Part one: the long trend in Individual Weapons

From the beginning of small-arms to the 19th century, the development of hand-held weapons was driven by the need i) to increase the safety and reliability ii) to increase the practical range and iii) to increase the practical rate of fire.

Safety and reliability was the first field of improvement, with the introduction of the matchlock, flintlock and percussion caps, along with improved quality controls for the black powder.

Evolution of the individual weapon’s practical range, against a 1.6 m standing man in average wind conditions, and practical rate of fire (RoF) is given in Figure 1. Weapons that actually entered into service are symbolized by a green dot and a black label; unsuccessful programs are symbolized by a red tag and a red label and will be detailed in this paper because unsuccessful programs provide valuable information.

Figure 1: Evolution of the range and rate of fire of individual weapons used by the French army during the last 150 years
The pre WWI industrial era

After the rifled barrel came into general use, there was little to do to increase the practical range apart from increasing the muzzle velocity (a solid way to reduce the projectile time of flight to the target). The introduction of streamlined bullets in 1898 with the “balle D” was the last improvement, reducing the projectile time of flight (ToF) without increasing the muzzle velocity.

The continuous reduction in bore diameter (and projectile weight) was a simple measure to avoid increasing the recoil and the gun weight.

In France, the rifle bore diameter decreased from 17.8 mm in 1857 (32 g bullet, recoil of 12.4 N.s), to 11 mm in 1866 (25 g bullet and 14.1 N.s) and 8 mm in 1886 (15 g bullet and 12.3 N.s)\(^i\).

During this time, the practical range against a 1.6 m standing man under average wind conditions steadily increased from ~230 m to ~510 m.

The introduction of the “balle D” in 1898 by Desaleux and Arthus was no small achievement. The trajectory improvement of the Mle 1898 D bullet compared to the Mle 1886 M was of the same order as the improvement of the Mle 1886 M compared to the Mle 1874, with just the need to change the iron sight calibration\(^ii\).

Increasing the rate of fire was not so straightforward and involved the introduction of:

- self-contained cartridge (first made of combustible paper in 1866, then the metallic cartridge in 1874 that also acts as an expendable chamber seal, increasing the gun’s safety and reliability),
- breech-loader (introduced with the self-contained cartridge in 1866),
- manually operated repeater (in 1886),
- fixed box magazine (loaded with 3-round and 5-round clips),
- detachable box magazine (as opposed to tubular and fixed box magazines),
- semi-automatic repeater.

Against large bodies of troops moving in compact formations (as in, for example, the Transvaal campaign), more than 50% of firefights occurred at what we now call “long range” (between 900 m and 2100 m); only 25% occurred at ranges shorter than 900 m (Figure 2).
Figure 2: Engagement distances during the 1880-1900 period according to Wolozkoï and battlefield depth according to Bircher.

According to J.B.A. Bailey, in the sixty years preceding 1914, artillery fire produced less than 10% of all battle casualties, the remaining 90% fell to small arms (mostly individual weapons), whose range and accuracy had come to rival those of artillery. This estimation is supported by medical and after-battle reports available from that era.

But the introduction of shells loaded with high-explosives (instead of black-powder) around 1890, the invention of reliable impact fuses, the development of rapid-firing guns like the famous French 75 mm Mle 1897 (with an oleo-pneumatic recoil-absorbing mount) and mathematic models for direct and indirect fire solutions (increasing dramatically the hit probability of long-range gunnery) during the same period radically changed the way armies were fighting, and it was anticipated (in 1901, long before WWI) that artillery fire could produce as much as 40% to 50% of overall casualties in future Europeans conflicts.

A good start, the first spitzer, boat tail, lead-free bullet, (all in once!)

The adoption by the French army of the “small calibre” 8 mm Lebel cartridge, loaded with (then new) smokeless “B” powder and firing a round nose, jacketed lead core, bullet (a design borrowed from the Swiss school of ballistics) in 1886 was a the first step towards the generalization of a “modern” rifle cartridge. This adoption will be followed by all other armies in the world.

As soon as this cartridge was adopted, another program to study further bore reduction was launched, devoted to the development of a new, lightweight cartridge for a bolt-action rifle that should have replaced the 8 mm Mle 1886”M” cartridge, providing the same trajectory improvement previously achieved with the shift from the 11 mm Mle 1874 cartridge to the 8 mm Mle 1886.

Calibres from 5 mm to 7 mm were studied and finally the 6 mm bore was selected, leading to the 6 mm APX 1893 (Figure 3), firing a 8.5 g FMJ round-nose bullet (a scaled down 8 mm Mle 1886 “M” bullet) at a velocity $(V_{25})$ of 731 m/s when loaded with 2.65 g of “BF” powder (cartridge weight of 23.8 g and 84.4 mm maximum length, compared with 30.6 g for the 8mm Mle 1886”M”, a ~25% weight reduction). The case used was called “étui de Puteaux n°3” and weighted 12.5 g for a capacity of 4.145 cm$^3$ (64 gr H$_2$O, similar to the current 240 Weatherby Magnum). This case was used in nearly all 6 mm and (necked up) 6.5 mm bullet developments, until the availability of even larger, rimless cases.
Unfortunately, the increase of the muzzle velocity (a 100 m/s gain compared with the 8 mm Mle 1886M) did not bring any trajectory gain at long range (1600 m and up).

At the same time, it was discovered that small differences in bullet shape could lead to significant difference in trajectory (fired at the same MV, the CPC bullet —Figure 4, centre left— needed 7 mils less elevation than the standard 6 mm RN APX bullet —Figure 4, far left— to reach a range of 1600 m), and investigations were performed between 1891 and 1895 to optimize bullet shape and trajectory, ending with the bullet CT22 (Figure 4, far right).

Meplat diameter was also investigated (2 mm, 3 mm and 4.4 mm) and the best results were achieved with the 2 mm meplat.
Compared to flat-base bullets, those long (30 mm to 33 mm or 5.0 to 5.5 calibres) boat-tail bullets needed a much shorter barrel twist and the optimum one was found around 150 mm (25 calibres).

Similar observations (that very small changes could lead to a large change in bullet BC, but this time in the opposite direction) were made during WWII production of military ammunition in the US. For ease of manufacturing, the 50 BMG APM2 bullet was slightly altered in 1943: the “French” cannelure (see an example in Figure 18) was changed to a simple “squared” cannelure, and the formerly “sharp” edge of the boat-tail was slightly rounded. Those minor changes were enough to reduce the bullet G5 BC from 0.493 down to 0.458, a full 7.5% reduction vii.

Ogive height remained comparatively short because common knowledge (and probably also manufacturing tolerances) “required” a bullet shank length of 2 calibres for proper in-bore travel (accuracy and bore sealing), combined with a 1.17 calibre boat-tail that leaves only 2.33 calibres for the nose ogive.

Following external ballistics studies made in 1894 and 1895 with lathe turned 8 mm bullets (weight 13.65 g, fired from a 200 mm twist barrel, according to “notes de la commission de Versailles” dated from 1894 October 2nd, 1895 January 17th, 1895 Mai 13th and 1895 September 4th”, written by Captain Desaleux ii) the development of what would become known as the “balle D” started in 1896, with 5 cold-pressed bullets (called A, B, C, D and E) having the same shape but made of different materials (the “balle C” was made of steel for example).

The exact shape is not known but a rough drawing could be found in vii (Figure 5).
The bullet length was 39 mm, with a 2.5 calibres ogive height and a weight of 13.2 g when made with 90/10 brass alloy (“D” version).

The choice of a 2.5 calibres height (around 7 calibres tangent radius) was probably an unlucky consequence of mathematical considerations (made possible by the relatively new method of differential calculation) showing that this was the shape of “least resistance” (minimum drag) according to Newton’s law. That “demonstration” was proved to be false but supersonic aerodynamics was not seriously investigated before WWII, too late for most small-arms military applications.

Soon, a variant of this bullet (known as the n°66) with a “3 calibres” (24.5 mm) ogive height was made at the request of Captain Arthus, (probably to make good use of the available space provided by the 74.8 mm cartridge length and 50.3 mm case length of the 8 mm Lebel cartridge) and this bullet demonstrated a better trajectory than the original “D” bullet, but was found unsatisfactory when manufactured from a cold-pressing process and fired from worn barrels.

Figure 5: Side-by-side drawing of the original “Balle D” and “Balle n°66” bullets, along the case markings of the 1895 test.
Both bullets were tried during the year 1895 (along with the 1886M bullet) with the following results.

<table>
<thead>
<tr>
<th>Bullet</th>
<th>Weight (g)</th>
<th>Powder load (BF, g)</th>
<th>MV (m/s)</th>
<th>Mean G7 BC (1000 m, ToF)</th>
<th>Mean G1 BC (1000 m, ToF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balle D</td>
<td>13.0</td>
<td>2.7</td>
<td>678-679</td>
<td>0.284</td>
<td>0.524</td>
</tr>
<tr>
<td>Balle n°66</td>
<td>12.2</td>
<td>2.7</td>
<td>688-689</td>
<td>0.291</td>
<td>0.541</td>
</tr>
<tr>
<td>Mle 1886M</td>
<td>15.0</td>
<td>2.7</td>
<td>622-623</td>
<td>0.213</td>
<td>0.387</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bullet</th>
<th>Measured</th>
<th>Computed (G7 model)</th>
<th>Computed (G1 model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>$y_{b}^*$ (cm)</td>
<td>$y_{o}^*$ (cm)</td>
<td>$y_{b}^*$ (cm)</td>
</tr>
<tr>
<td>Balle D</td>
<td>134.5</td>
<td>97.3</td>
<td>130.6</td>
</tr>
<tr>
<td>Balle n°66</td>
<td>124.1</td>
<td>90.9</td>
<td>124.9</td>
</tr>
<tr>
<td>Mle 1886M</td>
<td>198.7</td>
<td>155.0</td>
<td>189.1</td>
</tr>
</tbody>
</table>

It was a clear demonstration that using a pointed, boat tail bullet could bring a large increase of its BC (1/3 more for the n°66 compared to the Mle 1886M), while at the same time provide a reduction of the bullet weight (20% less) and hence an increase of the muzzle velocity (and a flatter trajectory) for a given powder weight.

At the end of 1896 the adoption of the “D” bullet was thought to be imminent, but some modifications were made to adopt the 3 calibres ogive height of the n°66 bullet.

The ogive base diameter (outside of the case) was oversized (8.30 mm min, 8.35 mm max and 8.32 mm average) for better in-bore sealing, leading to the n°139 bullet. An ultimate variant with a longer boat-tail and reduced shank (bullet n°142) was tried but sometimes did not take the rifling properly and the 12.8 g “balle D” (n°139) was finally approved for production in January 1898.

The aerodynamic properties of this bullet were absolutely astonishing compared to the round nose bullets used at this time, but even by today standard this bullet remains a top performer. The very low form factors deduced from military reports have been questioned on the basis that the i7 form factor of current bullets used by NATO are generally between 1.10 and 1.15, so it seems nearly impossible that a large scale military bullet (as opposed to low production Match bullet) could perform significantly better.

Figure 6 shows drag curves measured with WWI wartime production bullets, while Figure 7 refers to the TPM327D (current production bullet) based on the drawing of the n°139 (Figure 8) but with a slightly secant ogive (Rt/R = 0.80).
Figure 6: Drag curves of the 8 mm Mle 1898D bullets (7 shots, wartime production) and velocity banded G7 curves (red) with i7 form factor.

Figure 7: Drag curves of the 8 mm TPM327D (5 shots, current production) and velocity banded G7 curves (red) with i7 form factor.

Due to its truly excellent shape and stability, the mean G7 BC of the 12.8 g Mle 1898D in the supersonic domain is ~0.30 (between 0.287 and 0.312), providing a supersonic range ~900 m even when launched at a sedate (by now standard) MV of 690-700 m/s.
The introduction of the Mle 1886D cartridge (Mle 1886 cartridge loaded with Mle 1898D bullet) greatly increased the ballistic performance of the “Lebel” rifle and was possible only because of the lucky combination of i) a long COAL, ii) the “short” case of the original Mle 1886 M cartridge, and finally iii) the tight 240 mm twist used by the Lebel rifle.

At the same time some military authors thought that it was a “missed opportunity” and that a more modern cartridge (and rifle) should have been introduced in conjunction with the new bullet xxiv.

The “model D” bullet was manufactured from a 90/10 (copper and zinc) brass rod (initial diameter between 7.32 mm and 7.36 mm), with the addition of 0.4% of lead and 0.4% of tin x, but during WWI pure copper was also used.

Material acceptance test were very similar to those of common 90/10 brass used for bullets jackets xi, with a minimum tensile strength of 25 kg/mm² and an elongation limit of more than 42% for a 100 mm long test piece, without flaws, cracks or spots.
A first dead-end, the 6 mm program

In parallel with the development of the “stopgap” 8 mm Mle 1886D cartridge, a large effort was devoted to improve the 6 mm APX 1893 (6 x 62 mm R) cartridge, but with a new bullet.

Between 1895 and 1900, the “Ecole Normale de Tir de Châlons” (E.N.T.) made systematic investigations of bullet shape (16 different 6 mm bullets ranging from 22 mm to 36 mm in length, and between 4.5 g and 7.2 g in weight) with the following results:

- the length of the bullet cylindrical part could be reduced to less than 2 mm but at the cost of increasing the vertical dispersion (while not measured, this point is probably due to large muzzle velocity dispersions),
- bullets with long ogive (3.5 calibres) and 14+ calibre tangent radius needed “short” cylindrical bodies because of the already high contact area between the nose and barrel,
- For a given weight, the bullet with the longest ogive (3.5 calibres) gives the best trajectory, but bullets with 3 calibres long ogive were not far behind,
- The “best” bullet tested was the 7.0 g, 36 mm long (6 calibres!) “balle n°85”, but the cartridge OAL (using the 62 mm long Puteaux n°3 rimmed case) was 86 mm, a value considered impractical.

Finally, after several refinements, two nearly equivalent design emerged, the E.N.T. “balle n°29” (34.4 mm long, 6.8 g with a 3 calibres ogive height) and the E.N.T. “balle n°30” (34.4 mm long, 6.6 g with a 3.5 calibres ogive height), with a 6.24 mm bullet diameter in both case.

Comparative firing of those two bullets with BN₃F powder revealed than the maximum load was 2.90 g for the “n°29” bullet (muzzle velocity of ~851 m/s) versus 2.95 g for the “n°30” bullet (muzzle velocity of ~876 m/s), giving the latter a slight trajectory advantage.

For modern reloaders, a powder load of 45 gr in a 64 gr case capacity (58 gr net capacity, loading density of 0.77) is an indication that the powder used was probably not that good for the task.

A warning about using firing tables found in historical documents (at least French documents) to evaluate the ballistic qualities of bullets should be issued.

Before WWI, it seems that the French common practice was to measure the time of flight to 50 m (giving the mean velocity called \(V_{25}\), or the velocity at 25 m from the gun muzzle) and the ToF at a much longer distance (generally around 1500 m, but sometimes only 800 m or 1000 m, or up to 2400 m).

From those ToF, a polynomial expression was fitted to express the ToF as a function of the range \(P\) (in hundred meters). The velocity is thus derived from this polynomial expression and those values (ToF and remaining velocity) are the one found in the firing tables.
For the “Balle n°30” (fired at a $V_{25}$ velocity of 860.5 m/s), the time of flight is expressed as:

$$T = 0.11357 \cdot P + 0.005277 \cdot P^2$$

Hence, the remaining velocity (as a function of the range) is expressed as:

$$V = \frac{1}{0.11357 + 0.010554 \cdot P}$$

and the deducted MV is 880 m/s.

At a range of 800 m ($P = 8$), the calculated ToF (found in the firing tables) is 1.246 sec compared to 1.172 sec as found during actual firing (see below), a significant difference.

For the “Balle n°29” (fired at a $V_{25}$ velocity of 835 m/s), the time of flight is expressed as:

$$T = 0.11695 \cdot P + 0.005558 \cdot P^2$$

Hence, the remaining velocity (as a function of the range) is expressed as:

Figure 9: Actual firing results for the 6 mm “balle n°29” and “balle n°30”. $T_8$ is the ToF to 800 m and $y_4$ is the ordinate at 400 m for a 800 m zero.
\[ V = \frac{1}{0.11695 + 0.011116 \cdot P} \]

and the deducted MV is 855 m/s.

Of course, atmospheric conditions used in the model are different from those measured during actual shootings, but main sources of error were i) curve fitting and ii) experimental errors (mostly linked to the measure of the time of flight to 50 m).

<table>
<thead>
<tr>
<th>Bullet</th>
<th>Balle n°29</th>
<th>Balle n°30</th>
</tr>
</thead>
<tbody>
<tr>
<td>ToF to</td>
<td>Measured</td>
<td>From the model</td>
</tr>
<tr>
<td>800 m</td>
<td>1.223 s</td>
<td>1.291 s (+5.6%)</td>
</tr>
<tr>
<td>1000 m</td>
<td>1.673 s</td>
<td>1.725 s (+3.1%)</td>
</tr>
<tr>
<td>1500 m</td>
<td>3.173 s</td>
<td>3.005 s (-5.3%)</td>
</tr>
<tr>
<td>1900 m</td>
<td>4.551 s</td>
<td>4.228 s (-7.1%)</td>
</tr>
</tbody>
</table>

Anyway, using current numerical methods the following results could be found:

<table>
<thead>
<tr>
<th>Balle n°29 (6.8 g)</th>
<th>T₀.₅ and T₈</th>
<th>T₀.₅ and T₁₀</th>
<th>T₀.₅ and T₁₅</th>
<th>T₀.₅ and T₁₉</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>851 m/s</td>
<td>853 m/s</td>
<td>858 m/s</td>
<td>858 m/s</td>
</tr>
<tr>
<td>CB (G7)</td>
<td>0.307 (&gt;M1.2)</td>
<td>0.293 (&gt;M1.2)</td>
<td>0.293 (&gt;M1.2)</td>
<td>0.293 (&gt;M1.2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Balle n°30 (6.6 g)</th>
<th>T₀.₅ and T₈</th>
<th>T₀.₅ and T₁₀</th>
<th>T₀.₅ and T₁₅</th>
<th>T₀.₅ and T₁₉</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>876 m/s</td>
<td>878 m/s</td>
<td>884 m/s</td>
<td>884 m/s</td>
</tr>
<tr>
<td>CB (G7)</td>
<td>0.318 (&gt;M1.2)</td>
<td>0.294 (&gt;M1.2)</td>
<td>0.294 (&gt;M1.2)</td>
<td>0.294 (&gt;M1.2)</td>
</tr>
</tbody>
</table>

Based on the results shown above, both bullets showed an impressive BC (G7) of ~0.29 in the supersonic domain (i7 FF between 0.81 and 0.84) and ~0.25 in the transonic and subsonic domain (i7 between 0.97 and 1.0).

