Thermo-chemical erosion in gun barrels

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Abstract

When a gun fires the metal temperatures at the bore may reach $1100°C$ in a few milliseconds and decline to half this value by the time the projectile reaches the muzzle. Although the temperature fluctuation does not penetrate very far from the surface it does create a hard and brittle surface layer commonly referred to as the *heat-affected zone*. The diffusion of chemical species such as CO, CO_2, H_2, H_2O and N_2 into the hot surface forms a *chemically-affected zone*. Wear rate in guns is related to the thickness of this chemically-affected zone. From the equation of mass diffusion a simple equation of the Arrhenius type is derived relating the wear per round to the initial temperature, the maximum surface temperature, and the erosivity of the propellant. This equation is verified by trials on a vented vessel, which simulate gunfire, and also by data on the wear rates of numerous gun and propellant combinations. The erosivity of service propellants is correlated with their chemical composition and demonstrates that CO and H_2 are very erosive whereas CO_2, H_2O and N_2 are much less erosive. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

It has long been known that the performance of a gun is limited by the wear rate of its barrel. In the 16th century, Biringuccio [1] discussing the lack of range in a cannon, says: "if the defect comes from the powder, you must give it more so that it serves, although I do not recommend this because of the danger of wearing out the gun". Gun-wear remains, to this day, one of the main factors limiting a gun's muzzle velocity and range. It normally occurs as an increase in bore diameter at the commencement of rifling and from here it spreads down the barrel towards the muzzle. As a measure of wear it is conventional to quote the increase in bore diameter measured at 1 in. (25 mm) from the commencement of rifling. The increase in diameter that can be tolerated before a barrel is condemned depends on the accuracy that is required. For tank guns, which need to be very accurate in order to hit a target at the first attempt, the permissible wear is about 0.5–1% of the bore diameter. For indirect fire weapons, such as howitzers, the allowable wear may be as much as 5% or even 8% of the bore diameter. Gas leakage between the projectile and the worn barrel reduces the pressure and the projectile's muzzle velocity, range, and accuracy, gradually reduces as wear increases. Typical wear rates vary between 0.1 and $200 \mu m$ per round and usually exceed the fatigue crack propagation rate. As a rule the gun

designer arranges for the fatigue life of a barrel to exceed its wear life because fatigue failure is usually catastrophic and endangers the gun crew, whereas barrel wear simply reduces the accuracy of the projectile without putting the crew in danger.

Wear sometimes occurs at other places along a barrel. For example, Montgomery [2] reports wear at the muzzle in some US cannon, and some workers have reported a second maximum at a point midway between the breech and the muzzle. This paper, however, is restricted to wear at the commencement of rifling which may be considered the normal position. Besides being the point of maximum wear, the commencement of rifling is also the point at which heat transfer from the hot propellant gas to the barrel surface is greatest. Typically, the bore temperature reaches $600–1200°C$ at this place within a few milliseconds of exposure to the hot propellant gases. Heat transfer may be $500 \, MW/m^2$, and the propellant gas pressure may reach 600 MPa. Wear has always been related to the intense thermal conditions experienced at this point and as early as 1911, Jones [3] derived an empirical equation based on this assumption. Other early work of note includes Shulyer [4] and Kent [5]. Thornhill's work [6] is particularly interesting in that he looked for a linear correlation between wear per round and the maximum temperature at the bore, and many of the ideas he originated have found application here.

An excellent review of gun barrel erosion was given by Ahmad [7]. In the same volume Ebihara and Rorabaugh [8] describe various erosion mechanisms and Bracuti [9]

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Nomenclature

A_1	constant
A	erosivity of propellant (m/s)
B	diffusivity constant (m²/s)
c	concentration of diffusing species
C_v	specific heat at constant volume (J/kg K)
d	bore of gun tube (m)
H_∞	total heat transfer per round (J/m²)
k	thermal conductivity of solid (W/m K)
k_g	thermal conductivity of gas (W/m K)
m	projectile mass (kg)
m_c	charge mass (kg)
p	gas pressure (Pa)
p_{max}	maximum gas pressure (Pa)
R_0	universal gas constant (=8314 J/kg-mol K)
Re	Reynolds number (Eq. (11))
R_T	thermal property ratio (Eq. (11))
t	time (s)
t_0	time-constant (s)
t_1	time during which erosion occurs (s)
T	temperature (K)
T_f	propellant flame temperature (K)
T_i	initial surface temperature (K)
T_0	surface temperature (K)
T_{max}	maximum surface temperature (K)
T_x	temperature at distance x (K)
u	dimensionless time (t/t_0)
v	velocity (m/s)
v_m	muzzle velocity (m/s)
w	wear per round (m)
x	distance from surface (m)

Greek letters

ΔE	activation energy (J/kg-mol)
θ	$\Delta E/R_0$ (K)
κ	thermal diffusivity of surface $k/\rho C_v$ (m²/s)
μ_g	viscosity of propellant gas (Pa s)
ρ	density of surface material (kg/m³)

discusses the role of wear reducing additives. In the 1950s, polyurethane foam liners were found to reduce wear rates and in 1961 the "Swedish additive" (titanium dioxide powder in wax, coated on rayon cloth) was introduced and proved to be even more effective. It was assumed that these additives worked by reducing heat transfer. Eventually, Ward and Brosseau [10,11] succeeded in showing that these additives reduced heat transfer by up to 25% and this caused a hundred fold reduction in wear. Lawton [12] investigated some thermal and chemical influences on barrel wear and found that wear increased exponentially with temperature such that a 10% reduction in temperature reduced wear by about 300% and he reported a simple relation between the erosivity of a propellant and its chemical composition.

This relation was used by Kimura [13,14] to design a new range of low vulnerability propellants having very low erosivity.

In this paper, a more rigorous derivation of the relation between wear, bore temperature, and propellant erosivity is given and an improved relation between propellant erosivity and its chemical composition is derived. These relations are confirmed by vented vessel tests and by analysis of gun wear rates in service. The theory is restricted to normal wear at the commencement of rifling; muzzle-wear, melt-erosion, the use of chrome-plating is not considered.

2. Gun wear theory

Fig. 1 (top) shows the unworn section of a rifled gun that may be compared to the eroded section at the commencement of rifling of the same gun (middle). This is normal wear. The bore diameter increases uniformly around the barrel at the commencement of rifling and spreads along the barrel towards the muzzle. Occasionally, oval wear occurs, that is, wear is perhaps 20% greater in the vertical plane than in the horizontal plane. This type of wear occurs at temperatures between 900 and 1400 K, which is well below the melting point of gun steel. Gas wash past a faulty driving band can cause local melt erosion (Fig. 1 (bottom)), and such erosion is many times faster than normal erosion.

