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Understanding and Predicting Gun Barrel Erosion

Ian A. Johnston

Weapons Systems Division
Defence Science and Technology Organisation

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ABSTRACT

The Australian Defence Force will soon have to contend with gun barrel erosion issues arising from the use of new low-vulnerability gun propellants, the acquisition of new ammunition and gun systems, and possible modifications to existing propelling charge designs. A critical, technical review of advances in gun barrel erosion research, mitigation, and assessment over the last fifteen years is presented. Known and postulated erosion mechanisms, obtained through recent experimental and numerical modelling work, are described and contrasted. New approaches to erosion mitigation and updated knowledge of existing methods are reviewed. Also included is an assessment of the utility of the various erosion modelling and experimental techniques, and notes on their possible use for defence applications in Australia.

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*Weapons Systems Division
DSTO Defence Science and Technology Organisation
PO Box 1500
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Telephone: (08) 8259 5555

Facsimile: (08) 8259 6567

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EXECUTIVE SUMMARY

The erosion of gun barrels in service leads to reduced gun performance and availability, and the expense of barrel replacement over the lifetime of a gun system. It is particularly problematic for those guns which operate in high performance ballistic regimes. Although the Australian Defence Force has long had to contend with the problem of gun barrel erosion, it has recently received renewed attention. A new defence instruction mandating the future use of low vulnerability (LOVA) propellants, the near- and medium-term acquisition of new ammunition and weapon systems, and the possible modification of existing propelling charge configurations, all present the need for reliable prediction and assessment of the associated barrel erosion risks.

This report is a critical, technical review of advances in gun barrel erosion research, mitigation, and assessment, over the last fifteen years. Known and postulated erosion mechanisms, obtained through recent experimental and numerical modelling work, are described and contrasted. New approaches to erosion mitigation and updated knowledge of existing methods are reviewed. Also included is an assessment of the utility of the various erosion modelling and experimental techniques, and notes on their possible use for defence applications in Australia. A summary of key topics covered in the review follows.

In the past it has been commonly held that hotter-burning gun propellants are more erosive, however this is not always true. A significant number of cases have been reported where erosion does not increase with flame temperature, and chemical attack of the bore by propellant gas species has been the primary determinant of erosivity. Although there is some conflicting evidence in the literature, it is generally accepted that the most common LOVA propellants are more erosive than equivalent conventional propellants. Many LOVA propellant formulations contain RDX, and it has been convincingly shown by several investigators that RDX is highly chemically erosive.

New, experimental low-erosivity LOVA propellants have been produced by reducing RDX content and introducing nitrogen-rich energetic binder or filler compounds. The resulting propellant combustion gases, rich in nitrogen, act to re-nitride bore surfaces during firing and inhibit erosive surface reactions. The result is increased bore hardness, increased resistance to melting, and reduced chemical erosion. The lowered hydrogen concentration in the combustion gas of some of these propellants may also reduce hydrogen-assisted cracking of the bore surface. Of the high-nitrogen propellants under development, the majority possess impetus and flame temperatures lower than RDX: a compromise between performance, sensitiveness and erosivity must be reached in these cases.

Significant effort has recently been directed at understanding the erosion mechanisms for barrels coated with protective refractory metals. The most plausible mechanism is that microcracks in the coatings, present from the time of manufacture, propagate due to pressure and thermal stress cycling and eventually reach the gun steel substrate. Through numerical modelling and analysis of eroded barrels, a number of investigators have shown

that once cracks reach the substrate, chemical erosion, gas wash, and high interfacial temperatures cause pitting of the substrate and eventually undermine the coating. Segments of coating are subsequently removed by the flow or engagement with the projectile, and at this point the erosion rate of coated barrels may exceed that of steel barrels. A number of ways to mitigate this erosion pathway have been suggested, including: development of better coating techniques to avoid the initial microcracks, pre-nitriding the gun steel before coating to slow substrate erosion, introducing a protective interlayer, and controlled barrel storage and post-firing treatment to prevent oxidation of exposed substrate. Modelling and experiments have additionally shown that, with the notable exception of chromium, the erosion resistance of refractory metal coatings varies amongst different propellant gas chemistry environments.

Due to very good wear characteristics and thermal resistance, ceramic barrel liners have been identified as a promising technology for some time. However the susceptibility of ceramics to fracture, driven by stress induced by the different thermal expansion properties of steel and ceramics, have prevented their widespread use. New functionally graded ceramic-to-metal liners, which avoid an abrupt mismatch of thermal expansion at the ceramic/metal interface, are being developed to address this issue. For small calibres, fabrication of entire barrels using composite reinforced ceramics has been demonstrated.

Particularly for cooler propellants, it has been shown that charge arrangement can affect the severity and distribution of erosion due to gas wash, and that combustible cases can reduce erosion through cooling-layer effects. Several investigators have shown that propellant gas blow-by markedly increases heat transfer to the bore, and thereby thermal erosion.

Over the last ten years there have been significant advances in computational modelling of erosion, and two codes capable of simulating a broad range of erosion phenomena have been reviewed. Modelling results show reasonable agreement with the erosion of in-service gun barrels and laboratory experiments. In some cases, however, significant calibration via input of experimental data was required to achieve this agreement. A truly predictive and comprehensive erosion model, capable of supplanting experiment, does not yet exist. Nevertheless, in combination with experiment the existing computational erosion models have proved extremely useful in better understanding how the various erosion mechanisms act.

Near term work in Australia will most likely focus on the erosion assessment of new propellants, LOVA propellants, new and modified charge designs, and new weapon systems. Since numerical erosion models require experimental validation anyway, it is suggested that the limited resources available for research in this area are best directed towards establishing a modest experimental capability. Vented vessel testing has long been the primary small-scale erosion research tool, but the questionable applicability of results to full-scale gun barrel erosion has previously restricted their usefulness. New vented vessel testing methods, methodologies for the selection of appropriate and realistic test conditions, and empirical relations designed to reconcile vessel and gun results, have significantly alleviated this difficulty, however. Thus a properly designed vented vessel test facility, together with limited full-scale gun firings, is recommended as the most efficient approach to performing erosion research and assessment with restricted resources.

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Nomenclature

APFSDS	Armour Piercing Fin Stabilized Discarding Sabot
CAB	Cellulose Acetate Butyrate
CAN	Cellulose Acetate Nitrate
CAZ	Chemically Affected Zone
CFD	Computational Fluid Dynamics
EFC	Effective Full Charge
HAC	Hydrogen Assisted Cracking
HAZ	Heat Affected Zone
IWTC	In-Wall Thermocouple
KE	Kinetic Energy
LC	Low Contractile
LOVA	Low Vulnerability Ammunition
MOCVD	Metal-Organic Chemical Vapour Deposition
OR	Origin of Rifling
RAVEN	Sonic Rarefaction Wave Low Recoil Gun
RDX	Cyclotrimethylene Trinitramine
A	Wear Coefficient [m] or [m/s]
c_v	Specific Heat at Constant Volume [J/(kg K)]
d	Bore Diameter [m]
ΔE	Molar Activation Energy [J/mol]
f	Species Volume Fraction [%]
h	Convection Heat Transfer Coefficient [W/(m ² K)]
I	Propellant Impetus [J/kg]
k	Thermal Conductivity [W/(m K)]
μ	Dynamic Viscosity [Pa s]
m	Mass [kg]
M	Molecular Weight [kg/mol]
Nu	Nusselt Number
P	Pressure [Pa]
q	Heat Flux [W/m ²]
ρ	Density [kg/m ³]
R	Specific Gas Constant [J/(kg K)]
\mathcal{R}	Universal Gas Constant [J/(mol K)]
Re	Reynolds Number
T	Temperature [K]
t	Time [s]
T_{max}	Maximum Bore Surface Temperature [K]
u	Speed [m/s]
V	Volume [m ³]
w	Diametral Wear [m]
x	Axial distance [m]

1 Introduction

The erosion of gun barrels in service leads to two problems for the Australian Defence Force: (i) barrel replacement costs over the lifespan of fielded weapon systems, and particularly those guns frequently operating in high performance ballistic regimes, and (ii) reduced operational effectiveness due to variable gun performance and availability.

The erosion of a gun barrel under normal firing conditions is typically manifested in damage to the bore surface, and a bore diameter which progressively increases [1]. Typical erosion rates are in the range of 0.1–200 μm per firing [2], with the worst damage usually occurring near the origin of rifling (OR) position or, for smooth-bore barrels, at the analogous location. Erosion of the bore near the muzzle end is also often reported, though it is usually less severe than that occurring at the OR [3].

In some cases the rated fatigue life of a gun barrel, in terms of number of firing cycles, may be reached before the barrel is eroded past condemning limits, obviating erosion concerns. The possibility of immediate catastrophic fatigue failure, rather than the more benign effects of progressive erosion, raises even greater concerns in this situation. Normally, however, the rate of erosion exceeds the fatigue crack propagation rate [2], and erosion is the driving factor in barrel retirement. An example of an erosion-limited barrel is the M199 howitzer cannon, which has a normal wear life of 2 700 effective full charge (EFC) rounds and a fatigue life of 10 000 EFC rounds, using a triple-base propelling charge [1]. In comparison, the M126E1 howitzer has an expected wear life of 30 000 EFC rounds and a fatigue limit of 7 500 EFC rounds, using a slightly cooler single-base propellant [1]. The wear limits for these 155 mm guns are 2.5 and 2.0 mm respectively. The condemning erosion limit can vary considerably between guns, primarily depending on accuracy and performance requirements: for some indirect fire weapons, erosion of up to 8% of bore diameter may be tolerable, but the tolerance for tank guns is tighter and typically in the range 0.5–1% [2]. As would be intuitively expected, high performance guns with high muzzle velocities usually wear fastest [4]. For example the 105 mm M68 tank gun, operating at a 1 600 m/s muzzle velocity, has a normal wear life as low as 100 EFC rounds [1]. It has also long been assumed and often observed that hot propellants cause more erosion than do similarly-performing cooler-burning propellants. Although this is often true, there are significant exceptions which will be discussed later in this report.

Barrel erosion is unlikely to cause catastrophic failure, and thus condemning limits are primarily set to ensure the effects of erosion on gun performance do not become excessive. The effects of an eroded bore may include [3, 5]:

- range and range accuracy loss,
- directional stability loss and resultant dispersion,
- fuze malfunctions,
- excessive torsional impulse (rifled barrels),
- propellant gas blow-by,
- reduction in barrel fatigue life,

- excessive muzzle flash, and
- increased blast overpressure.

Some of these consequences have the potential to markedly reduce operational effectiveness.

Although the Australian Defence Force has long had to contend with the problem of barrel erosion, it has recently received renewed attention for several reasons. First, a new defence instruction, *Insensitive Munitions* [6], has mandated the use of low vulnerability ammunition (LOVA) for all new explosive ordnance procurement, unless a waiver is obtained. In addition, an implementation plan will be developed to address the issue of sensitiveness for munitions already in service. The resulting move to LOVA propelling charges means that it is likely that new propellants will be introduced to service. The different chemical composition, flame temperature and (usually higher) erosivity of LOVA propellants places increased emphasis on addressing the problem of erosion. Second, the imminent upgrade of the ADI Mulwala propellant manufacturing facility may lead to the production of new propellants with different erosive behaviour to those already in service. Third, procurement activities such as Land 17 (replacement or enhancement of the Army howitzer fleet) and MARAP (medium artillery replacement ammunition project) will result in new barrel, propelling charge and projectile configurations. These new or upgraded systems will likely not exhibit the same erosive wear characteristics as is currently encountered in existing systems.

