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ABSTRACT

A number of approaches to reduce the temperature sensitivity of ADF gun ammunition across the operational range (-6°C to +63°C) have been reviewed and analysed. Increases in range of about 5% for Hamel are possible, and a solution would maintain compatibility with the existing gun system. While successful in rocket propellants, no chemical additives have been identified which give similar control of temperature sensitivity in gun propellants. LOVA ammunition appears to offer the best potential and has the added advantage of enhanced munition and platform survivability. Two changes involving gun design are at early stages of R&D in the US; control tube primers and variable volume gun tube. Both should be monitored for future applicability, including fail-safe aspects.

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EXECUTIVE SUMMARY

The primary objective of gun propulsion research is to increase muzzle kinetic energy and hence system effectiveness via enhanced range, hit probability and terminal effectiveness on targets. Reductions in defence budgets are placing greater emphasis on system improvements to existing weapons, ideally requiring no major system modifications.

One such approach would be to reduce or eliminate the temperature sensitivity of propulsion systems, thereby permitting the gun to be fired at maximum pressure, i.e. that corresponding to the upper temperature qualification limit (63°C), over the operational range. In this way range would not have to be sacrificed at normal (ambient) temperatures where most firings are conducted. For the Australian L118 Hamel 105 mm gun firing Abbot ammunition at supercharge this represents a range extension of about 1 km. Coupled with other relatively low technology propellant changes such as increased grain perforation, higher burning rate formulations and grain splitting, additional range extensions could be achieved, matching the performance of other ammunition technologies such as base bleed or rocket assisted projectiles.

The propellant burn rate can be adversely affected by three mechanisms over the operational temperature range:

- temperature sensitivity of propellant burn rate
- grain fracture at low temperature
- grain deformation at high temperature

These mechanisms have been reviewed, and approaches to overcoming them have been discussed in terms of published results across a range of systems. Most emphasis has been placed on propellant formulation and grain design, with a lesser emphasis on gun design parameters.

Results for the following systems have been analysed.

Large and Medium Calibre Guns

- US 155 mm M198 Howitzer with M30A1 propellant
- 5"/54 Naval Gun propellants
- UK 105 mm L7 Tank Gun with NQ/M propellant
- UK 120 mm APDS Tank Ammunition with NQ/S propellant

Small Calibre Guns

- GAU-8 30 mm cannon
- 20 mm aircraft cannon
- 40 mm L/70 AA gun
- 7.62 mm rifle and 9 mm pistol

Design changes to guns identified as potentially overcoming temperature sensitivity included rapidly raising the ammunition (hence propellant) to the upper qualification temperature immediately before firing, and various approaches to control the combustion chamber volume.

Whereas temperature sensitivity (σ_P) in rocket propellants have been well controlled by chemical additives to the propellant, no "magic ingredient" was identified for gun propellants. The typical operating pressure of rocket motors is $\leq$ 20 MPa, while for guns it is 360-600 MPa; σ_P tends to increase with pressure, and the harsh and transient gun combustion cycle may not ultimately be amenable to effective control by combustion additives.

A number of formulation changes which assist in reducing σ_P were identified. These include finer NQ in triple base propellants, the addition of PVN to single base propellants and low vulnerability ammunition (LOVA) propellants based on the nitramines RDX and HMX. These influences are suggested to be primarily exerted through combustion phenomena; favourable effects of deterrents/inhibitors and changes in propellant geometry may also result from this mechanism.

The most significant effects on σ_P result from changes in propellant mechanical properties, particularly ball propellants and grain porosity. The LOVA propellant results, as well as plasticiser effects, also have a strong contribution from this factor. The different mechanisms at high and low temperature are described in detail.

Gun design is identified as potentially having the greatest effect on σ_P, with the position of propellant "all burnt" minimising σ_P if all propellant burns before shot start. Changes to gun design to give greater pressure control are being pursued in the US Army through gun chamber volume control mechanisms. A control tube primer with the ability to adjust the position of the projectile is one, but fail-safe features remain unproven. A more ambitious program is the variable volume control tube whereby the chamber itself is adjusted; in the limit this would be a "smart" chamber capable of sensing pressure rate rises and instantly adjusting chamber volume. Such technology is at a very early stage of R&D.

Neither of the control volume methods would be suitable for retrofit to existing gun systems without major changes.

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Tam T. Nguyen holds a BSc(Hons) in Inorganic Chemistry from Sydney University and a PhD in Physical Chemistry from Newcastle University (NSW). Tam transferred from CSIRO to DSTO as a Senior Research Scientist in 1986. At present, he works in the Explosives Ordnance Division at Salisbury, South Australia. In the past two years, Tam managed a DSTO task on the combustion characteristics of rocket propellants. The present publication is part of a series of three Technical Reports, to appear in 1992, which examine the temperature dependence of rocket and gun propellants. His other interests include kinetics and thermochemistry, FTIR and Raman spectroscopy of surfaces, heterogeneous catalysis and hydrocarbon conversion.

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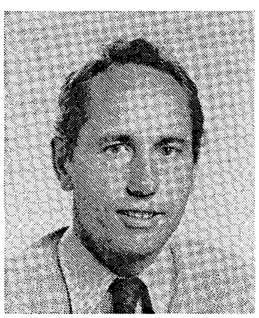

Robert Spear graduated BSc (Hons) in Organic Chemistry from University of Melbourne in 1969 and PhD in 1973 from University of Sydney. After post-doctoral studies for two years in the USA he taught in the Department of Organic Chemistry at University of Melbourne for three years. He joined AMRL in 1978 and has worked exclusively on explosives and their applications. His current position is Research Leader, Energetic Materials and encompasses managing research in explosives, propellants, pyrotechnics and rocket technology.

Contents

1. Introduction

The primary objective of gun propulsion research is to increase muzzle kinetic energy and hence system effectiveness, and provide enhanced range, improved hit probability and terminal effectiveness on target. Changing strategic circumstances, and corresponding reductions in defence budgets, have placed greater emphasis on extending the life of existing gun systems. Consequently approaches that offer significant system enhancement yet are compatible with existing weapons, ie, require no major system modification, are likely to be favoured as cost-effective alternatives to introducing new weapons systems. An excellent review of current US Army approaches to R&D on increasing the performance of medium and large calibre guns has recently been published [1].

The principal indirect firepower weapon for the Australian Army is the 105 mm Howitzer: the Hamel guns L118 and L119. There is an operational requirement to extend the maximum range of these weapons, and DSTO have been tasked to examine a range of procurement and technology alternatives, and to provide an analysis of the relative potential and cost-effectiveness of these alternatives. As part of this task, an analysis has been undertaken of the possibility of reducing the temperature sensitivity of the propulsion system. If successful, it would represent an easy, relatively low technology means of improving system performance, and be completely compatible with the existing gun systems.

Ammunition for small, medium and large calibre guns is typically assessed, and subsequently qualified for operational use, over an extensive temperature range. For NATO ammunition this can be as wide as +63° (climatic category A1/B3) to -51°C (C3) [2], while ammunition for Australian Service use is usually required to be qualified over the more limited range of +63°C (A2) to -6°C (CO(A)) [3]. At any particular temperature T over this range the gasification rate, dN/dt, of the burning propellant is defined by

$$dN/dt = r\rho_p S_b \tag{1}$$

where
r is the linear burn rate,
ρ_p is the propellant density and
S_b is the burning surface area

The peak pressure, which can determine both performance and safety, thus depends on r and S_b. There are three mechanisms which can impact on the observed peak pressure, and their importance over particular temperature ranges are summarised below.

a. Temperature Sensitivity of Propellant Burn Rate

Normally r shows an Arrhenius type dependency on temperature T;

$$r = Ae^{-Ea/RT} \tag{2}$$

where A is the Arrhenius frequency factor
Ea is the activation energy of the propellant gasification reaction, and
R is the universal gas constant.

A consequence of this relationship is that the rate of energy release increases with increasing propellant ambient temperature, with the result that the pressure generated from firing a particular propellant cartridge can be expected to increase over the operating temperature range.

b. Low Temperature Grain Fracture

At temperatures near or below the glass transition temperature of the propellant, the propellant grains become brittle (glassy) and grain break-up can occur following ignition and pressurisation. This leads to greatly increased burning surface area (Sb), higher gasification rate and increased chamber pressure, in the limit leading to catastrophic breech burst. Experimental evidence has clearly shown that this results from mechanical failure of the grains, typically through cracking along the grain length [4].

This type of behaviour is usually not observed till below - 20°C [5], i.e., below the Australian operating range, but can occur at higher temperatures in some systems. Such controlled grain break-up can potentially be used to overcome the reduced chamber pressures at low temperature firings resulting from the normal temperature sensitivity relationship described in (a) above.

c. High Temperature Grain Deformation

In contrast to (b), the grain may become physically softened at high temperature, eg, near the upper qualification temperature. Upon firing of the primer and initial pressurisation, the softened grains are susceptible to deformation with the result that partial closure of the perforations may occur. In addition compaction of the softened mass leads to a propellant bed of reduced porosity and permeability. The overall effect is to alter the flame spread and ballistics, and reduce the efficiency of burn and pressure generation. This also has the potential to counteract the normal temperature sensitivity of gun propellants near the upper firing temperature.

Charge compression could also raise the effective web size to such a degree that part of the charge is ejected from the muzzle without contributing to a rise in pressure or velocity.