A photomicrograph showing the sub-surface of gun steel, after firing 10 rounds, is shown in Fig. 2. Three layers are apparent, marked A, B and C. The layer marked A is the original structure. The layer marked B extends perhaps 200 μm from the surface and is called the *heat-affected zone*. In this region, the gun steel had been subjected to a large temperature fluctuation each time the gun was fired. The temperature fluctuation may be 1000°C at the surface but 1 mm from the surface it is only about 100°C, and the period of the fluctuation may be 5–50 ms. The microstructure of the heat-affected zone changes towards the surface and the steel becomes harder and more brittle. The layer marked C is called the *chemically-affected zone*. At high temperatures, chemical species from the propellant gas diffuse into the crystal lattice altering its chemical composition. These species include the main products of propellant combustion (CO, CO_2, H_2, H_2O and N_2) and a small quantity of dissociated atomic species. This further reduces the strength and increases the brittleness of the surface layers. Hardness increases from about 250 Hv in region A, to 500 Hv in region B, and 1000 Hv in region C. Micro-cracks form in region C, some normal to the surface and some parallel with the surface. The shear stress caused by high velocity gas flow, and the contact stress generated by the driving band, are sufficient to remove a portion of the cracked and brittle layer. The amount of wear depends on the depth to which the chemically-affected zone has penetrated which, in turn, depends on the chemical composition of the propellant and on the bore surface temperature.
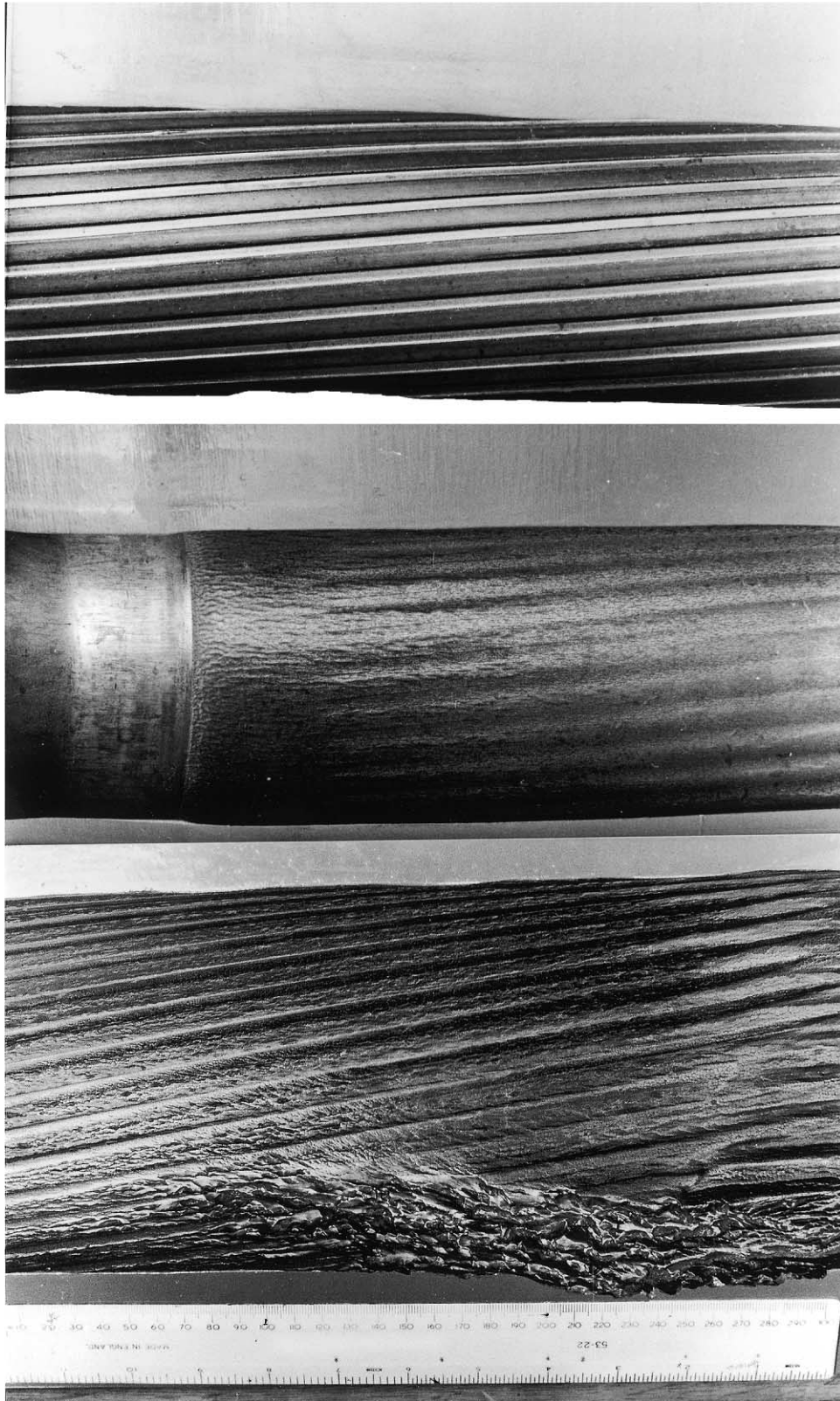
Fig. 1. Typical gun erosion at the commencement of rifling — top: unworn surface; middle: normal wear; bottom: abnormal wear (melt erosion).
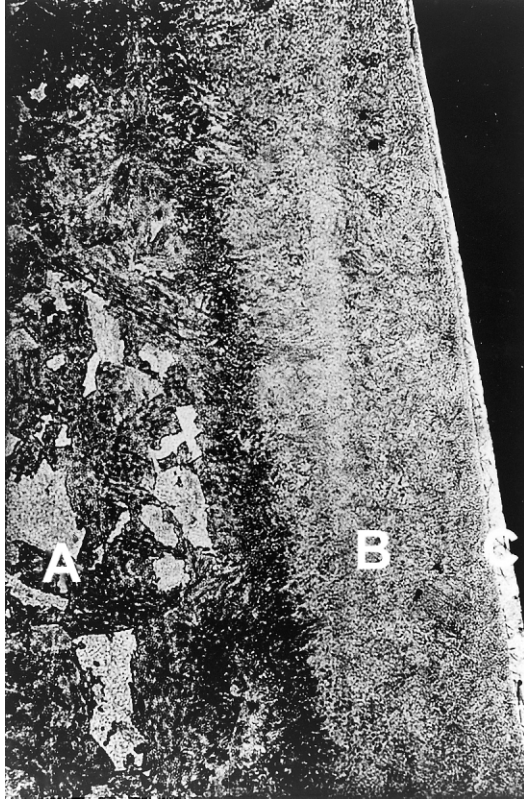
Fig. 2. Sub-surface microstructure after firing 10 rounds. (A) Original structure, (B) heat-affected zone, (C) chemically-affected zone.

