Blast from Moving Guns

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To investigate the blast loads from the guns of military aircraft, a 7.62-mm caliber rifle was fired in the RAE 3-ft × 3-ft wind tunnel over the speed range from $M = 0$ to 1.8, and over a wide range of static pressures. The blast wave arrival times and the local static pressure ratios were measured by transducers mounted on an adjacent plate, offset at spacings of 10, 20, and 30 calibers. These measurements generally were well correlated by Smith's theory, both with respect to the variation of speed and pressure. However, downstream of the muzzle, discrepancies between the measurements and the theory increased with speed, particularly when the plate was closest to the gun. Shock-wave/boundary-layer interaction occurred between the blast wave and the plate, but had a minor influence on the blast loadings upstream of the muzzle.

Nomenclature

a	= velocity of sound, m/sec
A,B	= constants in power laws [Eqs. (8) and (9)]
c	= caliber of gun, mm
c',c''	= transformed calibers [Eqs. (1) and (6)]
f	= distribution function [Eq. (1)]
G,H	= functions of R/c'' [Eqs. (4) and (5)]
l	= length of gun barrel, mm
M	= freestream Mach number
m,n	= indices in power laws [Eqs. (8) and (9)]
p	= static pressure, bar
Δp_s	= side-on static pressure jump, bar
Δp	= pressure jump on plate, bar
R,θ	= polar coordinates of point on blast wave from nozzle of static gun, or equivalent moving gun
T	= static temperature, K
t	= blast wave arrival time, sec
u	= freestream velocity m/sec
w	= energy in blast wave, J
s,y,z	= coordinates of blast wave relative to fixed gun (x positive forwards of gun)
X,Y,Z	= coordinates of blast wave from moving gun relative to an observer fixed in space

Subscripts

0	= sea-level conditions

I. Introduction

THERE is currently considerable interest in the influence of gun blast on military aircraft, but few reliable measurements are available to the aircraft designer. The main problem is the estimation of local blast loads on the structure near the muzzle of the gun, which could determine either the strength required or the fatigue life.

A theory to estimate the approximate level and duration of these blast loads for both static and moving aircraft was outlined by F. Smith in three published papers[1-3] and developed in more detail in an unpublished note[4] which received limited circulation. This paper presents a brief outline of the theory and summary of wind-tunnel measurements made to verify the theory. A full report of the experiment will be issued later.[5]

II. Experimental Details

Figure 1 shows the general arrangement of the gun blast experiment in the RAE 3-ft × 3-ft wind tunnel. A NATO rifle with a caliber c of 7.62 mm was mounted on the axis of the tunnel, adjacent to a horizontal plate which could be offset at vertical separations of $z/c = 10$, 20, and 30. This gun and the plate configurations were selected to reproduce the geometry of Smith's preliminary experiment made in a small shock tube at atmospheric pressure.[1,2] Twelve Kistler Type 603B pressure transducers were flush-mounted on the plate at the streamwise distances of $x/c = -5$, 9, 23, and 51 and spanwise distances of $y/c = -5$, 0, and 10.

The rounds fired from the gun traversed the working section and were collected in a catcher box supported by struts in the settling chamber. The catcher box was filled with telephone directories to absorb the energy of the rounds so that neither the screens nor the coolers of the tunnel were damaged during the experiment. Figure 2 shows some photographs of the main components. The tunnel test conditions are given in Table 1.

The static pressure on the plate p determines the strength of the blast wave, the pressures and temperatures within the barrel of the gun remaining nominally constant throughout the test series. In fact there is a significant variation in the barrel pressures and temperatures for every round so that some repetition of shots is essential to establish reliable measurements. From range tests of the gun and plate at atmospheric pressure, during which 30 rounds were fired, it was established[5] that with only three shots the 95% confidence limit of the plate pressure ratios $\Delta p/p$ was within about ±15% of the estimated mean. This number of shots was considered adequate for the tunnel experiment.