Terminal ballistics results in various targets (steel shields, human cadavers and living horses) were also excellent and a proposition is made in 1900 to adopt a 6 mm rimmed cartridge combining the 6.6 g solid copper “balle n°30”, the 12.5 g Puteaux n°3 rimmed case and 2.95 g of BN₃F powder xxiv, xii.

With modern powders, this cartridge could be duplicated using the smaller 243 Winchester case and a Very Low Drag 105 gr bullet like the Berger 105 gr Hybrid.
The comparison between the 6 x 62 mm APX and the short-lived 6 mm US Navy is difficult to avoid. The development of both cartridges took place during the same timeframe, driven by the same needs (increasing the practical range of small-arms and reducing the cartridge weight to allow more firepower for a given load weight) and the French army was well aware of the existence of the USN cartridge.

In its original form, the APX round was well behind the USN round, using a much bigger case while delivering a lower muzzle velocity (752 m/s for the French 8.5 g RN bullet compared with 777 m/s for the US 8.7 g RN bullet), but at the end of the 19th century, improved powders (2.95 g of BN₃F instead of 2.65 g of BF) and improved bullets (6.60 g spitzer boat-tail bullet instead of the 8.50 g round nose flat-base bullets) allowed the “magnumized” APX to outperform the USN round.

There’s little doubt that a 34 mm long solid copper, 6 mm VLD bullet launched at a MV of 880 m/s would have delivered the level of performance needed for a military cartridge, but at the beginning of the 20th century, the French army started thinking about self-loading rifles and instead of a rimmed round, a rimless round with even better external ballistics was asked for.

Unfortunately, when the muzzle velocity was increased from 880 m/s to more than ~920 m/s (and a bullet spin of 368,000 rpm), severe barrel fouling arose with the n°30 copper bullet, along with in-bore bullet deformations.

In order to solve those problems, bullet design was changed to include a long steel core and a semi-jacket (called “bimétal” bullets and developed by the E.N.T.) to avoid in-bore deformations and a deep groove to reduce copper fouling.

Due to the very long ogive of the “balle n°30” (3.5 calibres), it was found that even with a long groove there was still too much contact between the bore and the bullet, so the E.N.T. reverted to the “balle n°29” with a more practical 3 calibre ogive height and added a deep groove, the bullet being supported in the bore by the base of the ogive and the boat-tail.

This bullet was called “balle n°29,5” and the weight was reduced to 6.4 g (Figure 10).

![Figure 10: Drawing of the 6 mm E.N.T n°29,5 bullet](image)
The measured $y^*_8$ (ordinate at 400 m for a 800 m zero) of this cartridge was 1.76 m (versus 2.97 m for the Mle 1886D cartridge), making it a very flat shooting combination but still not able to hold a “800 m point blank” range against a 1.60 m tall target.

The difficulty to extract definitive ballistic information from firing tables is easily demonstrated by the fact that the polynomial expression for the ToF of the “balle 29,5” (when launched at a measured $V_{25}$ of [901 - 909] m/s by 3 g of $\text{BN}_3\text{F}$ powder loaded into the Puteaux n°3 case) is given in two different reports (xiii and xiv) as:

$$T = 0.103558 \cdot P + 0.006512 \cdot P^2 + 0.000140 \cdot P^3$$

Hence, the remaining velocity (as a function of the range) is expressed as:

$$V = \frac{1}{0.103558 + 0.013024 \cdot P + 0.00042 \cdot P^2}$$

Which gives a $V_{25}$ of 936 m/s (MV is 966 m/s), which is not coherent with the reported $V_{25}$ (900 m/s).

Unfortunately, the manufacture of this bullet by large-scale industrial methods was very difficult and the powders available at this time produced too much pressure and muzzle velocity dispersions (this problem will plague all and every French efforts to develop a flat-shooting, high velocity cartridge). German made Rottweil powders were discreetly brought from Portugal, analysed and loaded into French high velocity cartridges with good results, but French chemists did not manage to copy those powders until after WWI.

So the 6 mm calibre was abandoned in favour of 6.5 mm and 7 mm calibre cartridges for the 1910 rifle program, built around a 800 m “point-blank” range requirement against a 1.60 m standing man. This way, the French army followed other army trend towards “magnumized” and hyper velocity military rifle ammunition.

**A second dead-end, the semi-automatic rifle program of January 1910**

In France, the trend toward more firepower, delivered at the longest possible range, should have reached its apex just before WWI with the 1910 rifle program xv.

The goal of this program was to improve on the excellent ballistic properties demonstrated by the rimmed 6 x 62 mm APX and replace the tubular magazine Mle 1886 bolt-action “repeater” (mostly used as a single shot rifle, the awkward-to-refill tubular magazine was used only in emergency) with a box-
magazine semi-auto rifle firing a new, flat-shooting cartridge. The minimum rifle barrel bore was set at 6.5 mm.

Preliminary calculations and experiments, using a bullet shape similar to the German “S” flat-base bullet, shown that a $V_{25}$ velocity higher than 1015 m/s was required.

Several bullets were developed for those 6.5 mm and 7 mm cartridges, using cold-pressed brass (“solid”), or cold-pressed brass with a soft steel core and exposed tip, or cold-pressed with fully enclosed steel core (final development, used for the 8 mm Lebel “P” bullet and for the 7 mm Type 307 bullet).

Most of those bullets are shown in Figure 11. The two bullets on the left (n°111, 32.4 mm long and n°110, 37.3 mm long) have exposed steel tips while the third (n°123, 36 mm long) have a fully enclosed steel core. Steel core bullets with steel jackets and homogeneous steel bullets were also tested (Figure 11, bullet n°4, 5 & 6 from the left), with less success.

![Figure 11: Some French experimental bullets used during the 1909 program; Left from right: short 6.5 mm bimétal (bullet n°111, length 32.4 mm, weight ~6.5 g); long 6.5 mm bimétal (bullet n°110, length 37 mm, weight ~7.7 g); 6.5 mm steel core (bullet n°123, length 36 mm, weight ~7.5 g); two 7 x 59 mm NAS steel bullets (weight ~7.6 g) and two 7 mm Meunier bullets (courtesy of Y. Etievant).](image)

All 6.5 mm weapons used a 150 mm barrel twist, even if such short twist was only required for the longest (36 mm and 37 mm) bullets.

The first 6.5 mm bullet seriously investigated\(^1\) seems to be the 37 mm long “E.N.T. n°110” bimetal bullet (Figure 12) experimented between 1904 and 1906 \(^{ixv}\).

---

\(^{i}\) The first 6.5 mm bullet tested by the E.N.T. was the 8 g copper bullet n°31, with firings as early as June 1899.
Figure 12: Drawing of the 6.5 mm E.N.T n°110 bullet.

This bullet obviously benefited from the experience gained with the 6 mm E.N.T. n°29,5 bullet, with a 3 calibres ogive height and a long groove. Like other bimetal bullet it was made with a 4.5 mm to 5 mm steel core, with pure copper “jacket”, the 4.5 mm version giving the best results (the copper thickness on the 5 mm diameter core version was not enough to avoid jacket-core separation). At least four “pre-production” batches (between 1000 and 8000 bullets per batch) were made with bullet nominal weight between 7.5 g and 7.9 g, depending on the steel core diameter. The case was still the rimmed “Puteaux n°3” but necked up for 6.5 mm and with a capacity increased to 4.42 cm³ and a weight (with primer) reduced from 12.5 g to 11.8 g.

With the same powder load used as previously for the 6 mm (3 g of BN₃F powder), a $V_{25}$ velocity of 862 m/s was achieved.

According to the time of flight measured to 50 m, 800 m and 1600 m, the MV of this development cartridge was 877 m/s and the bullet G7 BC was .257 in the supersonic domain (0.94 i7 FF), and 0.241 in the transonic domain (1.0 i7 FF).

The manufacture of this 6.5 mm bullet was found to be easier than the 6 mm one, and much more tolerant to difference in bore size. With a land-to-land bore diameter of [6.50 – 6.51] mm and a groove-to-groove bore diameter of [6.75 – 6.76] mm, the bullet needed a nominal diameter of 6.73 mm (plus 0.02 mm, minus 0.03 mm) to achieve optimum results.

This bullet was later compared with a lighter (6.8 g) and shorter (32.4 mm long) 6.5 mm bullet, the E.N.T. n°111 (Figure 13) fired at higher muzzle velocity and with the 6 mm n°29,5 when fired from a self-loading rifle.
The ricochet behaviour and terminal ballistics properties of the E.N.T. n°111 bullet were found unsatisfactory and the Commission reverted around 1910 to a longer bullet, the E.N.T. n°123 (Figure 14, weight 7.5 g, length 36 mm), which solved problems found with the n°110 and n°111.

The small radius (0.165 mm) and angles at the base of the ogive and boat-tail greatly improved the bullet accuracy (compared to bullet n°110).

This bullet was used with both the “small capacity” E.N.T 1911 case (6.5 x 60 mm, 4.7 cm³ or 72.5 gr H₂O, 12.5 mm body diameter) and the “large capacity” C.A.P. case (6.5 x 61 mm, 5.1 cm³ or 78.7 gr H₂O, 13 mm body diameter). It was the “first” one to have an enclosed steel tip and finally achieved the
required performances (flat trajectory up to 800 m and lethality up to 2400 m) when launched at a $V_{25}$ of 960 m/s (with a 3.5 g load of S.L.50 powder in both E.N.T. and C.A.P. cases), but with so much chamber pressure and muzzle velocity dispersion that the powder was considered unsuitable for the 6.5 mm and 7 mm calibre.

Due to conflicting data found in technical reports, ballistic properties of the n°123 bullet are difficult to evaluate (a G7 BC of 0.247 seems a safe bet) so this author decided to manufacture a slightly shorter version of this bullet (only 34 mm long) with basically the same nose and boat-tail (only the shank was reduced and a driving band added, like the one found on the n°307 bullet) that should be more compatible with the 203 mm twist commonly found on current 6.5 mm weapons.

When fired from a 6.5 mm TCU case at moderate (800 m/s) velocity, measured G7 BC above Mach1.35 was 0.231 (Figure 15), but both the Miller formula and the JBM ballistics predicted a marginal stability (1.3 according to JBM ballistics).

Due to the lack of steel core, the weight of this “modern incarnation” was very close (7.45 g) to the original n°123, but stability was not (the 36 mm long bullet with a steel core was more stable when fired from a 150 mm twist than the 34 mm long homogeneous re-creation when fired from a 203 mm twist).

This bullet was then loaded in the 264 Winchester Magnum case and pushed at higher MV to increase bullet stability (reaching 1.4 according to JBM), achieving a G7 BC of 0.245 (mean) (Figure 16) above Mach 1.2 ($i_7$ of 0.964) but with a lot of dispersion, the plain brass bullet didn’t liked being driven at Mach3+.  

![Figure 15: Drag curves of the short 6.5 mm bullet when launched at moderate velocity.](image)
With a better stability and the lack of the central driving band, a G7 BC of ~0.25 in the supersonic domain should be easily achieved.

It should be noticed that during the 1912 trial of the 6.5 mm S.T.A n°7 rifle, the cartridges used were loaded with the NAS 725 FMJ bullet (6.45 g), and not the “bimetal” bullets (12 592 of such cartridges were delivered for the test, but not fired). During this trial, one ammunition lot using the NAS 725 bullet was found defective but even without taking into account the related results, the overall evaluation was not very successful and the self-loading S.T.A n°7 rifle did not demonstrate any tactical advantage compared with a well-served Mle 1886 M93 bolt action rifle. The rifle was difficult to reload due to poor ergonomics, and this point combined with too many stoppages and poor accuracy did not allow the shooter to deliver more firepower than the old bolt action rifle.

Parallel work was performed on the 7 mm calibre (7.3 mm from grooves to grooves). The “first” 7 mm bullet tested (during the year 1908) was the ECP bullet (spitzer boat-tail bullet made with pure copper, 8.53 g in weight and 33.5 mm long, only 4.6 calibres) with a G7 BC (based on measured ToF to 600 m, 800 m, 1000 m and 1600 m) around .208 (i7 FF 1.10), and launched at a MV of 869 m/s from the 750 mm barrel of the “NL” rifle.

The measured $y_8$ ordinate of this load was 2.43 m, better than the 8 mm Mle 1886D load (around 3 m) but very far from the objective of 1.60 m, and with limited possibilities to increase the muzzle velocity due to the pure (electrolytic) copper bullet.

In 1909, a longer bullet (37 mm long) was designed for the 7 mm A6 rifle A6F (also known as S.T.A n°8), and after several refinements evolved into the 9.0 g type 307 “bimetal” bullet.
Evaluation of the 7 mm NL and Meunier rifles made during the year 1912 used the even more conventional NAS 727 bullet, a 8.0 g FMJ spitzer, with the same lack of success as the 6.5 mm NAS 725. The lead-core NAS 727 bullet will later evolved into the 7.6 g steel-core, steel jacket NAS bullet shown on Figure 11.

So, after intensive work by the E.N.T. on various “Ultra Low Drag”, 6 mm and 6.5 mm bullets, resulting in the firing of several thousand projectiles (barrel endurance test needed 3000 to 4000 shots per barrel), most weapons evaluations were finally performed with conventional spitzer bullets designed along the lines of the German “S” bullet, an intriguing situation that still lacks explanation.

A large comprehensive work was done on both 6.5 mm and 7 mm cartridges with different case capacities and geometries, and efforts were finally focused (but not before December 1913) on large capacity cases, the 6.5 mm version loaded with 4.1 g of “mel.107 ter” powder and the 7 mm version loaded with 3.6 g of “mel. 105").

If most of those efforts lead to nowhere due to the outburst of WWI, the semi-auto Meunier A6 rifle selected for service in 1913 was actually produced and used in limited numbers during WWI, but firing the more practical 7 mm Meunier cartridge (7 x 56.95 mm, loaded with 3.2 g of powder and the type 307 bullet, Figure 17) instead of the “high intensity” 7 x 59 mm (powder load of 3.6 g).

Figure 17: the final version of the “balle 307” used in the 7 x 56.95 mm cartridge for the Meunier A6 (drawing on the left courtesy of J. Huon).

Like most bullets developed in France before WWI, this “type 307” bullet (37 mm long, 60 % ogive height and 23 % boat-tail) did not use a lead core with a gliding metal jacket structure, but instead was cold-pressed like the Mle 1898D but with an enclosed steel core pioneered by the 6.5 mm E.N.T. n°123 bullet, and also later found in the Lebel 8 mm 9.6 g AP bullet. Given the i7 of 0.946 measured for the scaled-down 6.5 mm presented previously, a G7 BC of 0.26 could be expected for this bullet.
The 1910 program was not successful because even though the required ammunition performance was actually achieved (but not before the end of 1913 - beginning of 1914, and the availability of improved BN3F powders \textsuperscript{xvi}), the required practical rate of fire (20 rpm) never was, due to weapon overheating.

Instead, an updated version of the “balle D” (called n°405) with a steel core, a weight of 11 g and a $V_{25}$ of 840 m/s when loaded with 3.30 g of “19-RA-36 quater” powder should have been issued at the end of 1914, but WWI broke out before formal adoption.

**Post WWI**

WWI saw (indirect) artillery fire replacing (direct) long-range small arms fire in its battlefield effectiveness and this trend continued well after the end of the war.

During WWII, small-arms fire (including individual weapons and machine guns) produced no better than 2/3 of enemy casualties (when fire support was lacking) and sometimes even less than 1/3.

With effective long range fire achieved by HE effects (artillery, tanks and planes), there was a huge pressure to reduce the practical range of weapons (or at least, no need to try to increase it) in order to increase still further the practical RoF.

**A third dead-end, the end of the first “lead-free” bullet**

Another experience from WWI not forgotten by the French army was that using main components as specific as the cold-pressed brass bullet Mle 1898D was not a good idea. Even if during the war, the daily production figure of the Mle 1886D cartridge ran between 2.65 million rounds (during November 1914) and 7.7 million (during August 1917, production peak), and that total war production of the Mle 1886D in France was 6,812,894,087 rounds \textsuperscript{xvii}, the various experiments to manufacture this ammunition outside France (in the US for example) were not very successful.

Combined with large and unpredictable effects on barrel life (the APX HMG had a reported barrel life of 6000 rounds with the original Mle 1886M bullet, but only 2000 rounds with the Mle 1898D bullet, while the Hotchkiss HMG, using the same steel and rifling, but a different gas port location, had a reported barrel life of 15 000 rounds \textsuperscript{xviii}), it was decided that the “new round” would need to use a conventional lead-core FMJ bullet.

There was also the question of the ammunition compatibility. During WWI, the various French bolt action rifle (Mle 1886, Mle 07-15-16), semi-automatic rifle (CSR 1917), fully-automatic rifle (CSRG 1915) and MG (Hotchkiss 1914, APX and St-Etienne 1907) all fired the same 8 mm ammunition, but reducing the effective range of the IW to 600 m could require the use of different cartridges for the IW and for the MG.
Development of a new cartridge in 7.5 mm started just after WWI (called “X1”), using the body diameter of the Swiss GP11 round and the case length of the 7.9 mm German round.

The flat shooting capability of the German “7.9 mm S Patrone” (between 0 and 800 m) was highly regarded by the French army, and the “availability” of German powders after WWI was the opportunity to duplicate the ballistic of this round.

Two loadings were tested, the first one using the “X1” case and the “X1” bullet (11.8 g) with a MV of 802 m/s (in a 800 mm barrel), and the second one using the lighter “X1c” bullet with a MV of 903 m/s (in a 600 mm barrel).

In all other words, a “super GP11” (the Swiss bullet was also loaded into the X1 case for comparison purpose) versus a “super S patronne”.

The X1 case loaded with a nominal load of 3.30 g of B.F.P1 powder and the X1c bullet became the 7.5 mm Mle 1924 cartridge, while the “X1” bullet saw some additional development before being adopted as the long-range Mle 1933D bullet.

Unfortunately, the B.F.P1 powder used in the 7.5 mm Mle 1924C round was a temperamental powder, difficult to ignite and giving dangerous pressure level when dry and hot.

A special primer (primer “1924 CF à 4 cgr”) was developed to solve the hang fire and out-of-battery fire problems that plagued the first ammunition produced.

Those ammunitions were made without case mouth sealing and did not age very well when stored in countries located in Northen Africa.

With a muzzle velocity that could reach 950 m/s (with according pressure) in recorded instance\textsuperscript{six}, catastrophic failures of the FM Mle 24 were not uncommon.