A simple model of an eroding surface with a heat-affected zone and a chemically-affected zone is illustrated in Fig. 3. The surface is assumed fixed at the origin ($x = 0$) and the gun steel moves towards the origin at a rate, v, depending
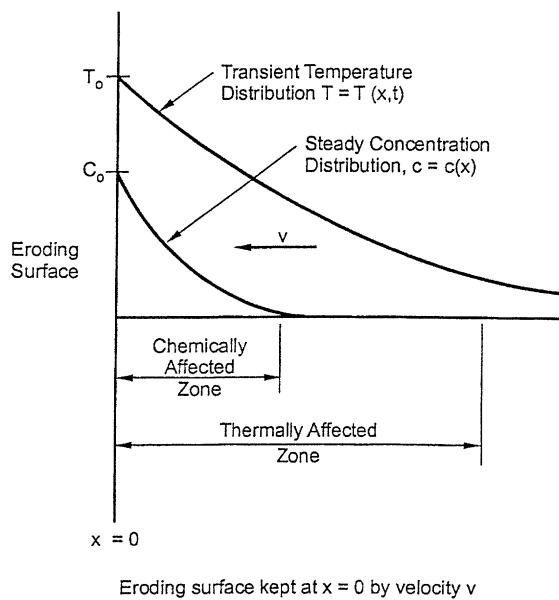

Fig. 3. Wear model showing heat-affected zone and chemically-affected zone.

on the wear rate of the surface. The diffusion equation for mass transfer into the eroding surface may be written as

$$\frac{\partial c}{\partial t} + v \frac{\partial c}{\partial x} = \kappa \frac{\partial^2 c}{\partial x^2} \tag{1}$$

where c is the concentration of the diffusing species, v the velocity of the eroding surface, t the time, x the distance from the origin, and κ the mass transfer diffusivity. The diffusivity is not constant, except over very a small temperature range, but is related to temperature, T, through an Arrhenius equation, $\kappa = B \exp(-\Delta E / R_0 T)$, having a constant B and an activation energy ΔE. Substituting the Arrhenius equation and integrating Eq. (1) over the period t_1, during which the surface temperature is high enough to cause erosion, gives

$$\int_0^{t_1} \mathrm{d}c + \int_0^{t_1} v \frac{\partial c}{\partial x}\, \mathrm{d}t = \int_0^{t_1} B \exp\left(\frac{-\Delta E}{R_0 T}\right) \frac{\partial^2 c}{\partial x^2}\, \mathrm{d}t \tag{2}$$

Now, after a few shots have been fired the concentration reaches a steady, cyclic condition, in which the concentration fluctuates during the shot but returns to its initial value after the shot. Thus, the first term on the left-hand side is 0. Putting $v = \mathrm{d}w/\mathrm{d}t$, where w is the wear, replacing the concentration gradients at the surface by their average values, taking them outside the integrals and replacing the temperature by the surface temperature, we obtain the wear over the period as

$$w = \left(\frac{B \mathrm{d}^2 \bar{c}/\mathrm{d}x^2}{\mathrm{d}\bar{c}/\mathrm{d}x}\right)_{x=0} \int_0^{t_1} \exp\left(\frac{-\Delta E}{R_0 T_0}\right)\, \mathrm{d}t$$
$$= A_1 \int_0^{t_1} \exp\left(\frac{-\Delta E}{R_0 T_0}\right)\, \mathrm{d}t \tag{3}$$

where A_1 is a constant that depends only on the diffusivity constant, B, and the average concentration gradients, and T_0 the temperature at $x = 0$. Eq. (3) is the fundamental wear equation for a gun barrel and may be integrated if it is known how the surface temperature varies with time when a gun fires. Fortunately this function is well known. It has been shown [16] that heat transfer into the surface of a gun barrel, H, may be treated as an exponential function $H = H_\infty[1 - \exp(-t/t_0)]$, having a time-constant t_0, and a total heat transfer per unit area per round of H_∞. For this boundary condition, the relation between the maximum bore temperature and the heat transfer per round is

$$T_{\max} - T_{\mathrm{i}} = 1.082 \times \frac{H_\infty}{k} \sqrt{\frac{\kappa}{\pi t_0}} \tag{4}$$

where $T_{\max}$ is the maximum bore temperature, T_{i} the initial temperature of the barrel, k the thermal conductivity of gun steel, and κ the thermal diffusivity of gun steel. The universal temperature–time relation at the bore surface may be represented by

$$\frac{T_0 - T_{\mathrm{i}}}{T_{\max} - T_{\mathrm{i}}} = \frac{\exp(-u)}{1.082} \int_0^u \frac{\exp(y)}{\sqrt{y}}\, \mathrm{d}y = f(u)$$
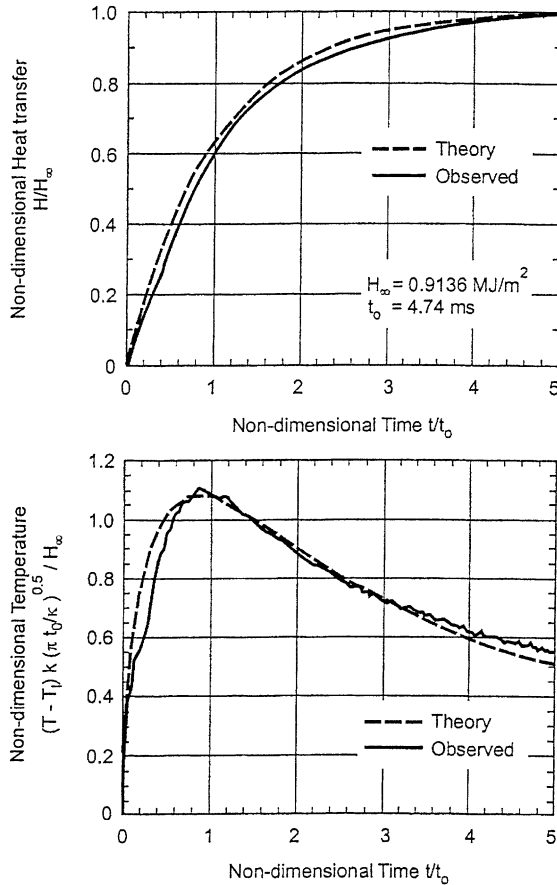$$= \frac{2\sqrt{u}\exp(-u)}{1.082} \sum_{n=0}^{\infty} \frac{u^n}{(2n+1)n!} \tag{5}$$

Fig. 4. Universal temperature–time curve at the commencement of rifling. It is always possible to find values of t_0 and H_∞ to convert the measure temperatures to the universal form.

