gas between the shock and the piston, M , is

$$M = \pi r^2 \int_0^b \frac{P_2(x)}{RT_2(x)} dx \quad (17)$$

and in the ideal case
$$M_0 = \pi r^2 \int_0^{b_0} \frac{P_{20}}{RT_{20}} dx \quad (18)$$

Equating M and M_0 and remembering $b = U_p f$, $b_2 = U_p f_0$ we get

$$\int_0^1 \frac{(1 + \alpha y)}{(1 - \beta y)} dy \frac{f}{f_0} \quad (19)$$

Since α and f_0/f are known, β and hence $\Delta T_2/T_2 |_{\text{mean}}$ may be calculated.

Mean values of the temperature drop calculated using this method were lower than those calculated from the heat losses and in closer agreement with the observed $\Delta T_s/T_s$. These measurements, however, were fairly crude and more accurate measurements are planned.

Nevertheless, both methods point to a substantial drop in temperature behind the initial shock and that the heat losses from the boundary layer dominate any reactivation due to the piston. Calculations can also be made to determine $\Delta T_3/T_3$ etc. and their contribution to a reduction in the final stagnation temperature, but these are small compared with $\Delta T_2/T_2$.

5. COOLING DURING THE RUN

Measurements of the variation of T_s during the run carried out at A.R.D.E. using flow-velocity methods⁽¹⁾ and at F.F.A. using both heat-transfer and sodium-line reversal methods, have shown about a 5% decrease in T_s over a period of 50 msec. Calculations by East⁽¹³⁾ showed that conduction losses from the stagnant gas were negligible and assumed convective heat transfer rates to the stagnation chamber walls, extrapolated from Hot-shot data, of about $250 \text{ cal cm}^{-2} \text{ sec}^{-1}$ to explain an apparent 50% temperature drop during a 500 msec run.

Direct measurements of the heat transfer rates to the end wall of the F.F.A. gun barrel were made using thin film gauges⁽¹⁴⁾. Fig. 7 shows a typical

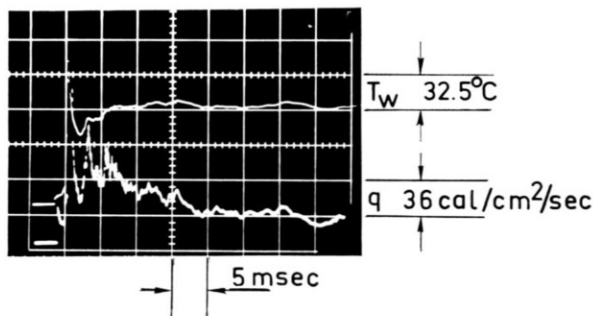


FIG. 7 — Heat transfer rate measured at end face of barrel. $P_4 = 150 \text{ atm}$.
 $P_1 = 0.25 \text{ atm}$.

record. Note that the wall temperature is essentially constant during the run and that the decrease in heat transfer with time, as $t^{-1/2}$, is consistent with conduction losses from a stagnant gas. The measured rise in wall temperature is also in good agreement with theoretical predictions considering conduction losses only. Consequently no significant decay in T_s during a 50 msec run is to be expected in the F.F.A. tunnel which is in accordance with experiment.

6. REDUCTION IN SHOCK HEATING DUE TO FINITE PISTON ACCELERATION

In a shock tube the shock forms almost instantaneously and the shock strength is essentially constant along the barrel, ignoring attenuation due to viscous effects. In a gun tunnel, however, the piston has some finite mass and therefore there is some finite length of the barrel over which the piston is accelerating. Indeed, if the piston is too heavy or the barrel too short, the piston will not attain its maximum steady velocity before reaching the end of the barrel. Consequently the shock will increase in strength along the barrel and, since the temperature and entropy rise through the shock increases with increasing shock strength, the air immediately ahead of the piston will be heated less than the air at the end of the barrel. If no mixing occurred this would be seen as a decay in the stagnation temperature from some level, T_{\max} , the temperature calculated using the maximum shock strength measured at the far end of the barrel, to some level, T_{\min} , which is essentially the temperature resulting from an isentropic compression to the same final pressure. Since mixing occurs the net effect will be a lowered stagnation temperature, T_{av} , given approximately by:

$$T_{\text{av}} \simeq T_{\max} - \frac{L_{\text{acc}}}{2L}(T_{\max} - T_{\min}) \quad (20)$$

where L_{acc} is the distance for the piston to reach its maximum velocity and L the total length of the barrel. Lemcke⁽³⁾ has calculated the limits T_{\min} and T_{\max} for the F.F.A. gun tunnel based on pressure measurements at the end of the barrel, ignoring heat losses (Fig. 1). Micro-wave measurements of the piston motion (see for example the lower curve in Fig. 9) indicate that $L_{\text{acc}} \sim 0.2L$ in the F.F.A. gun and so T_{av} will lie nearer to T_{\max} . Therefore no serious loss in performance is expected on this account. However, in other tunnels, where $L_{\text{acc}} \sim L$, a marked loss in performance can be anticipated.

