

Implications of Lead-free Shotgun Ammunition to Police Body Armour

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Abstract. Within the UK it is estimated that there are in excess of 1.33 million shotguns legally owned under licence. Therefore, with such large quantities of weapons in legal possession, there is the potential for some of these to be misappropriated by criminals. With the exception of “solid slug”, the majority of projectiles within shotgun ammunition consist of multiple spherical balls, known as “pellets” or “shot”. Traditionally, pellets or shot has been manufactured from lead, however an official review by the UK government has suggested that lead ammunition may be phased out, due to its toxicity to wildfowl and their predators. This paper initially reviews the current calibres of this weapon and ammunition. It then considers alternative materials for shotgun ammunition when moving away from lead to lead-free ammunition. Finally, this paper considers the effect of alternative shotgun ammunition on typical materials used in police body armour.

1. INTRODUCTION

According to UK government statistics, in March 2024 there were 495,798 shotgun certificates held legally within the UK and, it is estimated that, there are in excess of 1.33 million shotguns [1, 2]. Therefore, with these large quantities of shotguns, it is possible that some of these weapons may be misappropriated and used in criminal activity.

Traditionally, shotgun ammunition contains “pellets” or “shot” which are spherical projectiles manufactured from lead [3]. However, a recent government proposal considers the phasing out of lead, due its toxicity to wildfowl and their predators [4, 5, 6].

This paper describes shotguns, lead and lead-free shotgun ammunition, and their effect on typical materials used in police body armour.

2. SHOTGUNS

The principal use of a shotgun is for hunting game, such as flying birds, ground game (eg rabbits) or larger animals, such as deer. They are also used for International Sporting Shooting Federation and Olympic disciplines such as skeet and trap clay target shooting [3].

Shotguns are smooth-bore weapons; shotgun barrels do not have rifling cut into their inner surface, unlike handgun and rifle barrels, where rifling is used to impart spin stabilisation to bullets in flight. The effective range of a shotgun is approximately 30 meters and pellets typically fall to the ground within several hundred meters [3].

2.1 Gauge of shotgun

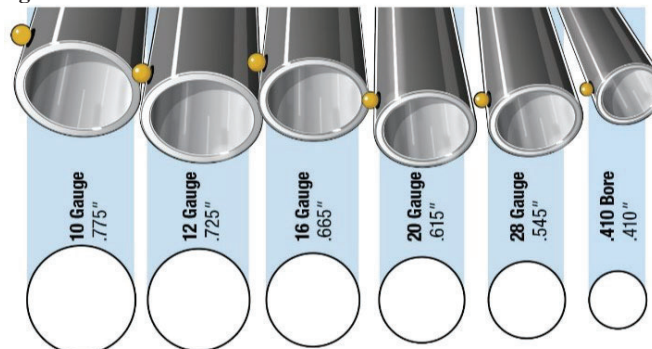


Figure 1. Common gauges, or sizes, of shotgun, reproduced from reference [7]

There are many gauges, or sizes, of shotgun. The nomenclature of denoting the gauge is based on an antiquated method of measuring the bore size of artillery, whereby the size of the shotgun barrel is determined by the mass of spherical lead ball that fits the bore. A shotgun that fits a lead ball with a mass of one twelfth of an imperial pound is known as a 12 bore, and this nomenclature is used for the majority of gauges of shotguns (see figure 1). The exception is the .410" gauge of shotgun, which was introduced later than other gauges, hence modern calibre notation is used [3, 8, 9].

2.2 Tapered and parallel sided barrels

Shotgun barrels are often tapered on the inside of the barrel, known as a choke, which narrows the bore toward the muzzle. This feature is designed to constrict the shot, and by restricting the width dispersion of the shot there is a higher probability of hitting the target at longer ranges. A parallel sided shotgun barrel is known as a cylinder [8].