For gun safety requirements, it is essential that there be an acceptable safety margin over the gun design pressure limit when firing at the highest pressure. Since gun firing pressures typically increase with (propellant) temperature, i.e. (a) above, this highest pressure will be at the upper firing temperature (63°C). Accordingly, pressure (and range) must be sacrificed at the temperatures over which most firings are conducted, say 10-35°C. If the temperature sensitivity of the propulsion system could be (ideally) reduced to zero, firings across the operational range could be carried out at the upper pressure limit.

The range of technologies which can potentially achieve this have been collectively termed temperature compensation techniques [1,6]. It cannot be stressed too strongly that any method used must be fail-safe since catastrophic over-pressurisation could potentially occur. This particularly applies to the controlled grain breakup and high temperature softening described briefly in (b) and (c) above; the current state of the technology would certainly not meet this requirement.

The analysis in this report addresses the status of temperature compensation techniques. It focusses primarily on methods to reduce the burn rate temperature sensitivity of propellants, including new techniques either proven or still undergoing R&D. Other methods involving the gun system itself or the ammunition design are covered to a lesser extent. The analysis also deals primarily with effects over the Australian operating range of - 6°C to + 63°C, and accordingly places most emphasis on mechanisms (a) and (c) above.

The review does not include ammunition technologies which are currently available to extend range, such as base bleed and rocket assist.

2. Approaches to Reducing the Temperature Sensitivity of Gun Propulsion Systems

Both propellant composition and grain configuration can significantly influence temperature sensitivity. The use of chemical additives to lower temperature sensitivity of rocket propellants has been particularly successful [7,8]. In contrast no such additives for gun propellants have been developed through to fielded systems [6]. This partly reflects the more fragmented approach and lower priority and resources historically accorded the subject. It should, however, be noted that the combustion regimes differ substantially; gun firing pressures are at least an order of magnitude higher than rockets, the combustion environment is transient throughout much of the ballistic cycle, and the mechanical environment is extremely harsh and ill-defined.

Gun design can also have a strong influence on temperature coefficients, e.g. it has been suggested the temperature coefficients are lower for gun systems in which the propellant is almost totally consumed before the projectile starts to move [9]. Other factors such as changes in charge weights, primer output, shot start pressure and chamber pressure can also influence temperature coefficients. However a gun meeting the requirement of all-burnt before shot start dictates high chamber pressure/large volume, hence a larger, heavier gun. This would be an unacceptable tradeoff unless very high velocities were necessary; the same argument applies to solid propellant travelling charge guns [1].

3. Potential Range Extensions from Temperature Sensitivity Reduction

Data taken from Ref [6] for the US M198 Howitzer (155 mm) and M256 Tank Cannon (120 mm) for performance over the operational temperature range are detailed in Table 1. Comparison between the two systems shows the typical trend that higher temperature coefficients are exhibited by higher pressure systems; the chamber pressures for the M256 are nearly 50% higher and the muzzle velocities roughly double those of the M198.

Table 1: Typical US Artillery Peformance Changes over Qualification Temperature Range [a]

System /Parameter [b]	Cold (-51°C)	Ambient (21°C)	Hot (63°C)
155 mm M198 Howitzer Firing M203A1 Charge [c]			
Chamber pressure (MPa)	311	363	394
Velocity (m/s)	782	833	860
Temperature coefficients			
Pressure (MPa/°C)	0.72		0.74
Velocity (m/s/°C)	0.71		0.64
Percent change from ambient			
Pressure (%)	-14		9
Velocity (%)	-6		3
Range (%) [d]	-12		6
120 mm M256 Tank Cannon Firing M829 Cartridge [e]			
Chamber pressure (MPa)	416	526	653
Velocity (m/s)	1535	1675	1768
Temperature coefficients			
Pressure (MPa/°C)	1.64		3.02
Velocity (m/s/°C)	2.09		2.21
Percent change from ambient			
Pressure (%)	-21		24
Velocity (%)	-8		6
Range (%) [d]	-16		12

a Data from Ref [6] except range;
b At maximum charge;
c System pressure limit 405 MPa;
d Calculated as in text;
e System pressure limit 670 MPa.

There is consequently a greater performance increase (velocity, pressure) between 21°C and 63°C for the M256, and a greater potential performance increase if temperature sensitivity was eliminated. For velocity these are 6% for the M256 versus only 3% for the M198, which can be converted to range increase by

$$\underline{R} = \frac{v^2 \sin^2 \varnothing}{g} \qquad \text{[ref 10]} \qquad (3)$$

where $\underline{R}$ = range
v = muzzle velocity
$\varnothing$ = angle of fire

Transformation from (3) gives

$$\frac{\underline{R}\,(63^\circ C)}{\underline{R}\,(21^\circ C)} = \frac{v^2(63^\circ C)}{v^2(21^\circ C)}$$

which calculates to a potential range increase of approximately 6% for the M198 Howitzer and 12% for the M256 tank gun.

The muzzle velocity for the L118 Hamel is reported as 704 m/s, hence the available range increase at ambient could be expected to be similar to, but slightly lower, than the M198; say 5%. At maximum range firing Abbot ammunition, 17.2 km, this represents a range extension of 0.9 km. For the lower performance L119 firing M1 ammunition, where the muzzle velocity is only 490 m/s to maximum range 11.5 km, the range extension would only be up to 0.5 km.

While these calculations are of necessity simplistic, they provide a basis for assessing the potential for performance increase. These increases can be compared with other propellant technologies which can extend range by more effective programming of the energy delivery during the ballistic cycle. Three examples are cited in ref [1].

(i) Changing from the standard 7-perforation to a 19-perforation propellant grain typically yields a 2-3% muzzle velocity increase.

(ii) Very high burning rate (VHBR) propellants can give 7-19% increase in muzzle velocity.

(iii) Programmed splitting propellant can give 5-10% increases.

Option (i) represents a manufacturing challenge to consistently produce 19-perforate grains, while (ii) and (iii) are very immature technologies. Nonetheless they point to the potential increases which could be achieved by applying a number of compatible technologies, including temperature compensation, to artillery range extension.

4. Analysis of Temperature Sensitivity Reduction Studies

4.1 Concepts of Burn Rate Sensitivity

The temperature sensitivity (σ_p) of burn rate (r) at pressure p for rocket propellants is defined [7] simply by

$$\sigma_p = [\delta(\ln r)/\delta T]_p \qquad (4)$$

In this case σ_p is readily determined by measuring the linear burn rate at a series of initial temperatures using a strand burner or mini-motor. This relationship can be expanded to reveal other fundamental physical dependences on σ_p [7].

However for gun propellants the temperature coefficients can be defined either as the change in peak pressure δp for a given change in operating temperature δT, ie, $\delta p/\delta T$, or in terms of change in muzzle velocity δv, ie, $\delta v/\delta T$. Examples of such results can be seen in Table 1. It should be noted that these are operational definitions, and imply nothing about the functional forms of the temperature dependence.

Hewkin [9] adopted a temperature coefficient defined in terms of the percentage change in pressure (or velocity) from the value at 21°C per 10°C change in temperature, i.e. at an upper firing temperature T (°C).

$$\sigma p = \frac{(p_T - p_{21}) \times 10^3}{p_{21}(T - 21)} \qquad (5)$$

A similar expression can be written to define δp for the temperature range below 21°C, or for δv for velocity change. For direct comparison with other published data, Hewkin's data has been reduced to %/°C in the analysis in this Report.

For many, perhaps most, systems the temperature dependence is not linear with temperature and often differs appreciably from linearity, eg, see the M256 results for pressure (Table 1). Both "low" and "high" temperature coefficients are often determined .

A further complication is that the propellant undergoes different physical processes in the chamber of a gun compared to an experimental apparatus such as a closed bomb, which is commonly used for laboratory determinations. In the gun, rapid expansion occurs as the combustion gases perform external work, while in the closed vessel, the volume is constant. A consequence is that closed vessel firings may yield information which cannot be directly correlated to weapon ballistic data. Sergo and Price [11] report that changes in propellant geometry result in only minor changes in closed vessel data, in contrast to results in gun firings. White et al [12], on the other hand, report excellent correlations. As a consequence the review has focussed on data from gun firings.

4.2 Large and Medium Calibre Guns

4.2.1 US 155 mm M198 Howitzer: M30A1 Propellant

The M198 Howitzer, discussed earlier in Section 3/Table 1, uses the M30A1 triple base propellant in the M203 propelling charge. The propellant grains are configured as 7 perforation.

The M203 propelling charge has shown a tendency to yield excessive pressures at the upper firing temperature (63°C); the relatively small pressure margin over the system pressure limit should be noted (Table 1). In particular substantial increases were observed in the temperature coefficients for both pressure and velocity at high temperatures for charges made from propellant produced in 1979 [12,13]. Temperature coefficients determined from acceptance test firings over the period 1977-1981 are listed in Table 2; the σ_P value can be seen to range from 2.00 to 0.50 MPa/°C.

Charges made from propellant prepared in 1977 exhibited normal temperature dependence, and the introduction of changes to processing procedures in 1980 and 1981 ultimately returned this parameter to an acceptable level in mid 1981. It was hypothesized [13] that a rapid drying process caused depletion of volatile ingredients such as NG from the propellant surface, producing a chemical gradient within the propellant grain or a porous structure at the surface. Changes in the drying treatment and a slight increase in the NG content were some of the changes implemented to improved temperature sensitivity [12,14]. However, no conclusive explanation could be offered. Furthermore, the problem seemed to be peculiar to the 155 mm system; other calibres using similar propellants did not show temperature sensitivity changes [14].