High-speed cine films were taken at about 18,000 frames per second of the blast waves shown by the tunnel Schlieren system with a horizontal knife edge. Figure 3 shows some typical photographs with the air at rest and in motion at $M = 1.5$; full details of the equipment used are given in Ref. 5.

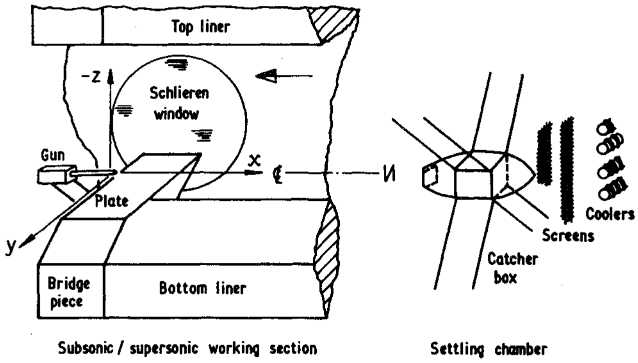

Fig. 1 General arrangement of gun blast experiment in RAE 3-ft × 3-ft tunnel.

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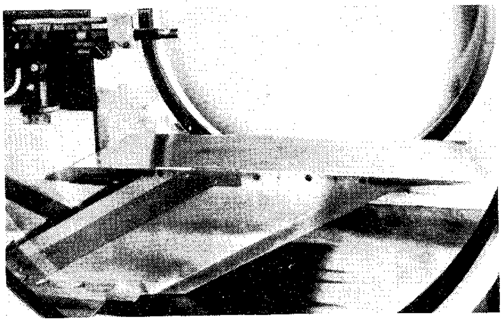
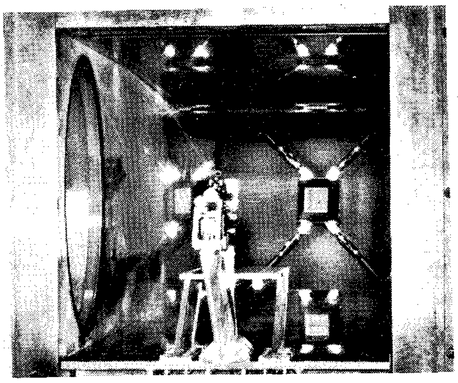
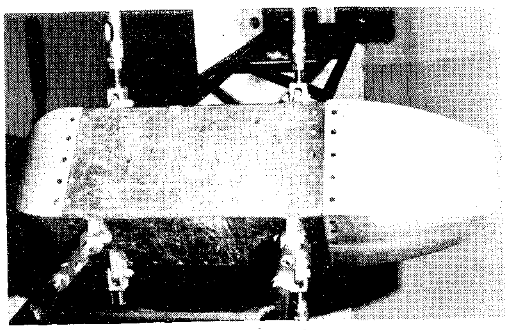


a) Schlieren window



b) View upstream



c) Catcher box

Fig. 2 Main components of experiment.

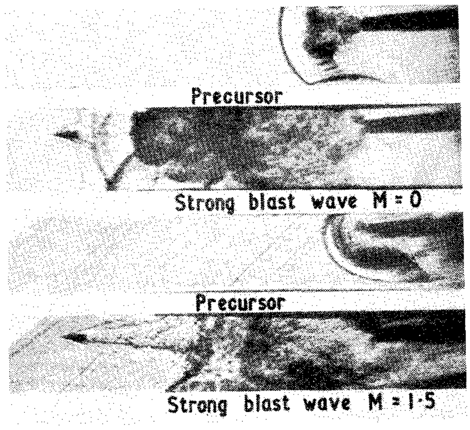


Fig. 3 Typical blast waves.