3. SHOTGUN AMMUNITION

Ammunition for shotguns is known as cartridges, which are parallel sided cylinders. The walls of shotgun cartridges are made from cardboard or plastic, and a brass base contains the primer. The shotgun's firing pin strikes the primer, thereby igniting the propellant within the cartridge. The wad, and sometimes a cup, sits behind the pellets to apply a force to the projectiles within the cartridge. The end of the shotgun cartridge is typically sealed with a card disc or plastic cover [8].

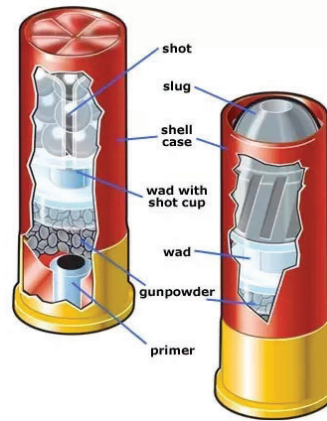


Figure 2. Diagram of shotgun cartridges [10] containing multiple pellets (left) and a solid slug on right

3.1 Mass and size of pellets

Most shotguns fire approximately one ounce to one and an eighth of an ounce (nominally 28 to 32grams) of pellets [8]. Pellet sizes are illustrated in figure 3.

Lead shot sizes:	12	9	8½	8	7½	6	5	4	2	BB
Pellet diameter (inches)	.05	.080	.085	.090	.095	.110	.120	.130	.150	.180
(mm)	1.27	2.30	2.16	2.29	2.41	2.79	3.05	3.30	3.81	4.57

Buckshot sizes:	No. 4	No. 3	No. 2	No. 1	No. 0	No. 00	No. 000
Pellet diameter (inches)	.24	.25	.27	.30	.32	.33	.36
(mm)	6.10	6.35	6.86	7.62	8.13	8.38	9.14

Steel shot sizes:	6	5	4	3	2	1	Air Rifle	BB	BBB	T	F
Pellet diameter (in.)	.11	.12	.13	.14	.15	.16	.177	.18	.19	.20	.22
(mm)	2.79	3.05	3.30	3.56	3.81	4.06	4.49	4.57	4.83	5.08	5.59

Figure 3. sizes of pellets reproduced from reference [11]

4. DISPERSION OF SHOTGUN PELLETS

When multiple pellets are fired from a shotgun, they initially emerge from the muzzle together. However, as the pellets travel away from the muzzle they spread out in three directions, in width, in height and in length. Figure 4 illustrates the dispersion of multiple pellets as the distance from the muzzle increases [12].

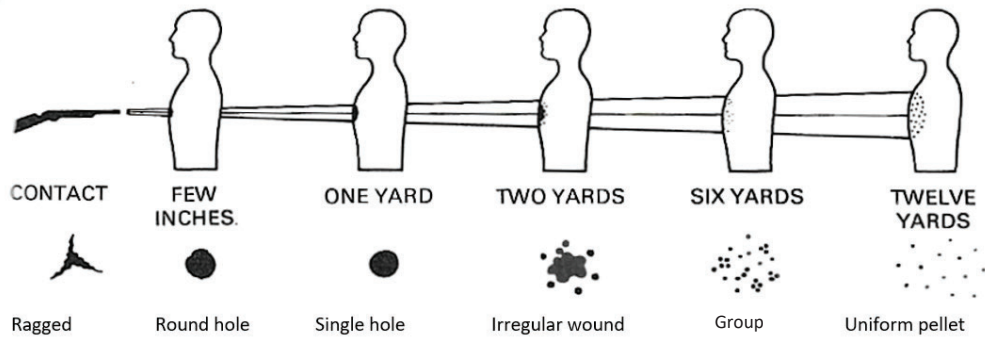


Figure 4. Characteristics of shotgun wounds at various distances, reproduced from reference [12]