Separate propellant lots were fired and a multi-regression analysis was carried out to determine the correlation between σ_P and parameters such as nitrocellulose (NC) viscosity, graphite and ash content. The highest correlation was only 0.45, for graphite content, while total volatiles showed no correlation.

An earlier study had found no significant correlation with either graphite content or the particle size of the flash suppressant potassium sulphate additive [13]. This discounted the hypothesis that because there was radiation feedback from the flame to the burning propellant surface, the optical absorption properties of the propellant might have been changed by either component [14]. No lot-to-lot variation was observed between σ_P and the chemical gradient within an individual propellant grain; material was extracted from a spot very close to the perforation, and a spot at the centre of the web [12]. No significant differences in density or propellant specific surface area were observed, although there was considerable data scatter in the latter

[13]. The most significant result from all these tests was the strong dependence of burn rate and temperature sensitivity on the nitroguanidine (NQ) particle size [13]. Lots made from small particle size NQ produced a very small variation between burn rate with either temperature or pressure. Scanning electron microscopy of old samples of NQ showed needle-like crystals sticking together into bundles while newly prepared NQ showed less tendency to agglomerate [14].

A good agreement between closed vessel firings and gun firings was shown, suggesting that the controlling factors on σ_p are probably combustion-related. The largest lot-to-lot deviation was observed at high (peak) pressure, when the outside surfaces of the grains have burned.

Table 2: Temperature Coefficient Data obtained from propellant Acceptance Test for US Triple Base Propellant M30 A1 [a,b] over the period 1977-1981

Propellant Lot Number [c]	Pressure Coefficient σ_P (MPa/°C)	Velocity Coefficient σ_v (m/s°C)
RAD77G-069805	1.05	0.74
RAD77H-069806	0.81	0.65
RAD77H-069807	0.84	0.64
RAD79D-069959	1.52	1.30
RAD79E-069960	1.21	0.93
RAD79E-069961	1.03	0.80
RAD79F-069962	1.04	0.89
RAD79K-069992	1.32	0.86
RAD79L-069994	1.31	0.98
RAD80E-070051	1.87	1.01
RAD801-070052	1.57	0.95
RAD80J-070053	1.10	0.93
RAD81A-070054	2.00	1.28
RAD81E-070056	0.89	0.61
RAD81E-070116	0.74	0.57
RAD81F-070117	0.55	0.45
RAD81F-070119	0.50	0.46
RAD81F-070120	0.71	0.62

a. Data from Ref [12]
b. Used in the M203 cartridge for the 155 mm Howitzer M198
c. 77, 79, 80, 81 refer to year of manufacture

4.2.2 5"/54 Naval Gun Propellants

Gun firings over the temperature range - 30°C to +50°C in the USN 5"/54 system have been reported for three propellant types: M26 double base, BS-NACO single base and NOSOL-318, a highly plasticised propellant [14]. Like the M30A1 described above, all three gave rises in both velocity and pressure during low temperature firings. Closed vessel testing was also carried out but no unusual temperature dependent characteristics were observed, strongly indicating that propellant mechanical failure was the cause of the low temperature ballistic irregularities.

The USN 5"/54 gun system using the in-service Mk41 projectile/pyro propelling charge has been utilized in a study of the accuracy required for propellant thermochemical data to give reliable gun performance prediction [15]. A range of parameters both for the propellant and igniter were investigated and those with the most significant effect on pressure and velocity are detailed in Table 3. Igniter parameters were not significant.

The burn rate coefficient a (from the relationship $r=ap^n$) had the second greatest effect to the burn rate exponent n. If the burn rate coefficient decreased by 1%, the pressure would decrease by 1.6%.

Table 3: Effect of propellant parameters on pressure and velocity [a]

Variable	Effect of 1% change in the variable's value		
	Pressure (%)	Velocity (%)	Relative Change Velocity/Pressure
Burn rate exponent (n)	15	2.8	0.19
Burn rate coefficient (a)	1.6	0.3	0.19
Specific heat ratio	-0.7	-0.8	1.14
Impetus	1.1	0.6	0.54
Covolume	0.6	0.1	0.25
Density	0.1	0.0	-----

a Data from Ref [15]

4.2.3 UK 105 mm L7 Tank Gun: NQ/M Propellant

Hewkin [16] reported an extensive study of the triple-base propellant NQ/M fired in the UK 105 mm L7 tank gun. The investigation covered an extensive temperature range (unfortunately not specified), changes in the number of grain perforations and some changes in composition. Results are detailed in Tables 4 and 5; σ_v and σ_p values have been reduced by a factor of 10 to give % change/°C for direct comparison with other data in this report.

Both σ_v and σ_p were very substantially higher at higher temperatures (Table 4). This was attributed to erosive burning in the grain perforations, which was postulated to be greater when the propellant is in the brittle state at low temperatures. The poor agreement between closed vessel and gun testings for granular propellant, in contrast to cord or slotted tubular forms, supported this hypothesis [16].

A decrease in σ_v and σ_p at both high and low temperatures was observed when the standard 7 perforation grain was substituted by 19 perforation grains. A further but smaller decrease was observed when 37 perforation grains were used (Table 4) [16]. This is the opposite to that observed for nitramine based gun propellants [17]; see Section 4.3.1.

Table 4: Temperature coefficients of propellant NQ/M fired in the L7 105 mm Tank Gun [a]

Charge Weight (kg)	No. of perforations	σ_v (%/°C)[b]		σ_p (%/°C)[b]	
		high temp	low temp	high temp	low temp
5.50	7	0.12	0.08	0.34	0.16
4.77	19	0.07	0.03	0.25	0.06
5.08	37	0.06	0.01	0.20	0.04

a Data from ref [16]
b Relative to 21°C, changed from the original % /10°C calculated using equation (5).

A wide range of triple base propellants have been assessed in the L7 105 mm gun, and the data have been collected in Table 5 [16]. The general impression from Table 5 is that even for major changes in propellant composition, the effect on temperature coefficients is usually small. σ_p at high temperature, the most important of the parameters for our considerations, covered a relatively narrow range of 0.31-0.44% /°C, with a few to 0.65% /°C. It was noted that the composition with lowest value for σ_v contained nitramine, presumably RDX, and had an ignition temperature of 170°C compared with about 155°C for the other propellants [16].

The effect of charge weight on temperature sensitivity is shown in Table 6 for two web sizes of this nitramine containing propellants [9].

For the smaller (1.5 mm) web size propellant, there was a gradual decrease in both σ_v and σ_p as the charge weight was increased from 3.97 to 4.54 kg. This reduction was rationalised as due to a reduction in distance travelled by the projectile at the time of all burn; an increased charge weight would result not only in an increase in the maximum chamber pressure but also in the rate of pressure rise and the burn rate of the propellant, hence reducing the time to "all burnt".

Table 5: Temperature Correction Firings in the L7 105 mm Tank Gun [a]

Propellant	Variant	Charge wt (kg)	σ_v (%/°C)[b]		σ_p (%/°C)[b]	
			high temp	low temp	high temp	low temp
NQ/M		5.68	0.13		0.65	
NQ/M PSBS 144		5.50	0.12	0.08	0.34	0.16
NQ/M BS 29596	NC high acetone insol.	5.78		0.11		0.35
NQ/M PSBS 383	NC mechanical nitration	5.53	0.10	0.10	0.44	0.30
NQ/M PSBS 382	NC Australian wood	5.50	0.10	0.08	0.31	0.17
F527/382	NQ with pyro NC	5.73	0.11		0.47	
F527/333 WACX 4677	Erosion additive in NQ	5.44	0.11	0.09	0.49	0.26
F527/333 WACX 4716	Novel granule shape	5.61	0.14	0.11	0.32	0.24
F527/354 WACX 4150	Fine additive	5.50	0.10		0.44	
F527/354 WACX4174	Coarse additive	5.40	0.10		0.51	
F527/422 WACX 6194	Nitramine additive	4.20	0.09	0.05	0.44	0.27

a Data from Ref [16]
b Relative to 21°C, converted from the original % /10°C

Table 6: Effect of increasing charge weight: F527/422 M15 and M20[a]

Batch	Web size (mm)	Charge Weight (kg)	σ_v (%/°C)[b]		σ_p (%/°C)[b]	
			high temp	low temp	high temp	low temp
WACX6194	1.5	3.97	0.099	0.072	0.552	0.340
		4.08	0.093	0.057	0.490	0.290
		4.19	0.092	0.054	0.431	0.275
		4.31	-	0.045	-	0.227
		4.41	-	0.046	-	0.250
		4.54	-	0.037	-	0.029
WACX6139	2.0	4.99	0.127	0.016	0.452	-0.076
		5.22	0.129	0.010	0.608	-0.114
		5.44	-	0.014	-	-0.069

a Data from Ref [9]
b Relative to 21°C, converted from the original % /10°C

For the propellant with larger web the position of "all burnt" moved further down the chamber toward the muzzle, and the ballistics accordingly became more sensitive to temperature.

Older data [16] on the obsolete QF 1716 gun for a wider range of propellants are detailed in Table 7. The highest temperature coefficients were obtained with the double base propellant F428/180, while the single base NH, the double base with dinitro-toluene added (L/P/M) and the diethylene glycol dinitrate (DEGN) containing triple base propellant F487/46 gave much lower values of σ_p.