III. Outline of Theory

The flow around the muzzle of a static gun at sea level has been described in detail in some recent papers.[6-8] In particular, Ref. 6 discusses both the weak precursor blast wave, formed by the air driven out of the barrel in front of the round, and the strong blast wave generated by the charge gases behind the round, which expand from a high pressure (quoted[7] as about 400 bar) down to ambient pressure (Fig. 3a). Reference 6 concludes that the structural features of both blast waves "are well described by inviscid considerations, despite the turbulent motions," and that gun muzzle blast corresponds with a constant rate of energy release, rather than an instantaneous release of energy, as in an explosion. Both of these conclusions were implicit in Smith's theory, which refers only to the strong blast wave. The strong, small-scale turbulent motions within the blast wave influence the duration and intensity of the muzzle flash[7,8] but make no contribution to the blast loads, which have a much larger scale related with the inviscid structure of the blast wave.

Smith assumed[1-4] that there was no essential change in character between the blast waves for static and moving guns (consistent with the typical photographs presented from this experiment compared in Fig. 3a and Fig. 3b) and suggested that the blast waves between static and moving guns could be related by appropriate similarity relationships (Fig. 4).

For a fixed gun at sea level with static pressure p_0, Smith suggested that at a point with polar coordinates R, θ, the blast wave time of arrival t and static pressure ratio $\Delta p_s/p$ were a function of an equivalent caliber c' where

$$c'/c = f\cos\theta + \sqrt{1 - f^2\sin^2\theta} \tag{1}$$

For a particular static gun at sea level f is a constant (0.80 for the 7.62-mm rifle tested) which could be calculated from the internal energy of the propellant and the composition of the products of combustion. For the same moving gun at sea level Eq. (1) still applied, but f became a function of the Mach number M, i.e.,

$$f = f(M) \tag{2}$$

and provided a more strongly directional blast field than for the static gun.

Table 1 Test conditions

Mach number, M	Static pressure, p, bar
0	0.98, 0.68, 0.34, 0.17
0.35	0.89, 0.19
0.70	0.71, 0.15
1.50	0.23, 0.054
1.80	0.13, 0.034

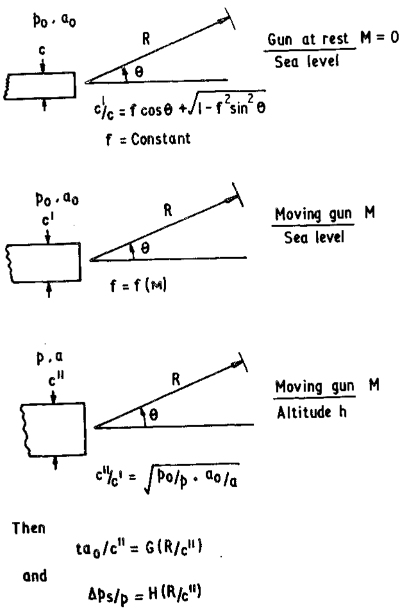


Fig. 4 Similarity relations for gun blast data, after Smith.

Variation in the altitude h at which the gun operated had a minor effect on the function f but a strong effect on the strength of the blast wave, because of the increase in $\Delta p_s/p$. The increase in strength of the blast wave corresponded with a further effective increase in caliber c'' given by

$$\frac{c''}{c'} = \sqrt{\frac{p_0}{p}\frac{a_0}{a}} = \sqrt{\frac{p_0}{p}}\left(\frac{T_0}{T}\right)^{1/4} \tag{3}$$

Then, the dimensionless arrival time could be written

$$ta_0/c'' = G(R/c'') \tag{4}$$

and the static pressure ratio could be written

$$\Delta p_s/p = H(R/c'') \tag{5}$$

Smith presented convincing evidence of the validity of Eq. (1) for the firing of a static 7.62-mm rifle, and some limited evidence for the validity of Eq. (2) for the same moving gun at sea level. However, he was unable to verify Eq. (3) directly and the present tests suggest that the simpler relation

$$c'' = \sqrt{p_0/p} \tag{6}$$

makes an adequate correlation of the measurements. (In the atmosphere between sea level and 36,000 ft, $(T_0/T)^{1/4}$ only increases by a factor of 1.06, so that this term can only have a minor influence in the values of c'' selected.) Mean correlation curves for Eqs. (4) and (5) for the static firing of the 7.62-mm rifle at sea level are reproduced from Ref. 3 in Fig. 5.