In the context of these gun and propelling charge replacements and upgrades, the capability to model, predict, test, measure and understand the associated erosion processes becomes important. Unfortunately, though, there has been little recent work in these areas at DSTO. There was no active Australian participation in the Technical Cooperation Program (TTCP) 2000–2003 *Gun Tube Wear and Erosion* research activities [7], for example. One possible reason for the dearth of Australian work is a lack of resources to approach the complex, cross-discipline nature of gun barrel erosion research: it crosses the fields of material science and metallurgy, solid mechanics, compressible gas dynamics, chemistry, interior ballistics, heat transfer, and statistical mechanics. Nevertheless, there will likely be a near-term requirement to establish at least basic erosion research competence to support the activities noted above.

The aim of this report, then, is to describe and assess the current state of analytical, numerical, empirical and experimental approaches to gun barrel erosion research, with a view to their practical use by Defence in Australia. Research prior to 1988 has already been thoroughly reviewed — by Ahmad [1] and Bracuti [5] for example — and it is not the intention of this report to re-examine the same ground. This report will focus on material omitted from these reviews, and work that has been conducted since their publication. Section 2 begins with a review of known and postulated erosion mechanisms, and a description of insights obtained through the most recent experimental and modelling work. Disagreements in the literature, including the relative erosivity of the various propellant gas species, the existence of protective species, and the effect of flame temperature on erosion, will be addressed. Section 3 continues with a discussion of erosion mitigation methods. With the background established, Sections 4 and 5 go on to critically assess the utility of modern approaches to erosion modelling, prediction and experimental assessment.

2 Erosion Mechanisms

Conventionally, gun barrel erosion mechanisms are categorized as chemical, thermal and mechanical. The categorization is fairly arbitrary, and probably of most use for assigning the erosion processes to the various associated scientific disciplines. It is important to realize, though, that the categories are tightly coupled to each other and act in concert to erode barrels. Chemical processes include carburizing or oxidizing reactions at the bore surface, resulting in ablation and inferior material properties. Diffusion of propellant gas species into the gun steel and subsurface reactions also occur. Thermal mechanisms include bore surface phase changes, softening and melting, as well as cracking due to expansion and contraction associated with thermal cycling. Mechanical erosion may be caused by the direct impingement of gas and solid particulate flow on the bore surface. The shearing action of the flow, removal of material by driving bands, and crack propagation due to ballistic pressure cycles, are also contributors.

2.1 Chemical Erosion

The combustion of solid propellant in a gun typically produces carbon monoxide, carbon dioxide, hydrogen, water vapour and nitrogen, in proportions which depend on the particular formulation. By establishing the erosive action of these gaseous species, it is possible to reduce erosion by modifying the solid propellant's composition. Some researchers have produced species erosivity correlations through analysis of large sets of experimental firings. Others, though, have approached the problem by trying to determine and understand the chemical reaction pathways which aid or hinder the erosion process.

Two semi-empirical correlations relating gas species to erosion levels have been produced by Lawton. His original correlation [3] was based on over 60 observations of the action of 13 different propellants in 30 guns with uncoated barrels. Further data was later incorporated, resulting in an updated correlation based on 70 gun and propellant combinations [2]. For the original correlation, Lawton provides a physically-based argument that diametral wear per round should be of the form

$$w = A \exp(bT_{max}), \quad (1)$$

where T_{max} is the maximum bore temperature during firing, b is a constant related to the bore surface hardness, and A depends on the propellant gas composition. Multiple linear regression of the experimental data resulted in the definition of A , in metres, as

$$A = \exp(0.23f_{CO_2} + 0.27f_{CO} + 0.28f_{H_2O} + 0.74f_{H_2} + 0.16f_{N_2} + 1.55f_R - 31.36), \quad (2)$$

where f is the volume fraction of each species in percent, and f_R represents the dissociated products. From this correlation it appears that, next to the dissociated products, H_2 is the most erosive gas species and N_2 the least. In Lawton's updated correlation H_2 remains the most erosive species, however CO_2 and H_2O (rather than N_2) are calculated as the least erosive. The variation in the correlation as a function of the sample set indicates that caution should be used in applying the fit to propellants that were not included in the study.

While useful, Lawton's correlations do not explain why erosivity is dependant on the composition of the propellant gas. Upon analysing the original correlation, Kimura [8] noted that the erosivity coefficient of a species i was approximately proportional to the square root of the inverse of its molecular weight $\sqrt{1/M_i}$. Because heat conductivity of a species is a function of a similar quantity, $\sqrt{T/M_i}$, Kimura postulates that variations in species concentration influence erosion primarily through corresponding changes in heat transfer from the gas to the bore surface.

Kimura proceeds to separate the thermal and chemical effects of gas composition, and estimates that the relative contribution of chemical erosivity to the total erosivity for each species is ordered as [9]:

$$\text{CO}_2 > \text{CO} > \text{H}_2\text{O} > \text{H}_2 > 0 > \text{N}_2 \quad (3)$$

where diatomic nitrogen is suggested to have a chemically protective influence. These results were used by Kimura to develop low erosivity, high nitrogen content, low vulnerability propellant, which will be further discussed in Section 3.1.

The propellant gas species are thought to cause erosion by two different processes. First, surface reactions between the hot gas species and the bore material produce weaker, lower melting point compounds, which are easily removed by thermal and mechanical processes. Second, rapid thermally-driven diffusion [3] of gas species in the radial direction, from the bore surface into the barrel material, results in interstitial atoms in the lattice of the bore metal, thereby altering the structure, physical properties and melting point of the gun steel. The result is typically a material of reduced strength and increased brittleness, which is more susceptible to erosion [2].

The chemically affected zone or layer (CAZ/CAL) of the barrel material, often referred to as the white-layer, is of the order of one to tens of microns deep [10] and often penetrated by cracks [11]. As would be intuitively expected, chemically driven erosion has been reported to be a function of the thickness of the CAZ [11]. Thermal effects, as will be discussed in the next section, penetrate much deeper into the barrel material than the white layer and thus also have a bearing on the formation of the CAZ. Heating of the CAZ drives phase changes, melting, crack formation, speed of diffusion and reaction rates, affecting not only the virgin barrel material but also the reaction product species.

The CAZ is sometimes observed to be composed of distinct outer and inner white layers. The so-called outer layer contains the bulk of products from the surface reactions, including iron carbides, oxides, nitrides and retained steel in both austenitic and martensitic phases [12]. In contrast, the inner layer primarily contains carbon and nitrogen precipitates distributed through retained austenite [13]. It is speculated that formation of the inner layer precedes the outer [1].

The described characteristics of the CAZ and the species contained within it have been established through metallurgical examinations, including electron microscopy and spectroscopy [10, 12, 13]. Though the produced species visible in these post-firing examinations suggest what reactions may be occurring, they do not definitively establish the exact nature of the reaction pathways. Numerical modelling [14–16] and targeted experiments [17, 18] have helped to suggest the most likely pathways, but there remains uncertainty in the literature as to which reactions induce the most erosion. The most commonly cited chemical processes are now discussed.

Carburization

The carbon-containing propellant combustion products CO and CO₂ provide monatomic carbon at the hot gas-bore interface via reactions such as [13, 16]



with the resulting carbon subsequently diffusing into the barrel and forming a solid solution with the gun steel. Although carburizing acts to increase the surface hardness of steel, excess carbon may precipitate out of solution upon cooling of the barrel. The carbon precipitates as iron carbide compounds [15] through reactions such as



Although Fe₃C (cementite) is the most commonly cited carbide formed, there is evidence that Fe₂C, Fe₅C₂ and Fe₂₀C₉ compounds can also be produced [12]. The cementite increases the brittleness of the bore surface and lowers its melting point (by 50–400 K [15]), rendering the material vulnerable to removal by thermal and mechanical means. According to Lawton [2], after a few ballistic cycles the concentration of diffused species reaches a steady-state. As a proportion of the CAZ is eroded during each firing, still more diffusion will occur, rendering a relatively steady species concentration profile as a function of depth and keeping the size of the CAZ constant.

Turley and coworkers [12] report disagreement regarding the physics of the diffusion process. Some researchers believe that the diffusion of carbon into the steel can occur as a purely solid state process, while others conclude that the slowness of solid diffusion means that carbon enrichment must occur through propellant gas interaction with a partially melted surface. Turley postulates that both mechanisms could occur: the melting point of the surface material could be lowered by initial solid diffusion, and any resulting surface melting could assist faster carbon diffusion into the liquid phase.

Further support for the theory of solid diffusion is provided by Conroy and coworkers [16]. Conroy supposes that, although slow, subsurface diffusion of carbon continues for a long period after combustion finishes and surface reactions freeze out. Thus when the barrel temperature is again raised in a subsequent firing, Conroy argues that the already diffused carbon is brought out of chemical equilibrium with the surrounding species and continues to react, presumably forming iron carbides, and thereby amplifying the importance of the diffusion process.

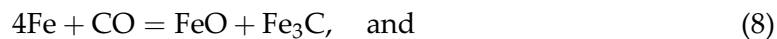
Oxidation

Oxygen from the propellant gas species may act to diffuse into the metal surface and oxidize it, in a process analogous to the formation of cementite. Depending on the environment produced by a particular propellant type and barrel material combination, iron at the bore surface may act to reduce the oxygen rich combustion species through reactions such as [13]



at the gas-metal interface initially, and subsequently at the subsurface interface between the generated oxide layer and the unaffected metal [14]. The iron oxide forms a brittle scale layer, highly susceptible to cracking and erosion [14]. For uncoated steel barrels, oxidation may lower the surface melting point by 100–200 K [14], thereby encouraging thermal erosion also.

A different pathway for the formation of both FeO and Fe₃C in the CAZ has been put forward by Kimura [8, 9]. This involves the formation of iron carbides and oxides in the same reaction:



Kimura reports that both of these reactions are strongly exothermic, producing the equivalent of approximately half the heat of combustion of his propellants [9]. It is supposed that the exothermicity gives a temperature boost which assists in the melting of the products and their subsequent removal from the surface. According to Kimura, hotter propellants tend to produce more CO₂ than CO, thereby favouring Reaction 9 in preference to Reaction 8. Hence, by stoichiometry, hotter propellants should generate more FeO relative to Fe₃C. This result is consistent with the observations of other researchers. Together with flame temperature, the propellant gas CO/CO₂ ratio has historically been cited [1] as a key determinant of the CAZ composition; Kimura's postulated mechanism would appear to support this.