Fig. 5. Numerical solution of the wear equation for the universal temperature–time curve.

where T_0 is the bore temperature, $u = t/t_0$, and y the variable of integration. It is almost always possible to choose a suitable time-constant and heat transfer per round to fit Eq. (5) to the observed temperature–time curve. Such a correlation, for a 155 mm gun having a time-constant of 4.74 ms and a heat transfer per round of 0.9136 MJ/m², is shown in Fig. 4. The accuracy of the correlation is typical rather than exceptional. Substituting the surface temperature from Eq. (5) into Eq. (3) gives the wear per round in the form

$$\frac{w}{A_1 t_0} = \int_0^{u_1} \exp\left[\frac{-1}{T_i/\theta + ((T_{max})/(\theta - T_i/\theta))f(u)}\right] du,$$
$$\theta = \frac{\Delta E}{R_0} \tag{6}$$

Eq. (5) defines the function $f(u)$. The integral, Eq. (6), depends only on the two dimensionless quantities, T_i/θ and T_{max}/θ, if u_1 is sufficiently large. However, it is too complex to integrate analytically but it may be integrated numerically over a suitable range and a simple curve fitted to the results. Such numerical integration over an adequate time period ($u_1 = 50$) is shown in Fig. 5 by the circled points and the straight lines are the best lines through these points. It is
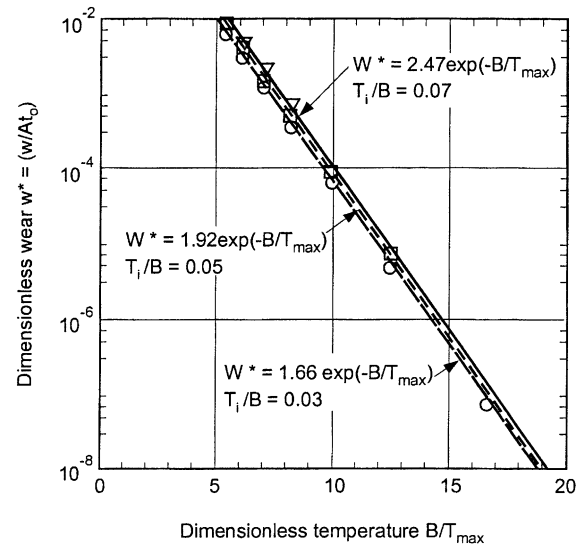
clear that the wear integral is very sensitive to the maximum surface temperature and only marginally sensitive to the initial temperature of the barrel. A reasonable approximation of Eq. (6) is then

$$w = A t_0 \sqrt{\frac{T_i}{T_a}} \exp\left(\frac{-\Delta E}{R_0 T_{max}}\right), \quad T_a = 300\,\text{K} \tag{7}$$

The constant A is proportional to the constant A_1, which depends on the concentration gradients; it may be called the propellant erosivity; it has the units of velocity. If the initial temperature of the barrel is 300 K, then the square root term is unity and thus A is the erosivity of the propellant when the barrel is at 300 K. Large guns do not exceed about 480 K, because of the enhanced risk of self-ignition of the propellant or the combustible cartridge case, so the maximum value of the square root term is about 1.26. The propellant erosivity is found to vary from about 20 to about 200 m/s depending on the chemical composition of the propellant. The activation energy is usually about 69 MJ/kg-mol so that wear is very sensitive to the maximum bore temperature. It should be noted that the propellant and gun steel uniquely defines the erosivity and activation energy but the time-constant and maximum temperature are not independent. The time-constant, t_0, in Eq. (7) has been determined [15] by measurements of bore temperature fluctuation at the commencement of rifling of gun barrels and it may be estimated using

$$t_0 = \frac{0.8 m v_m}{p_{max} d^2} \tag{8}$$

where p_{max} is the maximum pressure, d the bore of the barrel, m the projectile mass, and v_m the muzzle velocity. Such a relation is not directly applicable to vented vessels, much used in gun barrel erosion research, but a comparable

relation may be derived from the equation of motion of the projectile by equating its momentum at exit to the impulse, $mv_{\mathrm{m}} = \int (p\pi d^2/4)\mathrm{d}t$, thus Eq. (8) becomes

$$t_0 = \frac{\pi}{5} \int_0^\infty \frac{p}{p_{\max}} \, \mathrm{d}t \tag{9}$$

The time-constant is a measure of the average width of the pressure–time pulse.

3. Vented vessel tests

The relation between wear per round, maximum bore temperature, initial bore temperature, and propellant erosivity (Eq. (7)) has been demonstrated in a vented vessel (Fig. 6) and some results have also been published in [17]. The vented vessel is simply a standard CV21 closed vessel (700 cm^3), commonly used for testing gun propellants, but fitted with a vent tube at one end. A small quantity of gun propellant is ignited in the chamber and escapes to atmosphere through the vent-hole. The size of this hole may be adjusted to suit the type of propellant and to give a suitable pressure–time pulse. The gas also escapes through a 28 mm diameter annular slit between the vent tube and an erosion test piece. The radial clearance is 1 mm and its purpose is to enhance heat transfer to the test piece so that the compar-

atively low pressures, usually less than 150 MPa, can attain the levels of heat transfer experienced in gun barrels. The gases are choked at the slit and the vent hole, from where they flow to atmosphere through separate holes. The vessel is not fitted with a rupture diaphragm, which is sometimes used in vented vessels, because initially the combustion rate is faster than the leakage rate, if the vent hole is not too large.

The test piece is made of a medium carbon 2.5% Ni–Cr–Mo steel (British Standard 826M31, formerly EN25), which is similar to gun steel. The test piece is in two parts so that a fine wire thermocouple can be fitted exactly 1 mm from the eroding surface. The amount of erosion is determined by weighing the clean test pieces before and after firing; the average increase in diameter is determined from this measurement. Pressure is measured by a piezoelectric pressure transducer, and the pressure and temperature signals are amplified and captured by a digital oscilloscope, stored on a disc, and transferred to a digital computer for analysis and plotting.

Typical pressure–time and temperature–time curves are illustrated in Fig. 7 when firing a charge of 114 g of an experimental propellant; the bore of the vent tube was 10 mm. The maximum pressure occurs about 7.4 ms after ignition and is about 110 MPa. The time-constant, from Eq. (9), is 5 ms.