Smith attempted to quantify the blast loads on surfaces adjacent to the gun muzzle by two experiments. In the first, he measured the pressure ratios on a small flat plate aligned with the direction of motion of the blast wave from a static gun, giving the side-on static pressure ratio $\Delta p_s/p$ as predicted by the theory. He also measured the pressures on the small flat plate held normal to the blast wave, and found that the static pressure ratio was then

$$\Delta p/p \simeq 2\Delta p_s/p \tag{7}$$

consistent with the theory for the reflection of weak blast waves, rather than for strong blast waves.[9] In the second experiment he found that the pressures on the small plate normal to the blast wave from a static gun were almost the same as those for points on the long plates parallel with the gun muzzle at vertical separations of $z/c = 10$, 20, and 30 (Ref. 2, Fig. 8).

The time of arrival of the blast wave makes no assumption about the nature of the reflection process at the plate; hence, examination of the validity of Eq. (4) provides the most satisfying test of the theory. Some additional details of the theory are given in the Appendix.

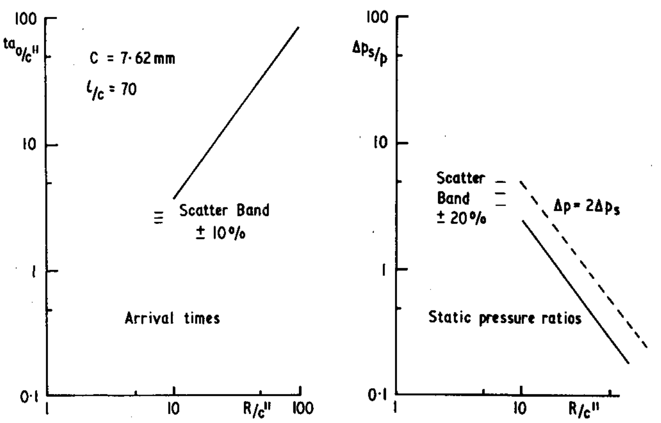


Fig. 5 Correlation of gun blast data, after Smith ($M = 0, p = p_0$).

IV. Results

A. Static Firings

Figure 6 shows the correlation of gun blast data achieved after firings in the RAE 3-ft tunnel with the air at rest. During this test the static pressure was reduced whereas the static temperature of the air in the tunnel remained constant at about 15°C. Hence there was no change in the velocity of sound and Eqs. (3) and (6) gave identical values for c''.

The arrival times of the blast wave are well correlated by the relation

$$ta_0/c'' = 0.221(R/c'')^{1.309}$$

which is displaced a little above Smith's correlation. The fair correlation of the arrival times for points both upstream and downstream of the muzzle implicitly confirms the validity of Eq. (1) for $M \equiv 0$.

The plate pressure ratios are well correlated by the relation

$$\Delta p/p = 126(R/c'')^{-1.379}$$

and this line is indistinguishable from the line $\Delta p/p = 2\Delta p_s/p$, where the values of $\Delta p_s/p$ were taken from Smith's correlation.

B. Wind-On Firings

The wind-on measurements are made effectively with an aircraft-mounted observer at a fixed point x, y, z relative to the aircraft (in this experiment, the flat plate). Smith conjectured that the blast wave is merely blown back by the main stream flow, whereas the interaction between a blast wave and a flowing stream must be more complex. However, the approximate theory requires a comparison of the measurements