Metallographic investigations of steel exposed to firings in a 20 mm test gun, reported by Seiler and coworkers [10], serve as a good example of the dependency of erosion on propellant formulation. Using a single-base propellant, Seiler observed 0.1 μm of erosion per shot, with a carburization depth of 0.3 μm. In contrast, when using a double-base propellant, oxidation occurred and most of the oxide layer (1.7 μm) was eroded during each firing. Experiments in a vented combustor with a variety of propellants, conducted by Schneebaum and Gany [4], showed slightly different results. Like Seiler and coworkers' double-base results, they report a white layer (2 μm thick) containing an oxidized sub-layer (0.6 μm thick) which is mostly removed during firing. However, they also report carburization throughout the whole white layer and even deeper into the barrel steel. An example somewhat contradictory to Kimura's postulate is provided by Turley and coworkers' examination of an eroded Australian 105 mm tank barrel. The barrel had been retired due to erosion after firing 220 EFCs, and relatively hot triple-base propellant had been used. They found little evidence of oxidation, and concluded that melting and wiping of cementite was the most likely cause of erosion in their specimen.

Hydrogen Erosion, Embrittlement and Cracking

Although majority opinion is that carburization and oxidation account for the bulk of chemical erosion [1, 9], a significant number of researchers believe that hydrogen is the dominant erosive species. Some of the earliest proponents of hydrogen erosion were Alkidas and coworkers [17], who proposed that gun steel could be attacked by post-combustion water vapour. It was originally suggested that iron on the bore surface could react with water to form gaseous FeOH₂, thereby vaporizing the steel [9]. It is possible

that carburization may act to enhance this effect. After carbon from the CO and CO₂ gas species diffuses into the barrel, the remaining oxygen could be scavenged by H₂, producing additional water, and thus increase FeOH₂ production.

We have already seen that Lawton's correlation, based on firing data, has diatomic hydrogen gas ranked as the most erosive species. We have also seen that Kimura's explanation is that the effect is primarily one of heat transfer: the thermal conductivity of hydrogen is six times higher than nitrogen, for example [9]. Lawton, however, explains hydrogen erosivity by reference to a study by Krishnan and coworkers [19], who concluded that atomic hydrogen diffuses into the barrel, reacts with carbon, and decarburizes the steel. Carburization increases the hardness of steel at the expense of simultaneously increasing brittleness. As already discussed, most researchers hold that carburization promotes erosion due to increased brittleness and cracking, allowing mechanical and thermal removal. However, the argument here is that it is decarburization which promotes erosion, by excessive softening of the bore surface [3].

Sopok and coworkers attribute still other erosive processes to hydrogen [20]. They cite Troiano's [21] work on hydrogen assisted cracking (HAC): the presence of interstitial hydrogen in the gun steel lattice reduces its strength and ductility, cause cracking, and promote brittle failure. Further, when hydrogen is adsorbed through an existing unoxidized crack surface, the surface energy required for the crack to propagate is reduced. It is also thought that atomic hydrogen may migrate along a crack until reaching its lowest energy state at the vulnerable crack tip [22]. Numerical modelling performed by Sopok [20] — for test cases including a generic howitzer and generic tank gun — indicates that hydrogen availability in the barrel environment is significantly increased by the addition of lubricants. Dissociation of diatomic hydrogen to monatomic hydrogen, due to localized adiabatic compression (and thus heating) of the propellant gas by focussed pressure waves, is also noted as a contributor. Interestingly, Sopok discounts the gaseous water-surface reactions cited by other researchers, as subtle effects. Development of stoichiometric propellant-lubricant combinations are suggested as a way of decreasing the hydrogen richness and relieving the problem.

Protective Effects of Nitrogen

There is unambiguous agreement in the literature that nitrogen in the propellant gas is either minimally erosive, or has a protective effect. Over a sample set of thirteen propellants, Lawton found that those containing more N₂ and less H₂ tended to be less erosive, even though their flame temperatures were higher [3]. Likewise, based on Lawton's data, Kimura [9] calculates that it is a chemically protective species after accounting for heat transfer effects.

Pre-nitriding of gun barrels during manufacture helps reduce erosion by hardening the surface. Nitriding may also occur during firing, via nitrogen diffusion into the gun steel from the hot propellant gas [3]. Although the barrel is exposed to hot nitrogen for a very short time during firing, the barrel surface temperature is significantly higher than that used in the pre-nitriding process. Hirvonen and coworkers recently reported finding high nitrogen concentration (8%) near the surface of gun steel exposed to firings of high nitrogen content propellants [23]. They also noticed that combustion-induced nitriding

tended to reduce erosion. In addition to improving hardness, increased diffused nitrogen may raise the melting point of the surface material.

Experiments have shown that the white layers of the CAZ do not form in pure nitrogen environments or nitrogen-air mixtures [12]. Conroy [16] has proposed that increasing the nitrogen content of propellant gases may inhibit CO and CO₂ dissociation, reducing the availability of carbon, and by this means mitigating carburization.

Other Chemical Effects

Potassium sulphate, commonly used to suppress muzzle flash and also found in some igniter formulations, may also have a bearing on barrel erosion. There is disagreement, though, as to whether this additive aids or moderates erosion. Some researchers claim that potassium sulphate acts to reduce chemical erosivity [11]. Others believe that the sulphur is absorbed by the barrel material and forms iron sulphide, which has a melting point approximately 250 K lower than gun steel, thus assisting thermal erosion [13].

There are also numerous chemical effects associated with the interaction of propellants with particular coating materials, but these will be addressed in Section 3.3.

2.2 Thermal Erosion

High flame temperature propellants may produce combustion gases at temperatures as high as 3 700 K [11]. The bore surface and subsurface temperatures resulting from exposure to these gases is dependant on several heat transfer and flow processes. Convective heat transfer through the gas boundary layer is the primary mechanism [24]. The boundary layer formed in the wake of the moving projectile is turbulent [25], enhancing both heat transfer and the introduction of chemically reactive gas species to the surface. Additionally, blow-by (gas leakage) of propellant gas past the projectile may induce flow conditions that transfer orders of magnitude more heat to the surface [25, 26]. Blow-by will be discussed in more detail in Section 2.3.

Besides convection, heating due to the sliding friction of the round and radiative transfer may also occur [27]. Because heating due to radiation is a strong function of temperature (proportional to T^4), it is of most significance for hot propellants and at locations near the chamber or in the early part of the barrel. Downstream, temperatures are reduced and solid particles entrained in the boundary layer may absorb some of the radiation [27]. The high temperatures of combustion exist for only a few milliseconds, and so while the bore surface at the OR may rise to temperatures of the order 1 000–1 500 K, at a depth of 1 mm the temperature may, for example, only reach a maximum of 370 K [2, 11]. Further downstream from the OR, after significant gas expansion has occurred, peak temperatures experienced are much lower. Hence peak temperature, exposure time, and temperature versus axial location, must be considered together to determine a gun's thermal erosion profile [1, 18]. For guns with a high firing rate, and especially machine guns, heat build up due to the limited cooling period between shots must be taken into account [28]. Even after a projectile leaves the gun barrel, residual heating during the blow-down phase adds to the cumulative heating.

Table 1: Typical onset temperatures for some erosion-related phenomena [22, 31]

1 000 K	Austenite phase transformation of gun steel
1 050 K	Oxidation of iron
1 270 K	Sulphidation of iron
1 420 K	Melting point of iron carbide
1 470 K	Melting point of iron sulphide
1 640 K	Melting point of iron oxide
1 720 K	Melting point of gun steel
2 000 K	Oxidation of chromium
2 130 K	Sulphidation of chromium
2 130 K	Melting point of chromium
2 741 K	Melting point of niobium
2 883 K	Melting point of molybdenum
3 269 K	Melting point of tantalum
3 453 K	Melting point of rhenium
3 683 K	Melting point of tungsten

We have already seen via Lawton's original correlation (Equation 1) that erosive wear at the OR is approximated by an exponential function of maximum bore temperature T_{max} . Lawton's improved correlation [11] goes further by taking exposure time into account. In both cases, though, the temperature dependence of erosion is strong. In the absence of changes in propellant gas composition, for gun steel of typical hardness a 10% increase in T_{max} results in an increase in erosion of 250% [3].

Since high flame temperature propellant formulations may lead to high bore temperatures, it is often reported in the literature that hot propellants are highly erosive. Thus it is commonly assumed that erosion will be reduced by developing low flame temperature propellants [1, 4]. This is not necessarily true. First, the quantity of heat conducted to the bore depends on parameters additional to flame temperature. The effect of propellant gas composition on the heat transfer rate through the boundary layer to the surface, for example, plays a part in the determination of T_{max} . Second, hot propellants may require a shorter ballistic cycle time and reduced charge weight. Third, the chemical reaction processes described in Section 2.1 influence wear through the coefficient A in Equation 1.

In a number of practical cases, an inverse relationship between flame temperature and erosion has been observed. Izod and Baker [29] reported that for five RDX-containing propellants of the same impetus, decreasing the flame temperature resulted in increasing erosion. In this case, flame temperature was reduced by the addition of extra RDX. From these and other results it appears that RDX is highly and principally chemically, rather than thermally, erosive [30]. Conroy and coworkers [16] point out that the erosivity of M30 propellant is lower than that of M43, although the flame temperature is higher. And as will be discussed in Section 3.1, Kimura has developed experimental LOVA propellants with significantly lower erosivities, but higher flame temperatures and higher or similar impetus, than existing LOVA and conventional propellants.

There are several physical processes identified in the literature as responsible for thermal erosion. In the so-called melt-wipe process, the bore surface material is melted and the liquid is wiped away through the mechanical action of solid particles entrained in the propellant gas flow or by the flow itself. As shown in Table 1 the melting point of gun steel is quite high, and many researchers have pointed out that full melting of virgin material is unlikely to occur, and that significant erosion can be observed at lower temperatures [3]. It is possible that thermal softening of the surface, though, is sufficient to enable significant mechanical erosion in the absence of melting. Table 1 also lists the melting points of products of the gas-surface chemical reactions described in Section 2.1. The lower melting points of these compounds render them more vulnerable to the melt-wipe process than gun steel [16]. Surface melting of Fe_3C was determined as the primary cause of erosion in Turley's study of the Australian 105 mm tank gun [12]. Strictly, though, this process represents thermochemical rather than pure thermal erosion.

Heat checking of barrels is a well-known and purely thermal erosion process [32]. Heating of the gun steel induces a phase change to austenite at relatively low temperatures (see Table 1). Upon cooling, untempered brittle martensite is formed and some austenite is retained [32]. As the barrel experiences temperature cycles with the associated phase changes, the disparate volumes of each phase results in stress and the formation of quench cracks. The cracked surface is then vulnerable to mechanical removal, and the austenite phase is reportedly more prone to chemical attack [32]. The depth of this thermally altered layer (also known as the heat affected zone, HAZ) is typically a few hundred microns [11]. The combination of heat checking and partial melting of the CAZ may also occur, and is referred to as pebbling. Interestingly, it has been reported that oxides in the CAZ may insulate the gun steel and reduce thermal erosion, providing the flame temperature of the propellant is below the melting point of the oxides [32].

Finally, the sudden presence of a steep temperature gradient from the bore to the cool barrel core may present a thermal shock [33], with the resulting disparity in thermal expansion causing cracking. A brittle and weak CAZ may be particularly vulnerable to thermal shock. Cote [13] suspects that, upon cooling, residual tensile stress from thermal shock may assist the hydrogen cracking process (Section 2.1) at ambient temperature.