Table 7: Temperature Coefficients in the QF 1716 Gun [a]

Propellant	Composition	Form	σ_v (%/°C)[b]		σ_p (%/°C)[b]	
			high temp	low temp	high temp	low temp
NH	NC/DNT	Cord	0.10	0.09	0.17	0.25
L/P/M	NC/NG/DNT	Multitubular	0.12	0.11	0.20	0.33
F428/180	NC/NG	Slotted	0.13	0.16	0.64	0.45
N	NC/NG/NQ	Slotted	0.10	0.11	0.34	0.31
F487/68	NC/DEGN	Tube	0.13	0.08	0.56	0.24
F487/46	NC/DEGN/NQ	Tube	0.09	0.07	0.15	0.16

a Data from Ref [16]
b Relative to 21°C, converted from the original % /10°C

4.2.4 UK 120 mm APDS Tank Ammunition: NQ/S 53-12 Propellant

The type of NQ has a small but measurable effect on σ_p for NQ/S 53-12. Result for firings in the 120 mm tank cannon are detailed below in Table 8. Welland NQ has a specific surface area of about 1.3 m^2/g compared to about 2.0m^2/g for ROF Bishopton NQ. The coarser NQ gave the higher temperature coefficients.

Table 8: Effect of NQ type on Propellant NQ/S 53-12 in 120 mm APDS/CCC[a]

Propellant Batch	NQ Source	σ_v (%/°C)[b]		σ_p (%/°C)[b]	
		high temp	low temp	high temp	low temp
BS 29629	Bishopton	0.109	0.092	0.299	0.213
BS 26388	Welland	0.122	0.102	0.353	0.284

a Data from Ref [9]
b Relative to 21°C, converted from the original % /10°C.

4.3 Propellants in Small Calibre Guns

4.3.1 GAU-8 30 mm Cannon

The temperature sensitivity of single base, double base ball powders, triple base and nitramine propellants in ammunition fired from the GAU-8 gun has been studied over a wide temperature range [14,17,18].

At low temperatures all propellants exhibited negative temperature coefficients which was shown to result from fracture of the embrittled grains [18]. The effect was greatest for the triple base propellant, which displayed reduced efficiency (high p) even at 0°C. The remainder were only affected at -55°C. This grain fracture became more prominent when the charge weights were reduced in the triple base and nitramine propellants.

A range of nitramine propellants were investigated as potential replacements for the standard single perforation inhibited double base GAU-8 propellant [17]. Initial formulations used HMX as oxidiser in the 7 perforation grain form. The temperature dependence was worse for the HMX (nitramine) propellant (Fig. 1), and changing to RDX accentuated the problem. Related work indicated that the increased σ_p was probably a geometry effect. An RDX/TAGN/NC/IDP formulation was investigated in 1, 7 and 19 perforation grain geometry [17] (Fig 2). The single perforation grains gave low σ_p across the temperature range from -60°C to + 70°C, better than the GAU-8 double base (Fig 1).

The effect of different plasticisers was also examined in the 7 perforation nitramine propellant. A plot of the results is shown in Fig 3. Of the four plasticisers used; dioctyl phthalate (DOP), acetyl triethyl citrate (ATEC), isodecyl pelargonate (IDP) and dioctyl azelate (DOZ), the propellant containing DOP was the least sensitive to temperature, particularly above 20°C.

Theoretical interior ballistic predictions for single base and nitramine propellants in 1 and 7 perforation geometries clearly indicate that the progressivity of 7 perforated burning always leads to higher σ_p (but see earlier comment in section 4.2.3). It was also noted that the high linear burn rate slope of the nitramine propellant leads to very sensitive pressure predictions. For example, an 8% increase in linear burn rate gives a 50% increase in predicted peak pressure. Greater progressivity shifts the position of all burnt toward the muzzle, and these results offer support to Hewkin's arguments [9,16]. The effect of NQ particle size was very important in the triple base propellants studied; fine NQ gave lower temperature coefficients [14] which was attributed to improved low-temperature brittle fracture properties in aircraft cannon firings [18].

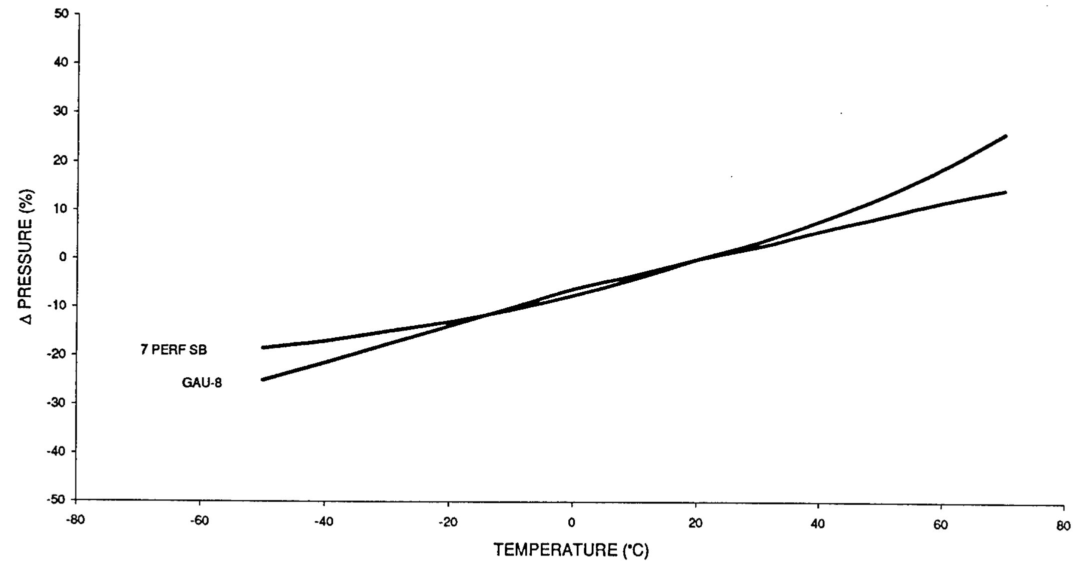

Figure 1: Comparison of temperature sensitivity for an experimental 7 perforation HMX based propellant with the in-service deterred double-base propellant in the 30 mm GAU-8 cannon, from Ref [17].

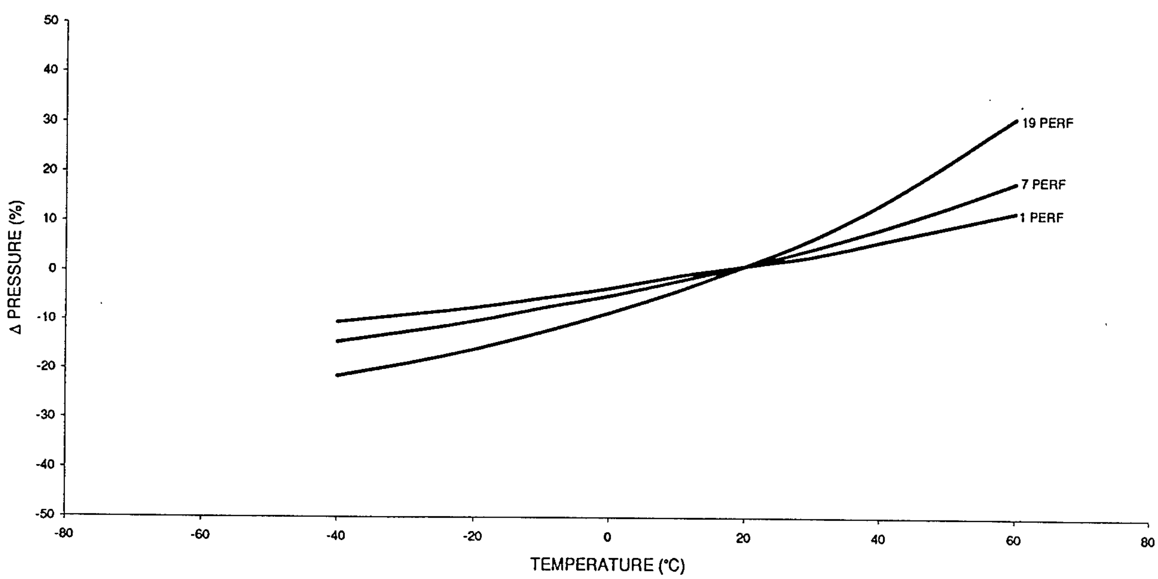

Figure 2: Effect of number of perforations (1, 7, 19) on temperature sensitivity of an experimental RDX/TAGN/NC/IDP propellant configured for GAU-8 ammunition, from Ref [17].