From these measurements, the heat transfer per round may be estimated from the measured temperature fluctuation by
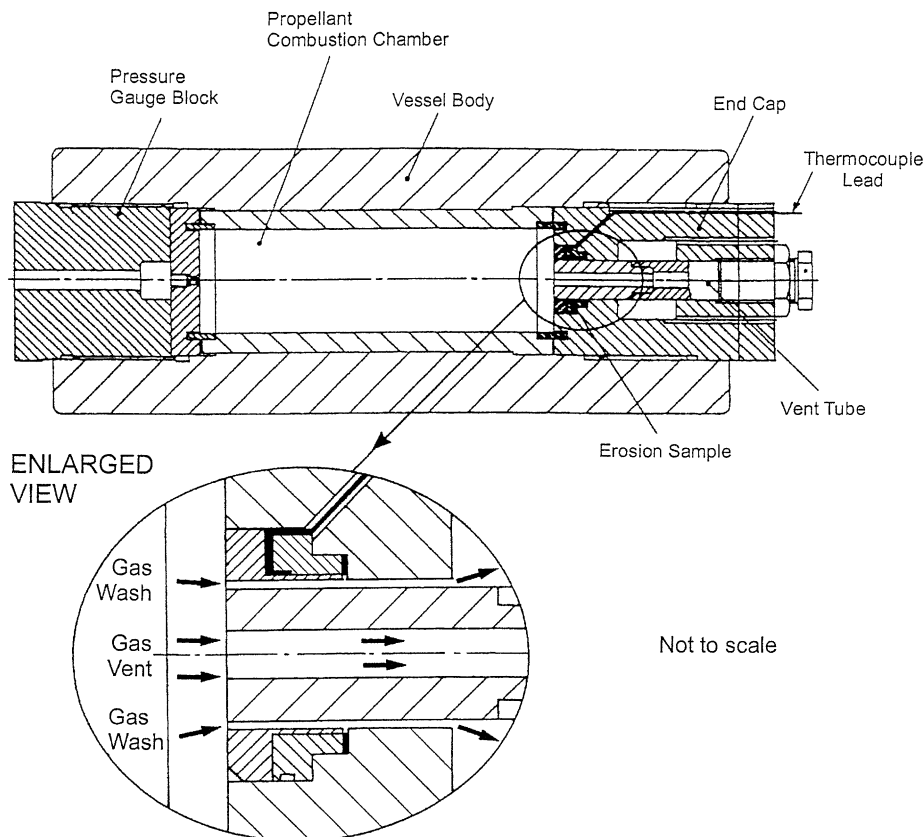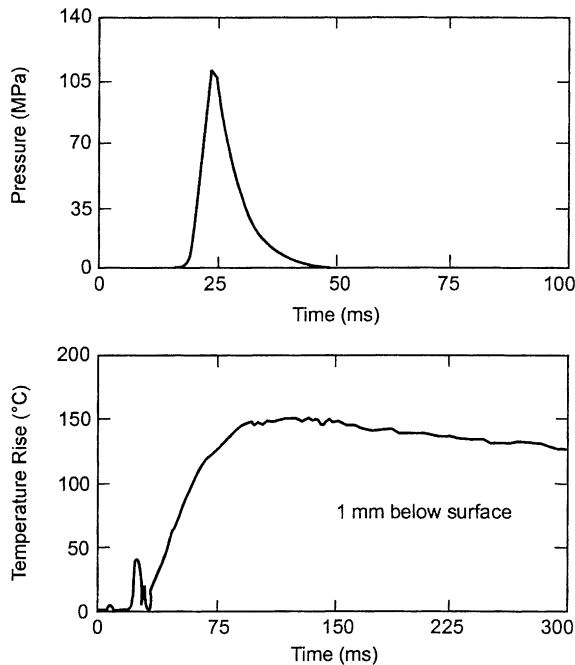

Fig. 6. Cross-section of the vented vessel.

Fig. 7. Typical pressure and temperature histories in a vented vessel firing 114 g of propellant.

assuming the heat input is impulsive [18], thus

$$H_\infty = \sqrt{\frac{\pi e}{2}} \rho C_v x (T_x - T_i) \tag{10}$$

where C_v is the specific heat at constant volume, ρ the density, x the thermocouple's distance from the surface (1 mm) and $T_x - T_i$ the measured temperature rise. Knowing the heat transfer per round the maximum surface temperature may be determined from Eqs. (4) and (9).

4. Vented vessel results

Five different propellants were tested in the vented vessel. Propellants DX, NQ, and HX are standard gun propellants having flame temperatures of 3418, 2834, and 3239 K, respectively. Propellant HT is simply HX plus 0.5% talc, and HP is propellant HX plus 0.5% potassium sulphate (K_2SO_4). The additives were mixed in during manufacture. Talc dust is a commonly used wear-reducing additive and potassium sulphate is a muzzle flash suppressant. Fig. 8 shows that maximum pressure increases with charge mass and the time-constant (proportional to the average width of the pressure–time curve) decreases with charge mass. NQ gives the highest pressure. Propellants DX and HX are rather similar to each other. The presence of the additives in HX tends to reduce the maximum pressure, but not greatly at high pressures. Propellant DX burns fastest and HX the slowest but the additives in HX do not alter the time-constant greatly.
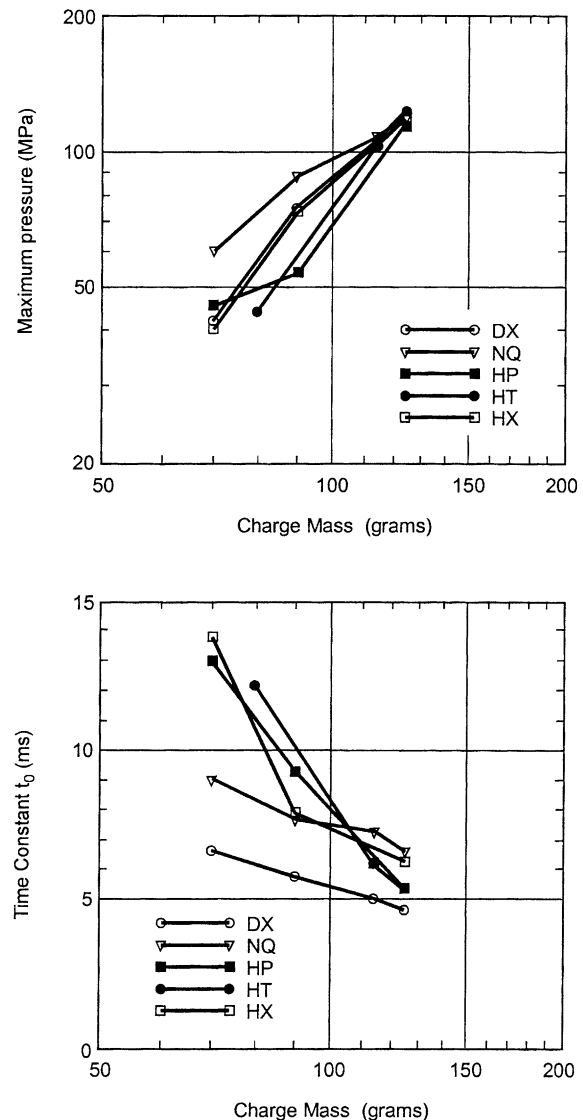

Fig. 8. Maximum pressures and time-constants when firing various charges of propellants DX, NQ, HX, HT, and HP.

The maximum surface temperature, calculated from the temperature fluctuation measured 1 mm from the surface, is shown in Fig. 9. DX gives the lowest temperatures and HX the highest. This suggests that DX should be the least erosive and this proves to be the case. The addition of talc to HX reduces the maximum temperatures by about 300°C, which implies that wear should be reduced significantly. The addition of potassium sulphate to HX does not greatly change the maximum temperature.