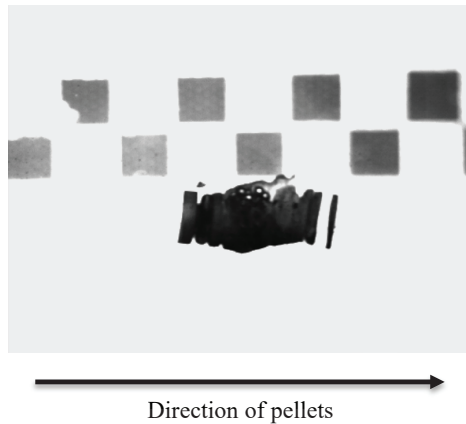


Figure 5. image taken from high-speed video illustrating the beginning of the opening of the plastic shotgun cup, and the ejection of the wads (on the right).

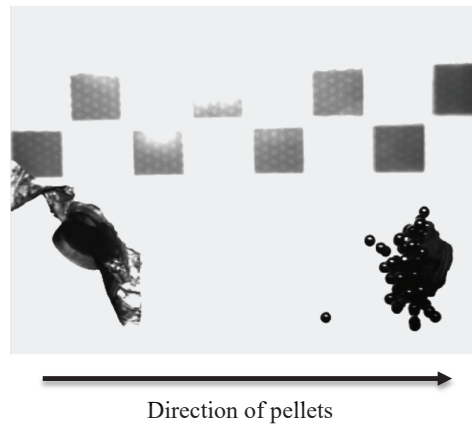


Figure 6. image taken from high-speed video illustrating the fully open plastic shotgun cup (on left) and the pellets on their flight path (on right).

5. MATERIALS USED IN SHOTGUN AMMUNITION

Traditionally shotgun cartridges have used lead pellets (or shot) however, this may be phased out due its toxicity to wildfowl and their predators. The main alternative materials to lead are steel, bismuth alloys (typically containing tin) and tungsten matrix (ie tungsten bound in a polymer) [4, 5, 6].

5.1 Density of lead and alternative materials

Table 1. Density of materials reproduced from reference [13]

Material	Density (ρ) kg/m ³
Lead	11,300
Mild Steel	7,860
Tungsten	19,300
Bismuth	9,790

5.2 Hardness of alternative materials

According to the Vickers hardness test [14] using HV 10kgf the steel pellets are 101HV and tungsten matrix pellets (13g/cm³) are 297HV. Hence, the tungsten matrix tested in this study is around three times the hardness of the steel pellets. (It should be noted that higher densities of tungsten matrix are manufactured, such as 18g/cm³, however these were not available at the point of testing).

The lead and bismuth pellets were subjected to the same hardness test, however using HV 1kgf the lead pellets are 9.9HV and the bismuth 17.5HV. Hence lead and bismuth are very soft metals, particularly when compared with steel and tungsten.

5.3 Price of alternative materials

Price comparisons for lead shotgun ammunition compared with alternative materials have been published by Thomas [15]. Although prices are subject to change, typically steel is a comparable price to lead, and other materials are more expensive than lead. For instance, bismuth shotgun ammunition is approximately 5 times the price of lead ammunition, and tungsten ammunition is 10 times the price of lead ammunition [15, 16].

6. UK HOME OFFICE BODY ARMOUR STANDARD

Within the UK Home Office body armour standard [17] there is a shotgun protection level, namely SG1, for plates (ie hard armour, typically used to augment soft body armour panels). The projectile used in the Home Office body armour standard is a one-ounce, rifled lead slug (see figure 2).

Currently, there is not a protection level for soft, body armour designs (eg HO1 and HO2 protection schemes) against lead shotgun pellets. However, as the lowest ballistic protection level (HO1) specifies a proof test against 9mm full metal jacket (FMJ) and jacketed soft point (JSP) ammunition at 365m/s (+/-10m/s) lead shot is likely to be stopped within soft, body armour designs accredited to HO1 and HO2.