A measure of the efficiency of a gun tunnel is the non-dimensional barrel length \bar{L} defined by

$$\bar{L} = \frac{P_4 \pi r^2 L}{a_4^2 m} \quad (21)$$

where P_4 and a_4 are the pressure and speed of sound respectively in the driver, r is the radius of the barrel, L its length and m the piston mass.

Lemcke has also calculated the temperature rise as a function of \bar{x} , the non-dimensional distance along the barrel, using the method of characteristics to determine the exact piston and shock velocities as a function of \bar{x} . We may use this technique to calculate T_{av} for a given \bar{L} .

The larger \bar{L} , the nearer we get to optimum, uniform shock-heating conditions. Now

$$m \propto \rho r^3 \quad (22)$$

hence
$$\bar{L} \propto P_4 \cdot L \cdot r^{-1} \rho^{-1} \quad (23)$$

However, we have already seen from equation (12) that the temperature drop due to heat losses is also a function of the dimensions of the barrel and the pressure level, i.e.

$$(\Delta T_2/T_2) \propto P_4^{-1/5} L^{4/5} r^{-1} \quad (24)$$

It is clear that increasing P_4 both increases \bar{L} and decreases $(\Delta T_2/T_2)$ as desired. However, any increase in L or decrease in r , while increasing \bar{L} will also increase $(\Delta T_2/T_2)$. Thus a tunnel should be operated at as high a driving pressure as possible, using a piston with the best possible strength to density ratio, i.e. as light as possible.

To illustrate this balance between acceleration limiting and heat loss limiting let us compare two tunnels, at F.F.A. and R.A.R.D.E., which have quite different dimensions yet have similar performance.

	F.F.A.	R.A.R.D.E. ⁽⁶⁾
P_4	150 atm	200 atm
L	5.85 m	2.69 m
r	0.02 m	0.03 m
a_4	348 m/sec	348 m/sec
m	8 gm	73 gm
\bar{L}	114	17
P_4/P_1	1000	1000
% reduction in T_s due to non-uniform shock heating ⁽³⁾	5%	22%
% reduction in T_s due to heat losses (equation 12)	42%	15%
Measured T_s	2100°K	2000°K

The F.F.A. tunnel thus has more efficient shock heating but higher heat losses than the R.A.R.D.E. tunnel. The fact that the F.F.A. gun gives slightly higher temperatures is probably due to the fact that equation (12) over-

estimates the net heat loss. Also, no pressure measurements were made in the R.A.R.D.E. facility and consequently it is not known what effects piston friction or poor diaphragm opening, which effectively lowers P_4 and the pressure ratio P_4/P_1 , could have had.

7. METHODS TO IMPROVE GUN TUNNEL PERFORMANCE

The acceleration section

We have seen that the performance of a gun tunnel is limited by heat losses and by the non-uniform shock heating, due to the finite acceleration of the piston. Suppose, then, that a tunnel is designed to reduce the heat losses to a minimum by using a short barrel and large bore. This means that \bar{L} will be small, resulting in a loss of performance, since the acceleration phase is very