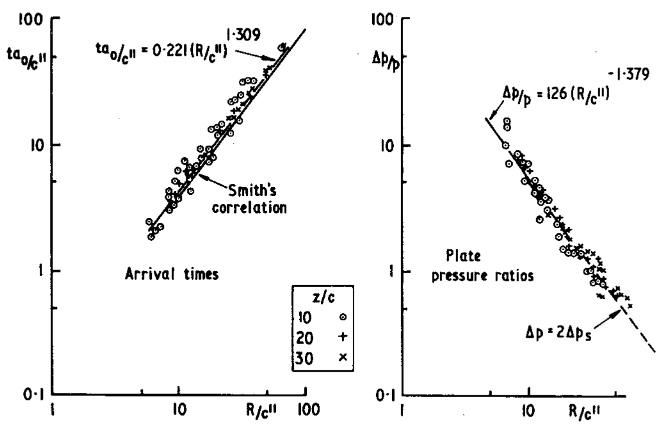


Fig. 6 Correlation of gun blast data ($M = 0$, p varies).

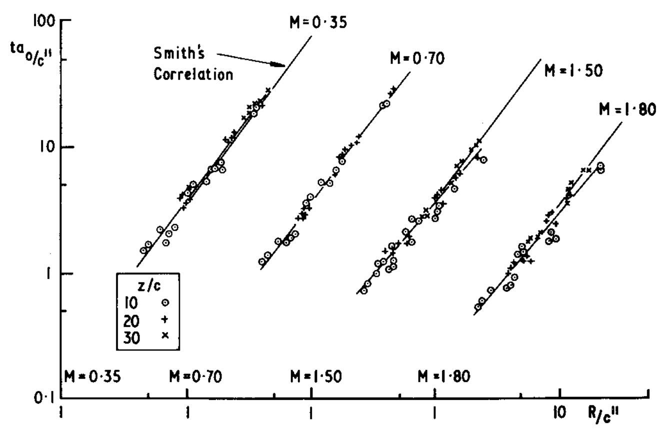


Fig. 7 Blast wave arrival times—upstream of muzzle.

Table 2 Values of A and n

M	A	n
0	0.221	1.309
0.35	0.176	1.344
0.70	0.170	1.349
1.50	0.205	1.214
1.80	0.202	1.196

Table 3 Values of B and m

M	B	m
0	126	1.379
0.35	185	1.509
0.70	267	1.671
1.50	507	1.839
1.80	510	1.830

relative to an observer fixed in space. This transformation may be achieved by writing $X=x+ut$, $Y=y$, and $Z=z$, so that we now have (instead of the geometric definitions of R, θ relative to the fixed gun),

$$R=\sqrt{X^2+Y^2+Z^2}$$

and

$$\theta=\cos^{-1}(X/R)$$

Equation (6) was used to calculate c'' in preference to Eq. (3) and the measurements downstream of the muzzle are considered separately (Sec. IVC).

Figure 7 shows the correlation of the blast wave arrival times measured upstream of the muzzle. These are well represented by power laws of the form

$$ta_0/c''=A(R/c'')^n$$

Table 2 shows that these measurements are in good agreement with Smith's correlation at subsonic speeds and in fair agreement at supersonic speeds.

The much lower static pressures at supersonic speeds (Table 1) produce stronger shock waves at a given point so that, in terms of the correlation, the measurements extend down to very small values of R/c'' (Smith's correlation only extended down to $R/c''=10$).

Figure 8 shows the excellent correlation of the plate pressure ratios measured upstream of the muzzle. These may be represented by power laws of the form

$$\Delta p/p=B(R/c'')^{-m}$$

although the constant B and the index m vary appreciably with Mach number, as Table 3 shows.

These variations may be partially attributed to the fact that, as the speed increases, the measurements extend down to progressively lower values of (R/c''), and that the power law should include additional terms to cover this wide range accurately. However, it is encouraging to note that at $M=0$, when the measurements are confined to the same range of R/c'' as the correlation ($10<R/c''<100$), the index $m=1.379$ is quite close to Smith's predicted "close in" value of $m=1.333$. The high values of m measured at low values of R/c'' are important because many aircraft guns are close to adjacent surfaces. (Values of $z/c=5$ to 10 are typical.) Hence, extremely low values of R/c'' occur in flight, particularly at high altitudes.