Protection level	Classification and calibre	Test round designation	Bullet mass	Range (min) (m)	Max. mean BFS (mm)	Single shot BFS limit (mm)	Velocity (m.s ⁻¹)
SG1	Shotgun 12 gauge True Cylinder	Winchester 1 oz. Rifled 12RSE	28.4 g	10	25.0	30.0	435 ± 25

Figure 7. Ballistic protection levels reproduced from the UK Home Office body armour (2017) standard [17]

7. IS LEAD-FREE SHOTGUN AMMUNITION MORE PENETRATIVE AGAINST ARMOUR MATERIALS?

A series of trials were conducted to determine whether alternative shotgun ammunition is more penetrative against armour materials, typically used in police protection schemes, when compared with lead ammunition. As the size and mass of shotgun pellet can significantly vary (as described in section 3.1) a nominal diameter of pellet was chosen in which lead and each of the alternative materials could be sourced. During these trials 3" magnum (76mm) ammunition was fabricated with 32g of i) lead ii) steel iii) bismuth (alloy unspecified) and iv) tungsten matrix pellets ($13\text{g}/\text{cm}^3$).

7.1 Test set up

Throughout this study a 12-gauge cylinder shotgun barrel (length 725mm) was coupled with a universal receiver. The shotgun ammunition (3" magnum, 76mm) was loaded by the Ballistic Test Facility (BTF) using the same mass of pellets (32g) in a "Gualandi" plastic cup and 2 off 4mm cork wads. An appropriate mass of propellant was used to achieve pertinent velocities of $425\text{m}/\text{s} \pm 25\text{m}/\text{s}$ [16]. The diameter of the lead, steel and tungsten pellets were nominally 4mm in diameter and, due to availability, the bismuth pellets were nominally 3.56mm.

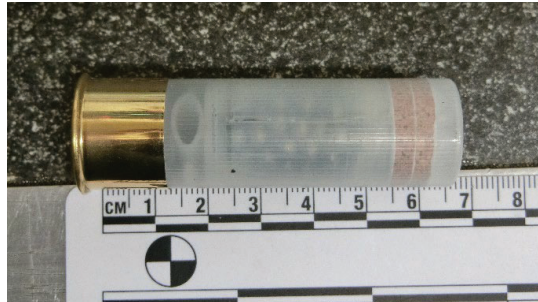


Figure 8. Photograph illustrating the shotgun ammunition, loaded by the BTF, prior to firing

When testing individual projectiles against armour designs typically the velocity of the projectile is varied and statistical techniques, such as V_{50} or Critical Perforation Analysis [18], are used to estimate the armour performance. However, in these tests the distance was varied (nominally 0.5m, 1.5m and 2.5m) so that the concentration of pellets decreases at longer distances.

A high-speed video (HSV) camera with known frame rate (30,000 fps) and a scale in the HSV footage were used to evaluate the average velocity of the pellets by measuring distance travelled over time. This method was employed as miscalculations often occur when chronographs estimate the velocity of multiple projectiles, and other objects (such as wads) can also produce erroneous results.

Each target was mounted on a microcrystalline wax block¹ (nominally 420 x 350 x 100 mm), which was affixed into a steel frame. This set up allowed for the backing to be perforated without damaging Home Office specified backing materials (ie Roma Plastilina No 1) which would be expensive to repair. Furthermore, the effect of momentum on the target, or back face signature, was not within the scope of these tests.

7.2 Targets

In this study the performance of the following generic armour materials, used within police body armour schemes, were evaluated. Firstly, a comparison of the performance of:

- 20 off layers of nominally $80\text{g}/\text{m}^2$ of ultra high molecular weight polyethylene (UHMWPE). Areal density of target $1.6\text{kg}/\text{m}^2$, and
- 8 off layers of nominally $200\text{g}/\text{m}^2$ of aramid. Areal density of target $1.6\text{kg}/\text{m}^2$.

Then a simple, generic armour target of 20 off layers of nominally $200\text{g}/\text{m}^2$ of aramid was evaluated. Areal density of target $4.0\text{kg}/\text{m}^2$.