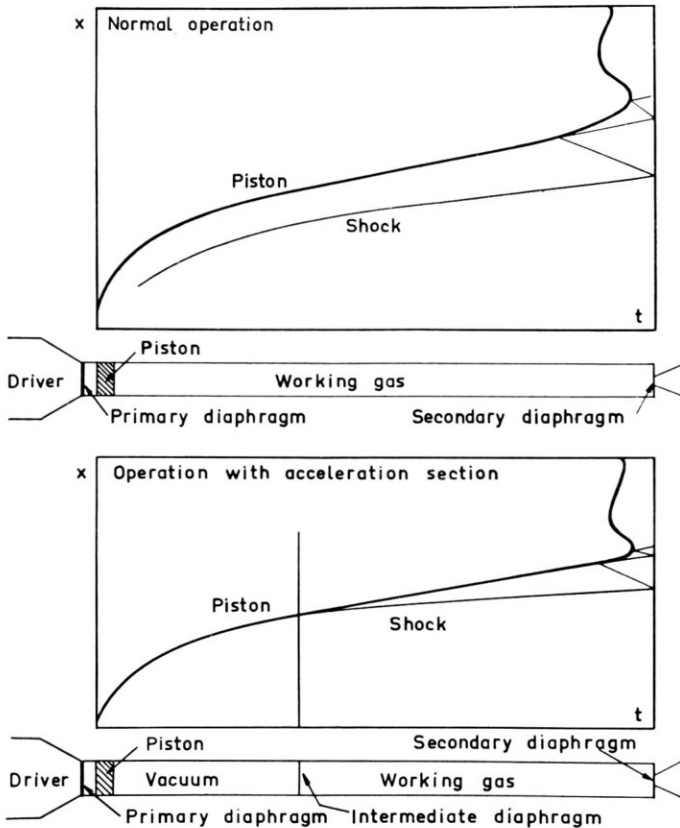


FIG. 8 — (x, t) diagrams for normal and modified operations

long. This may be overcome, however, by including an evacuated, 'acceleration' section between the driver and the driven gas. This arrangement is compared with the conventional arrangement in Fig. 8. The piston accelerates to some velocity equal to (or even slightly greater than) the maximum steady velocity under normal operating conditions and when it bursts through the intermediate diaphragm a strong shock wave is formed immediately and uniform shock heating is obtained along the barrel. Indeed, if the piston velocity at the intermediate diaphragm exceeds the maximum steady velocity then the shock heating and final temperature, for a given pressure ratio, is increased.

This arrangement was tried in the F.F.A. gun tunnel, following a suggestion by Professor S. Berndt of the Royal Institute of Technology in Stockholm, to evaluate the technique. This was purely a feasibility study as no marked increase in temperature could be expected in the F.F.A. tunnel since, as already explained, the reduction under normal conditions is very small. The intermediate diaphragms were made of Kodatrace and located half-way along the barrel, at a convenient joint. The pistons were the usual 8 gm Makrolon pistons. Micro-wave measurements were made to determine the piston velocity. The initial tests were concerned with the effects of varying the pressure, P_v , in the acceleration section. This has been reported by Brown-Edwards⁽¹⁵⁾ and Fig. 9 shows a typical test result. These tests demonstrated the following:

(1) The piston could be made to pass through a diaphragm without being damaged or tipping.

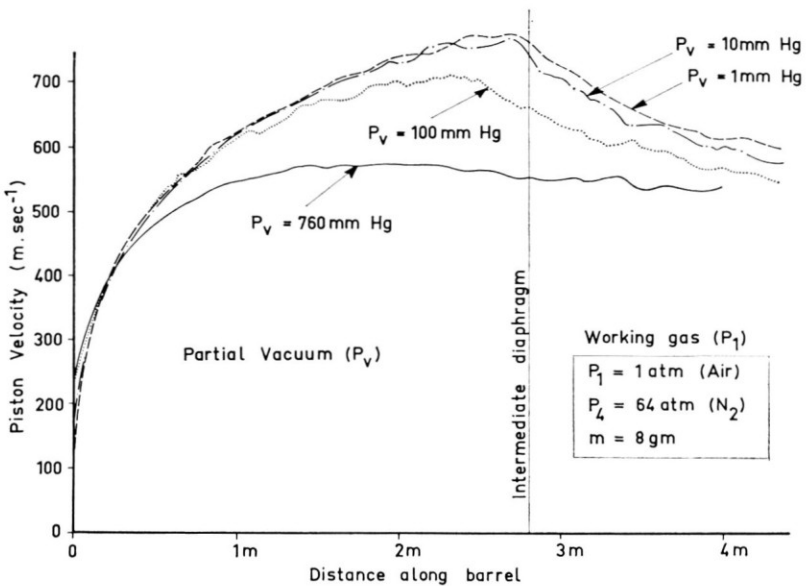


FIG. 9 — Effect of lowering the initial pressure in the acceleration section

(2) The length of the acceleration section needed was about 0.5 m at low pressure ratios ~ 100 increasing to about 3 m at higher pressure ratios ~ 1000 .

(3) No further advantage was obtained by reducing P_0 below 10 mm Hg. At this point friction between the piston and the barrel became the dominant mechanism. Recent tests to measure the stagnation temperature were less successful. Problems were encountered with burning of the Kodatrace diaphragm. Thin copper and aluminium foils were tried instead, but pitted the nozzle. Nitrogen was finally used as the working gas to inhibit burning. Measurements at low pressure ratios of 150–300 indicated a slight increase (~ 100 – 200°K) when the piston velocity exceeded the final steady velocity when it passed the intermediate diaphragm. At higher pressure ratios measurements were not possible because of the drastically reduced running time and increased peak pressures due to the fact that the volume of the working gas had been halved.