C. Downstream of Muzzle

The wind-on measurements downstream of the muzzle at $x/c=-5$ are distorted by the local flow around the gun, particularly with the plate closest to the gun ($z/c=10$), so that these measurements cannot be included fairly with the measurements upstream of the muzzle. Thus, Fig. 9 shows that the blast-wave arrival times at the downstream station are delayed significantly relative to the mean lines through the measurements at the forward stations on the plate, the delay time increasing with Mach number and being largest for $z/c=10$. Similarly, Fig. 10 shows that downstream of the muzzle the degree of correlation of the plate pressure ratios deteriorates progressively as speed increases. Thus, at $M=0.35$ there is still a fair degree of correlation with the forward measurements for all values of z/c, whereas at $M=0.70$ the correlation fails for $z/c=10$.

At supersonic speeds the downstream measurements at $z/c=10$ are an order of magnitude smaller than they are upstream, and $\Delta p/p$ actually increases with R/c''. This change occurs because the supersonic flow about the gun and its support modifies the development of the blast waves. These changes are thus peculiar to the present installation and cannot have general application. It is possible that the measurements downstream of the muzzle for $z/c=10$ at supersonic speeds are affected by the strong shock-wave/boundary-layer interaction on the plate, which is not included in the theory and which might be sensitive to variations in Reynolds number, particularly at low Reynolds numbers (i.e., small static pressures and hence small values of R/c'').

V. Discussion

Figures 6-8 show that Smith's correlation of the blast wave arrival times and the measurements upstream of the muzzle are in good agreement, considering the wide range of speed and static pressure. This suggests that Smith's conjecture that the blast wave is merely blown back by the mainstream flow, without significant modification, is a fair first approximation.

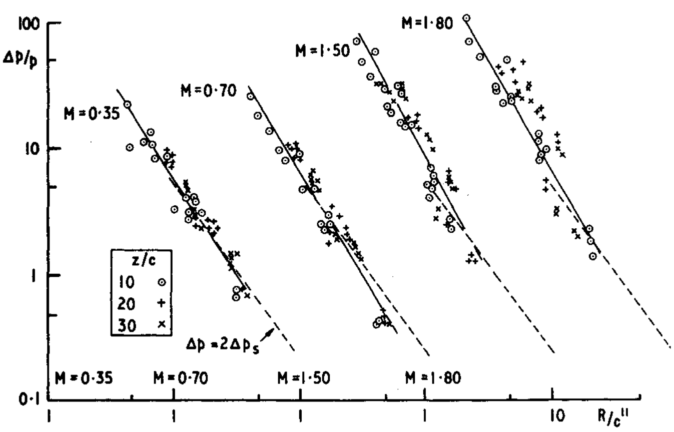


Fig. 8 Plate pressure ratios—upstream of muzzle.

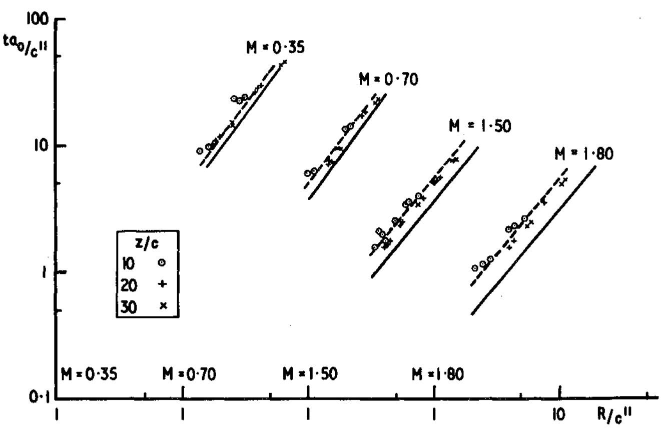


Fig. 9 Blast wave arrival times—downstream of muzzle ($x/c=-5$).