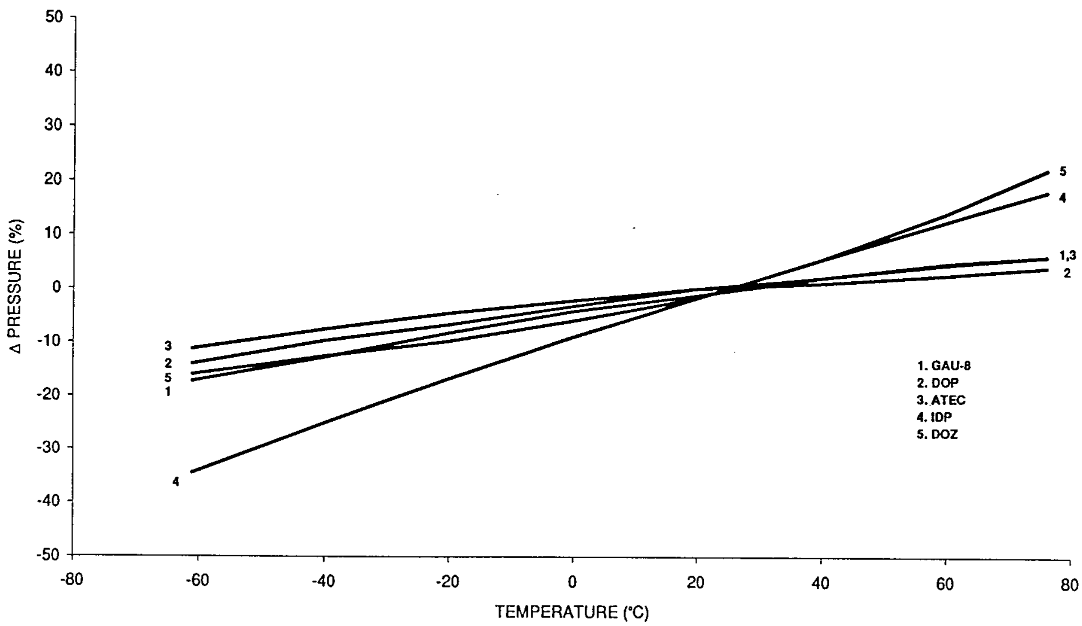

Figure 3: Effect of plasticiser on the temperature sensitivity of a nitramine propellant; from Ref [17].

4.3.2 Smaller Calibre Aircraft Cannon

The propellant study described above in the GAU-8 gun also covered firings in a UK Tornado 27 mm gun and a 20 mm M61 gun barrel [18]. All propellant types were evaluated by plotting piezometric efficiency v^2/p versus charge weight (CW) as were the firings described above for GAU-8.

An NC/DEGN propellant containing more than 20% DEGN plasticiser, configured as a 19 perforation grain, was evaluated in the 27 mm gun. The v^2/p versus temperature plot (Fig. 4) shows an anomolous dip between 40°C and 80°C. This was interpreted as resulting from severe compression of the softened propellant bed under primer blast, as described in mechanism (c) in the Introduction [18]. A related propellant containing N-(n-butyl)-N-(2-nitroxyethyl)nitramine (BuNENA) also showed abnormal temperature behaviour which was similar to NC/DEGN propellant in the 27 mm gun (Fig. 5). It was suggested that this behaviour may be common for highly plasticised propellants which are physically soft at high temperature [18].

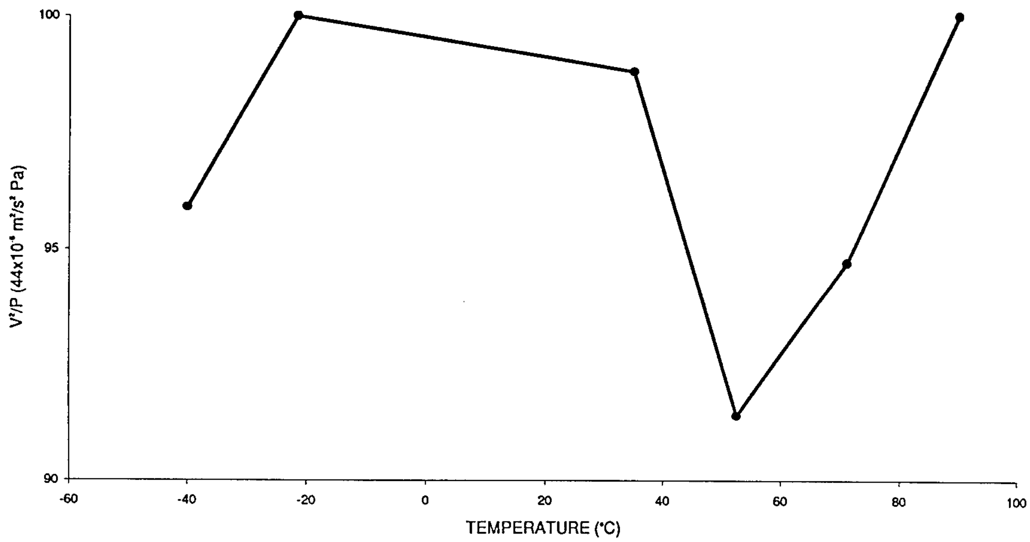

Figure 4: Abnormal ballistic behaviour as shown in plot of V^2/P versus T for a NC/DEGN propellant; from Ref [18].

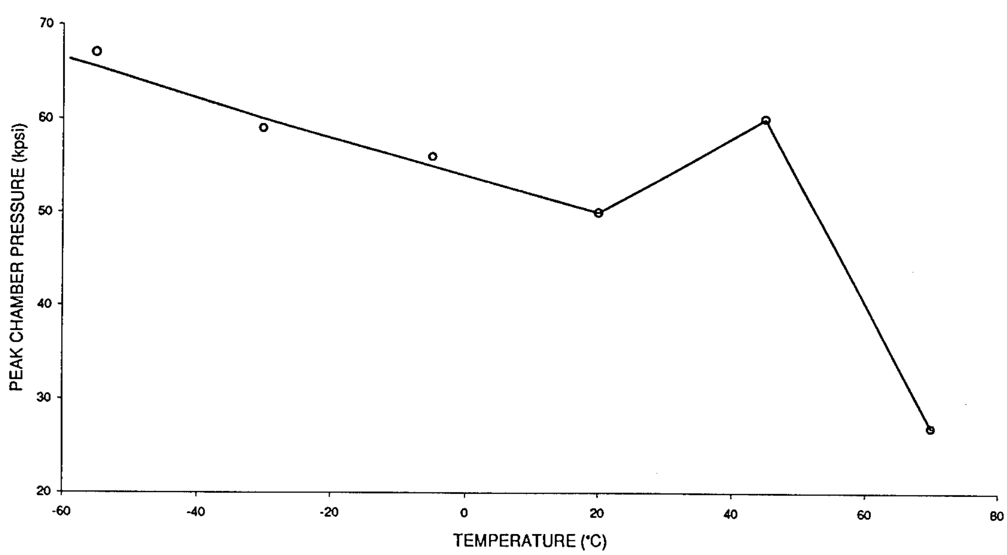

Figure 5: Abnormal ballistic behaviour from a plot of peak pressure versus T for a butyl NENA propellant; from Ref [18].

Nitramine propellants configured as 20 mm ammunition were fired at +20°C and -54°C [19]. The temperature sensitivity was shown to be a function of the concentration of the Paraplex G54 inhibitor (used in the standard GAU-8 double base propellant); data are listed in Table 9. The formulation with only 0.5% G54 exhibited very low σ_P, but pressures developed at -54°C were regarded as excessive. Cannon firings of propellant deterrred with ethyl centralite (EC) exhibited peak pressures at -40°C which were higher than those measured at ambient temperature for related propellants not containing EC. Comparison between EC and Paraplex deterred propellants (which had been subjected to high strain rate Hopkinson Bar testings at various temperatures) showed enhanced gas generation rate during closed vessel tests for the EC propellants; this was explained by changes in low temperature mechanical properties induced by the EC [20].

Table 9: Effect of change in concentration of inhibitor Paraplex G54 on 20mm cannon nitramine propellants temperature coefficient[a]

Paraplex level (%)	Firing Data -54°C		Firing Data 20°C		Temperature Sensitivity (%/°C)	
	Pressure (MPa)	Velocity (m/s)	Pressure (MPa)	Velocity (m/s)	σ_P	σ_v
2.5	391	1022	322	951	0.24	0.09
1.25	407	1043	374	1000	0.14	0.07
0.5	415	1023	406	985	0.03	0.05

a Data from Ref [19]

A strong correlation was established between propellant fracture toughness and temperature coefficients for nitramine propellants suitable for 20 mm cannon; see Tables 10 and 11, and Fig 6 [19]. Coarser RDX or TAGN, both fast burning ingredients, were used to raise the burn rate of nitramine propellants exhibiting low flame temperatures. This enabled a larger grain propellant size to be used, resulting in higher permeability of the propellant bed to combustion gas flow and reduced chamber pressures at low temperatures [20].