Authors noticed that the 7.5 mm Mle 1924 was indiscernible from the German 8 x 57 mm and speculated that using the wrong round in the wrong gun could lead to accidents. During the year 1928 alone, 115 catastrophic failures were recorded (leading to the destruction of 84 weapons), but only 13 occurrences were related to the incorrect chambering of a 7.9 mm round, the Mle 1924 cartridge being able to ruin any automatic weapon without exterior help.

After a gradual reduction of the powder load (and muzzle velocity) and an intensive work to define an alternate chamber that will avoid the chambering of the German 7.9 mm round (the “Chamber F”), the much troubled Mle 1924 cartridge was superseded by the shorter and more sedate Mle 1929 cartridge (7.5 x 54 mm).

This round fired the same 9.05 g Mle 1924C lead core FMJ bullet (Figure 18 left, 1-in-270 mm twist) loaded with 3.1 g of powder for the individual weapon and automatic rifle (\(V_{25}\) of >800 m/s), and a heavier 12.35 g bullet (Mle 1933D, Figure 18 middle, 1-in-235 mm twist) with a \(V_{25}\) of 694 m/s (closely following the external ballistics of the much revered Mle 1898D bullet) for the MG devoted to the “artillery” role.
Figure 18: French military lead-core bullets developed after WWI (from left to right, 7.5 mm Mle 1924C, 7.5 mm Mle 1933D, 8 mm Mle 1932N).

From an external ballistics point of view, the performance of those 7.5 mm bullets was pretty good (Figure 19).
Figure 19: Drag curves of the Mle 1924 C bullet (blue), Mle 1933 D bullet (green), G6 model (black) and G7 model (red).

If the light Mle 1924C does not follow the G7 curve well in the subsonic domain (due to its lack of boat-tail), the mean i7 value in the supersonic domain is around 1.14 for a G7 BC of 0.185. The G6 fit is better in both the supersonic and subsonic domain and produces an i6 of 0.98 and a G6 BC of 0.217. Due to the flat-base, a small dynamic instability (precession) could be seen at Mach numbers below M0.8 but without much consequence.

Combined with a MV around 850 m/s\(^2\), this cartridge delivered a performance similar to the .30-06” M2 or the 7.62 mm NATO M80.

The lower MVs which are often quoted for this cartridge (2600 fps or 793 m/s could be found in the 8th edition of “Cartridge of the World” and the cartridge is put in the same class as the 30-40 Krag for example) could be explained by the French military love for secrets - published velocities were measured at 25 m during cartridge development and not corrected for truly “muzzle” velocity - and finally that during the ‘20s and ‘30s the powders available to French ammunition manufacturers were greatly improved, leading to an “unpublicized” increased muzzle velocity. The same phenomenon could be found for 8 mm Lebel ammunition loaded during the ‘30s and ‘40s, with MV pushed around 735 m/s for both Mle 1886D and Mle 1886N cartridges (instead of 701 m/s and 715 m/s).

---

2 i)- up to 870 m/s have been measured in FRF1 bolt action rifle for Mle 1929 C ammunition lots produced during the ’70s, ii)- 840 m/s could be found in official firing reports for cartridges manufactured in 1963, iii)- a MV of 823 m/s is reported when loaded with the 9.55 g Mle 61 bullet designed for the 7.62 mm NATO, and iv)- finally 797 m/s was measured when loaded with the heavy 11.8 g “Is” type precision bullet, slightly better than the M118 LR load for the 7.62 x 51 mm.
Anyway, the 7.5 mm Mle 1929C load delivered a flatter trajectory up to 800 m than the previous 8 mm Mle 1886D, with less recoil and a case geometry more compatible with automatic loading, so the main requirements for a new small-arms ammo were fulfilled.

The heavy Mle 1933D shows a very good sub-0.94 i7 form factor in the supersonic domain for a G7 BC close to 0.31, similar to most current 250 gr / .338" bullets. Combined with “perfect” transonic and subsonic behaviour, this bullet was designed for very long range MG fire (up to ~4.5 km) and when loaded in a modern .30-06 Al or .300 Winchester Short Magnum case (and a 1-in-8” or 1-in-9” twist), could duplicate the external ballistics of the .338 Lapua Magnum with a 250 gr bullet in a much more compact platform, using 50% less powder. Unfortunately, this bullet is now a collector’s item.

It should be noted that if the French 7.5 mm cartridge design heavily borrowed from the Swiss 7.5 x 55 mm, the decision to use 2 different loads and bullet weight (9 g flat-base bullet for “infantry” weapons and 12.35 g boat-tail bullet for “artillery” weapons) is different from the Swiss choice to use only one load (with the excellent 11.3 g GP11 boat-tail bullet).

The German army followed a different path. They first developed the light (10 g) flat-base “S” bullet in 1905, then the heavy (12.8 g) boat-tail “s.S” bullet for long-range MG use during WWI and finally used the “s.S” as a “general purpose round”.

At the same time, the 8 mm 12.8 g Mle 1898D was superseded by the 15 g Mle 1932N (Figure 18 right) lead core bullet fired at 715 m/s muzzle velocity, providing even longer range and accuracy xx.

![Drag curve of the 8 mm Mle 1932N bullet and fitting of the G7 curve with a i7 FF of 0.97.](image)

If the shape of the Mle 1932N bullet generates a little more drag than the shape of the Mle 1898D in the supersonic domain (see Figure 20), the increase of the weight (15 g vs. 12.8 g for a G7 of 0.32 instead
of 0.30 in the supersonic domain) and the lower drag in the subsonic domain (0.28 G7 for the Mle 1932N versus 0.16 G7 for the Mle 1898D below Mach 0.7) allowed for another increase of the effective range of MG fire.

Finally, the manufacture of the heavy Mle 1933D bullet was stopped shortly after WWII and only the light Mle 1924C remained during the ‘50s and ‘60s, an indication that using a “two cartridge system” (even fully compatible), one tailored around IW requirements, and one tailored around MG requirements, while delivering exactly the required performances for both IW and MG, is not an optimal solution when balanced with industrial & “battlefield” logistics considerations.

**A fourth dead-end, the Ribeyrolles blow-back carbine**

The unsuccessful Ribeyrolles carbine of 1917-1918 (firing the 8 mm Ribeyrolles, a.k.a 8 x 35 mm SR) was an attempt to develop a rapid-firing weapon using a simple blowback system. The parent cartridge was the .351 WSL (which saw service in the French army during WWI) necked-down to 8 mm and loaded with the AP bullet developed for the Mle 1886P cartridge (weight 9.6 g, length 32.5 mm, powder weight 0.90 g). Due to the long ogive of this bullet (24.5 mm, the same as the Mle 1898D), the cartridge length was 59 mm.

![Figure 21: Drawing of the bullet for the 8 mm Mle 1886P cartridge.](image)

According to the French literature of this time, the “next generation” of small-arms ammunition intended for the individual weapon (IW) would need to be as light as possible and duplicate the external ballistics of the Mle 1898D up to 600 m (a large change from previous WWI papers on the same topic that asked for a 800 m “point blank” range, when just after WWI duplicating the external ballistics of old Mle 1886M ammunition up to 500 m was still considered adequate). The requirement for a simple blowback operation was thought to limit the maximum chamber pressure to around 1500 kg/cm² and the muzzle velocity to 500 m/s for an 8 g to 10 g bullet. The parent .351 WSL cartridge delivered an MV of 570 m/s (out of a 508 mm barrel) with an 11.7 g bullet.
Using the Powley computer and a case capacity of 23.1 grains / 1.5 g (16.1 grains / 1.04 g net) to emulate the 0.90 g powder load used at this time, indicates that a pressure of 35,500 CUP (39,000 psi, 2740 kg/cm²) was required to obtain an MV of 500 m/s with a 9.6 g bullet and a 450 mm barrel, far from the envisioned 1500 kg/cm² but in fact identical to the operating pressure of the 351 WSL.

The 300 m impact energy of the 8 mm Ribeyrolles should have been close to 550 J (using a G7 BC of 0.195), around \( \frac{1}{3} \) of the Mle 1886P rifle ammunition that used the same bullet (and less than \( \frac{3}{4} \) of the current 5.56 mm SS-109), and the effective range against a 1.6 m standing man would have been no more than 440 m to 450 m even without taking into account the probable large accuracy loss due to the transition from supersonic to subsonic velocity at a range less than 300 m.

The carbine itself (5.1 kg without magazine) was much heavier than the 4 kg that was considered the desirable weight of an individual weapon.

Even if this round was not successful, the concept of a "large" and light-for-diameter bullet pushed into a small case was not without merits as shown by the current (and very similar) .300 AAC Blackout (7.62 x 35 mm), based on the shortened .223 Remington case family (incidentally, sharing the same body diameter as the .351 WSL and with a similar case capacity, ~25 gr / 1.6 g, to the 8 mm Ribeyrolles) necked up to .30" calibre and using bullet weights of between 7.45 g and 8.1 g. The higher pressure of the .300 AAC (used in gas operated weapons) allowing a higher muzzle velocity (~675 m/s to 700 m/s in a ~400 mm barrel) and a slightly longer practical range, mostly due to a supersonic range of ~450 m vs. ~280 m for the 8 mm.

A nearly opposite approach to achieve the same goal of a small and compact round is the 6.5 x 43 mm "Super Z" cartridge, currently supported by Osprey Combat LLC, but using heavy for calibre bullets.

This cartridge, evolved from Mitch Shoffner’s 6.5 x 40 mm, is basically a necked down 6.8 mm SPC case designed to fire the heaviest (130 gr and 140 gr) 6.5 mm VLD bullets at moderate velocity. It seems that if the original 40 mm case was compatible with the AR-15 mag length, the new 43 mm case can be used only in dedicated rifles (the Osprey Invictus).

From a 14.5” M4 carbine length barrel, the claimed velocity of the 130 gr Berger “Hybrid AR” (G7 BC ~0.29) is 735 m/s, and still 721 m/s for the 140 gr Berger Hybrid (G7 BC ~0.32).

While a low velocity round by today standard, the external ballistics of this cartridge is similar to the 8 mm Mle 1886D and 7.5 mm Mle 1929D (G7 BC between 0.30 and 0.31, muzzle velocity around 700 m/s) and the increased vertical drop compared to “higher velocity” cartridge is balanced by the lower wind deflection which is much less predictable than gravity drop (Figure 22).
Figure 22: Example of hit probability (IPSC target at 300 m, only the right half shown for clarity) in “low confidence environment” for the WWI 8 mm Ribeyrolles (MV 500 m/s), the 300 AAC BLK (MV 680 m/s), 6.5 mm SZ (MV 721 m/s, 14.5" barrel), 7.62 mm NATO (MV 780 m/s, 14.5" barrel) and 5.56 mm NATO (MV 853 m/s, 14.5" barrel).

If the sedate muzzle velocity of the 8 mm Ribeyrolles was clearly a handicap at all ranges and a small limitation for the 300 AAC BLK, that's not the case with the 6.5 mm SZ which is on par with both 5.56 mm and 7.62 mm NATO when fired from the same barrel length.

The muzzle energy is around 2300 J from a 14.5" barrel and this round could be a huge step forward compared with the 5.56 mm, at the cost of a significant weight increase (18-19 g cartridge weight).

Post WWII

A fifth dead-end (?), the demise of the “battle rifle” and the rise of the “assault rifle”

As a member of the NATO alliance, France was supposed to replace its native 7.5 x 54 mm with the 7.62 mm NATO, but this transition was slow, mostly because of the very similar performances of both rounds.

Two 7.62 mm bullets were initially developed, the 9.5 g steel core Mle 1960 (length of 32.5 mm, similar to US M59) and the 9.55 g lead core Mle 1961 (length of 29.5 mm, with a 9.5 calibres, moderately secant ogive, and 7° boat-tail), along with a conventional brass case (weight of ~10.6 g) and a steel case (weight of ~9.8 g).

Just like the US M59, the Mle 1960 bullet did not last long and only the lead-core Mle 1961 saw extensive service, and was also loaded during the ’70s and ’80s in the 7.5 mm Mle 1929C cartridge as a replacement for the Mle 1924C bullet.

The drag characteristic of this bullet, while not as good as the Mle 1932N or Mle 1933D, was adequate for its intended purpose (G7 BC of 0.213 in the supersonic domain).
In the US, the experience of infantry engagements during WWII and the Korean war (both high intensity wars) was reviewed and the famous “Hitchman” report concluded that since most (~90%) infantry engagements occurred at a maximum range of 300 yards (274 m) and hit effectiveness with US M1 Garand rifle was “satisfactory” only up to 100 yards (91 m), a way to increase the individual weapon overall effectiveness (up to 300 yards) was to reduce the bullet and cartridge weight and use a “pattern dispersion” principle (controlled burst fired in full-auto mode) to compensate for human aiming errors.

“3. To improve hit effectiveness at the ranges not covered satisfactorily in this sense by men using the M-1 (100 to 300 yd), the adoption of a pattern-dispersion principle in the hand weapon could partly compensate for human aiming errors and thereby significantly increase the hits at ranges up to 300 yd.” (conclusion of the ORO-T-160 report).

It should be stressed that for the authors of the ORO-T-160 report, semi-auto fire was to be used only at short range (less than 100 yards), and “pattern-dispersion” full-auto fire reserved for ranges longer than 100 yards, the opposite of the current thinking of the effectiveness of full-auto fire and an indication that there could be some difference between the concept of “pattern dispersion” and the real realisation as found in current assault-rifles.

The addition of a toxic agent to the bullet (to increase the lethality) was also proposed.

The parallel work on a small-calibre, high velocity (SCHV) cartridge, using a 5.56 mm bullet launched at a very high velocity (1030 - 1200 m/s) indicated that a large reduction in ammunition weight and recoil could be achieved without decreasing hit probability or incapacitation capability against dismounted soldiers.
All those work lead to the development of the .223 Remington (M193) round and its adoption by the US Army in September 1963.

Studies with the .223 Remington round started this same year in France and finally led to the adoption of the “hesitation locked” FAMAS F1 in 1977 (without a 3-shot burst device, this device was adopted in 1979).

It was the first “assault rifle” adopted by France and replaced both the MAT 49 SMG (9 x 19 mm) and the FSA semi-auto rifle (7.62 x 51 mm).

Before the adoption of the FAMAS rifle, studies were performed during the 1974-1975 period xxvi using the very interesting IWK 5 g bullet (alongside other heavy bullets, with weights between 5 g and 5.5 g), trying to extend the practical range of the .223 Remington up to 600 m and requiring an impact energy of more than 647 J at this distance (M193 ~230 J; SS-109 ~340 J; IWK ~470 J).

To achieve the required impact energy, the IWK bullet needed an MV of ~950 m/s, a goal thought much easier to achieve than the >1400 m/s needed for the M193 bullet to deliver the same impact energy. Heavier bullets (5.5 g) sharing the same form factor would need only an MV of 900 m/s to be effective up to 600 m.

Those efforts were unsuccessful mostly due to the cartridge's limited overall length (57.4 mm) and the large bullet intrusion inside the case (due to unusually heavy bullets), even with lead-core bullets.

Using the .223 Remington case and the 5.0 g IWK bullet loaded to cartridge length greater than the maximum 57.4 mm allowed, a muzzle velocity of ~880 m/s was achieved and the Powley computer predicts a MV of ~900 m/s if the cartridge length is increased in such a way that the base of the bullet remained in the case neck (still slightly lower than the required 950 m/s). Unfortunately, following such a path would lead to a cartridge totally incompatible with existing weapons and the study was stopped.

Given the impossibility of extending the effective military range of the .223 Remington to 600 m, the decision was made to keep the M193-like ballistics for the FAMAS ammunition and upgrade the old bolt-action FRF1 precision rifle to the FRF2 standard which would provide effective fire at this distance (the demonstrated average first shot hit probability at 600 m is 0.89 on the French SC2 target representing a kneeling human target, 0.45 m wide by 0.95 m tall, and 0.63 for targets located at unknown distance between 300 m and 600 m).

Due to its very fast extraction cycle (~1200 rpm cyclic), aluminium alloy frame and heavy barrel, the FAMAS cook-off limit is higher than 250 rounds so even if the infantryman empties his unofficial daily load of 10 x 25-rounds magazines in a few minutes, no harmful situation will arise (except running out of ammunition in the middle of a firefight, but that’s potentially less harmful than bursting one’s own rifle just before running out of ammunition).
As other NATO countries already followed this trend (most notably the UK with the 4.85 x 49 mm and FRG with the 4.7 mm caseless), it was clear from the US side that the difficult consensus built around the adoption of the 7.62 x51 mm round was close to an end, so it was decided to perform an evaluation of those small-calibre rounds in order to adopt a second round for both Individual Weapon (IW) and Light Support Weapon (LSW).

The NATO Small Arms Test Control Commission (NSMATCC) was formed in 1976 and the evaluation of the second NATO round was performed between 1977 and 1979.

It should be noticed that if the goal was to provide a new round for both the IW and the LSW (the 7.62 mm NATO remaining the round used for the GPMG, vehicle mounted MG and sniper rifles), only two participating countries (Belgium and UK) provided IWs and LSWs for this evaluation. The other countries (USA, France, Netherland and the Federal Republic of Germany) only provided IWs and associated ammo.

Two rifles, the M16A1 (firing the 5.56 mm M193) and the G3 (firing the 7.62 mm DM41), were used as control weapons, with the following ballistic characteristics:

- 5.56 mm M193, ammo lot LC-4-27. 3.56 g bullet launched at a MV of 977 m/s and a C7 CB of 0.119 found from ballistic tables when fired from the 20" barrel of the M16A1. The MV deducted from the V_{10} measured at Meppen was 969 m/s ± 9.5 m/s (20 shots). It seemed that the initial requirement for a 55 gr bullet fired at 3300 fps (1006 m/s), later reduced to 3250 fps (991 m/s), was a thing of the past at the end of the seventies.

- 7.62 mm DM41, ammo lot MS-66-4. 9.33 g bullet launched at a MV of 809 m/s and C7 CB of 0.205 found from ballistic tables when fired from the 17.7" barrel of the G3. The MV deducted from the V_{10} measured at Meppen was 806 m/s ± 4.9 m/s (15 shots).

The IWs tested were the G11 (firing the 4.75 mm DE11), the XL64E5 (firing the 4.85 mm XL 1E1), the FN FNC (firing the 5.56 mm SS-109) and the M16A1 (firing the 5.56 mm XM777). During the trial, the MN1 (Netherland entry) fired the same US M193 as the M16A1 control weapon, and the FAMAS (French entry) fired the F1 ammo, a thick jacket version of the M193, designed to avoid fragmentation.