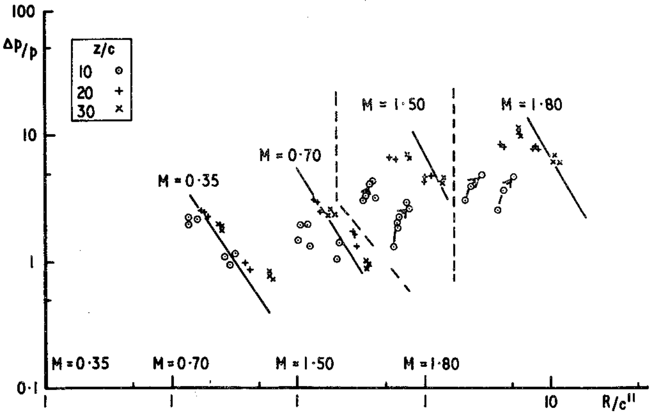


Fig. 10 Plate pressure ratios—downstream of muzzle ($x/c = -5$).

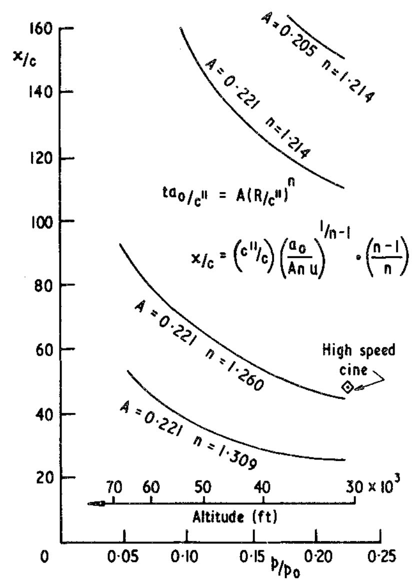
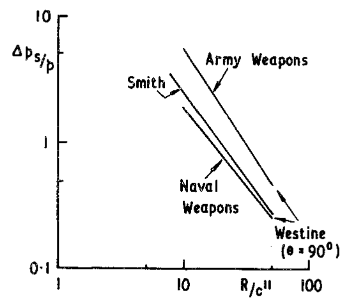


Fig. 11 Predicted and measured forward movement of blast wave, $M = 1.5$.

Fig. 12 Comparison with previous measurements ($M = 0, p = p_0$).



For the aircraft designer, the forward movement of the blast wave is of crucial importance, particularly at high speeds. If we assume that Eq. (4) can be represented by the power law

$$ta_0/c'' = A(R/c'')^n$$

we find that the maximum forward movement x of the blast wave along the axis of the gun ($\theta \equiv 0°$) is given by

$$x/c = (c''/c)(a_0/Anu)^{1/(n-1)}(n-1)/n \qquad (8)$$

where u = freestream velocity. This expression is sensitive to the values taken for n and A (see Fig. 11). The forward movement of the blast wave measured from the high-speed cine-film at $M = 1.5$ and a static pressure ratio of $p/p_0 = 0.23$

Table 4 Forward movement of blast wave; $M = 1.5, p/p_0 = 0.23$

z/c	x/c
10	45
20	34
30	31

for $z/c = 10$ was $x/c = 45$, which would correspond with values of about $A = 0.221$ and $n = 1.260$ from Eq. (8). In contrast, the constants inferred from the mean fit to the measurements (Fig. 11) are $A = 0.205$ and $n = 1.214$. With these values Eq. (8) predicts a much greater forward movement, $x/c = 150$. Two main factors may contribute to this discrepancy: 1) the local velocity varies along the axis of the gun and is not exactly equal to the mean freestream value u as Eq. (8) assumes; and 2) the blast wave arrival times at the plate are subject to small errors which indirectly affect the choice of A and n, particularly for $z/c = 10$. In contrast, the forward movement of the blast wave along the axis of the gun can be measured precisely from the cine-films (but much less easily along the plate) and is not, of course, subject to any timing errors. It is interesting to note that the forward movement of the blast wave along the axis of the gun increases slightly as the plate is brought closer to the gun (Table 4). This effect is small, but corresponds with a reduced Mach number of the flow between the plate and the gun consequent upon the blockage caused by the increased shock-wave/boundary-layer interaction between the blast wave and the plate. It does not appear as a systematic error in the correlations of the arrival times or plate over pressure ratios upstream of the muzzle, but it undoubtedly influences the discrepancies observed downstream of the muzzle which have been noted already.