The double piston/double compression technique

Another technique which has been tried at F.F.A. is based on a double compression of the working gas. The barrel is divided into two sections by an intermediate diaphragm. The downstream section is evacuated and the upstream section contains the working gas. A secondary piston, which is perforated, is located at the intermediate diaphragm station. When the run is initiated the working gas is compressed between the primary and secondary pistons, until a predetermined pressure level is reached, when the intermediate diaphragm opens and the working gas expands through the perfora-

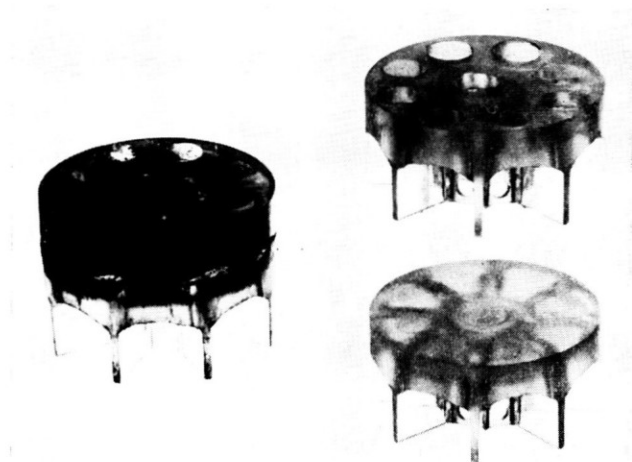
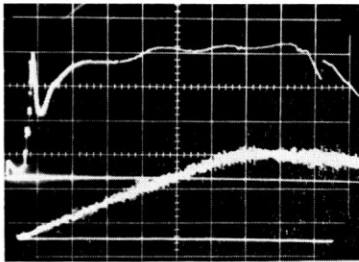


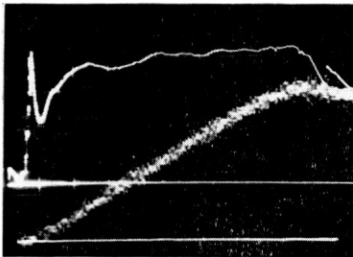
FIG. 10 — Primary and secondary (perforated) pistons before and after use. $P_3/P_1 = 150$. Nitrogen driving nitrogen

ted piston into the evacuated section. The primary piston then strikes the secondary piston, which is constrained by a shear ring, coalescing to form one piston, which continues along the barrel, compressing the working gas again. In this way something like a two-fold temperature increase over conventional operation is possible.

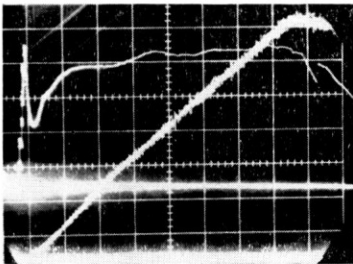
Initial tests in the F.F.A. tunnel using air as a working gas resulted in very high temperatures $\sim 2900^\circ\text{K}$ at a pressure ratio of 150. However, similar tests using nitrogen as a working gas produced temperatures of about 1800°K , although even in this case the piston was charred and there were signs of melting (Fig. 10). The high temperatures produced using air was shown to be due to total combustion of the oxygen together with Makrolon from the pistons and Kodatrace. In Fig. 11 the heat transfer rates, measured



100% N_2
 Upper trace: $P_s = 50 \text{ atm/cm}$
 Lower trace: $T_{cal} = 12.5^\circ \text{C/cm}$
 Sweep rate: 5 msec./cm



50% N_2
 + 50% Air



100% Air

FIG. 11 — Stagnation-point heat transfer, $M = 10$, demonstrating Makrolon/ O_2 combustion. Double piston. $P_4 = 150 \text{ atm}$. $P_1 = 0.5 \text{ atm}$.

at the stagnation point of a 15 mm diameter, 0.2 mm thick copper calorimeter, show clearly how the temperature increases as the amount of air is increased. Some tests were conducted using a metal secondary piston but resulted in failure of the primary piston.

Again tests at higher pressure ratios were not possible because of the reduced running time and even higher peak pressure since the piston mass had been nearly doubled.

However, the initial tests show some temperature increase at low pressure ratios and further tests are to be carried out.

8. CONCLUSIONS

It is seen that even if pistons can be developed which are sufficiently strong and resistant to burning, for use at very high pressure ratios in a gun tunnel, this will not guarantee high stagnation temperatures. Thus a conventional gun tunnel will be limited both by heat losses during the initial shock compression process and by inefficient shock heating due to the relatively long distance for the piston to reach maximum velocity.