Table 10: Effect of propellant grain size on temperature coefficient of nitramine propellants suitable for 20 mm cannon[a]

RDX particle size (μm)	Propellant grain size (mm)	Firing Data 21°C		Firing Data -40°C		Temperature Sensitivity (%/°C)	
		Pressure (MPa)	Velocity (m/s)	Pressure (MPa)	Velocity (m/s)	σ_P	σ_v
5	1.08	393	1023	442	1024	-0.20	0.00
11	1.12	362	1015	369	997	-0.03	0.03

a Data from Ref [20]

Table 11: Effect of propellant grain size, propellant toughness and TAGN on temperature coefficient of nitramine propellant suitable for 20 mm cannon[a]

Formulation Variation	Propellant Toughness (J/m^2)	Grain Size (mm)	Temperature Coefficient (%/°C)	
			σ_p	σ_v
NC/RDX	430	1.08	0.24	0.09
NC/RDX/TAGN	384	1.50	0.24	0.12
NC/RDX/TAGN	542	1.50	0.32	0.16

a Data from Ref [20]

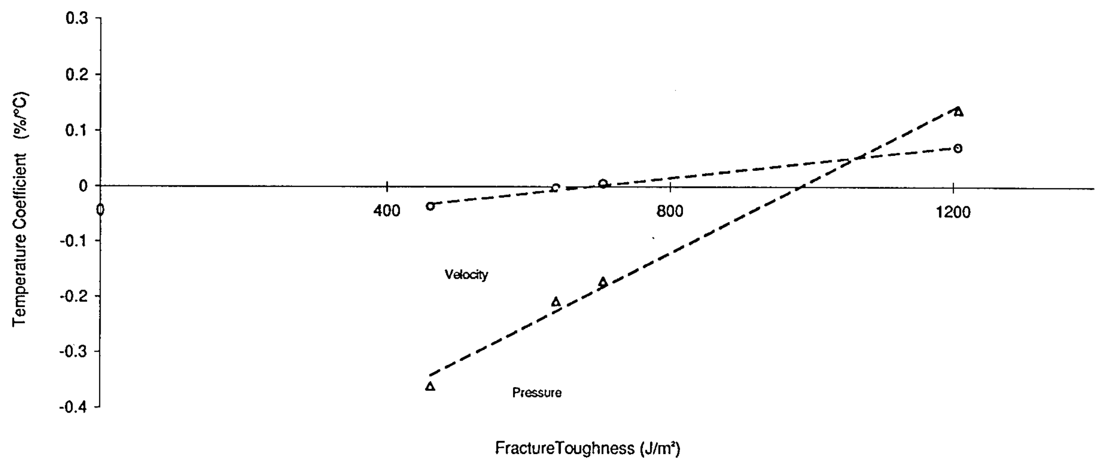

Figure 6: Effect of fracture toughness on temperature coefficient of nitramine propellants for 20 mm ammunition; from Ref [20].

German research [21] was conducted on RDX/TAGN/HTPB propellants for 20 mm ammunition in a closed vessel from -40°C to +50°C, with TAGN/RDX ratios of 8:77, 26:59 and 42.5:42.5 (all 11% HTPB). Vivacity, not the maximum pressure, provides the measure of gasification rate in the closed vessel test, and is therefore the relevant indicator of the pressure to be generated in a gun. The burn rates of the propellants containing NQ is generally less susceptible to temperature changes than is the rate of the propellants containing TAGN [21]. For the propellants containing 26 and 42.5% NQ the gasification rate was almost independent of temperature [21].

Ball propellants have been known to exhibit low σ_p across a wide temperature range [18]. Two types of ball propellants are considered: spherical propellant of the type WC870 (20 mm calibre) type, and rolled (oblate spheroid) propellant of the WC 872

(20 mm) and WC 895 (30 mm) type. The rolled propellant is more progressively burning, and therefore the more piezometrically efficient, form. It has been suggested that grain break-up occurred when testing all three propellants but that:

(a) the rolled propellants were more susceptible to grain fracture at the lower conditioning temperatures because the rolling process induced distortion of the grain resulting in the formation of small cracks;

(b) the rolled ball propellants showed higher than expected piezometric efficiencies at the higher conditioning temperatures and this was attributed to a lowering of the propensity for grain fracture as the temperature was increased and the propellant plasticity also increased;

(c) the ballistics of the rolled propellant in 20 mm ammunition therefore showed a much greater degree of temperature insensitivity than the analogous unrolled propellant; and

(d) rolled ball propellant tested in 30 mm ammunition appeared to be less prone to low temperature grain break-up than ball propellant tested in 20 mm ammunition and it was postulated that this may be due to improved mechanical integrity of the 30 mm ammunition propellant, or to a less harsh ballistic environment in the 30 mm calibre.

An extension of this technology is compacted ball propellants which display very small temperature dependence in 20 and 30 mm ammunition [6,22,23]. These propellant charges are first made by coating the balls with deterrent, rolling to alter the shape to oblate spheres, which probably induces fissuring, then finally compacting to a solid block. The deconsolidation rate of the compacted charge appears to be inversely related to temperature.

Propellants based on polyvinylnitrate (PVN) with NC have been investigated for 20 mm to 30 mm ammunition applications [24]. Temperature coefficients derived from strand burn rate data at 21°C and 50°C for a series of pressures were determined for NC/PVN of composition 100:0, 95:5 and 80:20; these are detailed below in Table 12.

Table 12: Temperature coefficients for NC/PVN propellants at a series of pressures [a]

Pressure (MPa)	Temperature coefficient (% /°C) for NC/PVN Ratios		
	100:0	95:5	80:20
100	+ 0.26	+ 0.24	+ 0.16
200	+ 0.18	+ 0.13	- 0.06
300	+ 0.17	+ 0.14	- 0.02
400	+ 0.14	+ 0.16	- 0.10

a Data from Ref [24]

An NC/PVN (75:25) propellant optimised for the French M693 20 mm cannon firing AP ammunition was tested by gun firings across the temperature range -54°C to +74°C. The propellant was in the form of 7 perforate grains, and the normal single base ammunition fired in this gun was tested in parallel for direct comparison; results are detailed in Table 13. The NC/PVN propellant displays markedly reduced temperature sensitivity at higher temperatures (21 to 74°C).

Table 13: Ballistic Performance of NC/PVN Propellant in the French M693 20 mm Cannon [a]

Propellant	Temperature (°C)	Velocity (m/s)	Pressure (MPa)
NC/PVN 75:25	- 54	1196	316
	- 15	1215	324
	+ 21	1234	332
	+ 51	1249	344
	+ 74	1252	348
Single base [b]	- 54	1181	321
	- 15	1202	335
	+ 21	1232	348
	+ 51	1248	367
	+ 74	1262	397

a. Data from Ref [24]
b. In service propellant in this ammunition, for comparison

4.3.3 LOVA Propellants

Temperature sensitivity of LOVA propellants is under intensive study in the US. For some high-energy LOVA formulations, reduced temperature sensitivity was observed, e.g. a temperature coefficient of 1.73 MPa/°C at high firing temperatures for a LOVA propellant compared to 3.11 MPa/°C for some non-LOVA propellants [6]. It is believed lowering of temperature coefficients of LOVA propellants occurred as a result of changes in surface area availability [6].

Results of firing tests for the LOVA propellant NL001 in the 40 mm L/70 AA gun indicated its temperature dependence to be moderate (0.17 - 0.20%/°C) over the temperature range -40 to 60°C [25].

4.3.4 7.62 mm Rifle: Propellants NRN 41 and AR2206

Firing 7.62 ammunition filled with the UK double base propellant NRN 41 gave a "normal" temperature dependence over the range -54°C to +54°C, but abnormal ballistics outside this temperature range (Fig 7) [16]. Pressures rose sharply at -62°C, and fell sharply at +71°C. Consistent with other examples described already the low temperature behaviour almost certainly resulted from grain fracture, while it is conceivable that the reduction in ballistic performance at high temperature was due to grain softening with resulting closure of perforations and inefficient burning.

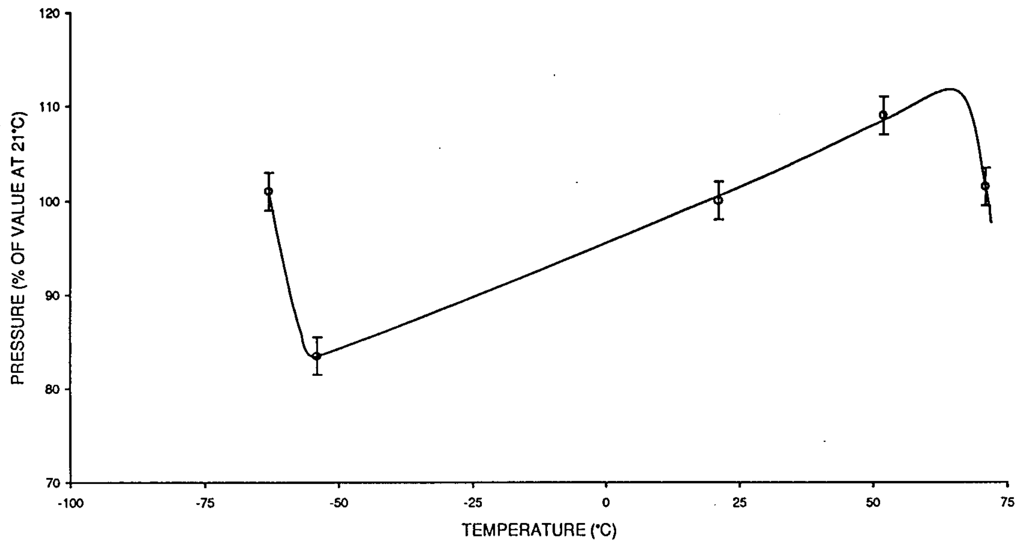

Figure 7: Abnormal ballistics for the UK double-base propellant NRN 41 in 7.62 mm ammunition; from Ref [16].

Low density or porosity of propellant granules has been proposed as a cause for the negative temperature coefficients for the propellant NPP 10 when fired in the 9 mm pistol [16]. The same weapon with normal density ball powder produced normal ballistic results (Table 14). In the latter case the σ_P values were relatively large at the high temperature ranges.