2.3 Mechanical Erosion

Of the erosion processes, mechanical erosion perhaps receives the least attention in the literature. It has been cited as most the most dominant erosion mechanism for low temperature firings [24], where there is insufficient heat to drive chemical reactions or cause thermal erosion. At higher temperatures, the three mechanisms act concurrently.

The degraded mechanical properties of the CAZ (white layer) make it susceptible to removal by mechanical means [14, 15]. For barrels with coated bores, subsurface production of loosely packed oxides may cause an expansion effect. If the expansion is sufficient to raise the coating or bore surface, the projectile will engage it and remove the protruding material during firing [34].

Even without a raised surface, the shear force introduced by sliding friction alone is enough to remove material from a cracked, degraded or thermally-softened surface.

There have been a number of studies conducted to investigate this kind of erosion. Seiler and coworkers [35] conducted experiments to compare the magnitude of erosion at the bore surface with that occurring at recessed grooves in the barrel (the recessed areas not being subject to erosion by sliding friction or mechanical engagement). The experiments were conducted with different driving band materials. Their results showed that a polyamide plastic driving band caused least erosion. Tombac (copper alloy) and plastic-fibreglass bands did not perform as well, and sintered iron was the most erosive driving band material. The differences in performance were significant, with a five-fold difference in erosivity between the polyamide and iron bands. It has also been reported that copper from copper driving bands may become entrapped in bore surface cracks. If there is poor obturation, this effect may be exacerbated by melting of the band by hot propellant gases [1]. The effect of the entrapped copper is to facilitate further cracking by liquid metal embrittlement [36]. Wear due to excessive engraving stress between rifling and band, has also been noted [1].

Abrasion, sweeping and washing actions of the propellant gas flow including any solid particles entrained within it, by virtue of momentum, are also classified as mechanical erosion. Significant leakage of high-pressure propellant gas past the projectile during firing can create jetting, thereby exacerbating erosive flow effects. Using numerical simulation, Andrade and coworkers [25] calculated the blow-by flow between a worn barrel and projectiles with and without obturators and driving bands. The test case was a 155 mm cannon using an XM230 charge. They found that at 2.2 m downstream from the OR, heating of the bore surface by blow-by flow was 30 (without obturator and band) to 2000 (with obturator and band) times greater than that at datum points slightly upstream of the projectile base. Due to differences in the datum point selection Andrade states that the two cases are not strictly comparable. Nevertheless it is suggested that, with the obturator and band present, the smaller gap increases the near-wall temperature gradient of the flow and thus increases heat transfer. Andrade additionally proposes that the blow-by flow contributes to projectile instability, causing balloting and muzzle-end mechanical wear.

The effect of blow-by on erosion has been observed by Lawton and Laird [26] during experiments using a 30 mm cannon and vented vessel. In approximately half of rounds fired, they observed a short-duration temperature pulse at the OR indicative of blow-by. The resulting temperature rise was calculated to locally increase erosion by 200–300%. Using numerical simulation to correlate vented vessel tests with these results, it was concluded that the temperature rise corresponds to a leakage diameter of 0.2 mm. Intense short-duration heat transfer was observed in 10% of fired rounds, raising the bore surface temperature to melting point. This was unable to be correlated with the vented vessel tests, and Lawton suggests tearing of surface micro-welds by sliding friction as a possible (though untested) explanation.

The interaction of the interior ballistic flow field and cracks in the bore surface present another means of mechanical erosion. Crack orientation has been identified as a key parameter. Conroy and coworkers [34] note that longitudinal cracks, aligned with the flow, allow gas to flow in and out of the crack without excessive additional heating of the crack surface. In contrast, cracks oriented radially engender gas recirculation. Recirculating gas has more time to transfer heat and reactants to the sides and the tip of the crack, and the Newtonian force of the flow and particulates against the exposed, perpendicular face

of the crack wall may widen it. For coated barrels, crack-related pressure spalling is also hypothesized by Conroy. The idea here is that the crack voids are pressurized during firing, with retarded gas outflow occurring upon blow-down and pressure relief. Flow choking at the crack mouth is thought to occur, thus retaining pressure and causing the ejection of surface plates from below.

Sopok and coworkers [37, 38] have investigated erosion due to flow-field effects in a 120 mm M256 gun barrel, comparing their numerical modelling results with analysis of a retired specimen. They found that the vena-contracta effect of the forcing-cone (acting as a converging nozzle) had an appreciable influence on the interior ballistic flow-field, affecting the location at which worst erosion occurred in the barrel. Also, boundary layer development was affected by the use of combustible-case ammunition. The cooler gas produced by burning of the cases was found to stay near the wall as a laminar boundary layer, reducing heat transfer until becoming turbulent further downstream. In later work, Sopok [22] noted an interaction between flow-field characteristics and cracks. It was suggested that erosive flow may serve to blunt crack tips and, depending on the flow pattern generated inside the barrel, does so unevenly as a function of axial position. For this reason, according to Sopok, the erosion profile within a barrel does not necessarily correlate with crack depth.

3 Erosion Mitigation

Many of the mechanisms by which erosion is thought occur have been described in Section 2. The understanding of these processes has led to the development of various means for combating erosion. The primary erosion mitigation tools are broadly: development of less erosive propellants; the use of coatings, treated barrel materials and liners; and erosion-reducing additives and lubricants. Many of these methods are well-known and for developments prior to 1988 the reader is referred to existing reviews [1, 5, 32]. In the following subsections more recent research in erosion mitigation techniques is presented, with an emphasis on two issues topical to the ADF: erosivity of LOVA propellants, and the use of barrel coatings for high performance guns.

3.1 Alternative Propellant Formulations

To recap Section 2.1, chemical erosivity is primarily dependent on the propellant gas composition, which is a function of the solid propellant formulation. Small formulation changes can greatly alter the erosive behaviour of a propellant [39]. Likewise, thermal erosivity depends on the quantity of heat produced and the efficiency with which it is transported to the bore surface.

Consider the definition of impetus, I , used to gauge the propulsive energy provided by a propellant,

$$I = RT_f = \mathcal{R}T_f / M, \quad (10)$$

where R is the specific gas constant, \mathcal{R} is the universal (molar) gas constant, T_f is the propellant flame temperature, and M is the molecular weight of the propellant gas mix-

ture. If chemical erosivity and thermal conductivity are invariant, then modifying the propellant formulation to reduce flame temperature should reduce thermal erosivity. By Equation 10, equivalent performance from a cooler propellant can only be achieved if molecular weight is lowered. Simplistically then, in the absence of chemical and conductivity effects, propellants producing low molecular weight gases would seem favourable from an erosion standpoint [40]. In practice, however, chemical erosivity and thermal conductivity effects do vary significantly and may outway the utility of low molecular weight propellant gases. Hydrogen gas is the prime example. Nevertheless, Equation 10 is still useful for propellant design. For example, when comparing N_2 and CO gases, their equal molecular weight gives them equal utility as far as the impetus-flame temperature relationship is concerned. Thus formulations that produce more N_2 gas, with its lower chemical erosivity, would be preferred outright to those producing more CO [16].

Conroy and coworkers conducted numerical experiments to gauge the simultaneous effects of nitrogen content and flame temperature on erosion [41]. They analysed four fictional JA2-like propellants, with flame temperatures varying over the range 3000–3840 K, in an uncoated M256 cannon. The flame temperature was reduced by increasing relative molar N_2 content by as much as 60%. Ballistic equivalence was maintained by altering grain geometry and charge mass to give consistent gun performance, thus allowing a fair comparison to be made. The hottest propellant required 25% less charge mass to obtain the same performance as the coolest propelling charge. In spite of the reduced charge, they still found a marked increase in erosion for the high flame temperature/reduced nitrogen propellants. The relationship was strongest over the range 3400–3600 K.

The trend towards use of LOVA charges raises associated concerns regarding the erosivity of these often hotter burning and more erosive propellants. A popular group of LOVA propellants are the RDX composites; RDX-cellulose acetate butyrate (RDX-CAB) propellants, for example, may contain up to 76% RDX [42]. Work by Caveny [30] reportedly showed that RDX propellant formulations were more erosive than those based on nitrocellulose. Ahmad also states that nitramines (a class including RDX) are often more erosive than nitrocellulose equivalents. More recent work by Hordijk and coworkers [40, 43], however, has failed to confirm these generalisations. In vented vessel tests, they found that RDX-based LOVAs exhibited a flame temperature versus erosivity trend similar to conventional, nitrocellulose-based, single, double and triple base propellants. These experiments may have been adversely affected, however, by relatively low test pressures and the possibility of significant heat leakage into the vessels. Based on experiments using a gun test-bed, Seiler and coworkers [35] similarly found that both LOVA and conventional propellants conformed to the same heat of explosion-erosion relationship. Seiler does not, however, reveal the composition of the tested LOVA propellants.

An excellent case study of reducing LOVA propellant erosivity through formulation changes has been published by Kimura [42]. Kimura believes that the erosivity of RDX is primarily due to the relatively high concentration of hydrogen gas it produces upon combustion. As discussed in Section 2.1 hydrogen is thought to be a highly chemically erosive species [9]. A typical CAB-LOVA produces 20% hydrogen by volume, and Kimura proposes that reducing this concentration to around 13% is more desirable. The reduction in hydrogen gas is achieved by significantly reducing the propellant's RDX content. At the same time, Kimura replaces the inert CAB binder with energetic cellulose acetate nitrate (CAN). This has the dual effect of increasing the concentration of low-erosivity nitrogen

gas in the combustion products, and replacing some of the energy lost by reducing RDX content. The resulting formulation, CAN-A20 LOVA, contains 50% CAN, 35% RDX and 14% TMETN as plasticizer.

The performance of CAN-A20 is reported in reference to M30A1, a conventional triple base propellant, and a typical CAB-LOVA (76% RDX, 12% CAB, 4% NC). Vented vessel tests showed CAN-A20 to be 40% less erosive than the M30A1, while have a 176 K higher flame temperature and 7% higher impetus. In comparison to the CAB-LOVA, the CAN-A20 was three times less erosive while having a 345 K higher flame temperature and similar impetus. The appealing erosion and performance characteristics of the CAN-A20 comes at the cost of increased sensitiveness. Although better than M30A1, performance in terms of impact sensitiveness and cook-off was significantly worse than CAB-LOVA.

The CAN-RDX propellants are but one example of the considerable worldwide research effort aimed at developing high-nitrogen low vulnerability propellants [44, 45]. A range of high-nitrogen filler compounds and propellants have been reviewed and summarized by Odgers [46]. The majority of high-nitrogen filler compounds identified, however, possess lower impetus and lower flame temperature than RDX: thus a compromise between performance, sensitiveness, and erosivity must be reached in these cases.

3.2 Additives

Over the last fifty years, a variety of additives to the propelling charge have been used to mitigate gun barrel erosion. Common additives have included titanium dioxide (TiO_2), talc (magnesium silicate $\text{H}_2\text{Mg}_3[\text{SiO}_3]_4$), wax, polyurethane, and a combination of these. The so-called Swedish additive, for example, is a mixture of titanium dioxide and wax coated on a rayon cloth [2]. The additives are generally applied either between the propelling charge and case, on the case closure plug, or dispersed throughout the propellant bed. There has been limited work on additive technology published in the open literature since Bracuti's 1988 review [5]. That is not to say that research into additive technology is not being conducted; commercial manufacturers [47] are developing and selling customized, proprietary pastes to customers such as the US Army. It is understandable that developers of additives would be reluctant to publicly furnish details of how their commercial products work and what they are composed of. Nevertheless, some of the research that has been published since Bracuti's review, and some material omitted from the review, is now presented.