Incidentally, Fig. 11 reminds us of the important prediction from the theory that the forward movement of the blast wave increases rapidly as the static pressure is reduced (or the altitude is increased in flight) and this is confirmed by the measurements. Figures 6 and 8 also suggest that the plate pressure ratios, and those inferred from Smith's correlation of static pressure ratios by Eq. (7) are in fair agreement. No measurements of the static pressure rise were made during the present experiments, but their general level may be inferred from Eq. (7) to be close to Smith's correlation. This agrees with Westine's predictions[10] for naval guns, if the appropriate term for the energy in the blast wave w is substituted (Fig. 12). Now Smith's correlation of the static pressure rise also has been confirmed by an unpublished BAC experiment on a larger gun ($c = 27$ mm, $M = 0, p = p_0$). Hence, for static guns the present authors recommend Westine's correlation for naval weapons, rather than his correlation for army weapons, which also is included in Fig. 12.

With the wind on, Figs. 9 and 10 show that downstream of the muzzle of the gun the theory should be used with caution, particularly close to the gun. It is likely that a similar qualification also would apply for aircraft installations with gun blisters, fairings, or muzzle brakes, because these would modify the local flow about the gun, and hence alter the development of the blast wave downstream of the muzzle.

It is possible that in the future a more accurate theory may be developed, perhaps even using some of the ideas presented by Oppenheim et al.[11] For the present, Smith's theory, complemented by the present measurements, should allow aircraft designers to make "ball-park" estimates of the blast waves from moving guns.

VI. Conclusions

The present measurements suggest that Smith's theory gives an accurate method for predicting the arrival times of blast waves upstream from moving guns, and a fair indication of the corresponding blast loads on adjacent surfaces. However, downstream of the muzzle and close to the gun, discrepancies occur between the measurements and the theory which increase with speed. These discrepancies are attributed to the influence of the local flow around the muzzle of the gun on the development of the blast wave, and to shock-wave/boundary-layer interaction at the plate. This interaction had a relatively minor influence on the blast loads upstream of the muzzle.

Appendix: Summary of Smith's Scaling Relations

The specific kinetic energy of the propellant gas is given[3] by

$$\epsilon = (a_e + u)^2/2 + (a_e^2 - a_r^2)/\gamma_e(\gamma_e - 1)\ (J/kg)$$

where a_e is the exit velocity of propellant gas from the gun (983 m/sec for the 7.62-mm rifle), a_r is the speed of sound in propellant gas when cooled to ambient temperature (300 to 233 m/sec in present tests), and γ_e is the propellant ratio of specific heats (1.285).

The distribution function f then is given by $f\ (1\text{-}0.2 f^2) = a(a_e + u)/K\epsilon$, where K=constant for a particular explosive. Smith finally recommended[3] using $K = 0.166$, rather than the original value,[1] $K = 0.185$.

If the gun barrel is lengthened from l to l' the equivalent caliber should be decreased[4] by the ratio $(l/l')\ \exp(3\gamma_e - 1)/4$. If changes in the propellant change the exit velocity from a_e to a_e' the effective caliber is changed[4] by the ratio

$$(a_e'/a_e)\exp(3\gamma_e - 1)/2(\gamma_e - 1)$$

Acknowledgment

The correlations presented in this paper are based on measurements made by the staff of Weapons Department, RAE, Farnborough.

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