Any improvement in gun tunnel performance will come only with radical changes in design. To reduce heat losses to, say, less than 5% at a pressure ratio of 1000 a short, wide-bore barrel is necessary.

However, if the barrel is too short peak pressures become very large. Also, as the barrel length is decreased the diameter must be increased to retain the desired running time. A barrel 3 m long and 10 cm diameter would, therefore, seem to be about the optimum. The heat losses are also reduced, peak pressures easier to handle and piston friction, less important if the overall pressure level is increased. This might imply using a nitrogen driver at 1000 atm. To take full advantage of the short barrel an evacuated 'acceleration' section, say 3 m long, would be necessary. This, however, would necessitate the development of a quick-opening valve (opening time ~ 1 msec) to replace the intermediate diaphragm, avoiding contamination of the working gas. Finally, the section of the barrel containing the working gas could be pre-heated to about 300°C. Of all these improvements probably the biggest gain would come from pre-heating. In the author's opinion stagnation temperatures of about 3500°K might be possible at a pressure ratio of 1000 in such a facility.

The double compression technique might also be developed as an alternative to yield higher stagnation temperatures, although the design problems are more severe. The use of a perforated piston might be avoided by the use of a two-stage quick-opening valve, which first opened half-way for the compressed gas to expand into the evacuated section, when some pre-determined pressure level had been reached and then opened fully to allow the piston to

continue down the barrel, compressing the working gas a second time. B. Överby of F.F.A. has even designed a double-barrel gun, with one gun acting as a pre-heater for the other. However, although these techniques yield spectacular temperature increases on paper, it is expected that the losses will be much higher than in a conventional tunnel and the net result may be a modest increase only in stagnation temperature.

ACKNOWLEDGMENTS

The author wishes to thank B. Lemcke and E. G. Brown-Edwards for their collaboration in much of the work reported here. The author is also grateful to K. H. Sehlberg for help in conducting experiments in the F.F.A. gun tunnel. This work has been supported jointly by F.F.A. and the Royal Swedish Air Force Board.

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DISCUSSION

R. N. Cox (R.A.R.D.E., Fort Halstead, England): First I would like to congratulate Mr. Edney on his detailed and masterly paper.

There seems to be a law operating on both sides of the Atlantic that the temperatures claimed for high enthalpy facilities vary inversely with the year of the statement! Now that we have hit rock-bottom on the temperatures obtained, it is perhaps time we started climbing back up again.

One point which the speaker made with which I would disagree concerns his statement that the highest possible pressure ratio will give the maximum temperature. This is not true when operating with the equilibrium (plateau) pressure mode. Pennelegion and East at Southampton have shown that the quasi-equilibrium pressure existing behind the piston while the deceleration shock moves back down the barrel and reflects back again, reaches a maximum as the initial pressure ratio is varied. This means that there must also be an optimum pressure ratio at which the highest temperature is obtained.

In general, I feel that preheating the barrel is the simplest way to obtain higher temperatures, and that if temperatures in excess of, say, 3000°K are required, then one might consider adding more heat by electrical discharge.

J. L. Stollery (Aero Dept., Imperial College, London, England): First let me add my congratulations; I think that the F.F.A. have shown great qualities of ingenuity and perseverance in developing the gun tunnel. There is, however, still far too much emphasis on the 'hunt for high stagnation temperature'. The gun tunnel, in my opinion, is not a high enthalpy device. If one wants high temperature then the 'radical design change' needed is to throw the piston away and operate the facility as a shock-tunnel. The gun tunnel is essentially a cheap, 'cold' facility, ideal for producing high Reynolds number flows and it is these virtues that should be emphasised and further explored. I wonder if the Author would agree?

Mr. Edney: I fully agree that the most attractive feature of the gun tunnel is its high Reynolds number capability, as I pointed out in the introduction to my paper, and for most people this is reason enough for building one.

However, it is a little misleading to suggest that higher temperatures can be obtained by simply throwing away the piston. Assuming that the resulting

shock tunnel should be operated 'tailored', then the nitrogen driver must be replaced by a heated helium driver if higher temperatures are to be reached (a cold helium driver yields only 2000°K which is no improvement!). In Sweden, at least, this is an expensive proposition. Probably a combustion-driven shock tunnel is the only solution but before abandoning the gun tunnel, which is cheap and simple to operate and which has other advantages over the shock tunnel, as I have mentioned, we have chosen to spend a little time and money to see what improvements are possible. Apart from the work of Cox on pre-heating of the barrel I do not think much thought has been given to this matter before.