Seiler and coworkers investigated the effectiveness of Swedish additive for conventional single- and double-base propellants [35] in a 20 mm gun test bed. Trials were separately performed with the additive inserted as a liner between the charge and chamber wall, and placed in tablet form at the base of the projectile. In both cases, a quantity of additive corresponding to 4% of the charge mass was used. For both propellants and both application methods, the Swedish additive significantly reduced erosion (by around 15-25%). The liner application was slightly more effective than the tablet. Thermocouples at the barrel wall showed that the additive caused a reduction in heat transfer.

There is general consensus in the literature that titanium dioxide acts to mitigate erosion primarily by reducing heat transfer to the barrel, and this is supported by Seiler and

coworkers' Swedish additive results. Shelton [48] reasons that titanium dioxide particles are the correct size (5–10 μm) to fill surface crevices, and it is the resulting reduction in exposed bore surface area which reduces heat transfer and can lower surface temperatures by up to 300 K. The reduction in peak bore temperature confers the additional benefit of reducing crack propagation due to thermal cycling, thereby extending barrel fatigue life [49]. Shelton notes that all additives of micron particle size show evidence of deposits left inside the barrel.

Lawton also agrees that Swedish additive's primary action is to reduce thermal erosion [50]. He cites three mechanisms through which this occurs: (i) the titanium dioxide forms an insulating layer between the propellant gas and bore surface, (ii) the additive absorbs heat from the flow boundary layer and thus lowers its temperature, and (iii) the additive reduces turbulence in the boundary layer, thereby reducing convective heat transfer to the wall. However, he also notes Zimmer and Hankland's [51] suggested mechanisms by which Swedish additive may also reduce chemical erosion. The oxygen resulting from titanium dioxide dissociation could react with hydrogen and carbon monoxide to form water and carbon dioxide, reducing hydrogen embrittlement and carburizing of the bore surface. These reactions must occur in the boundary layer, however, in order to be effective. In experiments using a 40 mm gun, Lawton found that a quantity of Swedish additive equivalent to 23% charge weight reduced heat transfer to the barrel by 42%. Build-up of additive between subsequent shots acted to reduce heat transfer further, but the firing of a shot without additive was found to immediately cancel any residual effects. The use of a very small amount (0.5% charge mass) of an alternative additive, a sticky mixture of talc and silicon grease, was found to reduce heat transfer by 4% while simultaneously reducing blow-by.

As noted in Section 2.1, there is disagreement in the literature as to the effects of the flash-suppressing additive potassium sulphate on erosion. Vented vessel tests conducted by Lawton [11] using 0.5% potassium sulphate dispersed throughout the propellant showed a four-fold reduction in wear, but no significant reduction in heat transfer. Hence a reduction in erosivity by chemical mechanisms is indicated. In the same test series Lawton also showed that 0.5% talc reduced wear by a factor of two, primarily by reducing heat transfer to the surface of the test material.

3.3 Surface Coatings and Liners

Although coatings have been used to protect barrels since World War II, there has been renewed, active research in this area over the last decade [13, 16, 18, 22, 34, 52–54]. Rather than the development of new coating materials, recent work has mostly been directed at understanding the mechanisms of coating failure, performance assessment of known potential coatings, and proposed new coating application techniques.

Conroy and coworkers [34] have proposed several criteria for a successful coating:

- The coating should not react with the propellant gases.
- The coating should help insulate the base material from the heat load, distribute the heating, and be resistant to thermal erosion.

- The coating must be resistant to mechanical wear from projectile passage.
- The coating must adhere well to the base material.
- The coating must have a coefficient of thermal expansion similar to that of the base material to prevent thermal stress cracking.
- The coating material and application method must be cost effective.

According to Conroy, these myriad requirements may explain the paucity of new coatings and application techniques. Electrodeposited chromium remains the most popular barrel coating in fielded guns, despite being originally developed over sixty years ago. Other coating and liner materials that are still being actively pursued as alternatives include ceramics, and refractory metals such as molybdenum, niobium, tantalum, rhenium and tungsten.

The most common commercial technique for chromium coating is aqueous electrodeposition [54], where chromium is initially deposited as chromium hydride. During deposition and the subsequent heat treatment to outgas hydrogen, residual stress causes microcracks to form in the coating [13]. Usually the cracks do not penetrate through the entire coating thickness, however, and a crack-free sublayer exists near the base material. Refinements to the process have led to the development of low contractile (LC) chromium coatings. LC chromium coatings exhibit fewer cracks and higher strength, at the expense of reduced hardness [1, 13]. Mawella [54] reports that recent studies on pulsed electrodeposition have demonstrated that reduced cracking or crack-free coatings are possible. A number of other experimental coating methods are also cited. Physical vapour deposition, via magnetron sputtering or the use of an RF plasma discharge, can reportedly produce crack-free coatings and deposit a range of refractory metals which cannot be electrodeposited. Chemical vapour deposition, where a volatile vapour containing the coating material decomposes on the bore surface, is noted as producing highly uniform coatings. Conventional chemical vapour deposition requires high temperatures (over 1100 K) for decomposition, thus triggering phase changes in the gun steel. Mawella proposes metal-organic chemical vapour deposition (MOCVD) as more amenable to gun barrel applications, which requires temperatures of 700 K or lower. He cites firing trials where barrels coated with chromium using MOCVD showed improved erosion resistance, compared to those coated with electrodeposited chromium. A more thorough description of these and other possible coating processes is contained in Reference [55].

Through numerical modelling and vented vessel tests, Sopok has assessed the compatibility of different refractory metal coatings and propellant types [18]. Bare gun steel, and chromium, tantalum, molybdenum, rhenium and niobium coatings were subjected to oxidizing, carburizing, and intermediate propellant gas environments. Erosivity was gauged by the threshold surface temperature at which erosive processes (melting, phase transformation, and reactions) initiated. In an oxidizing propellant gas environment, rhenium and niobium had the lowest threshold (corresponding to most erosion), chromium and tantalum had the highest threshold, while the thresholds for gun steel and molybdenum were intermediate. In a carburizing environment, tantalum had the highest threshold temperature, followed by similar thresholds for chromium, molybdenum, rhenium and niobium, with gun steel performing worst. Chromium was the only material not to

show a variation in threshold temperature between the different environments, which may explain its popularity as a coating material. For the other materials, the significant difference in threshold temperatures between the propellant gas environments highlights the need to match propelling charge to coating type. The chemical mechanisms responsible for the variations are discussed at length by Sopok in the paper.

The high melting point, low reactivity and high hardness of coating materials render them resistant to direct thermal, chemical and mechanical erosion. The melting point of chromium (Table 1), for example, is much higher than typical bore surface temperatures [52]. Coated barrels still erode, however, and once erosion is initiated they may erode at a faster rate than uncoated barrels [54]. Much attention has recently been given to understanding the erosion process for coated barrels.

As already noted, surface microcracks are present in chromium coatings from the time of manufacture. The pressure and thermal cycling of firing causes the microcracks to grow deeper until reaching the substrate material, and also propagate laterally to combine and form a network [54]. The result is fragmented but contiguous coating elements still attached to the substrate, described by Cote and Rickard [13] as a series of separate, isolated islands or plates of chromium. The dimensions of these plates are of the same order as the coating depth. Conroy and coworkers contrast these microcracks with their theory of macroscopic cracks caused by stresses at the coating-substrate interface [34]. These stresses are generated by direct loading from the barrel internal pressure, and the difference in thermal expansion of coating and substrate at the interface itself. They formulate an analytical treatment to calculate the spacing of such macroscopic cracks and, subject to a number of assumptions, find that tantalum should show less cracking (a greater spacing between cracks) than chromium. It is also determined that neither chrome nor tantalum should fail by debonding from the gun steel; instead the analysis indicates that cracking and plastic strain are the most likely results of interfacial thermomechanical stress.

Once cracks in the coating have reached the substrate, the exposed gun steel begins to erode. Jets of hot combustion gases wash through the crack, recirculate, react with the substrate, and cause pitting via thermal and chemical erosion. It has been discovered that, at the interface, oxides of refractory metal coatings may seed cracking in the substrate [22]. Specifically, Conroy and coworkers calculated that tantalum engenders more rapid pit growth in the substrate compared to chromium [34].

Numerical modelling of a 20 mm gun by Heiser and coworkers [53] showed that chromium coatings lower bore surface temperature because they conduct heat to the substrate faster. Thus the temperature at the coating-gun steel interface is higher than it would have been at the identical depth for a steel-only barrel. The high temperature at the interface encourages thermochemical erosion to traverse laterally under the coating, from the initial crack site, attacking the substrate material [16]. Eventually the coating is undermined, and susceptible to removal by mechanical processes. The small plates of coating may simply lift out due to complete separation from the steel, or be removed by engagement with the projectile or spallation [52] driven by choked high pressure gas [34] (see Section 2.3). Underwood and coworkers have experimentally observed that deep, open cracks are the preferred site of plate loss [56]. However, Sopok notes that erosion in coated cannon barrels always correlates with interface degradation and substrate exposure, regardless of whether or not this actually occurs at the deepest crack sites [22].

Hordijk and Leurs have additionally observed that once erosion of a coated barrel begins, after further firings the number of exposed spots tends to stay constant, while the damaged area per spot increases [40]. While the described process is generally agreed to be the prime cause of erosion for high temperature propellants, Cote suggests that fatigue fracture of the coating due to sliding forces may be more significant for cooler propellants [13].

Methods to prevent or reduce the undermining process have been suggested. Conroy and coworkers suggest that, after firing, storage conditions may induce oxidation of the newly exposed substrate gun steel [34]. Corrosion control through post-firing treatment of coated barrels is thus advocated as a possibility of extending barrel life. Also suggested is pre-nitriding of the steel bore before coating, to increase hardness and reduce chemical erosion at the interface once the coating is penetrated by cracks. Likewise, reducing the carbon content of the steel near the interface may decrease its susceptibility to hydrogen cracking after the coating is breached [56]. Alternatively, a tough cobalt interlayer located between the coating and substrate may prevent cracks penetrating through to the gun steel, and has been successfully trialed in the past [1, 13]. Underwood and coworkers also suggest that interlayers may aid in preventing the exposure of the gun steel to chemical attack, as well as decrease the transfer of shear stress from coating to substrate [56].