Firing tests were done in order to measure the external ballistics of those new rounds, and the V_{10} was also measured during the various plate perforation tests made at the Meppen firing range.
According to those sources, the ballistics characteristics were:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Lot number</th>
<th>Bullet weight</th>
<th>Tabulated MV</th>
<th>Measured MV &amp; SD</th>
<th>G7 CB</th>
<th>Weapon &amp; barrel length</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.75 x 21 mm DE11</td>
<td>DAG-77-14</td>
<td>3.4 g</td>
<td>920 m/s</td>
<td>911 ±9.6 m/s</td>
<td>0.161</td>
<td>G11; 21.3&quot;</td>
</tr>
<tr>
<td>4.85 x 49 mm XL1E1</td>
<td>103-N/76</td>
<td>3.63 g</td>
<td>902 m/s</td>
<td>893 ±5.7 m/s</td>
<td>0.185</td>
<td>IW; 20.4&quot;</td>
</tr>
<tr>
<td>4.85 x 49 mm XL1E1</td>
<td>103-N/76</td>
<td>3.63 g</td>
<td>926 m/s</td>
<td>927 ±6.7 m/s</td>
<td></td>
<td>LSW; 25.4&quot;</td>
</tr>
<tr>
<td>5.56 x 44.6 mm SS-109</td>
<td>FN/76</td>
<td>4.0 g</td>
<td>906 m/s</td>
<td>924 ±4.2 m/s</td>
<td>0.169</td>
<td>FNC; 17.7&quot;</td>
</tr>
<tr>
<td>5.56 x 44.6 mm P-112</td>
<td>-</td>
<td>4.0 g</td>
<td>-</td>
<td>909 ±3.0 m/s</td>
<td></td>
<td>FNC; 17.7&quot;</td>
</tr>
<tr>
<td>5.56 x 44.6 mm SS-109</td>
<td>FN/76</td>
<td>4.0 g</td>
<td>906 m/s</td>
<td>926 ±3.6 m/s</td>
<td></td>
<td>Minimi; 18.4&quot;</td>
</tr>
<tr>
<td>5.56 x 44.6 mm XL1E1</td>
<td>LC-81-3</td>
<td>3.54 g</td>
<td>977 m/s</td>
<td>990 ±10.2 m/s</td>
<td>0.124</td>
<td>M16A1; 20&quot;</td>
</tr>
<tr>
<td>5.56 x 44.6 mm Mle F1</td>
<td>2 ALM-77</td>
<td>3.52 g</td>
<td>965 m/s</td>
<td>970 ±3.8 m/s</td>
<td>0.127</td>
<td>FAMAS; 19.2&quot;</td>
</tr>
</tbody>
</table>

Against 7 mm RHA, the lead-core FMJ bullets (F1, M193, DE11 and XL1E1, in that order) provided the best results (due to the mechanism of adiabatic shear), while bullets with steel insert (XM777 and SS-109) had more difficulties (or even failed) to defeat the target, even at close range and with a higher impact velocity.

<table>
<thead>
<tr>
<th>7 mm RHA plate</th>
<th>F1 (FAMAS)</th>
<th>US M193 (M16A1)</th>
<th>DE11 (G11)</th>
<th>XL 1E1 (XL64E5)</th>
<th>XM777 (M16A1)</th>
<th>SS-109 (FNC)</th>
<th>DM41 (G3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V50</td>
<td>830 m/s</td>
<td>850 m/s</td>
<td>854 m/s</td>
<td>863 m/s</td>
<td>891 m/s</td>
<td>&gt;900 m/s</td>
<td>789 m/s</td>
</tr>
<tr>
<td>Range for 50% defeat probability</td>
<td>&gt;100 m</td>
<td>85 m</td>
<td>55 m</td>
<td>41 m</td>
<td>44 m</td>
<td>&lt;30 m</td>
<td>31 m</td>
</tr>
</tbody>
</table>

Against softer targets (5 mm steel or 15 mm aluminium), the SS-109 performed slightly better than the other rounds, and at longer range and against thin targets (3.5 mm NATO plate, helmets and body armour), the SS-109 clearly outperformed all the competition, the XM777 showing only a slight improvement over the M193 family (see below).

<table>
<thead>
<tr>
<th>10 gauge steel plate</th>
<th>SS-109 (FNC)</th>
<th>XL 1E1 (XL64E5)</th>
<th>DE11 (G11)</th>
<th>XM777 (M16A1)</th>
<th>FR M193 (FAMAS*)</th>
<th>US M193 (M16A1)</th>
<th>DM41 (G3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V50</td>
<td>470 m/s</td>
<td>586 m/s</td>
<td>566 m/s</td>
<td>534 m/s</td>
<td>606 m/s</td>
<td>611 m/s</td>
<td>488 m/s</td>
</tr>
<tr>
<td>Range for 50% defeat probability</td>
<td>525 m</td>
<td>401 m</td>
<td>386 m</td>
<td>359 m</td>
<td>300 m</td>
<td>291 m</td>
<td>495 m</td>
</tr>
</tbody>
</table>

As all other metrics (sandbags & brushes defeat, terminal ballistics…) lead to inconclusive results, this significant performance increase at long range was considered sufficient and the 5.56 mm SS-109 became the second NATO calibre in 1982.
This adoption was not without consequences for France because the 1-in-12” twist used in the FAMAS F1 rifle was not sufficient to properly stabilize the SS-109 bullet. But as the NSMATCC evaluation showed that technological breakthroughs were possible in a short timescale, the FAMAS was viewed as an “interim” system, waiting for the development of more advanced caseless ammo firing even smaller bullets. Any reader familiar with the “one time buy” and adoption of the M16 rifle by the US army and the SPIW / ACR / OICW programs knows how this story will end.

A sixth dead-end, the 1985-1995 caseless rifle program (MSD)
Since the case represents roughly 50% of the weight of a conventional cartridge, caseless rounds promised to double the ammunition capacity of the infantryman without increasing his burden.

Unfortunately, this promise has never been delivered and in the absence of active cooling, the cook-off limit of guns firing caseless ammunition was found to be much lower than similar guns firing cased rounds, so the sustained rate of fire was not increased.

Lower cook-off limits combined with increased ammunition capacity did not provide a tactical advantage, but more potential safety problems, as demonstrated by the German G11 rifle firing the 4.7 x 21 mm caseless rounds during the 1977-1979 NATO (NSMATCC) small-calibre review.

The evaluation of the G11 rifle was stopped just after performing the cook-off test, but results were still promising. At the end of the evaluation phase, the position of France was to “adopt the 5.56 mm in the standard M193 calibre only as an intermediate measure and will adopt the G-11” xxviii which was supposed to be available on a mass-production basis in 1987.

Internal discussions about the strength and weakness of the H&K G11 design, and the interest of launching a similar (but strictly “Franco-French”) program, should have started not long after this announcement because the experimental FAMAS MSD (“Munitions Sans Douilles”, caseless ammunition) rifle program started in January 1985, and it was decided to incorporate a kind of “active” cooling to the gun chamber, enabling a maximum objective chamber-wall temperature of only 130°C after firing 150 rounds in less than 1 minute.

Two demonstrators were planned, the first one (demonstrator n°1, rifled 7.62 mm calibre) was conceived around a dual requirement, to be able to successfully engage targets at 300 m (using saboted 5.56 mm “duplex” ammunition) and up to 600 m (using saboted 5.56 mm “simplex” ammunition, PUC 600).

The second one (demonstrator n°2, rifled 5.56 mm calibre) was designed around a 300 m practical range (PUC 300, using saboted 4 mm “simplex” ammunition).

Both ammunition concepts relied on subcalibre tungsten-alloy (DX2M) bullets fired at extreme muzzle velocity (around 1300 m/s) to achieve a good balance between short ToF (hence high hit probability), decent terminal ballistics (flechettes were abandoned because of random terminal effectiveness) and recoil reduction.
Preliminary phase ran between January 1985 and May 1987, while validation took place between May 1987 and January 1990. Development phase should have occurred during the ‘90s, followed by the production phase.

It soon appeared that the concept behind demonstrator n°1 was not satisfactory and the research phase was limited to the manufacture and firing of 2 heavy (5 g and 6.4 g) jacketed 5.56 mm bullets made with a DX2M tungsten alloy core, along the already existing 5.56 mm PPA\(^3\) bullet. All those bullets were loaded in polyamide or polycarbonate “push-type” sabots and fired from a 7.62 mm NATO case and barrel.

![Figure 24: Drawing of the 5.56 mm PPA bullet (left), 5.56 mm tungsten alloy bullets (5 g) loaded in “short” push-type polyamide and polycarbonate sabots (centre) and 5.56 mm bullet loaded in “long” sabot for the 7.62 mm NATO.](image)

Due to the high cost of tungsten alloy, only a handful of DX2M bullets were manufactured and shot, the program used mostly the 5.56 mm PPA bullet for proof of concept.

The 7.62 mm demonstrator was abandoned by the end of 1989 when it was found that the practical range of the ammunition was around 450 m instead of 600 m.

At the end of the validation phase, the selected concept for the 5.56 mm demonstrator n°2 combined electric ignition, variable rate of fire (from 0 to 400 rpm) and chamber advanced passive cooling (Figure 25).

\(^3\) PPA stands for “Projectile à Perforation Améliorée” or “Improved Perforation Bullet” and was a 3.6 g APHC bullet using a 1.0 g tungsten carbide penetrator. Initially developed at the beginning of the ‘80s to give the FAMAS the capability to engage lightly armoured vehicles (7 mm of RHA are easily defeated at a range of 200 m), it was found later that this task was best fulfilled with a 7.62 mm steel core AP than a 5.56 mm APHC.
The 5.56 mm caseless ammunition first used a solid NC bloc (slow combustion behaviour), replaced by nitramine impregnated PU foam (too fast), then (and with much more success) by BTu(0.24) powder agglomerated with NPV and DNPS.

At the end of the project (around 1992), blocs of YH Tu(0.25) powder (similar to the US XM39 composition but using 80% of RDX based propellant instead of 76%) were also tested (low mechanical properties compared to agglomerated BTu).

The powder load was protected by a thin layer of special conductive lacquer to allow for good electric conductivity and reliable cartridge ignition (according to some reports, early versions of the ammunition were gold plated).

The final 5.56 mm cartridge (Figure 26) used a 4 mm brass bullet (1.30 g), a 2-piece 5.56 mm polycarbonate sabot (0.50 g) and a 2.45 g (primed) agglomerated powder load.

Internal ballistics test were performed with a “full calibre” 5.56 mm bullet with an aluminium core instead of a lead core, and the bullet weight was 1.77 g, close to the 1.80 g of the 4 mm brass bullet and sabot.
With a 39.4 mm COAL, a diameter of 9.7 mm and a weight of 4.2 g, this cartridge was significantly smaller and lighter than the 223 Remington used in the FAMAS F1.

A MV around 1200 m/s from a 450 mm barrel was achieved with maximum chamber pressure less than 400 MPa.

![Figure 26: The PUC300 brass bullet and sabot (left) and 4 mm bullet drawing (right).](image)

A 2.61 g, DX2M (tungsten alloy) bullet was also planned for the definitive version, but it is not known if actual bullets were actually manufactured and fired. The bullet shape closely follows the G7 shape, with a slightly larger secant ogive radius (12.5 calibres versus 10 calibres for the G7 shape) due to the respectively bigger meplat diameter (1 mm meplat diameter for a 4 mm bullet diameter).

Compared with the M193, the “PUC300” round used a lighter bullet (1.30 g the vs. 3.56 g) with a lower SD (0.115 lbs/in²) launched at a higher velocity (~1200 m/s vs. ~970 m/s), but needed a relatively heavy load (2.4 g vs. 1.8 g) of high energy (935 cal/g) powder and finally demonstrated a very low propulsive efficiency (<15% vs. ~30% for conventional brass-case, full-calibre, ammunition).

Unfortunately, trying to solve at the same time the problems of caseless ammunition, electric ignition, sabotted bullets and advanced chamber cooling (even only in the form of an advanced heat sink) proved to be a real technical challenge and the study was stopped circa 1995 after the evaluation of the demonstrator n°2 (PUC300).
A seventh dead-end, the PAPOP program
In the 1950s, the answer to the low hit probability of the average soldier at ranges higher than 100 m was the “controlled dispersion” concept of full-auto fire, leading to the reduced-recoil 5.56 mm round.

The difficulty in implementing this concept (the recoil of the 5.56 mm round was still high enough to induce too much dispersion in a lightweight rifle), led to a shift from a burst of multiple kinetic energy projectiles to the use of a single high-explosive, fragmenting round, the fragmentation pattern taking care (at least on paper) of aiming errors.

The PAPOP project (Polyarme-Polyprojectile, similar to the US OICW) launched in June 1994 was intended to combine grenade launcher (for long range engagements) and a “kinetic energy” system for engaging targets at shorter range xxii.

As commonly found in all French small-arms programs, several demonstrators were planned.

Figure 27: Ergonomic demonstrator of the PAPOP concept 1, 30 mm grenade launcher and 7.62 mm rifle.

Demonstrator C1 (Figure 27) combined a “side-by-side” 20 shots 7.62 mm NATO rifle (using a beefed-up FAMAS mechanism) and a 5 shot 30 mm medium velocity HE grenade (157 g at 225 m/s) with a programmable fuse for air-bursting. The quoted effective range of this version was 600 m, with an objective dry weight of 7.22 kg and 8.49 kg fully loaded.
Demonstrator C2 (Figure 28) combined an “over-and-under” 30 shot 5.56 mm NATO rifle (using the FAMAS mechanism) and a 2-shot 25 mm medium velocity HE grenade (135 g at 150 m/s) with a programmable fuse for air-bursting. The quoted effective range of this version was 500 m but this system was significantly lighter than the “600 m demonstrator n°1”, with an objective dry weight of 5.78 kg and 6.56 kg fully loaded.
Demonstrator n°3 (Figure 29) was a 5 shot 35 mm medium velocity HE grenade (200 g at 225 m/s) with a dual-use programmable fuse (projecting fragments in a cone shape if initiated from the rear or radially if initiated in the centre). The quoted effective range of this version was 600 m and the objective loaded weight was 6.88 kg.

The project did not go very far, as the weight of the combined weapon was found to be too high and the grenade carrying capacity too low.

The effective casualty area of air-bursting grenades was also found to be very small (between 14 m² against unprotected standing target and only 4 m² against protected prone target in the most favourable case of the 35 mm grenade), and very sensitive to bursting height & grenade falling angle.

All in all, it was found that in order to be effective, the detonation of air-bursting grenades needed to be triggered with an accuracy of ~1 m in both range and direction, and 0.5 m in height, an unreasonable expectation for a hand-held weapon on the battlefield.

It should be pointed out that due to their low velocity, grenades are a very different beast than bullets and that without the help of a laser rangefinder, aiming errors with a grenade launcher are a full two orders of magnitude higher than for a rifle, nearly negating all of the benefit of the large casualty radius produced by the grenade fragmentation warhead at long range.

According to US results, the typical range estimation error for trained soldiers is around 30%, so for a target at a “true” distance of 288 m (for example), even a trained soldier will hesitate between the 250, 275, 300 and 325 m setting on his grenade-launcher sight (an average miss distance of 25 m before even taking into account the intrinsic weapon dispersion, compared with a typical grenade effective radius of 5 m to 10 m), and will need to “walk his fire” to the target at range longer than 150 m, a very difficult task with single-shot grenade launchers.

Even with a tripod-mounted laser rangefinder, operated by a trained spotter in a prone position, the average range error measurement is around 5% of the distance, and could be as high as 9.3% xxxix. At 600 m range, that’s an average error of 30 m, much more than the expected casualty radius of this class of warhead.

Typical defensive hand grenades that use a very simple (compact and lightweight) fuse weigh in between 400 g and 500 g, and have a reported casualty radius of around 10 m, so it is doubtful that a 20 mm to 40 mm spin-stabilized grenade with a weight between 100 g and 200 g could achieve a much better casualty radius.

If the same range measurement error could be achieved with a hand held (or shoulder held) device, combined with a 5 m to 10 m effective radius grenade, then a 300 m practical range could be claimed, but a 600 m practical range will require the measurement error to be halved.
Historical trend conclusion

The rise and fall of the effective range of the individual weapon can be seen as a direct effect of the “competition” between infantry fire and artillery fire in producing battlefield casualties, and a compromise between the effective range and the practical rate of fire.

If in the 60 years before 1914, less than 10% of the battlefield casualties were produced by artillery fire, during (at least) the 60 years after 1914 artillery fire replaced long-range small-arms fire as the main casualty factor.

The need to continuously increase the volume of fire led to the reduction in the practical range of small-arms to less than 400 m, and allowed the rifleman to carry and fire more cartridges with his individual weapon.

Before the Hitchman report, infantry fire was mostly considered as a form of “collective fire”, but after WWII infantry fire effectiveness was often considered only from the point of individual fire, aimed at individual targets, and “collective fire” was replaced by MG fire.

For example, the lowest hit probability reported in the Hitchman report, “marksmen firing simultaneously”, at a distance of 500 yards, is around 5%, and less than 10% at 400 yards.

![Figure 30: Marksmanship using the M1 rifle.](image)

This report paved the way to numerous studies that 1)- tried to evaluate the rifleman's effectiveness under what was considered “realistic” stress conditions and 2)- tried to provide a technical answer to the perceived lack of effectiveness at ranges longer than a hundred meters.
The founding idea of those studies (like ORO-T-160, but also SALVO I & II, SAWS and several others) was that “only bullets that hit count”, and that the only military effect of small-arms fire (and Individual Weapon fire in particular) was hitting and disabling a target. Suppression effects that are known to greatly reduce enemy fire effectiveness and enemy movements (two very interesting military effects) were simply not taken into account and no effort was made to try to evaluate them, or incorporate results of other studies devoted to such topics.

This idea of limiting the effectiveness of small-arms fire to hitting and disabling enemy soldiers immediately calls upon past visions of glorious battlefields where dense masses of soldiers were shooting at each other, or where a handful of brave souls stand against a “human wave” assault of mechanized infantry (“high density” battlefields), but seems totally remote from the “low density battlefields” so frequently encountered during “decolonization” wars or peacekeeping / stabilization engagements.

![Figure 31: Small arms fire in a “high-density” context (left) versus small arms fire in a “low density” context (right).](image)

From a methodology point of view, this choice (deliberate or not) to reduce military effectiveness of Individual Weapon fire to “bullets that hit” had major implications.