¹ ref:3795, Poth Hille & Co Ltd, RM13 9BP

8. RESULTS

The following tables 2 to 8 summarise the results.

Table 2. Performance of 20 layers of UHMWPE (80g/m²) at nominally 0.5m, against lead and 3 lead-free materials for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
PE-1	32g LEAD	4.00	407	0.53	NP	Considerable indentation of target into backing.
PE-2	32g STEEL	4.00	427	0.53	P	
PE-3	32g BISMUTH †	3.56	426	0.53	NP	† alloy unspecified Considerable indentation of target into backing.
PE-4	32g TUNGSTEN MATRIX ‡	4.00	403	0.53	P	‡ 13g/cm ³ density

*P = Perforation NP = Non-perforation

Table 3. Performance of 8 layers of aramid (200g/m²) at nominally 0.5m, against lead and 3 lead-free materials for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
A-1	32g LEAD	4.00	429	0.50	NP	Considerable indentation of target into backing.
A-2	32g STEEL	4.00	450	0.50	P	
A-3	32g BISMUTH †	3.56	426	0.50	NP	† alloy unspecified Considerable indentation of target into backing.
A-4	32g TUNGSTEN MATRIX ‡	4.00	449	0.50	P	‡ 13g/cm ³ density

*P = Perforation NP = Non-perforation

Table 4. Performance of 20 layers of UHMWPE at nominally 1.5m, against 2 lead-free materials for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
PE-5	32g STEEL	4.00	433	1.49	P	
PE-6	32g TUNGSTEN MATRIX ‡	4.00	449	1.49	P	‡ 13g/cm ³ density

*P = Perforation NP = Non-perforation

Table 5. Performance of 8 layers of aramid (200g/m²) at nominally 1.5m, against 2 lead-free materials for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
A-5	32g STEEL	4.00	428	1.50	NP	
A-6	32g TUNGSTEN MATRIX ‡	4.00	428	1.50	P	‡ 13g/cm ³ density

*P = Perforation NP = Non-perforation

Table 6. Performance of 20 layers of UHMWPE at nominally 2.5m, against 2 lead-free materials for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
PE-7	32g STEEL	4.00	407	1.49	P	Borderline perforation, the majority of pellets were stopped in the armour.
PE-8	32g TUNGSTEN MATRIX ‡	4.00	431	1.49	P	‡ 13g/cm ³ density. Borderline perforation, the majority of pellets were stopped in the armour.

*P = Perforation NP = Non-perforation

Table 7. Performance of 8 layers of aramid (200g/m²) at nominally 2.5m, against 1 lead-free material for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
A-7	32g TUNGSTEN MATRIX ‡	4.00	448	2.50	P	‡ 13g/cm ³ density. Borderline perforation, the majority of pellets were stopped in the armour.

*P = Perforation NP = Non-perforation

Table 8. Performance of 20 layers of aramid (200g/m²) at nominally 0.5m, against lead and 3 lead-free materials for shotgun pellets

#	Mass and material of shot	Nominal diameter of pellets (mm)	Average velocity of pellets (m/s)	Distance between muzzle and target (m)	P / NP*	Notes & observations
A-8	32g LEAD	4.00	416	0.53	NP	Considerable indentation of target into backing.
A-9	32g STEEL	4.00	421	0.53	NP	Considerable indentation of target into backing.
A-10	32g BISMUTH	3.56	426	0.53	NP	Considerable indentation of target into backing.
A-11	32g TUNGSTEN MATRIX ‡	4.00	438	0.53	NP	‡ 13g/cm ³ density Considerable indentation of target into backing.

*P = Perforation NP = Non-perforation

9. DISCUSSION

At close proximity to the shotgun muzzle, nominally 0.5m, the UHMWPE and aramid (8 layer) targets (both with an areal density of 1.6 kg/m²) were not perforated by either the lead or bismuth shotgun pellets. However, the steel and tungsten matrix pellets, which are much harder than lead and bismuth, perforated the UHMWPE and aramid (8 layer) targets at this range.