As alternatives to refractory metals, ceramic liners have been identified as a promising technology due to very good wear and thermal resistance. The propensity of ceramics to fracture due to susceptibility to stress concentration and flaws, however, must be addressed before widespread practical use is possible [1, 57]. Grujicic and coworkers present structural reliability studies of segmented and monolithic ceramic liners using finite-element analysis, and for their 25 mm barrel test case find a failure probability of once per 400 single shots [57, 58]. The primary cause of failure was identified as cracking of the ceramic liner near the barrel ends, as a result of stress due to axial thermal expansion of the steel jacket. The use of segmented liners was found to reduce failure probability by as much as 18%, by relieving tensile stress in the ceramic. Functionally graded ceramic-to-metal barrel liners provide an alternative means to avoid the abrupt mismatch of thermal expansion between a ceramic and metal interface. The response of candidate functionally graded liner materials to thermal shock, conductivity, and wear tests, are reported in an initial study by Huang and coworkers [59]. As an alternative to using ceramics as liners, Kohnken describes the use of composite reinforced ceramics for the construction of entire small-calibre barrels [60]. The concept is to use a carbon fibre/resin composite as an outer wrap, to reinforce and compress a zirconia-ceramic tube from the outside.

3.4 Novel Erosion Mitigation

A novel way to reduce barrel erosion, especially at the chamber end, has arisen out of the development of a new low-recoil gun concept [18, 61]. The sonic rarefaction wave low recoil gun (RAVEN) works by venting the combustion chamber at the breech during firing, after the projectile has travelled approximately one-third the length of the barrel. If correct timing is achieved then the resulting expansion wave, due to pressure loss in the chamber, will not reach the muzzle until after shot exit. Hence the projectile base pressure, and thus muzzle velocity, is unaffected, while the early chamber venting significantly

reduces gun recoil. Following on from successful 35 mm trials, fabrication of a 105 mm gun was reported due to commence at the time of writing [62].

Early venting of the chamber means that thermal, chemical, pressure and gas wash effects have a much shorter period over which to cause erosion. The RAVEN developers expect that erosion will be substantially reduced in their gun [61]. However operational difficulties associated with fielding a rear-venting gun may limit the usefulness of the concept in practice.

4 Erosion Modelling and Prediction

The capability to model or simulate erosion phenomena ultimately allows the erosion characteristics of a particular gun system to be assessed and predicted before it is built, tested, purchased or modified. Although this predictive utility could be partially achieved through targeted experiments, models provide a range of additional benefits. The extreme interior ballistic environment makes experimental instrumentation and measurement difficult, whereas it is normally possible to determine all modelled physical quantities throughout a simulation domain. The ability to add or remove different physical phenomena at will, allows models to be used to identify the relative importance and action of the various erosion mechanisms. Automated optimization to minimize erosion relative to a particular parameter, quicker generation of trend data, reduced test time, and reduced overall cost, are also possible.

Models need to produce credible, accurate results before these advantages can be realized. All models require careful validation against trusted, measured data before being relied upon for critical tasks, while computational models additionally require verification of their numerical accuracy and consistency. In practice, the combination of modelling and experimental approaches generally produces the best outcomes.

Due to the complexity of the barrel erosion problem, pure analytical modelling has so far only been successfully applied to specific sub-problems of limited scope. In contrast empirical methods, based on both physical arguments and observed statistical trends, have been employed to describe the erosion of gun systems as a function of a quite limited number of input parameters. Empirical methods, however, do not explicitly establish the physical mechanisms through which the erosion occurs. Computational models, drawing together analytical descriptions of the physical processes, approximate and exact numerical solution techniques, and observed experimental data, have been applied to solve, understand, and predict gun barrel erosion with varying degrees of success.

4.1 Empirical

The quantity of heat transferred from propellant gas to the barrel, and the resulting surface temperature, strongly influences the magnitude of barrel erosion. As will be discussed in Section 4.2, it is a fairly straight-forward task to calculate these quantities using modern computational fluid dynamics codes. A Navier-Stokes solver coupled with

an appropriate turbulent boundary layer approximation can be used to directly calculate surface heating as part of the numerical solution. Questions as to the accuracy of commonly-implemented turbulence models, though, have lead Lawton and Laird to develop semi-empirical treatments for surface heating [28, 63]. Additionally, an independent surface heating formula is convenient when a full computational fluid dynamics solution is not warranted and a quick solution is all that is required. In practice, Lawton and Laird use a simple, lumped parameter interior ballistics model to calculate core flow properties, and with this input data employ their semi-empirical correlation to calculate heat transfer to the barrel.

Based on measurements from 200 firings using 30, 40 and 155 mm barrels at ambient temperature, and five different propellants, the Nusselt-Reynolds number correlation [63]

$$\text{Nu}_d = 0.7 \text{Re}_d^{0.65} \quad (11)$$

was found, where d is the bore diameter. Reynolds number is defined by core flow properties only,

$$\text{Re}_d = \rho u d / \mu, \quad (12)$$

where ρ is gas density, u is flow speed, and μ is gas viscosity. The Nusselt number indicated by the correlation may be used to calculate the heat transferred to the surface, q , by its definition

$$\text{Nu}_d = h d / k = q d / [k(T_{gas} - T_{surface})], \quad (13)$$

provided that the gas conductivity k and gas-surface temperature differential are known. The accuracy of the correlation is reported as $\pm 10\%$, and varies with axial position.

An improved correlation was later developed primarily to account for initial barrel temperatures above ambient [28], making it useful for repeated firings and machine guns. In the improved correlation, the non-dimensional quantities are based on axial distance from an effective breech face location, x , rather than bore diameter, better accounting for the effects of boundary layer development. It is more complex, and given by

$$q_x = k[0.85 \text{Re}_x^{0.7}(T_{gas} - T_{surface}) - 2000 E T_{surface}] / x, \quad (14)$$

with the non-dimensional expansion number, E , defined as

$$E = \frac{\gamma - 1}{V} \frac{dV}{dt} \left(\frac{m_c c_v x^3}{k V_c u_{base}} \right)^{0.5}. \quad (15)$$

Here, γ is the ratio of specific heats, c_v the mixture specific heat at constant volume, V the volume occupied by propellant gas, V_c the initial chamber volume, m_c the charge mass, and u_{base} is the gas velocity at the base of the projectile. The improved correlation is claimed to have an accuracy of $\pm 8\%$. Besides being useful for erosion studies, calculation of barrel heating is also relevant to the modelling of propellant cook-off.

Lawton also produced a direct correlation for calculating erosion without the intermediate step of explicitly determining heat transfer [2]. This correlation is an improvement of the original that was described in Section 2.1 as Equation 1. For a barrel at ambient temperature, the improved equation can be written as

$$w = A t_0 \exp \left(\frac{-\Delta E}{\mathcal{R} T_{max}} \right), \quad (16)$$

where t_0 is introduced to account for the ballistic cycle time, and may be approximated as the quotient of bore diameter and muzzle velocity. The activation energy of the propellant is ΔE , and the maximum bore temperature is approximated, in SI units, by

$$T_{max} = \frac{T_f - 540}{1.8 + 7130 d^{2.22} m_c^{-0.86} v_m^{-0.86}} + 300, \quad (17)$$

where v_m is muzzle velocity. The erosion coefficient A , accounting for chemical effects, is redefined as

$$A = 114 \exp[0.0207(f_{CO} - 3.3f_{CO_2} + 2.4f_{H_2} - 3.6f_{H_2O} - 0.5f_{N_2})], \quad (18)$$

with the advantage that the disproportionately large influence of dissociated products is removed, in comparison with Equation 2. A worked example of the use of Lawton's improved correlation, showing a calculation comparing the erosivity of two different propellants in the Royal Australian Navy's 5"/54 gun, is presented in Appendix A.

4.2 Computational

Accurate mathematical descriptions of physical processes significant and relevant to erosion are required for the development of a computational model. These processes can be divided into two coupled sets, (i) those principally on the exterior of the surface, relating to the production and transfer of heat and reactants, and (ii) those occurring on or under the surface, causing the actual barrel mass loss. For the first set, the physical processes can be summarized as:

- Production of gas species and heat release due to propellant combustion.
- Development of the unsteady interior flow field both before and after shot start.
- Establishment of a boundary layer, and its transition from laminar to turbulent.
- Entrainment of solid propellant particles and ablated surface materials in the flow.
- Flow through, or recirculation in, surface cracks and defects.
- Convective and radiative heat transfer from the core flow, through the boundary layer, to the barrel surface.
- Non-equilibrium chemical kinetics and diffusion of species in the core flow and boundary layer.
- Heating of the bore surface due to viscous skin friction.

For the second set, the processes can be summarized as:

- Heat conduction through the coating and/or gun steel.
- Thermal expansion and stressing of barrel materials.

- Barrel melting and/or phase change.
- Surface chemical reactions, including catalytic effects.
- Sub-surface chemical reactions.
- Removal of barrel material and ablative cooling of the surface.
- Solid diffusion of species.
- Formation and growth of cracks.
- Coating spallation and delamination.
- Surface-projectile engagement.

A complete, automated simulation, accurately covering all of these phenomena has yet to be achieved. Current approaches are to either concentrate on simulating a subset of the above processes to high accuracy, or to provide erosion estimates by including many of the above processes but making simplifying assumptions to render them solvable. Some of the most recently developed computational models are now compared, with reference to the above framework.

While not directly calculating erosion, Heiser and coworkers [53] present a comparison of two methods implemented for the determination of heat transfer to the bore surface of a 20 mm gun. The first is a computational fluid dynamics (CFD) approach. The full Navier-Stokes equations, describing the interior gas flow, are solved in two-dimensional axisymmetry. Turbulent boundary layer effects are accounted for using a one-equation turbulence model, and the bore surface is taken to be defect-free. The simulations are single-phase only, so solid entrainment and the associated drag is not included. Direct source terms of the conserved variables are used to simulate the generation of combustion gases. While not explicitly stated in their report, it appears that flow chemistry is not simulated, and that the gas is considered a homogeneous mixture (where individual gaseous species are not considered). Consequently, no gas-wall chemical interactions are modelled. The wall boundary condition assumes that the bore surface temperature and adjacent gas temperature are equal, which is reasonable considering the density of the flow. The resulting axial and radial temperature gradients on the gas side of the wall are used as inputs to calculate conduction of heat to and within the solid in two-dimensions, in a time-accurate manner. Inclusion of the axial temperature gradient in the barrel heating model is unusual; this effect is often ignored due to its relatively small magnitude in comparison to the radial temperature gradient.

The CFD simulations are compared with results from an analytical boundary layer model. In the analytical model, two coupled boundary layers are used to represent the actual, continuous boundary layer. A breech boundary layer (originating at the upstream breech wall) and a projectile boundary layer (which has zero thickness at the projectile base) are coupled at an intermediate axial location where their thicknesses match. Prandtl's boundary layer equations and an empirical power-law velocity profile are used to solve for wall shear stress and heating. In contrast to the two-dimensional CFD method, the analytical method is coupled with a one-dimensional heat conduction model, which is solved iteratively.

Both the CFD and analytical models were checked against experimental firing results [53]. For an uncoated steel tube, CFD simulation matched the peak subsurface wall temperature (at a depth of 10 μm) measured in experimental firings. Considering that the model assumed single-phase flow of an homogeneous mixture, this is an excellent result. Although good agreement near the surface was reached, at a depth of 100 μm temperature was underpredicted by approximately 80 K. By comparison, the analytical model overpredicted temperature at the 10 μm depth by about 100 K, but achieved good agreement with experiment at the 100 μm depth. These results indicate that, in both models, heat conduction through the solid is occurring faster than in the experiments.