First, the complexity of evaluating small arms effectiveness was greatly reduced, “scientific” evaluations could be performed and focused on hit probability ($p_H$) and terminal effectiveness ($p_{TH}$) against unprotected targets, or after defeating personal protection (but not intermediate barriers).

Second, since the maximum effective range considered (300 m) is relatively short, almost any bullet pushed fast enough could do the assigned job (hitting and delivering “sufficient” terminal effectiveness).

For example, a 17 gr (1.1 g) / .14” diameter bullet launched at 1340 m/s will have a much shorter ToF to the 300 m line (or 600 m line) than a 147 gr / .308” launched at 850 m/s if both bullets share the same shape (form factor). The lighter bullet could be fired from a lighter rifle that will be quicker “on target”,

41/130
without inducing too much recoil, so the shooter will also benefit from a better hit probability, and the terminal effectiveness of both rounds will be “similar” from 0 to 300 m xxxi.

The total absence of suppression measurement and criteria was pinpointed in xxxii.

“Because of the importance of suppression effectiveness, thorough testing of near miss perception is badly needed. Little or nothing is known on this subject at present [1975] (see also the footnote, p. V-15).”

“The initial Infantry Board instrumentation included wide, low (8 inches high) strips of the target body hit-sensing material, hidden in front of each target to record near-miss impacts forward of the target. These strips were abandoned because they increased target maintenance and the Board showed no interest in measuring suppression effectiveness.”

But is this emphasis on hit probability so well established?

Of course, the capability to hit something is very valuable, but what is the hit probability of a soldier in a real combat, as opposed to simulated combat?

The “shots to casualty” ratio of small-arms fire is a highly debatable issue, and numbers as high as 100,000 have been quoted, but without a strong database to sustain that claim.

More reliable values could be found in the experience of the First Australian Task Force (1ATF) during the Vietnam war xxxiii, with (mean) values of 187 shots per casualty for the 7.62 mm SLR and 232 shots per casualty for the M16 in the context of day patrol.

Nearly 80% of those engagements took place at ranges shorter than 30 m, not really long range, and still the average hit probability was around 0.5%, compared to a hit probability of ~100% found in ORO-T-160 (see Figure 30).

Of course, “mean” values are only average and in particular events close to “ideal” shooting scenario, shots-to-casualty ratio around 30 to 1 were achieved. While this number (pH ~3%) is definitively higher than 0.4% or 0.5% (nearly one order of magnitude), it’s still a very substantial difference from results commonly found during simulated combat.

The French operation in Mogadiscio in June 1992 could be seen as a very good example of effective firing, but even in this scenario ~3500 small arms (5.56 mm and 7.62 mm) rounds and ~500 12.7 mm rounds were expanded to produce a maximum of ~50 casualties (pH of 1.25 %) xxxiv.

Police shootings that take place at very short range (generally less than 7 feet) exhibit the same symptoms of very low hit probability, one or two orders of magnitude less than expected.

For example, during the famous 1997 North Hollywood shootout, the two heavily armed bank robbers fired approximately 1100 rounds during a 44 minutes battle and wounded 11 police officers (pH ~1%) and 7 (probably untargeted) civilians.
In return, police officers fired an estimated 650 rounds and killed both perpetrators (it is possible that one committed suicide after being wounded). Both bank robbers wore homemade bulletproof garments and one was hit several times in rapid succession in his legs until he surrendered (he died later from blood loss), so it’s difficult to evaluate the hit probability of the law officers, but even at a few feet, with good visibility and superior training (the final part of the shootout was conducted by SWAT members at a distance around 3-4 meters), one should expect results probably not much higher than 5% to 10%, again a substantial difference between “real life” results and results recorded during simulated combat.

This difference could be easily explained because of course, during simulated combat, no matter the amount of “realism” of the shooting scenario (sounds, fumes, explosions, fatigue or even electric shocks on the shooters), the targets are not returning fire so soldiers could focus on “clearing the range” (and freely expose themselves during the process), while during real combat trying to minimize exposure time to avoid being hit is mandatory.

So, if we look back at Figure 30, we have an idea of the hit probability of a soldier firing his M1 rifle at a human-size target with an exposure time of 3 seconds.

In order to be able to hit this target, the soldier needs also to expose himself to incoming fire (from his target, or from other people waiting for a shot of opportunity, the battlefield is not a place for a duel) during roughly the same amount of time.

Now, if we try to describe this reality from a soldier’s point of view, what would be the probability of hitting an opponent without being hit, during this attempt against “peer” opponents (using the same kind of weapon and with the same level of proficiency)?

Mathematically, the answer is simple; it’s the probability of hitting ($p_{H1}$) multiplied by the probability of not being hit ($1 - p_{H2}$) (see Figure 32).

If $p_{H1}$ equals $p_{H2}$ (same kind of weapon and same level of proficiency) and if we use $p_{H}$ given by ORO-T-160 (blue curve below), then the reality we try to evaluate is given by the red curve.
Of course, that does not mean that the “system” (soldier and IW) will have an efficiency of “zero” at short range (but after all, “zero” is not that far from the average of ~0.5% found previously), but it means that the “system” (mostly soldier) will behave very differently on the battlefield than on the shooting range, trying to minimise body exposure (area and time) at the expense of steady shooting position or proper aim, and the closer he is to enemy fire, the more different his behaviour will be.

Evaluating the dispersion of hand-held weapons and trying to improve the hit probability was at the heart of both ORO-T-160 and ORO-T-397 (Salvo II study). Most results found in ORO-T-160 used a target exposure time of 3 seconds and shooters were discriminated between “experts” (highest skill) and “marksmen” (lowest skill).

During those tests, “experts” scored significantly higher than “marksmen” (this result was used as another “argument” against long-range firing in the hands of the masses).

For example, during the second test, “experts” scored 8 hits (25% hit probability) on a man-size target at 310 yards (Figure 33), when “marksmen” scored only 2 hits (6% hit probability, Figure 34).
During those tests, a large cloth was used to record as many shots as possible (hits and near-misses), and it’s interesting to notice that in both cases:

- the number of shots recorded was nearly the same (25 for “experts” and 26 for “marksmen”),
- the dispersion of shots was nearly the same (~7.25 mils for “experts” and ~7.5 mils for “marksmen”),
- the number of rounds impacting in a 1 m circle around the head of the target was the same (23 shots, or 72%, in both cases),
- the only significant difference is the mean point of all impacts, “on target” for “experts” and slightly off target by 35 cm for “marksmen”, this shift of MPOI alone explains the difference between a hit probability of 25% and 6%. A deviation of 35 cm (~14 inches) at 310 yards is what you can expect from a 15 mph lateral wind acting on the .30-06 M2 bullet, so this large difference in hit probability between “experts” and “marksmen” could simply be due to different weather conditions4.

- a third test was performed, using a 1 second target exposure time and a random schedule between two targets, one located at 110 yards, and one located at 265 yards (table A3 in ORO-T-160, p.100), and under those firing conditions the “marksmen” greatly outperformed the “experts”. Unfortunately, results obtained during this third test were not reviewed as deeply as results obtained during test n°1 and n°2, and no conclusion was drawn from it.

In order to increase the IW hit probability, the concept of “controlled dispersion” was introduced. The idea was to replace 5 individual shots with a 5 shot burst that would deliver a “diamond shape” pattern of 20 inches Extreme Spread at 300 yards (1.85 mils).

Achieving such a dispersion required either a large reduction of the ammunition impulse (leading to “micro calibres” and flechettes fired at very high rpm), or the firing of several missiles for each trigger pull (leading to 12 gauge rounds loaded with numerous flechettes, or to “duplex” and “triplex” ammunition; multi-barrel weapons were also tried but without much success).

Anyway, up to now such a “perfect” dispersion pattern has not been practically achieved. Even the H&K G11, firing a “reduced impulse” (4.7 x 21 mm and 4.93 x 34 mm) round from a free recoiling mechanism in a 3 shot burst, could not demonstrate this level of dispersion.

A witness target found in H&K commercial literature showing first, second and third impact location of ten, 3-shot bursts resulted in a second and third shot mean dispersion of 4.6 mils (compared to first shot location, first shot dispersion of 6.1 mils compared to PoA), and informal off hand full-auto firing by this author of a 5.45 mm AKS-74 produced a vertical dispersion around 6 mils, far above the 1.85 mils used in ORO-T-160.

During the SALVO II study (ORO-T-397), a similar test was performed. The dispersion of each individual soldier was measured (“Experts”, mean dispersion between 1.97 mils and 2.93 mils; “Sharpshooters”, mean dispersion between 2.12 mils and 3.67 mils; “Marksmen”, mean dispersion between 2.30 mils and 4.01 mils)

---

4 As a side note, a (probably) similar situation occurred at the beginning of the 80’s in France during a firing test devoted to evaluate a panel of sniper rifles. Post-treatment of those results using the “Applied Ballistics Analytics” software revealed that the difference in hit probabilities at 600 m between the “best” systems and the “worst” systems could simply be attributed to an increase of the wind velocity dispersion from ~10 km/h to ~30 km/h along the firing line. The change of the wind conditions was referenced in the original report, but potential effects were not evaluated.
3.70 mils) and from the conclusions of this report, it is clear that the level of marksmanship (for a given training program) plays only a small role in hand-held weapons dispersion compared to target exposure time and visibility (Figure 35).

![Figure 35: Hand-held weapons dispersion as a function of target exposure time, according to ORO-T-397.](image)

The 7.5 mils and 7.25 mils obtained for “marksmen” and “experts” respectively, for a target exposure time of 3 seconds found in ORO-T-160 (published in 1952) are close to the “upper bound” found in ORO-T-397 (published in 1961) and probably reflect the change of marksmanship training, from “bull’s-eyes” targets to “pop-up” targets (TRAINFIRE I was introduced in 1954, and TRAINFIRE II in 1957).

Mean dispersion found in ORO-T-397 was around 3 mils for a target exposure time higher than 5 seconds, and this dispersion was increasing as the exposure time was decreasing, up to 7 – 7.5 mils (24 MoA to 26 MoA).

For the same exposure time, the mean dispersion can change dramatically if the target is difficult to locate, or if the shooting range configuration leads to erroneous distance evaluation.

During the ORO-T-160 study, no relationship was found between angular dispersion and target range (i.e. the angular dispersion remain constant regardless of target range) but results from ORO-T-397 shows (at least) a weak relationship between angular dispersion and range, but it could be argued that for a given target size (E-type target), increasing its range increases also the time needed to visually detect it, effectively reducing the time allowed to engage the target.
So, there is a wide difference between the way we evaluate small-arms hit probability and “real-life” results which seem to range from 0.3% to 3%, even at fairly close distances.

From an individual fire perspective (one soldier, one target and one bullet), this value could be considered low, but from a tactical point of view, with tens to hundreds of soldiers, each carrying more than a hundred rounds, it’s high enough to produce decisive military results.

For example:

- during the battle of Magersfontain in December 1899, fire from the 8,500 Boers' individual weapons (Mauser bolt action rifles) at a range of around 400 yards (366 m) was sufficient to kill and wound 665 British soldiers (24.5% of the total) in the first 10 minutes of the battle,

- a few days later, during the battle of Colenso, 2 British batteries (12 guns) of field artillery were engaged by rifle fire at a distance of 700 m. Suffering heavy casualties, the British were forced to fall back to their camp, losing 10 guns in the process.

In France, the experience gained during numerous post-WWII “low intensity” conflicts indicates that, as envisioned during the 1920’s, the capability to “reach and touch” a target at a distance of up to 600 m was necessary at the lowest organisational level, hence the mix of 9 mm SMG (MAT 49), 7.5 mm semi-auto rifle (MAS 49/56), 7.5 mm bolt action precision rifle (FRF1), 7.5 mm automatic rifle (MAC 24/29) and sometimes an added 7.5 mm LMG (light version of the AA-52) in French platoons after WWII.

The adoption by the US, followed by NATO, of the .223 Remington cartridge as the 5.56 x 45 mm, was not the result of concluding that the battlefield depth (measured in kilometres before WWI) was now
reduced to 300 m, but an acknowledgement that effective HE support could be provided now at very short range in most conditions, and that the fire delivered by the infantry individual weapon should be used only for defeating adversaries in the 0 to 300 m bracket, longer ranges being devoted to collective weapons firing heavier ammunition.

The 1980 declaration of the Federal Republic of Germany \textsuperscript{xxviii}, made after the NSMATCC evaluation, summarize this position:

“FRG Position

a) Will not field the second NATO round in either the individual weapon or light support weapon role but will adopt the G-11 circa 1987.

The steel core SS109 type round as specified in NATO STANAG 4172 is too complicated and expensive for manufacture.

b) FRG internal position of the test impact and FRG future rifle/machine gun plans are as follows:

The NSMATCC evaluation weighted the 5.56 mm cartridge so heavily (because of its low weight and volume) that the 7.62mm cartridge was at disadvantage before the tests even started.

However, the results of the shooting test have proven without doubt the superiority of the cal. 7.62mm and thus reinforce the FRG position that two calibres will be required for the infantry rifleman as small as possible within effective terminal ballistics limits and light machine gun in 7.62mm calibre.

In consequence, the only logical result is to take advantage of the G-11 4.7mm caseless technology which reduces volume of the cartridge in comparison to 5.56mm by over one third and reduces weight by about one half. At the same time, the 4.7mm caseless ammunition, during side by side test with the SS109, shows equal test results as that recommended for the SS109. Thus, the final decision would be to complete development and produce the G-11 to have it ready for mass production in 1985, for eventual introduction into the FRG Armed Forces starting in 1987, continue with a light machinegun in calibre 7.62mm developing a caseless machinegun in that same calibre for MG / light machinegun utilization.”

The light recoiling 5.56 x 45 mm greatly increased the infantryman’s efficiency at short range (at the expense of longer range capability), but also opened the door to a potentially unsafe situation not really encountered before, in which the infantryman could carry (and fire) more ammunition than his rifle could safely shoot.
For example, the cook-off limit of the very light M16A1 was between 120 and 140 rounds (depending on the rate of fire) when the official load of the infantryman was 6 x 20-round magazines (120 rounds overall) and 10 x 20-round magazines (200 rounds) unofficially.

When the magazine capacity of the rifle was extended to 30 rounds (between 180 and 300 rounds overall), the cook-off limit remained at around 120-140 rounds until the adoption of the “heavy-in-the-wrong-place” barrel M16A2, so thermal considerations should be taken into account when studying new ammunition and new weapons.

During the ‘90s, medium-velocity grenades of limited diameter (20 mm – 35 mm) with “effective” ranges around 600 m, were seen as a way to compensate for the infantryman's lack of accuracy at long range, but without a proper “all weather” Fire Control Module enabling a fast acquisition of the target (it is doubtful that any soldier will be willing to expose himself to enemy fire for more than ~2 seconds), the average miss distance of such medium-velocity grenades will remain much higher than their effective casualty radius and the improvement of the infantryman's hit probability is open to question.

The current trend toward “medium velocity” 40 x 46 mm grenades is also open to question, because between 0 to 350 m (and particularly between 50 m and 150 m), medium velocity grenades will impact the ground at shallower angle than a low velocity round, increasing the fuse malfunction rate and also reducing the warhead effectiveness if the round actually detonates.

Anyway, shoulder launched grenades (low-velocity, medium velocity or rifle grenades) have a definitive place on the battlefield because they provide both additional capabilities (against defilade targets for example) and effective suppressive effects.

A few grenades exploding behind enemy lines is a known way to distract opponents firing at you, making them thinking that they are attacked on two sides, even with a miss distance between 20 m and 50 m. Of course, for this task there is no need for expensive programmable fuses and even more expensive FCM, a simple HE-FRAG or HEAT rifle grenade will do the job.

Additionally, with a simple 3-axis accelerometer and a GPS chipset (like those found in every smartphone) wired into the grenade-launcher, it’s probably easy to design a simple “indirect sight” that will show the grenadier the expected point of impact and CEP radius of its grenade on “Google Earth” (or something similar), enabling this high trajectory weapon to be used without exposing the shooter to returning fire.

As a side note, readers should be interested to read that a “Mortar Ballistic Computer” is (or at least was) available for download on the App Store (“designed for iPhone, compatible with iPad!”)

Being involved more and more in “low intensity” conflicts (without HE support) or with restrictive Rules of Engagements (RoE) that severely limit the access to HE support, the infantryman needs to be able to engage opposing forces at longer ranges than previously thought (up to 600 m for point targets), and fix them or limit their mobility up to 800 m (area targets).
The debate over whether these engagement distances should be achieved by the Individual Weapon or left to "collective" weapons like the DMR and LMG is still open, but the weight and recoil of the 7.62 mm ammunition in its current incarnation militate against its use in a lightweight Individual Weapon, hence the mix of 5.56 mm and 7.62 mm weapons in the same fire team.

In order to further increase the effectiveness of dismounted infantry, two new paths could be followed.

- The ideal path would be to develop the lightest possible round capable of delivering the terminal performances of the 7.62 mm ammunition at 600 m, with the weight and recoil of the 5.56 mm, along with a new generation of modular weapons, preferably with a bullpup configuration (short rifle length with a proportionally long barrel).
- The second path is to keep a mix of 5.56 mm and 7.62 mm weapons and “improve” the 7.62 x 51 mm with a lightweight and “low recoil” load, compatible with current weapons.

Those two possibilities will be detailed in the following parts.

A third path, not anticipated by this author, is to retain the 7.62 mm NATO cartridge volume, energy level and weapon weight, and aggregates:

- a better-shaped bullet, lighter than the original 136 gr T65 bullet, with a slightly reduced diameter and increased sectional density (to achieve a better BC),
- a light case (to reduce the cartridge weight),
- an efficient muzzle break (to reduce the weapon signature)
- a barrel made of “superalloys” instead of steel (to allow for good thermal management & barrel life without increasing weapon weight even with a “high intensity” round).

This way, it seems that the objectives of the “light rifle” program as originally envisioned by Col. R. Studler could be finally fulfilled.
Part Two: Criteria for the evaluation of a “600 m” round

Terminal ballistic considerations

“Sufficient” terminal effectiveness is very easy to achieve with rifle bullets, regardless of calibre, and even a tiny 4.6 mm solid brass (non-fragmenting) bullet impacting at more than 600 m/s could produce a severe wound (better than a 5.56 mm M193 fragmenting bullet), as shown in Figure 37.

![Figure 37: High speed film of 4.6 x 36 mm type 614 solid brass bullet impacting a 20% ballistic gelatine bloc (15 x 17 x 38 cm), impact from the left side of the bloc. Left picture, bullet yawing inside the bloc; Right picture, maximum temporary cavity size.](image)

At the beginning of the 20th century, it was demonstrated that a 3 g steel sphere impacting a human target at 240 m/s (86 J) could easily penetrate and break even the biggest bones of the human body and inflict lethal wounds xxxvii so a “minimum” level of effectiveness is very easy to achieve but trying to define a level of “sufficient” terminal effectiveness is like opening the proverbial Pandora box.