Fig. 10 shows the observed erosion of the five propellants. The magnitude of erosion, 20–200 μm per round, is similar to that observed in service guns because the maximum temperature and time-constant are similar. It will be noted that erosion occurs at temperatures well below the melting point of steel. An important difference between the vented vessel and real guns is that the latter are subjected to addi-
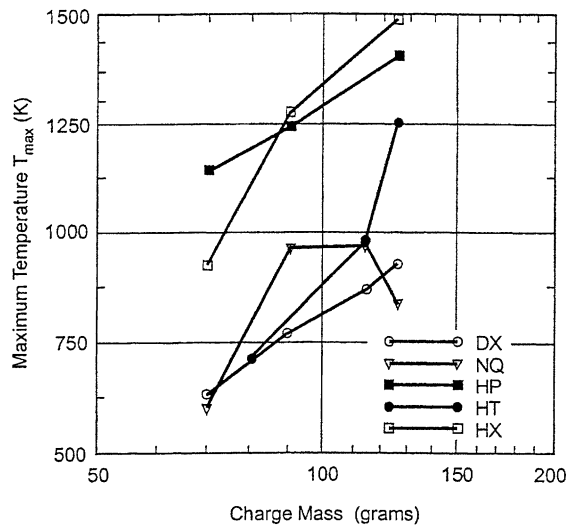
Fig. 9. Maximum surface temperature at the eroding surface when firing various charges of propellants DX, NQ, HP, HT, and HX.

tional erosion caused by the passage of the projectile's driving band along the bore, but significant erosion occurs even in the absence of a projectile. As expected from the temperature measurements, HX is the most erosive and DX the least erosive. However, the addition of talc to HX not only reduces the maximum temperature by about 300°C but it also reduces the wear by a factor of about 2.5. Talc reduces wear in gun barrels because it reduces heat transfer to the surface and thus reduces the maximum temperature. This, in fact, is quite well known [10,11] but the exact mechanism by which the talc and other inert particles reduce heat transfer remains unclear. It is likely that fine talc particles (<1 μm diameter) reduce turbulence in the boundary layer and thus reduce heat transfer. Certainly, if the particles do not reach the boundary layer then they are ineffective.
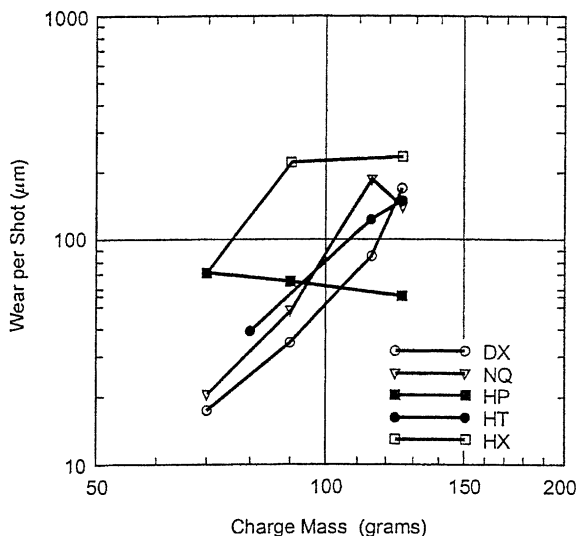

Fig. 10. Influence of charge mass and propellant additive on wear per shot.

Potassium sulphate, as we have seen, does not reduce the maximum temperature but it does reduce erosion, even in very small quantities. At low charge mass it is equally as erosive as HX and the potassium sulphate has no effect, but as charge mass increases the wear per round actually decreases. The reason for this is that the time-constant reduces and there is less time for erosion to occur. The erosion rate of propellant HP, w/t_0, actually increases with charge mass.

The ultimate test of the erosion theory (Eq. (7)) is that the observed wear data should plot as a straight line when the logarithm of the wear rate is plotted against the inverse of the maximum temperature. This is shown in Fig. 11 for each of the five propellants. The activation energy of each of the propellants is slightly different but as there are only three or four points per line an accurate estimate for each propellant is unobtainable, so the average value for all propellants, 37.4 MJ/kg-mol, has been used. Despite the apparent scatter in the observed wear rates the data on the Arrhenius plot aligns quite reasonably and confirms the theory. NQ and DX appear to be the most erosive, having a propellant erosivity of 3.8 and 2.6 m/s, respectively. HX is considerably less erosive, having an erosivity of 0.8 m/s. The addition of 0.5% talc to HX increases the erosivity to about 1.5 m/s, but there is a net reduction in wear per round because the talc reduces the maximum temperature by about 300°C. The addition of 0.5% potassium sulphate did little for the temperature, but as Fig. 11 shows, it reduced the erosivity of the propellant to 0.27 m/s, and it was the least erosive of the propellants tested.

Clearly, the two wear-reducing additives have different mechanisms, both of which may be explained by Eq. (7). Talc reduces wear by reducing the maximum temperature whereas potassium sulphate reduces wear by reducing propellant erosivity.

5. Application to guns

The wear equation (Eq. (7)) may be applied to gun barrels in service if sufficient data can be gathered on guns using the same propellant and if a reliable method of estimating the maximum bore temperature is available. Thornhill and coworkers [6,19] have collected data on the wear per round of service guns firing conventional propellants without the use of additives. To these, Lawton [20] has added data relating to more recent guns to give a databank of over 70 guns and propellant combinations specifying bore, charge mass, propellant type and composition, flame temperature, muzzle velocity, and wear per round.

The maximum bore temperature may be estimated from a simple, explicit equation that has been derived from observed surface temperature measurements in gun barrels [15]. These temperature measurements were obtained using true surface thermocouples, having a response time of about 1 μs, fitted close to the commencement of rifling of guns which varied in calibre from 20 to 155 mm, and firing a va-
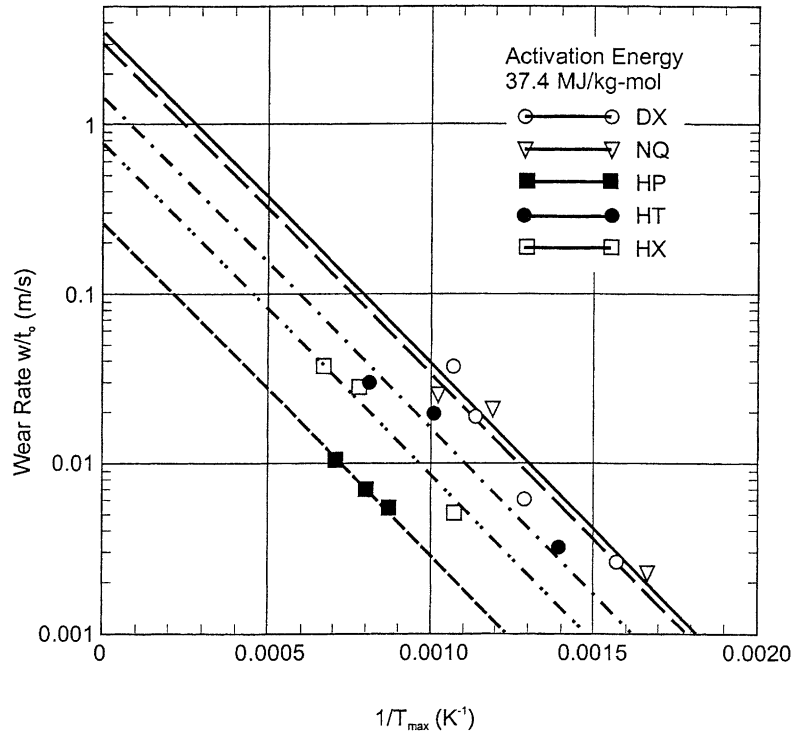
Fig. 11. Arrhenius plot of wear per shot for propellants DX, NQ, HX, HT and HP.