CFD was also used by Andrade and coworkers [25] to investigate the flow-field of projectile blow-by gas. Again erosion processes are not included in the calculations; heat transfer to the barrel is taken as an indicator of erosivity. Two-dimensional axisymmetric grids covering a domain from slightly upstream of the projectile, and an eroded gap between projectile and bore surface are used. The entire chamber and barrel are thus not simulated, and results from an interior ballistics lumped parameter model are used to define upstream inflow conditions. The Navier-Stokes equations are solved for the steady-state flow of perfect gas. In the absence of experimental evidence as to boundary layer type, the authors assume that it is laminar. In total, these assumptions are appropriate for calculation of quantities such as drag, pressure, and streamline behaviour. However, the essentially unsteady nature of the flow, the importance of real-gas high-temperature effects in the gap, and the assumption of an isothermal surface, may act to reduce the accuracy to which this model can realistically simulate heat transfer. The authors justify the assumptions, though, with the stated intention of creating a simplified model appropriate for comparison with controlled laboratory measurements.

Extensive development of numerical erosion models, particularly with respect to coatings and cracks, has been conducted by Conroy and coworkers at ARL since 1991. Early work [27] involved coupling a one-dimensional (radial) barrel heat conduction code with a one-dimensional (axial) two-phase interior ballistics solver (NOVA [64]). An analytical turbulent boundary layer treatment due to Chandra and Fisher [65] was employed, to translate core flow properties derived from the NOVA code into a surface heating input. Gas and surface chemistry was ignored. The model was used to simulate barrel heating during repeated firings of an M203 charge in a 155 mm howitzer. The predicted temperature rise at the OR was approximately 1.8 times higher than was measured.

In later work, a new model was constructed offering both improved heat transfer calculation, and simulation of erosion via the melt-wipe mechanism [39]. An updated version of the NOVA code, XKTC [66], was used to establish core flow properties. The concentration of chemical species in the core flow were calculated using the BLAKE [67] code coupled with a lumped parameter interior ballistics model, assuming chemical equilibrium. The transfer of heat and diffusion of species through the boundary layer to the bore surface is included in the model, although reactions are frozen while this occurs. Chemical equilibrium is reactivated at the surface, the species are reacted, and chemical energy is released as a source term. If sufficient heat is transferred to the bore to cause melting, the liquids are immediately removed as surface erosion. No subsurface reactions or diffusion of species is modelled. The model was used to predict erosion in an uncoated (perhaps chipped) area of an M256 barrel, using M829A1 and Advanced KE Penetrator rounds. In both cases reasonable agreement was achieved: erosion depth per

round was slightly overpredicted for the former, and underpredicted for the latter case. The main limitation of this model is the inability to simulate erosion through mechanisms other than melt-wipe. The melt-wipe process does not apply when cool propellants are used, producing surface temperatures below the melting point of the surface material. Likewise, if defect-free high melting point surface coatings are used, the model is also not applicable.

A range of improvements and extensions were made to the model to address this and other limitations [16, 34, 41, 68, 69]. These included thermal variability of barrel material properties, incorporation of user-defined surface coatings, steel lattice phase change, treatment of macroscopic cracking, modelling of pits under coatings, carbon and oxygen diffusion into the substrate, and carburization/oxidation reactions in the barrel material. A surface chemistry freeze-out temperature was also introduced to exclude chemical equilibrium at unrealistically low temperatures. However, this was later replaced with the provision of true finite-rate (non-equilibrium) surface reaction kinetics based on the NASA Lewis database. Compared with equilibrium surface chemistry, the use of finite-rate reactions tended to increase the predicted erosion rate of pits near the OR, but decreased erosion further down the barrel. This may be explained by an increased erosion-temperature sensitivity due to the high dependence of reaction rates on temperature.

Rather than develop a new model from scratch, Sopok and coworkers take the approach of modifying and piecing together a series of well-used, existing tools to form an erosion modelling capability [14, 15]. In common with Conroy and coworkers, the interior ballistics core flow is computed by the one-dimensional, two-phase XKTC code, with BLAKE used to determine its equilibrium chemical composition. Two codes from the rocket community, TDK/MABL (two-dimensional nozzle mass addition boundary layer [70]) and TDK/MACE (materials ablation conduction erosion [71]) were adapted for modelling the gas boundary layer and heat conduction within the barrel, respectively. The MABL code simulates turbulent boundary layer flow using the Reynolds-averaged Navier-Stokes equations, and incorporates the mixing of gas products from surface reactions with the existing boundary layer using an eddy-viscosity model. Although MABL was modified to incorporate finite-rate chemical kinetics, Sopok and coworkers perform their modelling based on the assumption of a boundary layer in chemical equilibrium. Similar to Conroy's earlier work, chemical equilibrium of gas-surface reactions is assumed (using an additional module called TDK/ODE, and in later work CCET [72, 73]) and combined with a freeze-out temperature at which these reactions no longer occur. The MACE code is used to solve one-dimensional heat conduction through the barrel wall, and includes species diffusion and chemical reactions within the solid, and thermally variable material properties. Surface mass loss due to both thermochemical erosion and mechanical erosion are output by MACE.

As well as reducing model development time, an advantage of constructing the erosion model from well-established codes is a reduced burden of validation. The disadvantage, however, is that Sopok's model requires significant manual intervention to reconcile the input/output requirements of the various codes when trying to string the modules together, and the most modern and efficient numerical solution techniques are not necessarily implemented.

Sopok and coworkers have applied their model to a range of gun systems, including the M242 Bushmaster 25 mm cannon with M919 cartridge [74], and the M256 cannon with M829A2 [37, 38, 75, 76] and M829E3 [22] APFSDS rounds. In general, good agreement in both erosion levels and distribution is claimed. The work, however, is calibrated or supplemented by the input of a range of experimental data. Although this means that the modelling results may not be truly predictive, the use of experimental results to fill model deficiencies (such as the lack of a crack model) does extend its usefulness. Examples of physical calibration data, derived from experiments and observations of retired barrels, include: thermocouple data, gas-surface reaction rate data, measurements relating to diffusion, reaction, phase change and coating/steel losses at cracks, pits and interfaces, and the spacing and geometry of cracks and pits [22, 75].

5 Experimental Assessment Techniques

In spite of the recent advances in computational model development, experimental methods continue to be the principal erosion research tool. Recent erosion experiments have been conducted to investigate: the relative erosivity of different propellants, driving band materials, barrel materials and coatings; the effect of additives; the validation of numerical models and creation of empirical models; barrel heating characteristics; the effect of gas blow-by leakage; and details of how the different erosion mechanisms function.

Vented vessels have been widely used for experimental erosion research [4, 9, 11, 18, 26, 40, 42, 43]. Propellant is ignited and combusted within the vessel and the contents are vented past a test material, eroding it in the process. The technique is popular due to its low cost, relatively fast turnaround time, and convenience for parametric studies. Vented vessels are particularly suited for the assessment of relative erosivity of different propellant and barrel material combinations. To obtain realistic results, though, care must be taken to reproduce the pressure, flow velocity, and heat transfer characteristics of the gun system in the vessel experiment. Using an excessive charge, for example, may unrealistically favour high surface temperature melt-wipe erosion in comparison to chemical degradation and gas wash [11]. Sopok notes that vented vessel firings are typically an order of magnitude more erosive than gun firings [18]. For these reasons, it is difficult to apply vented vessel results to the quantitative prediction of erosion on full-scale guns. Likewise, it is inconclusive to directly compare results obtained from two vessels of different specification or design [18]. Problems of scale, such as excessive heat loss due to smaller charge weights, have also been reported [40]. Finally, the mechanically erosive action of projectile passage is not accounted for in most vented vessel tests.

The simplest vented vessel arrangement is to construct the vent nozzle out of the candidate barrel material. A number of improved techniques have been devised, though, to produce more realistic erosion data from vented vessel tests. To simulate blow-by, Kimura [9] uses a small diameter vent nozzle made from the test material to generate high speed flow, thus promoting erosion by gas-wash. In contrast, Lawton and Laird [26] simulate blow-by with a more complex venting configuration. A central vent path, used to relieve the bulk of the gas, contains a regulator used to adjust the blow-down rate. Meanwhile, a separate, annular, outer slit is used to generate test flow past the sample

material. Due to the narrowness of the slit, Lawton and Laird are able to generate relatively high heat transfer rates at low vessel pressures [11]. To produce flow representative of the OR region, Kimura uses what he refers to as a double-choke nozzle [9]. A small vent orifice is placed downstream of the test material, and used to choke the gas and generate subsonic, high temperature flow over the sample. Other investigators have used burster disks or pseudo-projectiles to simulate shot start conditions or allow the build-up of sufficient pressure before the test begins [18]. By using appropriate burster disk, nozzle and propellant combinations, good reproduction of gun pressure-time profiles has been achieved in vented vessel tests at DSTO [77]. To simulate erosion at different axial locations along a barrel, Sopok varies the loading density of propellant in the vessel [18]. Loading density is strongly related to peak pressure and gas velocity, and can be tuned to produce conditions appropriate to the OR region, or further downstream.

There have been a number of approaches to extend the usefulness of vented vessels by relating vessel-derived data to gun erosion. Lawton proposes that his empirical wear correlation (Equation 16) can be applied to both vented vessel and gun firings, provided an appropriate characteristic time t_0 is used to normalize the equation [2, 11]. The definition

$$t_0 = \frac{\pi}{5} \int \frac{P}{P_{max}} dt \quad (19)$$

is introduced as a measure of the pressure pulse duration in both vessel and gun firings. In principle, then, it is possible to use vented vessel results to determine the wear coefficient A to aid the prediction of gun erosion via Equation 16. For the simulation of gun blow-by leakage, Lawton and Laird used the results of their vented vessel blow-by experiments to validate a lumped parameter code modified for this application [26]. Once validated, the code was then used to predict blow-by temperature and pressure fluctuations in a 30 mm cannon with reasonable success. In a like manner, Sopok uses the computational erosion model described in Section 4.2 to reconcile vented vessel and gun firing erosion results [18].

To determine the effect of thermal erosion, in the absence of chemical and mechanical effects, Cote and coworkers have successfully used laser pulse heating to simulate the surface thermal loads of firing [78]. They found an absence of subsurface cracking in the case of thermal loading only, while similar samples subjected to vented vessel tests exhibited numerous subsurface cracks. The laser pulse heating alone, however, was enough to cause severe plastic deformation, blunting of crack tips, and generation of residual compressive stresses within the HAZ.

Erosion experiments using full-scale guns retrofitted with appropriate instrumentation are able to capture the full range of real erosion phenomena [50, 52, 63]. For large calibre weapons, however, the expense of acquiring the gun, fitting instrumentation, and trialling at ranges, may be prohibitive for parametric studies or long-term experimentation. Some investigators have used gun test beds as an intermediate between vented vessels and real gun firings. Seiler and coworkers [10, 35] describe an experimental gun device used to fire 20 mm projectiles. An exchangeable inner sleeve, which includes the forcing cone, is used to house instrumentation and erosion test materials.