Medical (anatomopathology) studies (i.e., examination of bullet path and tissue damage) involving shooting living animal (dogs or goats) revealed only minor differences between bullets of various calibres and impact energy, to the extent that “from wound examination alone, it was never possible to distinguish the calibre of rifle or machinegun bullets nor the size of explosive shells. It was frequently impossible to judge with any accuracy whether the wound had been produced by a bullet or grenade shell or bomb fragment” xxxviii.

Leaving the medical field to instrumented studies (tissues simulant) leads us to two different approaches (if we leave aside shooting at vessels filled with water). The oldest one is to follow the bullet during impact (energy deposition and temporary cavity) while the other is to look at the final state of the gelatine bloc (permanent cavity and “cracks” due to non-elastic deformation).
Kinetic energy ("force vive") was probably the first criterion used to "scientifically" (or at least "mathematically") evaluate bullet terminal effectiveness. The relationship between kinetic energy loss and hydraulic pressure in closed vessels filled with water was established at the beginning of the 20th century, and later the same relationship was established between kinetic energy loss and temporary cavities in ballistic gelatine (Figure 38).

Figure 38: Relation between kinetic energy loss in the first 15 cm of uncalibrated ballistic gelatine and maximum temporary cavity.

Unfortunately, most studies performed before the ‘90s measured energy deposit only in the first 15 cm of bullet travel in non-calibrated ballistic gelatine (models were developed and validated for high-velocity fragments then extended to bullets), and the validity of those studies, results and models derived from them, could be questioned xxxix.

The KE deposit model used during the ‘60s and ‘70s was later superseded by the EKE model that uses energy deposit in the first 38 cm of bullet path, combined with a probability law (the probability of a bullet to be inside the target body after “x” cm of bullet travel, see Figure 39) xl. While this model addresses some issues found in the previous KE model, others (like energy “consumed” by bullet deformation or fragmentation and not transferred to the ballistic medium, or the very shallow penetration considered against unprotected ballistic bloc) are still unsolved.

For example, a 5.56 mm or 7.62 mm bullet aimed toward the spinal cord and impacting a standing human at right angle need to penetrate an equivalent of 40 cm to 60 cm of NATO ballistic gelatine to reach the spinal cord 90% of the time xli. This result could be compared with the distribution probability used in the EKE model that nearly do not take into account kinetic energy deposit after 25 cm of penetration into said NATO ballistic gelatine (see Figure 39).
Figure 39: Probability to cause immediate incapacitation as a function of the Distance of Penetration (DOP) in NATO ballistic gelatine and distribution probability used in the EKE model.

Finally, it should be noted that the mathematic equation selected for describing missile effectiveness is sensitive to energy deposit only in a very narrow range of energy (between 0 and 200 J, see Figure 40 for the “Defence” and “Assault <30 s” criteria).

Figure 40: Relationship between EKE and P(i/h) for the “Defence” and “Assault <30 s” cases.
This range is useful for discriminating high velocity fragments and FMJ handgun bullets, but it's much more difficult to discriminate between rifle bullets.

According to the “defence” criteria, a bullet delivering an EKE of 500 J (handgun power level) will have a $p_{0.01}$ of ~45%, compared to ~50% for a bullet delivering 3000 J (full-power rifle, six times as much).

Most hunters will probably disbelieve that the difference of terminal effectiveness between a full-power rifle round and a handgun round (both using expanding bullets) is 50% compared to 45%, but this very small difference in effectiveness could be easily explained if one considers that this model 1)- is based on random impact (so impacts to extremities play a major role compared to impacts to the torso or abdomen), and 2)- while using “kinetic energy” as a driver it is in fact a “medical” model based on several (first 10, then 16 later) “functional loss” or “disability” classes xlii, xliii (see Figure 41).

![Table III: Percent Disability vs. Functional Group for Four Tactical Situations (U)](image)

Figure 41: Extract of the sixteen functional groups and disability classes, based on hits to extremities xliii.
For example, in the above table a soldier “losing” one leg (N,T) or two legs (T,T), but with no wounds to the arms (N,N), torso or head is classified as a “group IV” (losing one leg) or “group V” (losing two legs) disability class, and in the “defence” scenario an incapacitation rating of 50% is applied. Said differently, if you shoot in the legs 100 soldiers with .50 BMG bullets, the model predicts that 50 soldiers will still be able (and willing) to return fire.

With the same wound and disability class (group V), but in the “assault” scenario, an incapacitation rating of 100% is applied because the soldier can’t move anymore, so ironically the “Expected Kinetic Energy” model is a strong function of the shooting scenario and respective human body areas, but finally a weak function of the kinetic energy.

With a methodology that does not set a lower practical limit to bullet diameter and weight, it’s not difficult to understand why the current 5.56 mm was considered only an interim cartridge pending the development of high velocity “micro-calibres” (lower than 5 mm) and saboted flechette during the ‘70s that promised significant ammunition weight reduction without a decrease of terminal performance.

Setting an energy level sufficient to inflict a lethal wound is debatable but a value of 82 J is commonly found in the literature and according to Figure 40, this value is well above the level needed to inflict a wound that will significantly reduce soldier’s effectiveness. This value will be used in the following part.

The work of M.L. Fackler \textsuperscript{xliv} led to the use of calibrated ballistic gelatine of a different composition and temperature (10% gelatine at 4°C compared to 20% gelatine at 10°C) and the examination of the bullet track and real damage done to the gelatine block. Contrary to models based on kinetic energy, this approach explains why hunting arrows (or a cut from a slashing weapon of sufficient size, as informally demonstrated by the “Cold Steel” video channel) could kill, with less than 90 J, as efficiently as a soft-point hunting bullet delivering more than 3000 J.

While sound, the main limitation of this model that relies on tissue simulant quality and size (the measured temporary cavity changes with the size of the gelatine bloc) is that nearly all the previous work done back from the ‘60s needs to be done again.

In addition to those considerations related to defeating non-protected soldiers, one could expect that opposing force will be equipped with some kind of ballistic protection.

The protection generally considered on the battlefield is the 3.5 mm NATO steel plate. The impact energy needed to perforate such plate is a function of the bullet diameter (to the power 3/2).

\[ E = k \cdot d^{3} \]
For common “soft” core bullets (lead, brass, common steel), a value of 41.6 could be used for the parameter $k$ and the table below summarize the energy requirement at 600 m.

<table>
<thead>
<tr>
<th>Bore &amp; bullet diameter “soft core” bullet</th>
<th>Energy needed to defeat the 3.5 mm plate</th>
<th>Energy needed to produce a lethal wound</th>
<th>Total energy required at 600 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.56 mm (.224&quot;)</td>
<td>565 J</td>
<td>82 J</td>
<td>647 J</td>
</tr>
<tr>
<td>6 mm (.243&quot;)</td>
<td>638 J</td>
<td>82 J</td>
<td>720 J</td>
</tr>
<tr>
<td>6.35 mm (.257&quot;)</td>
<td>694 J</td>
<td>82 J</td>
<td>776 J</td>
</tr>
<tr>
<td>6.5 mm (.264&quot;)</td>
<td>722 J</td>
<td>82 J</td>
<td>804 J</td>
</tr>
<tr>
<td>6.8 mm (.277&quot;)</td>
<td>776 J</td>
<td>82 J</td>
<td>858 J</td>
</tr>
<tr>
<td>7 mm (.284&quot;)</td>
<td>806 J</td>
<td>82 J</td>
<td>888 J</td>
</tr>
<tr>
<td>7.62 mm (.308&quot;)</td>
<td>910 J</td>
<td>82 J</td>
<td>992 J</td>
</tr>
</tbody>
</table>

In order to increase the efficiency of existing cartridges against personal protections, more efficient bullets than FMJ were designed and for those bullets using an “arrow like” heat treated steel insert a value of only 14 could be used for the parameter $k$ (hence reducing significantly the energy needed to defeat the steel plate), but since they lose around 50% of their weight during plate perforation (jacket stripping) the required energy to produce a lethal wound should be increased to 164 J instead of 82 J (so the fragment representing half the bullet weight will still have 82 J after plate perforation).

The reduction of the energy needed to defeat the steel plate and produce significant wound greatly opens the “solution space” towards the smaller bores.

<table>
<thead>
<tr>
<th>Bore &amp; bullet diameter “semi AP” bullet</th>
<th>Energy needed to defeat the 3.5 mm plate</th>
<th>Energy needed to produce a lethal wound</th>
<th>Total energy required at 600 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.56 mm (.224&quot;)</td>
<td>190 J</td>
<td>164 J</td>
<td>354 J</td>
</tr>
<tr>
<td>6 mm (.243&quot;)</td>
<td>215 J</td>
<td>164 J</td>
<td>379 J</td>
</tr>
<tr>
<td>6.35 mm (.257&quot;)</td>
<td>233 J</td>
<td>164 J</td>
<td>397 J</td>
</tr>
<tr>
<td>6.5 mm (.264&quot;)</td>
<td>243 J</td>
<td>164 J</td>
<td>407 J</td>
</tr>
</tbody>
</table>

This requirement is sufficient to guarantee that a bullet that will defeat a protected soldier at 600 m will also defeat an unprotected soldier at 800 m.

While better protections (NIJ level III & IV) are available today, this point should not be overstressed because those protections are designed to cover mainly the torso (representing only ~16% of the wounds) and, if they are tailored to stop full-power rifle lead-core FMJ and (most) steel-core AP bullets respectively, they are defeated by APHC bullets with tungsten carbide inserts at a distance higher than a hundred meters.

The specific weight needed to achieve multi shot level III ballistic protection is between 40 kg/m² (composite plate) and 50 kg/m² (AR500 steel plate, thickness slightly higher than 6 mm).
As a comparison, the 5.56 mm M193 family could defeat a 7 mm RHA plate between 60 m and 100 m depending on bullet manufacturer.

Composite plates with the same specific weight could also achieve a level IV ballistic protection but generally against one hit, and in order to truly resist multiple hits, an AR500 steel plate would need a (quite impractical) specific weight in the vicinity of 80 kg/m².

Ceramic plates could sometimes protect against up to 3 hits if the distance between each impact is large enough, but for example the ESAPI plate is commonly defeated by the third hit of a 7.62 mm NATO ball (not AP).

At the higher end of the threat spectra, the first generation of NAMMO 5.56 mm and 7.62 mm APHC rounds could repeatedly defeat 12 mm (specific weight of 95 kg/m²) and 18 mm of RHA (specific weight of 140 kg/m²), respectively, at a distance of 100 m.

Even without relying to tungsten carbide, pretty good penetration capability could be achieved with tool steel core (hardness >60 HRc), bullets, the longer the core the better the penetration capability, as shown in Figure 42.

![Figure 42: velocity limit for 50% plate penetration as a function of the ratio of plate thickness to bullet core length (blue, steel core; red, tungsten carbide).](image)

Steel cores impacting RHA plates at a velocity higher than ~800 m/s have a tendency to break or shatter, limiting their AP capability to a ratio around 0.63 at impact velocity above 900 m/s, so a 27 mm long steel core with an impact velocity above 900 m/s could defeat up to ~17 mm of RHA, while a 34 mm long core could defeat up to ~20 mm.
With a 32 mm long core, the SFM PPI / RUAG HC is showing the same perforation limits (in terms of impact velocity) as the NAMMO AP8 (20 mm long tungsten carbide core).

If the higher muzzle velocity of the light AP8 allows a better penetration capability at short range (18 mm RHA at 100 m for the AP8 against 16 mm RHA for the PPI), the higher ballistic coefficient of the SFM PPI allows a better penetration capability at longer range (after 400 m), against RHA plates with a thickness around 10-12 mm.

Special AP bullets with long (~30 mm) tungsten carbide cores have already demonstrated the capability to defeat ~20 mm RHA at impact velocity around 700 m/s.

While homogeneous tungsten carbide core is expensive, it seems that a composite “core” that use two different materials (a hard tip and a backing rod) could achieve the same level of performance, as long as both materials share a similar acoustic impedance.

So even with the constant progress of ceramic materials a practical “all around” protection against such threat is highly unlikely in near term future.

In conclusion, if heavy ballistic vests are very useful to reduce the ratio of soldiers killed versus the number of soldiers wounded, they would probably have a very limited impact on the number of casualties caused by small-arms fire.

**Trajectory**

The time of flight to the target should be as short as possible and wind drift should be minimised. The bullet drop (vertical plane) and wind drift (horizontal plane) in average wind conditions (~5 m/s) are combined in a single number called “Combined Distance from Centre” (CDFC). This way, “flat-shooting” bullets (generally light weight, high drag, launched at high muzzle velocity) could be easily compared with “wind buckling” bullets (generally heavy weight, low drag, launched at a lower muzzle velocity).

The vertical drop (Z) equals to \( \frac{1}{2} \cdot g \cdot (ToF)^2 \) (with \( g \) the gravitational constant, and \( ToF \) the time of flight to the target), and the Didion formula for wind drift (Y) is \( W \cdot \left( ToF - \frac{X}{V_0} \right) \), with \( W \) the wind speed and \( \frac{X}{V_0} \) the time of flight in vacuum conditions.
Since \( g \) equals 9.81 m/s\(^2\), then \( g/2 \) (4.905) is very close to the average wind velocity measured in France (4.5 m/s) or the “10 mph” used by US shooters, and so, for comparison purpose, the CDFC could be practically reduced to \[ T_{oF}^4 + (T_{oF} - \frac{K}{V_0^2})^{\frac{1}{2}} \]

Contrary to the previous requirement (impact energy), not exceeding the CDFC of the current 7.62 x 51 mm M80 bullet at 600 m and 800 m can’t be easily reduced to a single distance requirement, but with few exceptions (high BC bullets launched at low muzzle velocity), a round that matches the M80 CDFC at 800 m also matches the M80 CDFC at 600 m.

**Thermal considerations**

Small arms are internal combustion systems with limited efficiency (generally between 20% and 40%). Heat not converted into kinetic energy or rotational energy (between 60% and 80% of the overall energy) will be used to heat the weapon chamber and barrel, or will remain in the combustion products (increasing the weapon muzzle signature with flash and blast).

According to the “Powley computer”, the thermal efficiency of both the 5.56 mm SS-109 and 7.62 mm M80 bullets when fired from a 20” (508 mm) barrel is around ~31%, so that means that the amount of “wasted heat” (thermal load) is a little higher than 3900 J for the 5.56 mm round (1700 J of bullet muzzle energy) and 7450 J for the 7.62 mm round (3300 J of bullet muzzle energy).

Heat load (wasted heat divided by bore area) for both rounds is around 15.5 kJ/cm\(^2\).

If we extended those calculations to more well-known cartridges (also using the Powley computer and a uniform 508 mm barrel length), we obtain the following results.

![Figure 43: Thermal load for different civilian cartridges.](image)
Without much surprise, at the “low end” of the scale (<<15 kJ/cm²) we find the wildcats 6.5 mm TCU and 6-223 Remington, cartridges that use the small .223 Remington case necked up to 6 mm or 6.5 mm. The .300 AAC Blackout and the 7.62 x 40 mm WT, not shown here, would exhibit even lower heat load.

Those rounds could be of historical interest since the casehead of the .223 Remington is the same (9.6 mm) that that of the .351 WSL, and the unfortunate 8 mm Ribeyrolles (8 x 35 mm SR) could be seen as a kind of necked-up, low-pressure “8 mm AAC Blackout”.

At the other side of the scale (>30 kJ/cm²) we find “high intensity” cartridges like the .220 Swift, .240 Weatherby and the .264 Winchester Magnum that have a well established reputation of being “barrel burners” even for civilian applications. The barrel length of 508 mm used for those computations does not do justice to the big 7 mm Remington Magnum in terms of barrel life, but is a clear indication that a lot of wasted heat will flow through the barrel and that one could expect a large muzzle report. In the case of the .264 Winchester Magnum fired from a 508 mm tube, you will achieve both low barrel life and large muzzle report.

Between those two extremes, we have the “comfortable” 15-20 kJ/cm² zone where we could find military cartridges and civilian equivalents (.223 Remington, .308 Winchester and 7-08), and the 25-30 kJ/cm² zone with high velocity cartridges (.243 Winchester and .22-250 Remington) that represents what is generally considered the “high-end” of the usable range.

According to results obtained with the “Powley Computer”, the 7 x 59 mm of the 1909 automatic rifle program, with a cartridge length of 79.3 mm, a case length of 58.9 mm and a case capacity of 4.5 cm³ (3.6 g of powder) could launch a 7.6 g steel bullet (7.24 mm diameter and 27.4 mm length) at a muzzle velocity of 1030 m/s (4030 J of muzzle energy) out of an extra-long (for now) 715 mm barrel length, when loaded at a standard chamber pressure of 48 000 CUP (330 MPa).

Those predicted results are very similar to what was actually achieved in 1913.

The calculated thermal efficiency is 28.8% for a total of lost energy of 9960 J (33% more than the current 7.62 mm M80 ball) and a thermal load of 24.5 kJ/cm² (60% higher).

Depending on the applications, cartridges in the 20-25 kJ/cm² range could be used but the failure of the 7 x 59 mm as a military round is an indication that a heat load lower than 20 kJ/cm² is a safer bet (and closer to 15 kJ/cm² even better).

While this model is useful to get a first idea of both barrel life and muzzle report when trying to compare different cartridge loaded to the same pressure and fired from the same barrel length, it’s not a fine indication of barrel erosion, weapon heating and muzzle report, considered separately.

Due to their small bore diameter, small-arms are showing a large ratio of wetted area to case volume and energy lost to weapon heating is significant (higher than 20% of the total energy) when for a 30 mm gun heat loss inside the barrel and chamber account for only 5% to 8% of the total energy.
According to for the M193 round fired from a 20" barrel (expansion ratio of 7.3), the breakdown between kinetic energy, heat losses and combustion products internal energy is the following:

- around 28% (~1750 J) for the kinetic energy,
- around 23% (~1400 J) for the heat losses inside the weapon,
- around 49% (~3000 J) for the energy remaining in the combustion products.

For the M80 round fired from a 22" barrel (expansion ratio of 8.5), the breakdown between kinetic energy, heat losses and combustion products internal energy is the following:

- around 32% (~3450 J) for the kinetic energy,
- around 20% (~2200 J) for the heat losses inside the weapon,
- around 48% (~5200 J) for the energy remaining in the combustion products.

Small bore diameter also leads to a disproportionally large boundary layer, so analytic models developed for medium calibre automatic cannon are not usable.