In order to reduce the intensity of concentration of the pellets, the distance between the muzzle and the target was increased to nominally 1.5m for the lead-free pellets, which had perforated the target at 0.5m. At nominally 1.5m both the steel and tungsten matrix pellets perforated the UHMWPE target, and the steel pellets were stopped within the aramid (8 layer) target, whereas the tungsten matrix pellets perforated it.

Once again, to reduce the concentration of pellets, the distance between the muzzle and the target was increased to 2.5m for perforating lead-free shotgun ammunition. Perforations from the steel and the tungsten matrix pellets were observed within the UHMWPE target. However, as the majority of the

steel and tungsten matrix pellets were retained within the armour (ie partial perforations) this performance indicates that 2.5m is close to the threshold of this armour/projectile combination. A similar performance threshold was observed with the tungsten matrix pellets impacting the aramid (8 layer) target at 2.5m.

The simple, generic armour target of 20 layers of 200g/m² of aramid was able to stop all of the lead and lead-free pellets at 0.5m. Many body armour schemes used in UK frontline policing have greater quantities of ballistic resistant materials in their construction, hence all of the nominal 4mm lead-free shotgun pellets tested here are unlikely to defeat such armours.

Finally, although the effect of momentum was outside of the scope of this project, considerable indentation of the target into the backing material, particularly at short range, was observed in non-perforations in both UHMWPE and aramid targets.

10. CONCLUSIONS AND FURTHER WORK

In the UK shotguns are common weapons, with over 1.33 million shotguns legally owned under licence. Traditionally, pellets or shot has been manufactured from lead, however an official review by the UK government has suggested that lead ammunition may be phased out, due to its toxicity to wildfowl and their predators.

The main alternative materials to lead pellets are steel, bismuth alloys and tungsten matrix. Bismuth alloys are the closest match in density and hardness to lead, compared with steel and tungsten matrix. In this study typical armour materials (used in police body armour) were tested with commercially available bismuth shot, and a similar performance to lead shot was observed.

Steel shotgun ammunition is a similar price to lead and is readily available. Steel is less dense than lead and, therefore, more pellets are required to produce same total mass of pellets in the cartridge (if they are the same diameter). Due to the difference in mass, if fired at the same velocity, steel pellets will have less kinetic energy per pellet than lead. However, as steel pellets are harder than lead, steel pellets are less easily deformed.

Tungsten is approximately ten times the price of lead and is a material of significantly higher density and hardness. Although tungsten pellets are fabricated from tungsten powder within a polymer matrix, when subjected to the Vickers hardness test the pellets in this study were around three times the hardness of the steel pellets. As the tungsten matrix pellets have a higher density than the lead equivalent, for the same mass of pellets (32g), the kinetic energy per pellet is higher for tungsten matrix pellets than for lead pellets since there are fewer of them for the same total mass.

Both steel and tungsten pellets were found to be significantly more penetrative against typical armour materials than lead pellets of the same diameter.

The simple, generic armour target of 20 layers of 200g/m² of aramid was able to stop all of the lead and alternative, lead-free pellets tested at 0.5m. Many body armour schemes used in UK frontline policing have greater quantities of ballistic resistant materials in their construction, hence all of the nominal 4mm lead-free shotgun pellets are unlikely to defeat such armours.

Finally, this study focuses on nominally 4mm pellets of lead and alternative, lead-free shotgun ammunition, fired from a 12-gauge shotgun barrel. As the choice of shotgun pellet size was determined by the availability of pellets, it is recommended that further work is undertaken on larger sizes of pellets since each pellet will have a higher kinetic energy than those with smaller diameters. Furthermore, it should be noted that the 4mm tungsten matrix pellets under test had a density of 13g/cm³, however tungsten matrix of higher density is also commercially available.

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