The harsh interior ballistic environment presents difficulties for experimental instrumentation in both vented vessel and gun tests. Instruments need to have fast response (a

typical ballistic cycle lasts around 10 ms) and also be resistant to high pressures, temperatures and an erosive chemical environment. While Kistler-type piezoelectric pressure transducers are commonly available and used in ballistic research, measurement of heat transfer is more difficult. In order to have fast response characteristics, thermocouples with very fine hot junctions must be used. The thickness of the hot junctions is generally of the same order as the per-shot erosion level, which limits their useful life [63]. Eroding-type thermocouples, where the erosive action of the flow acts to continually re-form the hot junction have been successfully used by Lawton to instrument vented vessels and guns [50, 63]. The junction is made from a nickel alloy, rather than steel, and the difference in thermal conductivity of the materials must be accounted for to obtain a surface temperature representative of a steel barrel. While difficult to obtain commercially, thermocouples of this type are routinely constructed and used by the shock- and expansion-tube research community in Australia and internationally [79]. If surface temperature is not required, then in-wall thermocouples (IWTCs) can also be used. Bundy and coworkers describe the installation of IWTCs in blind holes drilled into the exterior of a 120 mm barrel. Using ultrasound to determine the barrel thickness, the thermocouples were located within 1.3 mm of the bore surface [52]. To ensure good thermal conduction, spring tensioners were used to hold the hot junction against the barrel surface at the bottom of the hole. When comparing results from IWTCs installed at the same axial location but separated circumferentially, Bundy and coworkers found temperature variations of up to 25% (K). They cited several possibilities for the discrepancy: nonuniform thickness of barrel between the thermocouple and bore surface; variation in the extent of delamination between barrel and coating; contamination at the bottom of some of the blind holes; and real circumferential variation in heat input from the firing.

If experiments are conducted with removable samples of barrel materials, erosion is easily measured as the mass lost during firing [9, 11]. Alternatively, direct measurement of bore enlargement and comparison of pre- and post-shot barrel interior contour profiles is also possible [11]. Where cracking and sub-surface pit erosion occurs, however, bore enlargement may not give a true indication of the eroded mass. Dechoux has demonstrated the possibility of using a radioactive gauge to quantify mass loss [80]. The portion of barrel where erosion is to be measured is irradiated, and the activity remaining after firing gives an indication of mass loss. Knoop indentations — pyramidal surface indentations usually used for hardness testing — have been used by Seiler and coworkers as another method for gauging erosion [10, 35]. Indentations are pressed into a sample of the barrel material, and as the material erodes the length of the indentation is reduced and may be used to infer the eroded depth. This technique obviates the need to make absolute bore diameter measurements. As has already been noted in Section 2.3, Seiler and coworkers determine the erosive contribution of projectile friction by comparing the erosion occurring in recessed grooves with that occurring at the bore surface. The eroded profile of the grooves is also used to characterize the behaviour of erosion within cracks and at crack-surface interfaces.

Finally, microscopy and metallographical examination of materials eroded in vented vessel and gun experiments, as well as retired barrels, can help elucidate the action of the various erosion mechanisms. Optical and scanning electron microscopy have been used to examine surface deterioration, heat checking, and crack penetration through cross-section samples [12, 13, 35]. Information about steel phase changes, the presence of dif-

fused species from the propellant gas, and the products of gas-subsurface reactions, has been obtained through Auger electron microscopy, X-ray diffraction, ion beam analysis, and nuclear reaction analysis [4, 10, 12, 23].

6 Conclusion

The push towards higher muzzle velocities, more energetic propellants, and less vulnerable propellants, has continued to drive research into gun barrel erosion over the last fifteen years. Advancements in understanding the different erosion mechanisms have arisen through the development and improvement of erosion modelling and prediction tools, targeted experiments, and the analysis of eroded barrels from fielded guns. Based on this understanding, a number of new ideas in low-erosivity propellant formulation and erosion mitigation have resulted.

In the past it has been commonly held that hotter-burning gun propellants are more erosive, however this is not always true. A significant number of cases have been reported where erosion does not increase with flame temperature, and chemical attack of the bore by propellant gas species has been the primary determinant of erosivity. Although there is some conflicting evidence in the literature, it is generally accepted that the most common LOVA propellants are more erosive than equivalent conventional propellants. Many LOVA propellant formulations contain RDX, and it has been convincingly shown by several investigators that RDX is highly chemically erosive.

New, experimental low-erosivity LOVA propellants have been produced by reducing RDX content and introducing nitrogen-rich energetic binder or filler compounds. The resulting propellant combustion gases, rich in nitrogen, act to re-nitride bore surfaces during firing and inhibit erosive surface reactions. The result is increased bore hardness, increased resistance to melting, and reduced chemical erosion. The lowered hydrogen concentration in the combustion gas of some of these propellants may also reduce hydrogen-assisted cracking of the bore surface. Of the high-nitrogen propellants under development, the majority possess impetus and flame temperatures lower than RDX: a compromise between performance, sensitiveness and erosivity must be reached in these cases.

Significant effort has recently been directed at understanding the erosion mechanisms for barrels coated with protective refractory metals. The most plausible mechanism is that microcracks in the coatings, present from the time of manufacture, propagate due to pressure and thermal stress cycling and eventually reach the gun steel substrate. Through numerical modelling and analysis of eroded barrels, a number of investigators have shown that once cracks reach the substrate, chemical erosion, gas wash, and high interfacial temperatures cause pitting of the substrate and eventually undermine the coating. Segments of coating are subsequently removed by the flow or engagement with the projectile, and at this point the erosion rate of coated barrels may exceed that of steel barrels. A number of ways to mitigate this erosion pathway have been suggested, including: development of better coating techniques to avoid the initial microcracks, pre-nitriding the gun steel before coating to slow substrate erosion, introducing a protective interlayer, and controlled barrel storage and post-firing treatment to prevent oxidation of exposed substrate.

Modelling and experiments have additionally shown that, with the notable exception of chromium, the erosion resistance of refractory metal coatings varies amongst different propellant gas chemistry environments.

Due to very good wear characteristics and thermal resistance, ceramic barrel liners have been identified as a promising technology for some time. However the susceptibility of ceramics to fracture, driven by stress induced by the different thermal expansion properties of steel and ceramics, have prevented their widespread use. New functionally graded ceramic-to-metal liners, which avoid an abrupt mismatch of thermal expansion at the ceramic/metal interface, are being developed to address this issue. For small calibres, fabrication of entire barrels using composite reinforced ceramics has been demonstrated.

Particularly for cooler propellants, it has been shown that charge arrangement can affect the severity and distribution of erosion due to gas wash, and that combustible cases can reduce erosion through cooling-layer effects. Several investigators have shown that propellant gas blow-by markedly increases heat transfer to the bore, and thereby thermal erosion.

Over the last ten years there have been significant advances in computational modelling of erosion, and two codes capable of simulating a broad range of erosion phenomena have been reviewed. Modelling results show reasonable agreement with the erosion of in-service gun barrels and laboratory experiments. In some cases, however, significant calibration via input of experimental data was required to achieve this agreement. A truly predictive and comprehensive erosion model, capable of supplanting experiment, does not yet exist. Nevertheless, in combination with experiment the existing computational erosion models have proved extremely useful in better understanding how the various erosion mechanisms act.

Near term work in Australia will most likely focus on the erosion assessment of new propellants, LOVA propellants, new and modified charge designs, and new weapon systems. Since numerical erosion models require experimental validation anyway, it is suggested that the limited resources available for research in this area are best directed towards establishing a modest experimental capability. Vented vessel testing has long been the primary small-scale erosion research tool, but the questionable applicability of results to full-scale gun barrel erosion has previously restricted their usefulness. New vented vessel testing methods, methodologies for the selection of appropriate and realistic test conditions, and empirical relations designed to reconcile vessel and gun results, have significantly alleviated this difficulty, however. Thus a properly designed vented vessel test facility, together with limited full-scale gun firings, is recommended as the most efficient approach to performing erosion research and assessment with restricted resources.

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Appendix A Wear Calculations for the 5"/54 Gun

The purpose of this appendix is to demonstrate the application of Lawton's improved correlation [2] using a gun fielded by the Australian Defence Force as the example. The relative erosion produced by two different propellant formulations in a 5"/54 gun will be calculated. A LOVA propellant formulation, XM-39, will be compared to the currently-used BS-NACO propellant.

For a fair comparison, we begin with the constraint that both propellants must produce the same muzzle velocity. In practice, this means that a smaller charge of the more energetic XM-39 is required. Since, in both cases, bore diameter and muzzle velocity are equal, the corresponding characteristic times t_0 of Equation 16 are also equal. Denoting the XM-39 as X , and BS-NACO as N , we can thus write the relative erosion as

$$\frac{w_X}{w_N} = \frac{A_X}{A_N} \exp \left[\frac{\Delta E}{\mathcal{R}} \left(\frac{1}{T_{max,N}} - \frac{1}{T_{max,X}} \right) \right]. \quad (\text{A1})$$

To produce a muzzle velocity of 840 m/s, charge weights of approximately 9.25 and 8.60 kg are required for the BS-NACO and XM-39 propellants, respectively [81]. The corresponding flame temperatures of these propellants are 2244 K and 2654 K. With this data, Equation 17 predicts maximum bore temperatures of

$$T_{max,N} = 1230 \text{ K} \quad \text{and} \quad T_{max,X} = 1450 \text{ K}. \quad (\text{A2})$$

The combustion product gas composition for BS-NACO has been calculated as 6.5% CO₂, 46.1% CO, 18.0% H₂O, 19.7% H₂ and 8.7% N₂ by volume [82]. Likewise, for the XM-39, it is 2.4% CO₂, 39.2% CO, 11.9% H₂O, 24.3% H₂ and 21.4% N₂ [82]. From Equation 18, the resulting erosion coefficients are

$$A_N = 120 \text{ m/s} \quad \text{and} \quad A_X = 240 \text{ m/s}. \quad (\text{A3})$$

Assuming a common activation energy ΔE of 69 MJ/kg-mol [2], and substituting Equations A2 and A3 into A1, we have:

$$\frac{w_X}{w_N} = 5.6 \quad (\text{A4})$$

Thus, to a first approximation, it is expected that the LOVA propellant would be significantly more erosive than the currently-used BS-NACO. However, since this particular gun type and these particular propellants were not part of the database used to construct the correlation, caution should be applied in interpreting the result. The calculated wear ratio should be taken as indicative only, rather than an accurate prediction. A simplistic calculation such as this is most useful as a starting point for designing erosion experiments, or as a quick check before conducting comprehensive computational modelling.

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19. ABSTRACT The Australian Defence Force will soon have to contend with gun barrel erosion issues arising from the use of new low-vulnerability gun propellants, the acquisition of new ammunition and gun systems, and possible modifications to existing propelling charge designs. A critical, technical review of advances in gun barrel erosion research, mitigation, and assessment over the last fifteen years is presented. Known and postulated erosion mechanisms, obtained through recent experimental and numerical modelling work, are described and contrasted. New approaches to erosion mitigation and updated knowledge of existing methods are reviewed. Also included is an assessment of the utility of the various erosion modelling and experimental techniques, and notes on their possible use for defence applications in Australia.					

DSTO Defence Science and Technology Organisation
PO Box 1500
Edinburgh, South Australia, Australia 5111