riety of propellants. The equation is

$$\frac{T_f - 1.8T_i}{T_{max} - T_i} = 1.8 + 288\frac{R_T}{Re^{0.86}};$$

$$R_T = \frac{k}{k_g}\sqrt{\frac{v_m d}{\kappa}}, \quad Re = \frac{m_c v_m}{\mu_g d^2} \quad (11)$$

where T_f is the propellant flame temperature, T_i the initial barrel temperature, T_{max} the maximum barrel temperature, R_T a thermal property ratio, Re the mean Reynolds number, k the conductivity of the barrel, k_g the conductivity of the propellant gas, v_m the muzzle velocity, d the gun bore, κ the thermal diffusivity, m_c the charge mass, and μ_g the viscosity of the propellant gas. The constants 1.8 and 288 were chosen to make the equation fit the measured performance of guns. By making reasonable assumptions for the thermal properties of the gun steel and propellant gas, this equation simplifies, if strict SI units are used, to

$$\frac{T_f - 1.8T_i}{T_{max} - T_i} = 1.8 + 7130\frac{d^{2.22}}{m_c^{0.86} v_m^{0.86}} \quad (12)$$

The time-constant cannot be estimated from either Eq. (8) or (9) because there is insufficient data available for the guns in the database. However, the muzzle velocity and bore is known and a time-constant may be defined as $t_0 = d/v_m$. This is not identical to that defined in Eqs. (8) and (9) but it is proportional to them and is a satisfactory substitute.

An Arrhenius plot of wear rates for all the guns in the database is shown in Fig. 12. The maximum bore temper-

ature is estimated from Eq. (12) and the wear rate is the measured wear rate firing service ammunition. There is, of course, very considerable scatter in these data, because a large number of different propellants were fired, but the general trend is clear and confirms the validity of the theory. The average erosivity of gun propellant is about 80 m/s and the activation energy is about 69 MJ/kg-mol. In the vented vessel trials the erosivity varied from 0.28 to 3.8 m/s, depending on the chemical composition of the propellant, and
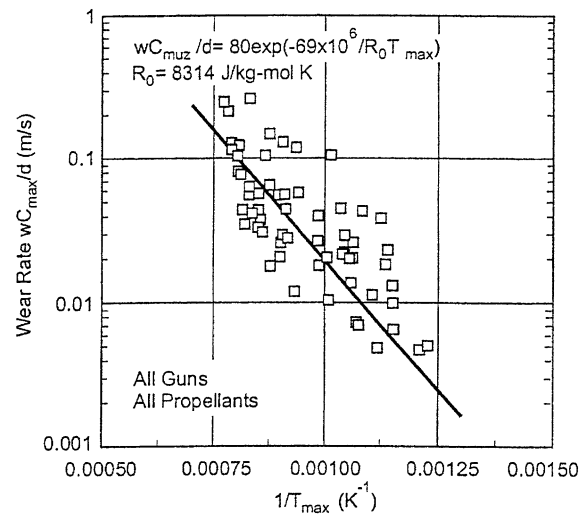

Fig. 12. Arrhenius plot of wear per round for all guns and propellants in the database.
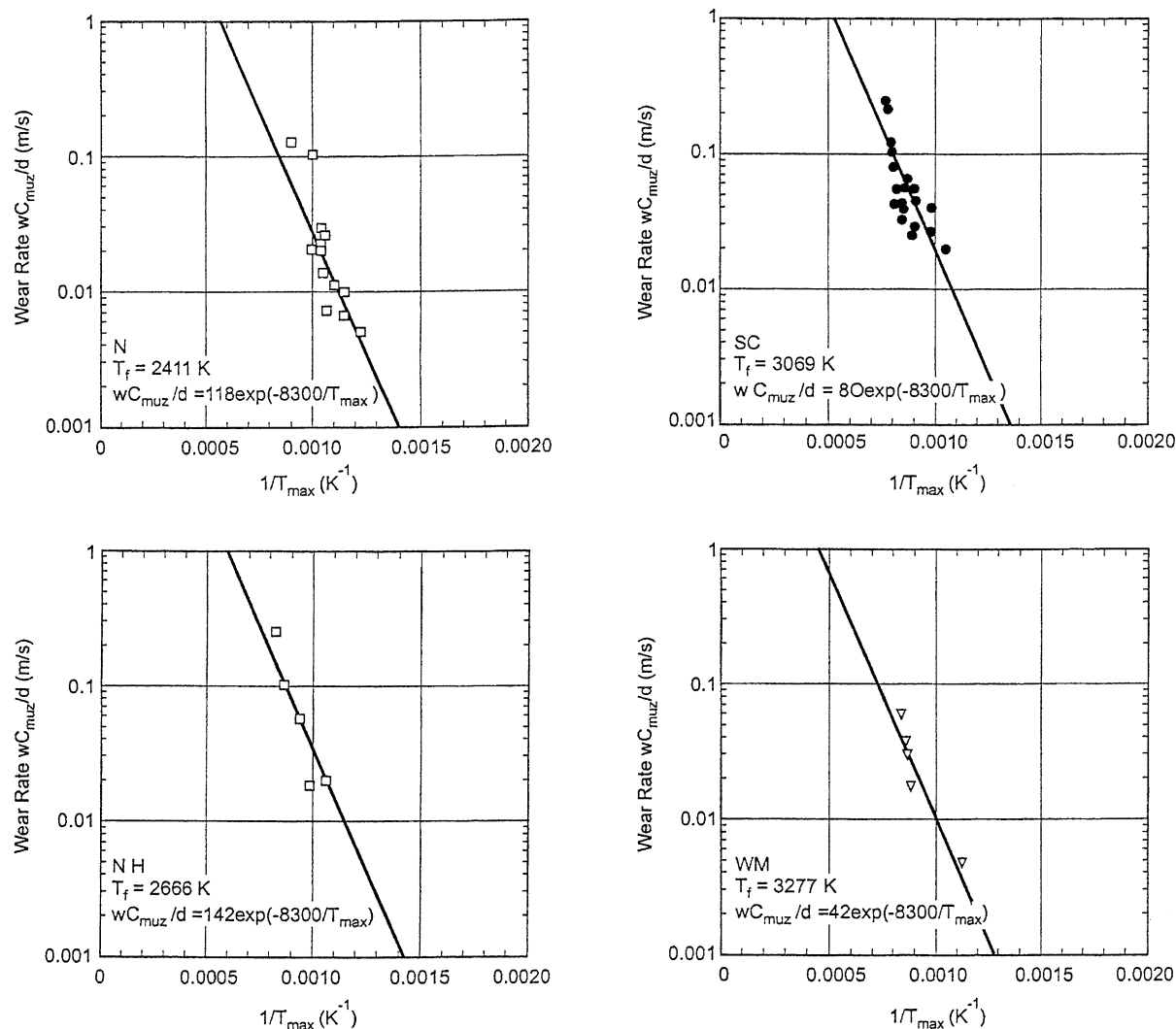
Fig. 13. Arrhenius plot of gun wear per round for propellants N, NH, SC, and WM.

the activation energy was 37.4 MJ/kg-mol. The differences in erosivities are caused mainly because of the presence of a driving band in the guns but not in the vented vessel trials. The extra stress generated by the driving band increases the wear per round by removing a larger proportion of the chemically-affected zone. The difference in activation energy is more difficult to explain but is due partly to the use of steel 826M31 (formerly EN25) rather than gun steel in the vented vessel and to the different method of determining the maximum bore temperature.