AR2206 is a DNT-coated, single base extruded powder gun propellant which was introduced in 1979 as a result of the requirement by the Australian Army to keep the chamber pressure in the 7.62 mm rifle below 334 MPa at 80°C. To achieve this goal, it was manufactured with microporosity deliberately induced by leaching out potassium nitrate to leave a solid matrix honeycombed by discrete air pockets. The pore size directly resulted from the particle side of the leached potassium nitrate, and was observed to have a very strong influence on burn rate [26, 27].

The interior ballistics for AR2206 and the AR2201, a propellant in the same family as AR2206 but not formulated with potassium nitrate, are compared in Table 15. A very useful characteristic of AR2206 is that it not only gives a markedly lower chamber pressure at 80°C, but it also has much lower σ_P. It is possible to tailor σ_P from positive to zero and negative if required [26]. Production of propellant with uniform size, shape and dispersion of pores was successful using microballoons, but the ballistic results were unsatisfactory because the glass or carbon microballoons inhibited permeability and did not burn compatibly with the matrix [28].

Table 14: Temperature Coefficient in Propellant Interchange Trials in the 9 mm Pistol [a]

Propellant	Charge Weight (g)	Temperature Sensitivity (%/°C)[b]			
		σ_v		σ_p	
		High temp	Low temp	High temp	Low temp
UK NPP10 D 19213	0.39	- 0.032	- 0.022	- 0.032	- 0.132
UK NPP10 D 19150	0.39	- 0.041	- 0.001	- 0.080	0.004
FRG DNG 71/7	0.39	0.075	0.017	0.498	0.018
CAN DA 192	0.47	0.034	0.014	0.194	0.034
BEL FN 71	0.45	0.133	0.040	0.771	0.111

a Data from Ref [16]
b Converted from %/10°C in the original data.

A review of the literature on theoretical modelling of the combustion of porous gun propellants was completed in 1985 [28]. The first objective, to account for burn rate enhancement, was successfully achieved through emphasis on transition from conductive to convective burning. However the second objective, to account for the reduced temperature coefficients, was not; it was claimed that no steady-state data on reduced temperature coefficients existed at that time [28].

Table 15: Comparison of Ballistic Data for AR2206 and AR2201 Single Base Propellants over the Temperature Range -40°C to 80°C [a]

Propellant [b]	Temperature (°C)	Pressure (MPa)[c]	Velocity (m/s)
AR2201	- 40	390	827
	- 18	392	830
	20	395	837
	80	450	869
AR2206	- 40	312	798
	- 18	321	805
	20	313	801
	80	334	826

a Data from Ref [27]
b AR2206 contains 3% potassium nitrate, AR2201 contains none
c In a 7.62 mm test fixture using 2.6 g charge weight

4.4 Control by Gun Design Changes

Gun design can have a marked effect on propellant temperature sensitivity, and in some cases the effect can considerably exceed the range for a series of propellant types in a particular gun. Although there is little published information on this subject, the results in Table 16 compiled by Hewkin [16] adequatelyindicate the potential for variation; N/S is a triple base propellant (N) in a slotted tubular shape.

Table 16: Temperature Coefficients for Propellant N/S 41-12 in Different Gun Systems [a]

Gun System	Propellant Batch	Temperature Sensitivity (% /°C)[b]			
		σ_v		σ_p	
		high temp	low temp	high temp	low temp
3.7" Mk3	BS 15615	0.121	0.136	0.497	0.342
BL 5.5 Mk3	T1394	-	0.113	-	0.306
Abbot 105 mm	BS 26451	0.097	0.108	0.369	0.310
BL 4.5					
Charge 2		0.068	-	-	-
Charge 3		0.076	-	-	-

a Data from Ref [16]
b Converted from the original %/10°C

Hewkin [16] suggested that these changes in σ_p related to the position of shot at all burnt. Consequently gun designs which are least susceptible to changes in temperature are those in which the highest proportion of propellant is burned before the projectile has started to move. Because the thrust of the analysis in this report is changes that could be made to existing systems, the folowing analysis is necessarily brief.

4.4.1 Raising Ammunition Temperature to Hot Temperature Limit

Maintaining ammunition at the upper temperature limit would enable maximum (upper firing pressure) range to be achieved at any firing across the operational temperature range. This raises a number of logistic quesitons, and would presumably only be feasible for self-propelled systems with their own power supply. It would also require the main power supply to be constantly operating, which may be unacceptable in some operational scenarios. Soaking of the propulsion units at the upper firing temperature would accelerate degradation and performance loss while the warheads would need to be kept separate and not heated to avoid unacceptable rates of prematures.

One possibility would be to rapidly heat the propellant in situ using microwaves just before or during firing. Laser stimulation to enhance propellant reaction rates is another alternative. All these concepts are unproven but are believed to be under investigation in the US [1].

4.4.2 Combustion Chamber Volume Control

Recent US research has centred on volume control [6], defined as the ability to control the initial free volume in a weapon chamber as a function of the propelling charge temperature. A second feature impacting on this process is that most studies described so far in this report have mentioned the considerable effect that primer design can have on temperature sensitivity. One means of volume control also alters primer/propellant interactions.

One concept is Control Tube Primers, which enables adjustment of the projectile position prior to ignition. For example the effective chamber volume for a hot temperature firing can be increased by moving the projectile forward just prior to ignition, as shown in Fig. 8. The maximum charge weight for (say) +10°C could be used right up to +63°C, enhancing range at the lower temperatures. Recent firings have demonstrated the feasibility of the concept [6]. However comparatively complex designs may be required, and the fail-safe features remain to be proven.

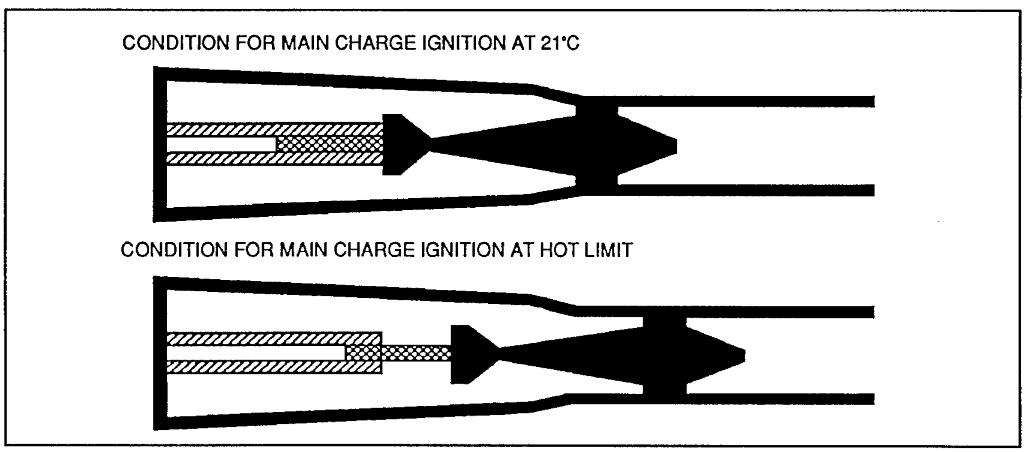

Figure 8: Control tube primer concept for neutralising the effects of temperature sensitivity of artillery ammunition; from Ref [6].

A second concept is called Variable Volume Gun Tubes [6]. This would involve modifying the gun tube so that the chamber volume can be adjusted either up or down, to neutralise the effects of temperature sensitivity across the entire operational range. The system exists at present in concept only, and might vary in complexity from a simple variable intrusion breech set by the soldier from sensor information in the charge storage chamber to a "smart" chamber capable of sensing pressure rise rates and instantaneously adjusting chamber volume. Other intermediate solutions are possible.

5. Discussion

The controlling factors affecting peak pressure in a gun breech during firing are the volume available during the combustion cycle, the burn rate of the propellant, its chemistry, and the amount of propellant surface area available at any point during the combustion; cf equation (1). Transposed from equation (2), the temperature sensitivity σ_p of the peak pressure can be written as

$$\sigma_p = (1/r)\, dr/dT \qquad (7)$$

The control of σ_p in rocket propellants/motors has been very successfully achieved by chemical additives [7]. In contrast there would appear to be no "magic ingredient" available, or even close to being available, to give the same control to gun propellants. The additives to rocket propellants seem to be effective only up to 20 MPa operating pressure, and while adequate for rocket motors falls well below the typical operating range for guns of 360-600 MPa. It is well known that σ_p tends to increase with pressure, and the gun combustion cycle is harsh and transient and ultimately may not be amenable to significant or effective control by combustion additives.

A number of formulation changes have been identified which assist with lowering σ_p. In triple base propellants fine particle size/higher surface area NQ, and in single base propellant the addition of PVN tended to reduce σ_p across the operational temperature range. Low vulnerability ammunition (LOVA) propellants tended to exhibit lower σ_p values than their conventional counterparts, particularly at higher firing temperatures. While these LOVA propellants have not been individually highlighted as such in the text because their LOVA (IM) status is generally not known, they typically will be the nitramine (RDX and HMX) propellants given as examples. As the ADF implements an Insensitive Munitions (IM) policy [29], the lower temperature sensitivity could be an additional benefit from LOVA ammunition.