Shooting test performed with a M60 GPMG modified to chamber the .220 Swift showed that the same barrel erosion was reached after 10 bursts of 50 rds (1 burst per minute at a cyclic rate of 600 rpm, maximum barrel temperature of ~340°C), or 1250 rounds being fired in short strings with a M70 receiver (maximum barrel temperature of ~120°C), or more than 2500 rounds being fired in a single-shot mode (barrel being allowed to cool to room temperature after each shot).

This example shows that, while barrel erosion can be mitigated with strict control of the rate of fire, “high intensity” rounds are simply not suitable for automatic weapons using steel barrels.

**Impulse and the SAWS study**

Even if the 7.62 mm NATO (~11.5 N.s) was originally designed to be fired from semi-auto “lightweight” IWs, the ammunition impulse does not really allow its use in a ~4 kg IW (free recoil energy of 16 J).

The interest of a low-recoil, light rifle seems pretty well demonstrated in the context of sport shooting, where target locations are known and the limiting time is the time needed to point, shoot and reload.

In a context closer to military application, with several people trying to maneuver, spot and engage elusive targets without shooting at each other, the benefits of a low-recoiling rifle seems to be less established.

During the CDCEC-SAWS study, several 9 men squads trialled a mix of different weapons in order to achieve the maximum effectiveness, as measured by target effects and sustainability.

The IWs used were the M14 (7.62 x 51 mm), the AK (7.62 x 39 mm), the Stoner M63 and the M16A1 (both firing the 223 Remington cartridge).
While this study definitively worth an in-depth review (some have already be written\textsuperscript{a}), only the main results will be exposed here, and the reader will reach his own conclusions.

**Individual weapons mixes**

If we remove the AK from the individual weapon mixes (due to a small number of previously used rifles and no support, the evaluation of the AK rifle was not performed to the same standard as the other rifles), the 3 “rifle squads” configurations used in the CDCEC-SAWS were the following:

<table>
<thead>
<tr>
<th>Code</th>
<th>Weapons</th>
<th>Calibre</th>
<th>Ammo load</th>
<th>Total</th>
<th>Magazine capacity</th>
<th>Firing mod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UA</td>
<td>7 M14 (IW) 2 M14 (AR)</td>
<td>7.62 mm</td>
<td>7 IW x 100 ball 2 AR x 295 tracer</td>
<td>1290</td>
<td>20 rds</td>
<td>Semi-auto</td>
</tr>
<tr>
<td>SA</td>
<td>7 Stoner (IW) 2 Stoner (AR)</td>
<td>5.56 mm</td>
<td>7 IW x 180 ball 2 AR x 546 ball &amp; tracer</td>
<td>2352</td>
<td>30 rds</td>
<td>2 rds burst</td>
</tr>
<tr>
<td>CA</td>
<td>7 Colt M16 (IW) 2 Colt M16 (AR)</td>
<td>5.56 mm</td>
<td>7 IW x 300 ball 2 AR x 759 ball &amp; tracer</td>
<td>3618</td>
<td>30 rds</td>
<td>2 rds burst</td>
</tr>
</tbody>
</table>

The number of rounds was adjusted to achieve a common rifle squad weight of ~86 kg per squad.

**Situations & measured parameters**

The various scenarios relevant to IWs were:

<table>
<thead>
<tr>
<th>Situation</th>
<th>Title &amp; goal</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>“Rifle Squad In Line Assault” designed to “evaluate rifle squad weapons mixes in marching fire against targets in foxholes at ranges of 148 to 15 meters”.</td>
<td>2 minutes</td>
</tr>
<tr>
<td>2</td>
<td>“Rifle Squad as Base of Fire Supporting the Assault” designed to “evaluate rifle squad weapon mixes firing supporting fire from hastily prepared foxholes. Range from the foxholes to enemy targets was from 269 to 326 meters”.</td>
<td>4 minutes</td>
</tr>
<tr>
<td>4</td>
<td>“Rifle Squad in Approach to Contact” designed to “evaluate the rifle squad mixes in standing quickfire at briefly exposed visible targets. This situation, in which firers were time stressed, was designed especially to evaluate the pointing characteristics of small arms”.</td>
<td>25-30 minutes</td>
</tr>
<tr>
<td>5</td>
<td>“Rifle Squad as a Base of Fire Supporting the Advance” designed to “evaluate the technique of distributed fire used throughout the sector, with point fire used when targets were seen or weapon simulators gave specific cues to a target's location.” Two groups of targets were used, the first one located 379 m to 445 m from the firers, the second one located 477 m and 560 m from the firers.</td>
<td>4 minutes</td>
</tr>
</tbody>
</table>
“Rifle Squad in Defence Against Attack” designed to “evaluate rifle fire from hastily prepared foxholes at enemy targets appearing at ranges from 345 meters to 45 meters.” This scenario was played twice with the UA mix firing semi-auto and the SA and CA mixes firing fully-auto, and a second time with half the UA, SA and CA mixes firing fully-auto (and half firing semi-auto).

Those scenarios were “played” by at least 6 squads in order to calculate a significant mean value.

Effectiveness was evaluated along various parameters:

- Targets hit and total hits (self-explaining, some targets could be hit more than once before falling),
- Near-misses (impacts in a semi-circular zone 2 m around the main target),
- Cumulative Exposure Time (CET). This parameter needs some explanations. Each target of an array was programmed to be exposed for a predetermined period that was identical for each squad in a given tactical situation, hitting targets reduced the exposure time of this target, and hitting fast reduced the CET even more. CET of the target system is a primary measure of fire effectiveness; it reflects both the number of targets in a group that were hit and the timeliness in which they are hit. The lower the CET value, the higher the fire effectiveness.
- Sustainability. The measure of sustainability used in the CDCEC-SAWS is the percentage of ammunition remaining for a given weapon mix when the squad weapon system weight constraint (starting system weight), tactical situation, and record run time are held constant for all squad mixes. The maximum number of rounds that could be safely fired by each weapon before cook-off problems arose was not taken into account for evaluating sustainability, which greatly diminish the relevance of this parameter.

**Raw results**

The CET, Near Miss and Sustainability of the 3 weapon mixes is given below, for each situation.

<table>
<thead>
<tr>
<th>Situation</th>
<th>CET</th>
<th>NM</th>
<th>Sus</th>
<th>CET</th>
<th>NM</th>
<th>Sus</th>
<th>CET</th>
<th>NM</th>
<th>Sus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.8</td>
<td>393.8</td>
<td>72.2</td>
<td>24.8</td>
<td>469.8</td>
<td>51.1</td>
<td>25.5</td>
<td>312.8</td>
<td>47.5</td>
</tr>
<tr>
<td>2</td>
<td>78.2</td>
<td>323</td>
<td>50.5</td>
<td>82.0</td>
<td>236</td>
<td>28.5</td>
<td>77.5</td>
<td>259</td>
<td>22.0</td>
</tr>
<tr>
<td>4</td>
<td>1.97</td>
<td>N/A</td>
<td>80.2</td>
<td>2.11</td>
<td>N/A</td>
<td>69.3</td>
<td>2.04</td>
<td>N/A</td>
<td>78.7</td>
</tr>
<tr>
<td>5</td>
<td>42.6</td>
<td>121.5</td>
<td>84.8</td>
<td>38.6</td>
<td>207.3</td>
<td>68.0</td>
<td>40.2</td>
<td>130.3</td>
<td>60.3</td>
</tr>
<tr>
<td>7</td>
<td>5.2</td>
<td>N/A</td>
<td>77.1</td>
<td>5.6</td>
<td>N/A</td>
<td>91.4</td>
<td>5.4</td>
<td>N/A</td>
<td>72.5</td>
</tr>
</tbody>
</table>
**Statistical analysis**

Since we are trying to evaluate the gain of “hit ability” of low recoiling rounds compared with high recoiling rounds for IW application, the various weapon mixes are rated (first, second, third) based on the mean CET results, along with the p factor value for statistical analysis (the lower the “p” factor, the higher the confidence that the difference is statistically significant).

<table>
<thead>
<tr>
<th>Situation</th>
<th>Best weapon mix</th>
<th>Second</th>
<th>Third</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SA</td>
<td>UA (0.16)</td>
<td>CA (0.09)</td>
</tr>
<tr>
<td>2</td>
<td>UA</td>
<td>CA (&gt;0.40)</td>
<td>SA (0.14)</td>
</tr>
<tr>
<td>4</td>
<td>CA</td>
<td>UA (0.26)</td>
<td>SA (0.09)</td>
</tr>
<tr>
<td>5</td>
<td>SA</td>
<td>UA (0.22)</td>
<td>CA (0.02)</td>
</tr>
<tr>
<td>7</td>
<td>CA</td>
<td>UA (&gt;0.40)</td>
<td>SA (0.27)</td>
</tr>
</tbody>
</table>

During situation 1, the SA and UA weapon mixes performed similarly, with CA slightly dragging behind.

During situation 4, the CA and UA weapon mixes performed similarly, with SA slightly dragging behind.

During situation 5, the SA and UA weapon mixes performed similarly, while CA was significantly performing worse than SA.

The performance of CA, SA and UA weapon mixes were similar (not statistically different) in scenario 2 & 7.

As could be seen, the UA mix performed pretty well during those five situations and never ranked at the third place. In fact, given the value of the "p factor", the difference of “target effects” between the best weapon mix and the “second best” weapon mix in those five scenario is never statistically significant.

Of those five scenario, two (situation 1 and situation 4) were devoted to close range engagements, situation 4 being expressly devoted to the evaluation of weapons point firing.

**Detailed point firing results**

For **situation 1**, the mean CET was 24.8 ±1 minute for the SA (stoner) system, 25.5 ±1.2 minute for the UA (M14) system and 25.8 ±1.4 minute for the CA (M16A1) system.

The scenario lasted for 2 minutes, and during this time:

- the UA squad fired up to (mean value + 2SD) 850 rounds (or 94 rounds per rifle, close to the allocation of 100 rounds per rifles for 7 rifles),
- the CA squad fired up to 1418 rounds (or 157 rounds per rifle) and,
- the SA squad fired a mean 1536 rounds (or 171 rounds per rifle, again close to the allocation of 180 rounds per rifles for 7 rifles).
It was a pretty intensive firing, even more if you take into account the fact that the squad have to move (an average 100 m distance was covered in 2 minutes), shoot and reload.

All 3 systems were pushed to their thermal limits (or beyond), but the “light and low recoiling” 5.56 mm systems did not showed a significant “point & hit” advantage over the “heavy and hard recoiling” 7.62 mm, as shown in the statistical analysis (“F test”) provided in the study.

According to this analysis, the only significant differences (p score <0.06) were that:

- the SA (Stoner) system scored more near miss (a mean 470 for 1150 rounds fired) than the CA (M16A1, a mean 394 for 1005 rounds fired) and UA (M14, a mean 313 for 677 rounds fired) systems,
- the SA system scored more hits (4.5 ±0.8) than the CA system (3.0 ±2.0) (difference between the SA and UA mixes was not significant),
- the “sustainability” of the CA system was significantly higher than both SA and UA systems, so compared with the SA system, the CA system could simply be viewed as unable to shoot a significant proportion of the ammo carried.

**Results for the “Situation 4”** designed to “evaluate the rifle squad mixes in standing quickfire at briefly exposed visible targets. This situation, in which firers were time stressed, was designed especially to evaluate the pointing characteristics of small arms” (as found in the study report) were hardly more demonstrative.

The mean CET (for the 12 events of this scenario) was 1.97 ±0.2 minute for the CA (M16A1) system, 2.04 ±0.1 minutes for the UA (M14) system and 2.11 ±0.1 minutes for the SA (Stoner) system.

Squads needed 25 to 30 minutes to perform this scenario, and the total cumulative exposure time for all 40 targets was 180 seconds. During this time the UA squad fired up to 399 rounds, the CA squad fired up to 1064 rounds and the SA squad fired up to 990 rounds. Thermal stress was probably much lower during this 25 minutes scenario than during the 2 minutes of situation1.

The mean number of targets hit (30.4 for the CA mix, 30.0 for the UA mix and 29.2 for the SA mix) was also more or less constant for the 3 systems and again, the M14 ranked in-between the two 5.56 mm systems but the difference was not found significant.

The situation is even more blurred if we look at the sub-scenario shown in “Table c -- Rank order of weapon mixes and associated standard scores for the ambush situation (ten enemy targets at a range of 21 to 34 meters)".
Figure 44: Results of the “ambush” event.

Even in this sub-scenario, the difference between the SA (ranking 4th on target effects), CA (ranking 7th) and UA (ranking 2nd) mixes does not sustain the idea that a light, low recoiling rifle is inherently superior to a heavy recoiling rifle in a military context.

A last remark concerning the “overall effectiveness” scoring. Due to the selected balance between “target effects” and “sustainability”, the UC weapon mix would have scored better without shooting a single round during this sub-scenario, achieving 0 in “target effects” but 100 in “sustainability”, for a final score of 33.3 instead of 25.0... this same comment apply to other scenario where several weapon mixes are scoring lower than 33.3, which is the score of a weapon system achieving precisely no military effect.

At the end of the day, it is clear that the methodology used during the CDCEC-SAWS greatly favoured systems using the lightest cartridge.

If the ammo load was effectively expended (like in the case of the Stoner rifle and a weight of 3.6 kg unloaded), then the system would score a large number of near-miss (and then achieve a good rank in “target effect”), if the system won’t shoot the ammo due to thermal issues (like the M16A1 and a weight of 3.0 kg unloaded) then the system will still achieve a large “sustainability rating”.

If the CDCEC-SAWS study showed the interest of carrying as much ammo as possible for a given system weight, it was hardly a clear and definitive demonstration of any intrinsic military advantage of a light-recoiling round.
As a side note, exploratory firing during the CDCE-SAWS study demonstrated that the best mode of fire for the UA mix was semi-auto and 2 round bursts for the SA and CA mixes, supporting the current trend in western armies to use “controlled pairs” instead of full-auto fire.

Additional considerations

Regarding weapon controllability in full-auto firing, reducing the ammo impulse below 5.56 mm level to simply approach the ideal dispersion pattern envisioned during ORO-T-160 would be a difficult task.

This ideal “diamond pattern” (5 shots) dispersion used to demonstrate the potential increase of hit probability was 20 inches (ES) at 300 yards, or 1.9 mils.

This value could be compared with mean extreme spread (MES) values found in xix for a compensated M16A1 firing the 5.56 mm round (5.3 N.s impulse with the muzzle break) or a 4.32 mm experimental round (2.5 N.s impulse with the muzzle break), during 3 shots burst:

- 5.56 mm; 17.6 mils (standing) and 12.6 mils (prone);
- 4.32 mm; 14.7 mils (standing) and 10.2 mils (prone), a reduction of ~50% of the recoil reducing the dispersion by ~20%.

The “in burst” dispersion (between the first round and the third round) of the M16 firing the 4.32 mm cartridge was 14 mils (standing) compared with 12.5 mils for the SPIW firing at 800 rpm, or 9.2 mils for the SPIW firing at 1500 rpm.

This reduction of the dispersion of a hand-held weapon firing at high rpm was well documented during the studies made for the FAMAS development, when it was discovered that due to muscular response, the lowest dispersion would be achieved for a firing frequency lower than 10 Hz (600 rpm) or higher than 20 Hz (1200 rpm), the highest dispersion of a hand-held rifle would be achieved with a firing frequency between 14 Hz (840 rpm) and 18 Hz (1080 rpm)¹.

All in all, the “best case” MES recorded with the 4.32 mm (.17 SBR) was 9.2 mils when the ideal pattern dispersion asked for 1.9 mils (and 5 shots).

According to H&K commercial flyer, the MES of the HK G11 firing 3 shots burst is 4.6 mils (standing), with the best MES scoring around 2.5 mils. While closer to the 1.9 mils goal, such dispersion is still much higher than the ideal “controlled dispersion” pattern.

If the linear relationship between ammo impulse and dispersion area is true, then in order to achieve the 1.9 mils ideal dispersion pattern used in ORO-T-160 study (and achieve the predicted increase of the hit probability), one needs to combine the “high rpm, free linear recoil” of the G11 rifle and a huge reduction in the ammunition impulse with an impractical goal of 0.9 N.s (.22 LR impulse level).
With the current availability of the .17 WSM round propelling a 1.3 g bullet at 1000 m/s (nearly duplicating the experimental rimfire 4.5 x 26 mm MKR), dispersion during full-auto fire could be studied with “off the shelf” components.

If the ammo impulse is a primary factor to calculate weapon free recoil energy (the round impulse squared divided by twice the weapon weight) this parameter does not take into account the fact that for the same amount of impulse, the felt recoil (linked to weapon acceleration and not final velocity) is greatly influenced by other factors, one being the amount of bolt travel, the other one being the muscular response (or lack of) of the body.

Since bolt rearward velocity is very similar among automatic rifles (close to 7 m/s), the greater the bolt travel, the lower the bolt deceleration (and weapon acceleration), so instead of “kicking” the gun will “push”, even if the final recoil velocity is the same for a given ammo impulse and weapon weight.

For IWs, the weapon cyclic RoF is a close function of the bolt travel. High rpm is produced by short bolt travel (~85 mm of bolt travel for the FAMAS firing at 1100 rpm, ~108 mm for the M16 firing at 850 rpm and ~135 mm for the FN SCAR and the AK firing at 600 rpm), so a first order parameter to evaluate the felt recoil is to divide the ammunition impulse by the bolt travel.

This hypothesis, which does not take into account the weapon weight, if of course only usable for comparing weapons of similar weight class and reflect the fact that the bolt end travel is the major source of weapon acceleration (hence felt recoil), as illustrated by the Figure 45 which is showing the acceleration behaviour of the M4A1.

The first peak is the acceleration due to the bullet & gases travel in the barrel, the second peak (the largest) is the bolt & buffer slamming into the tube, and the (very weak) third peak is the bolt closure.

Figure 45: M4A1 acceleration profile during repetitive shooting (left), and focus on a single shot (extract from²).
This graph is a simple illustration of the possibility of reducing the felt recoil using a long bolt travel (Ultimak 100), a balanced system (several implementations) or making the bolt impacting the buffer in a vertical plane (KRISS Vector).

The benchmark used for comparative evaluation is the 5.56 mm NATO round fired from the M16 platform (impulse ~6 N.s; bolt travel ~108 mm) or the 7.62 x 39 mm fired from the AK platform (impulse ~7.5 N.s; bolt travel ~135 mm) because the “felt recoil” is 55.6 kg/s in both case.