The scatter in the Arrhenius plot can be greatly reduced, and the erosivity of individual propellants determined, if the plot is restricted to a single type of propellant. This is illustrated in Fig. 13, which shows the Arrhenius plots for propellants WM, SC, NH, and N. There is some variation in the activation energy of these propellants but as in the vented vessel trials, the average activation energy is assumed for all. Propellant WM has a high flame temperature, 3277 K, and the lowest erosivity, 42 m/s and propellant N has the

lowest flame temperature, 2411 K, and the highest erosivity, 208 m/s. The other two propellants shown have intermediate flame temperatures and intermediate erosivities that confirm the general trend for high temperature propellants to exhibit low erosivity. The total wear in a barrel is due not only to the erosivity of the propellant but also to the maximum temperature of the barrel and it is usually found that high temperature propellants produce a high bore temperature and so, despite being less erosive, they produce more barrel wear.

As the erosivity of a propellant depends on its chemical composition there should be some correlation between them. Table 1 shows the chemical composition at the flame temperature of seven frequently used UK propellants for which propellant erosivity has been determined from service wear rates. The method of calculating a propellant's composition is set out in reference [21].

It is clear that as the flame temperature rises the erosivity tends to reduce and one could derive a simple, but not

Table 1
Propellant composition at its flame temperature and erosivity

Propellant	W	WM	SC	NQ	NH	FNH	N
Flame temperature (K)	3289	3277	3069	2782	2666	2496	2411
CO_2 (%)	9.96	8.85	7.33	4.29	5.5	4.48	2.77
CO (%)	42.8	42.6	45.0	28.7	50.9	52.1	32.0
H_2O (%)	23.7	24.2	21.5	21.9	16.1	13.9	15.7
H_2 (%)	10.3	11.8	13.6	15.9	16.9	19.4	22.0
N_2 (%)	12.6	12.0	12.3	29.1	10.6	10.1	27.4
Observed erosivity A (m/s)	31	42	80	37	142	209	118
Theoretical erosivity (m/s)	35	40	61	49	140	207	128

very accurate, correlation between the observed erosivity and the flame temperature. However, a better correlation of a propellant's erosivity is obtained using its chemical composition. This is shown in Fig. 14 and the equation for propellant erosivity may be expressed as

$$A = 114 \exp\{0.0207[(CO) - 3.3(CO_2) + 2.4(H_2) - 3.6(H_2O) - 0.5(N_2)]\} \quad (13)$$

The constituents in the round brackets are in vol.%. The erosivity has been chosen to be an exponential function of x, where x is a linear function of the chemical composition of the propellant at its flame temperature. The exponential relation was chosen to avoid the possibility of negative erosivity and also because it fits the observed data. There is no theoretical foundation for this correlation. The constants in the square brackets were determined from a best fit between erosivity and composition. Although a better correlation may be possible, that shown in Eq. (13) seems adequate, given the accuracy of the data. Hydrogen is seen to be the most erosive constituent of propellants. This is reasonable because hydrogen atoms have a small diameter and easily diffuse between the lattice structure of the steel, particularly

at high temperature when the atoms in the lattice oscillate with high amplitude. As shown in Table 1, the chemically erosive propellants are those having large amounts of H_2 and CO. For low erosivity it is necessary to convert the H_2 into H_2O and the CO into CO_2. Increasing the O_2 in the propellant composition can do this but it invariably increases the flame temperature and hence it also increases the maximum barrel temperature and the wear rate. To oxidise the H_2 and CO without increasing the flame temperature, it is also necessary to increase the N_2 content, which is relatively inert. This has been done by Kimura [13,14], using an earlier version of Eq. (13). From this idea, Kimura has successfully developed a new range of low erosivity, low-vulnerability propellants.

6. Conclusion

The high temperature occurring at the commencement of rifling when a gun is fired is the primary cause of gun barrel erosion. Melting and melt erosion does not generally occur. This high temperature, although it persists for only a few milliseconds, allows chemical species from the propellant gas to diffuse into the gun surface forming a weak, cracked, chemically-affected zone. The weakened material may be removed by the flow of high velocity gases over the surface, as in the vented vessel trials, or by the passage of a driving band, as in gun barrels.

A simple relation for gun wear was derived from an analysis of these processes combined with the characteristic thermal pulse of a gun. This relation shows that wear depends: exponentially on the maximum temperature at the bore of the gun, linearly on the erosivity of the propellant, and on the square root of the barrel's initial temperature. A simple equation relates the maximum temperature to the mass of propellant, its flame temperature, the muzzle velocity, the gun-bore, and the thermal properties. A further correlation has been found between the propellant's chemical composition and its erosivity and this equation has been used to design new, low erosivity, propellants.

Two types of wear reducing additives were tested in a vented vessel. One type, talc particles, reduced wear because it reduced heat transfer to the metal surface. The other type,
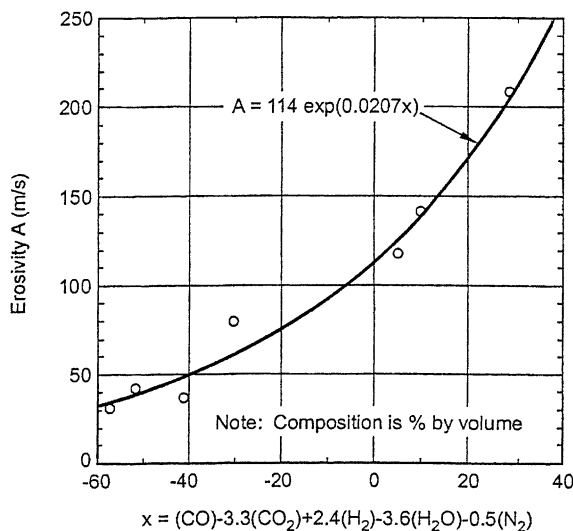

Fig. 14. Correlation of observed propellant erosivity with chemical composition of typical UK gun propellants.

the muzzle flash suppressant K_2SO_4, reduced the erosivity of the propellant without changing the heat transfer to the surface. Wear reducing additives used in guns usually reduce the heat transfer because wear is very sensitive to the maximum temperature. The exact mechanisms involved in these processes are not yet fully understood.

The absence of a driving band in the vented vessel tests means that these results are not directly applicable to gun barrel erosion but the vented vessel tests confirmed the erosion theory and gives a useful insight into problems that may be applicable to guns.

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