Some of these formulation changes may primarily exert their influence through combustion phenomena. It has been suggested [13] that at high temperatures these are more important. The rate of chemical reaction is temperature dependent (equation (2)). In the low pressure/high temperature limit the solid reactions (Fig 9, C-D) will dominate and their energy release will be used to increase the propellant from its initial temperature to that where significant reaction can take place. In the high pressure or low temperature limit (Fig 9, A-B) the burn rate is controlled by the combined energy release of solid and gaseous reactions. Since this heat is substantially larger than from the solid phase alone, the initial temperature will not have such a large effect and σ_p will be lower. The overall σ_p therefore depends on the relative control exerted by each phase; an increase of σ_p with temperature increase can result from a temperature dependent shift from the less sensitive gas phase reactions (A-B) to the more sensitive solid reactions (C-D).

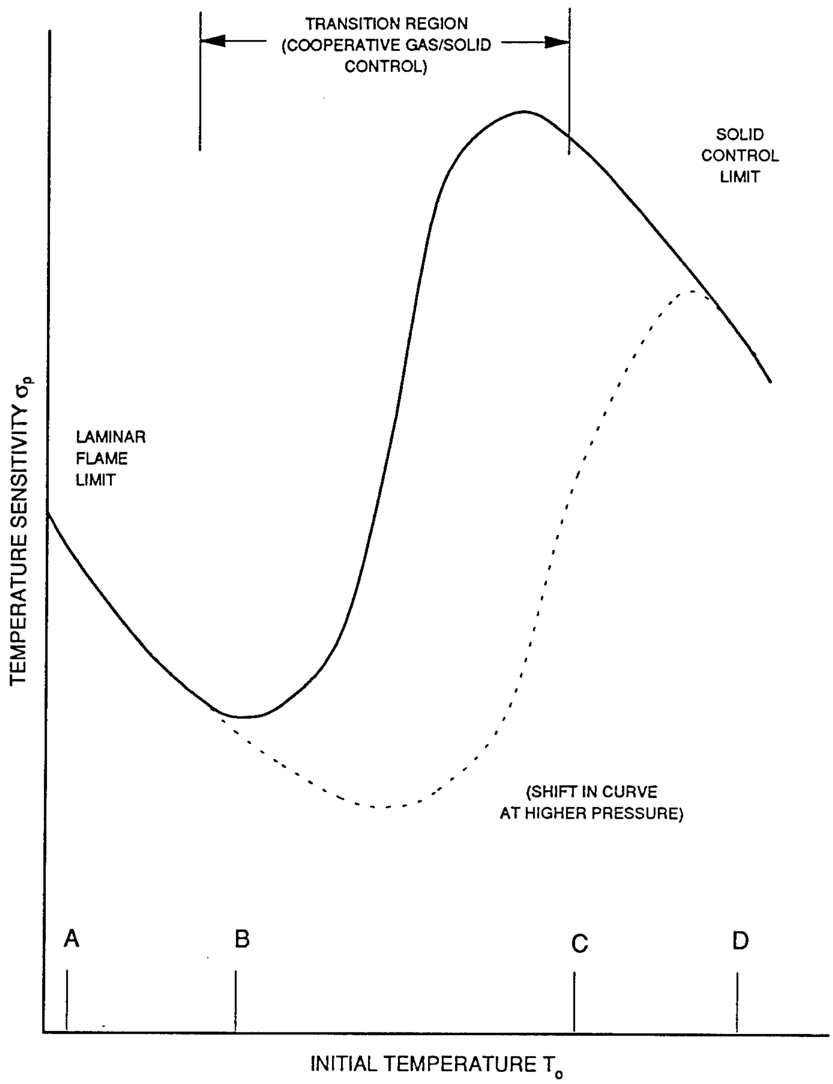

Figure 9: Simplistic model showing variation of temperature sensitivity with initial temperature; from Ref [14].

The favourable effects on σ_p produced by deterrents/inhibitors and changes of propellant grain geometry, e.g. number of perforations, presumably are manifestations of combustion effects. Alternatively, they may be attributed to the influence by the deterrent/inhibitor on the propellant mechanical properties [20]. The hypotheses invoked to explain the effects due to the number of grain perforations differ depending on whether the temperature coefficient increases [17] or decreases [16] with the number of perforations.

Notwithstanding the above, the major effects on σ_p from propellant formulation changes are due to changes in mechanical properties. The effects of NQ morphology, the LOVA propellants and the effects of plasticisers all probably result from this mechanism. Ball propellants, including compacted ball propellants, would appear to depend for their lower σ_p on controlled breakup during combustion; the increased surface due to increased grain breakup at lower temperatures counteracts the reduced burn rate. At the high temperature limit highly plasticised propellants become physically soft and inhibit the natural tendency to increased burn rate. Grain porosity similarly operates by changing grain mechanical properties. At low temperatures the propellant is relatively rigid and non-compressible, and the pores contribute to the overall gasification rate. At high temperatures, the propellants becomes more compressible, and the pores may collapse thereby reducing the gasification rate. The overall effect would offset the increase in gasification rate which tends to increase with increasing temperature [20].

While these mechanical effects can counteract the tendency for reaction rate changes with temperature, to lower σ_p, they must be fail safe. A propellant that fractures at low temperatures to increase peak pressure must controllably fracture such that catastrophic overpressure is not created, similarly inhibition of combustion by propellant softening at high temperatures must work every time. Any technology advances in these directions might ultimately be limited by safety concerns, and an ability to effectively operate at both extremes of the temperature spectrum. Keeping the ammunition at the upper design temperature, or heating in situ to achieve this, might ultimately be rejected as an unacceptable risk, apart from the logistic problems involved.

Gun design can have an even greater effect on σ_p. The position of propellant all burnt profoundly affects σ_p which is minimised if all (most) of the propellant is burnt before shot start, and increases with shift of the all burnt position down the chamber. Igniter design can also be important, since uniform ignition of the propellant bed will result in a peak pressure less dependent on propellant mechanical properties than a more localised ignition process.

The variables available to a gun designer to control temperature related performance follow from

$$p = \frac{nRT}{V - mb} \tag{8}$$

where n = moles of gas from propellant combustion,
R = universal gas constant,
V = total chamber volume
m = propellant gas mass and
b = covolume

Attempts to control p by gun chamber volume control are at very early stages of R&D in the US [6]. Two concepts were described in section 4.4. A control tube primer with the ability to adjust the position of the projectile prior to ignition is under investigation, but fail-safe features remain to be proven.

A more ambitious program is the variable volume gun tube whereby the chamber itself is automatically adjusted to compensate for temperature changes. In the limit this would be a "smart" chamber which is capable of sensing pressure rise rates and instantly adjusting the chamber volume. Such technology is at a very early stage of R&D [6].

Neither of the volume control methods would be suitable for retrofit to existing gun systems without major changes.

6. Conclusion

A number of approaches to increase the range of ADF artillery across their operational temperature spectrum have been reviewed and analysed. All are focussed to counteract the tendency of propulsion system peak pressures to increase with increasing temperature. Range is sacrificed at normal operating temperatures in order that the pressure generated at the upper temperature limit (63°C) has adequate safety margin over the gun design pressure.

Changes to reduce the temperature sensitivity (σ_p) of the propulsion unit represent a relatively low technology option compatible with existing gun systems. Increases in range for the L118 Hamel light gun would be up to 5%, or 0.9 km with Abbot ammunition at maximum charge. Other propellant changes such as grain geometry and formulation could give further incremental increases.

Unfortunately no obvious chemical candidate to lower σ_p has been identified, either in large, medium or small calibre ammunition. The most promising propellant types are LOVA propellants which have the added advantages of reducing munition vulnerability and compliance with the ADO IM policy [29]. Compacted ball propellants exhibit low σ_p but their suitability for artillery ammunition is not proven.

Potential changes to gun design have been examined to a lesser extent. Two technologies; control tube primers and a variable volume gun tube, are at early stages of R&D in the US [6]. The latter, perhaps in the limit as a smart computer controlled chamber, represents the highest long term potential. Neither would be suitable for easy retrofit to existing gun systems and their fail-safe features remain unproven.

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Glossary

ATEC	Acetyl triethyl citrate
ButylNENA	N-n-butyl-N-(2-nitroxyethyl) nitramine
CW	Charge weight
DBP	Dibutyl Phthalate
DEGN	Diethyleneglycoldinitrate
DNT	Dinitrotoluene
DOZ	Dioctyl azelate
DOP	Dioctyl Phthalate
EC	Ethyl Centralite
HMX	Cyclotetramethylenetetranitramine
IDP	isodecyl pelargonate
k	Rate constant of reaction
NC	Nitrocellulose
NG	Nitroglycerine
NQ	Nitroguanidine
RDX	Cyclotrimethylenetrinitramine
R	Universal gas constant
P	Chamber pressure
P_{21}	Chamber pressure at 21^{o}C
TAGN	Triaminoguanidine Nitrate
T	Temperature
T_F	Flame temperature
v	Muzzle velocity

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ABSTRACT

A number of approaches to reduce the temperature sensitivity of ADF gun ammunition across the operational range (-6°C to +63°C) have been reviewed and analysed. Increases in range of about 5% for Hamel are possible, and a solution would maintain compatibility with the existing gun system. While successful in rocket propellants, no chemical additives have been identified which give similar control of temperature sensitivity in gun propellants. LOVA ammunition appears to offer the best potential and has the added advantage of enhanced munition and platform survivability. Two changes involving gun design are at early stages of R&D in the US; control tube primers and variable volume gun tube. Both should be monitored for future applicability, including fail-safe aspects.

Approaches to Reducing the Temperature Sensitivity of
Propulsion Systems for Artillery Ammunition

Tam T. Nguyen and Robert J. Spear

(DSTO-TR-0102)

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