<table>
<thead>
<tr>
<th>System</th>
<th>Ammo</th>
<th>Impulse</th>
<th>Bolt travel</th>
<th>“Felt recoil”</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAL</td>
<td>7.62 x 51 mm</td>
<td>11.6 N.s</td>
<td>119 mm</td>
<td>97.5 kg/s</td>
</tr>
<tr>
<td>SCAR</td>
<td>7.62 x 51 mm</td>
<td>11.6 N.s</td>
<td>135 mm</td>
<td>85.9 kg/s</td>
</tr>
<tr>
<td>AR15</td>
<td>6.8 mm SPC</td>
<td>8.0 N.s</td>
<td>108 mm</td>
<td>74.1 kg/s</td>
</tr>
<tr>
<td>SCAR + effective muzzle break</td>
<td>7.62 x 51 mm</td>
<td>8.0 N.s</td>
<td>135 mm</td>
<td>59.3 kg/s</td>
</tr>
<tr>
<td>AK</td>
<td>7.62 x 39 mm</td>
<td>7.5 N.s</td>
<td>135 mm</td>
<td>55.6 kg/s</td>
</tr>
<tr>
<td>M16</td>
<td>5.56 x 45 mm</td>
<td>6.0 N.s</td>
<td>108 mm</td>
<td>55.6 kg/s</td>
</tr>
<tr>
<td>AK74</td>
<td>5.45 x 39 mm</td>
<td>5.0 N.s</td>
<td>135 mm</td>
<td>37.0 kg/s</td>
</tr>
</tbody>
</table>

At the upper end of the scale, the 7.62 mm NATO fired from a FAL is delivering a “felt recoil” of ~97 kg/s.

Below that, a “felt recoil” of 86 kg/s could be calculated for the 7.62 mm NATO fired from a FN SCAR; 74 kg/s for the 6.8 mm SPC fired from a M16 platform and at the lower end 37 kg/s for the 5.45 x 39 mm.

Interestingly, since around 30% of the impulse generated by a 7.62 mm NATO cartridge is produced by the exhaust of the combustion products, a rifle equipped with a reasonably efficient muzzle brake (impulse ~8.0 N.s as measured by ballistic pendulum with a very effective muzzle break ii, ~8.5 N.s for a more practical one) will have a “felt recoil” around 60-63 kg/s and there is anecdotal evidence that this level of “felt recoil” is not detrimental to weapon stability.

On the opposite side of the scale, some snipers using both bolt action and semi-auto rifles chambered for the .50” BMG round, have reported that bolt action rifles (with zero bolt travel), while having a “sharper” felt recoil, allowed for less disturbance of the shooting position and an easier observation of the bullet impact through their scope, compared with long-recoil semi-auto rifles firing the same round.

This counter-intuitive observation could be explained using the recoil profile of the guns (Figure 46), and the fact that, as previously stated for full-auto fire, there is a positive effect (i.e. increasing rifle stability) of the muscular response below 10 Hz (20 ms), a negative effect (i.e. reducing weapon stability) of the muscular response between 10 Hz and 20 Hz (20 ms and 5 ms), and no effect of the muscular response above 20 Hz (less than 5 ms).
So, for bolt-action rifles delivering all their recoil force in less than 5 ms (as shown on Figure 46), the felt recoil could be brisk but doesn't induce parasitic muscular response. Long-recoil action, on the other hand, while efficiently reducing the maximum peak force (from 430 N down to 170 N) and making the gun more comfortable to shoot, could induce parasitic muscular response, the force being delivered to the shooter for more than 5 ms (27 ms in the measured case).

All in all, it seems that a recoil limit of 8.5 N.s (without muzzle break) is not high enough to reduce the tactical effectiveness of semi-auto or full-auto fire as long as the weapon cyclic RoF stays around 600 rpm (or lower).
Suppression, or the “Crack & Splash” effectiveness

The importance of suppression effects for small-arms fire was pointed out in the first part of this article, but without quantification or evaluation.

Since the “1 m” criterion does not account for specific bullet characteristics, using acoustic (bullet relative “loudness”) and visual (impacts) criteria is a way to improve suppression evaluation.

Limited results are available in the literature, but some could be found in the CDEC study reported in \[iii\] and \[liv\].

In the first report, the acoustic and visual signature of several rounds are compared, including the XM645 “flechette” round fired from the XM19, the 5.56 mm M193 fired from the M16, the 7.62 x 39 mm fired from the AK, the 7.62 x 51 mm fired from the M60, the .45 ACP fired from the M1A1 SMG and the .50 BMG fired from the M2 HMG.

Those results will serve to identify physical parameters that could be used to build a relative scale for suppression, accounting for both acoustic and visual stimuli.

Results from the second report will be used to correlate this relative scale to real life “threatening” distance.

This scale will be used in the third part (theoretical study), along bullet time of flight (trajectory parameters), retained energy, heat load and impulse, to try to narrow the “solution space” for optimal parameters study.

Acoustic index, the “Crack” part

Live fire test performed at a distance of 150 m revealed that:

- the mean dangerousness of both the XM19 and the M1A1 SMG were rated significantly lower than other weapons, the XM19 being rated significantly lower than the M1A1,
- subjects failed to discriminate the AK from the M60, and the AK from the M16 (“From Table 5-14 it can be seen that only the comparisons of the AK47 with the M60 (+0.16) and the AK47 with the M16 (+0.23) fail to reach the ICI of 0.38 necessary for the demonstration of a significant difference in the mean perceived dangerousness for the two weapons”), but the difference between the M16 and the M60 could be considered significant (a ICI of 0.39 was achieved between those two weapons).
- the .50 BMG scored the highest mean dangerousness value, but the result was not found “off scale” compared to other weapons,
- mean dangerousness decreased linearly with the miss distance (minimum miss distance considered was 2 m).
A relationship between kinetic energy and perceived mean dangerousness was established, but the remaining velocities at 150 m for the various rounds quoted are in some cases suspiciously low (2200 fps for both the M16 and the M60).

More recently, investigations were made to properly measure bullet noise between Mach 0.5 and 3.0. Peak pressure for 4 bullets diameter (.224"; .308"; .338" and .510") sharing the same shape (the exact G7 shape) was measured at a distance of 61 cm from the bullet path (Figure 47).

![Figure 47: measured peak pressure of bullets following the G7 shape, fired at different velocities.](image)

The peak value reached in the supersonic domain corresponds to a sound value between 155 dB and 163 dB, which is similar to the noise range of some stun grenades.

As could be seen in Figure 47, for a given bullet diameter the measured pressure level is pretty constant in the whole supersonic domain and a .50" calibre G7 bullet traveling around ~400 m/s (the remaining velocity of the M33 ball at ~1200 m) will still produce a higher overpressure (0.288 psi or 160 dB) than a .338" G7 bullet (0.257 psi or 159 dB) traveling at 900 m/s (the typical MV of the 338 Lapua Magnum).

The same is true with the 7.62 mm and the 5.56 mm G7 bullets, the first one producing more overpressure at Mach 1.16 (0.190 psi or 156 dB at a distance around ~700 m for the M80 bullet) than the 5.56 mm at Mach 2.95 (0.173 psi or 155 dB at typical MV of the M193 bullet).

The mathematical expression based on global bullet drag \( \left( \ln(C_D, (d/V)^2 + 1) \right) \) proposed in a previous version of this paper was reviewed in the light of those results and was found insufficient, with too much sensitivity to bullet diameter and Mach number.

The mathematical model proposed in \cite{ref} for predicting the relationship between bullet characteristics and overpressure \( \left( \frac{\rho c^2(M^2-1)^{1/6} S_{max}^{1/2}}{2^{1/4}\rho V^{1/2} \frac{\pi}{3/4} L^{1/4} K} \right) \) is restricted to bullet supersonic domain because the peak pressure is found to be proportional to \( (M^2 - 1)^{1/8} \) and the bullet form factor \( K \) used
in this formula (not to be confused with the i7 form factor generally used in this paper), instead of being constant (as presumed from results obtained with artillery projectiles), was found to be a function of both the Mach number and the bullet diameter.

To avoid those limitations, a simplified and empirical model was developed (the Acoustic Index E2) which is pretty effective at predicting the measured overpressure of a passing bullet (Figure 48) in the supersonic domain, but also in the subsonic domain (with less accuracy, particularly in the transonic region).

![Figure 48: correlation between measured passing bullet overpressure and proposed mathematical model (acoustic index E2).](image)

As a sidenote, in the above formula the distance is elevated to the power (-3/4), so the reduction of the bullet overpressure as a function of the distance is not proportional. If at a given distance a bullet “A” is producing 40% more overpressure than bullet “B”, then bullet “A” will produce the same overpressure as bullet “B” at a distance 56% greater, and an increase of the threatened area by 145%.

With those findings, the proposed mathematical expression for the evaluation of perceived acoustic dangerousness is:

\[
AI(E_2) = M \cdot d \cdot (C_D)^{4/3}
\]
With *M*, the local bullet Mach number (dimensionless), *d*, the bullet diameter (in mm) and *C_D*, the drag coefficient (dimensionless) relative to the local velocity.

This value could be approached using the bullet form factor *i_7* and the *G_7* drag table, and for a 7.62 mm NATO M80 bullet at a range of 150 m (residual velocity ~Mach 2.18) the acoustic index is 3.78 (2.18*7.82*0.323^1.33).

Results for some projectiles tested during the CDEC study.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Acoustic index</th>
<th>Relative Acoustic Index</th>
<th>Relative Acoustic Index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E2 (at 150 m)</td>
<td>E2 (at 150 m)</td>
<td>E1 (for information)</td>
</tr>
<tr>
<td>.45 ACP</td>
<td>1.07</td>
<td>0.28</td>
<td>0.42</td>
</tr>
<tr>
<td>.223 Remington M193</td>
<td>2.89</td>
<td>0.76</td>
<td>0.85</td>
</tr>
<tr>
<td>7.62 x 39 mm</td>
<td>3.69</td>
<td>0.98</td>
<td>0.89</td>
</tr>
<tr>
<td>7.62 x 51 mm</td>
<td>3.78</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>.50 BMG</td>
<td>6.16</td>
<td>1.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Even if the new model is significantly different from the previous one, the overall trend is very similar but with a slightly better sensitivity. For example, during previously mentioned live fire tests, the acoustic signature of the 7.62 x 39 mm M43 and the 7.62 x 51 mm M80 were found very similar, which is supported by the E2 model (0.98 for the M43 versus 1.00 for the M80, compared with 0.89 versus 1.00 with the E1 model). During those same tests, the difference between the 223 Remington M193 and the 7.62 x 39 mm was found significant, a reality also better supported by the E2 model (0.76 for the M193 versus 0.98 for the M43) than the previous E1 model.

**Visual index (impact signature experiments), the splash**

Again, live fire tests performed at a distance of 150 m revealed that:

- the M1A1 SMG in the visual signature mode received a higher mean suppression scale value than did the M16,
- the visual effect of the .50 BMG M2 HMG was so much "off the scale" compared to other weapons that it was not possible to find a statistically significant difference between the M1A1 SMG, the M16 AR and the M60 MG (the XM19 was not rated),

It was anticipated that the visual signature of impacting bullets would be related to kinetic energy (because cavity volume in soft soils is directly a function of the kinetic energy), but the rating of the M1A1 SMG over the M16 suggests that other mechanisms could be involved.
This unexpected observation could be linked to the ricochet characteristics of those very different bullets, a low velocity, round nose .45 ACP bullet on one hand and a high velocity, spitzer M193 bullet on the other hand.

The military interest of ricochets is not new (the bullet “E.N.T. n°111” previously described was discarded in favour of the bullet “E.N.T. n°123” on ground of ricochets requirements) and was also highlighted in ORO-T-397:

“One factor not recognized in SALVO I and not previously recognized as being significant in combat rifle effectiveness was isolated in the SALVO II experiment—the importance of the ricochet characteristics of ammunitions. The best example of this is the difference in hits of .22-cal duplex ammunition compared with .30-cal duplex ammunition. Here a difference in total hits recorded of almost 10 percent is due directly to the superior ricochet characteristics of .22-cal duplex ammunition. This particular effect is worthy of further study.”

Unfortunately, ricochets are now mostly regarded as a firing range safety hazard and ammunition “safety fan” can’t be used to evaluate the military interest of ricochets, because those safety fans do not discriminate between rounds that produce dangerous ricochets 30% of the time versus 5% of the time.

In the absence of a clear indication of the physical effect that produced this rating, momentum (in N.s) instead kinetic energy will be used for building a Visual Index. This choice is not totally arbitrary because momentum is a relevant parameter for the physical description of elastic collisions.

\[
VI(E_1) = \frac{M \cdot V}{1000}
\]

With \( M \), the bullet weight (in g) and \( V \) the local velocity (in m/s).

Results for some projectiles tested.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Visual Index (at 150 m)</th>
<th>Relative Visual Index (at 150 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.223 Remington M193</td>
<td>2.7</td>
<td>0.41</td>
</tr>
<tr>
<td>.45 ACP</td>
<td>3.6</td>
<td>0.51</td>
</tr>
<tr>
<td>7.62 x 39 mm</td>
<td>4.6</td>
<td>0.66</td>
</tr>
<tr>
<td>7.62 x 51 mm</td>
<td>7.0</td>
<td>1.0</td>
</tr>
<tr>
<td>.50 BMG</td>
<td>35</td>
<td>5.0</td>
</tr>
</tbody>
</table>

If the acoustic signature of the .50 BMG bullet was “only” 63% more than the acoustic signature of the 7.62 x 51 mm, the visual signature is 5 times more according to momentum and much higher than all other visual signatures.
Building a Relative Suppression Index (RSI)

Balancing visual and acoustic signature to obtain a single suppression index is not an easy task, because if acoustic signature is detected much more often than visual signature by soldiers, visual signature seems to play a much bigger role if detected \[ i_1 \]. A more practical problem is that adding mm (acoustic index) and N.s (visual index) doesn’t make sense.

So, the easiest way to build a composite index using acoustic and visual data is to use non-dimensional values, using the 7.62 mm NATO as the reference case.

Unfortunately, while this scale could be used to compare probable “suppression effectiveness” of two different rounds, this would not answer the basic question of “what is the average distance at which a given bullet will be considered dangerous and could be expected to deliver a given suppression probability”.

Available data from CDEC \[ i_2 \] resulting from DUCS (“Degradation Under Controlled Stimuli”, April 1975), SASE (“Small Arms Suppression Experiments”) and SUPEX (“Suppression Experiment”) experiments shows that the relationship between miss distance and “suppression probability” is not linear (Figure 49).

![Figure 49: Suppression probability as a function of miss distance, as found in DAR (Data Analysis) report.](image)

Unfortunately, no indications are given for the distance between the firing line and the “targets”, so we will make the assumption that this distance was the same as in the previous test (i.e. 150 m).
As can be seen, the miss distance could be very large (several meters) and still effective suppression (> 50%) could be achieved.

For the 7.62 mm, a miss distance around 6 m will produce 50% of suppression, compared to around 3 m for the 5.56 mm and the .45 ACP, and 24 m for the .50 BMG (a class of its own, and ~4 times the miss distance of the 7.62 mm).

Presented differently, at a (presumed) distance of 150 m a single 7.62 mm NATO (24 g cartridge) could be expected to suppress 50% of a group located in a 113 m² area, compared with 28 m² for the .223 Remington (12 g cartridge) and 1,800 m² for the .50 BMG round (115 g cartridge).

So, if we divide the suppression area by the cartridge weight, we found that at a distance of 150 m, 1 kg of .223 Remington ammunition will provide a 50% suppression effect in a 2,350 m² area, 1 kg of 7.62 mm NATO ammo will cover 4,710 m² (twice as much for the same ammo load) and 1 kg of .50 BMG will cover 15,700 m².

The miss distance for achieving suppression 90% of the time is much shorter, around 0.7 m for the 7.62 mm NATO, less than 0.5 m for the 5.56 mm and the .45 ACP, and 5 m for the .50 BMG (again, a class of its own in the realm of kinetic energy small-arms).

During the tests, the miss distance was not measured with an accuracy of 10 cm (the step was probably closer to 1 m), but it's the result of a statistical data reduction. According to those results, the miss distance achieving suppression 90% of the time for the 7.62 mm NATO is around 1 m, very similar to the old “1 m or 3 ft. rule” and this value will be used for further validation.

Other results available from iii are given below. The suppressive quality of several weapons (M1A1 SMG, M16A1 rifle, M60 GPMG and M2 HMG) was compared by 8 subjects that rated their acoustic signature (two consecutive 3 round burst), their visual signature (2 consecutive 3 round burst impacting at a distance of 15 m in the soil), and the combined visual / acoustic signature (one 3 round burst fired in the ground and one 3 round burst fired overhead at the same time).

The statistical analysis of this test is presented in Figure 50, with Delphi suppression value for acoustic mode, visual mode and combined visual and acoustic mode.
Figure 50: Mean Delphi scale suppression values for each weapon for each signature mode.

With this result, the following Relative Suppression Index (RSI) is built using 2 strong (but not totally arbitrary) assumptions:

- The RSI value of a round delivering an acoustic index of 3.78 (mm) and a visual index of 7.0 (N.s) (7.62 mm NATO at 150 m) is 1 meter,
- The relative weight of the acoustic index is 0.3 and the relative weight of the visual index is 0.7, in order to achieve the best linear correlation ($R^2 = 0.9987$, cf. Figure 52) for the scenario used in the above study that could be qualified as “defence, daylight”, and also the ~4 to 1 distance ratio of the 12.7 mm versus 7.62 mm (24 m vs. 6 m, cf. Figure 49 & Figure 51).

This proposed ratio (70% visual and 30% acoustic) is most probably “scenario dependant” but in the absence of other reliable data, this ratio will be used for all bullet / calibre / ammunition comparisons.
The reduction of this ratio below 65% (visual) and 35% (acoustic) reduce both the linear correlation and the threatened distance ratio of the 12.7 mm compared with the 7.62 mm. With the new acoustic index, the previously proposed 60% (visual) and 40% (acoustic) balance leads to a 3.6 to 1 ratio that does reflect less accurately the difference between the 12.7 mm and the 7.62 mm.

Model sensitivity and validation, the 5.56 mm M193 vs. the 7.62 mm M43 vs. the 7.62 mm NATO

The change of the Acoustic Index (from E1 to E2) and the balance between acoustic and visual threat (like selecting 40%+60% with the E1 model -case B- instead of 30%+70% with the E2 model –case C- for a “defence, daylight” scenario) have a limited effect on the global trends of this study, as shown by the Figure 53.
Figure 53: Relative Suppression Index (7.62 x 51 mm equals 1 m at 150 m) with a balance of 60% visual threat and 40% acoustic threat (case B, bottom) and a balance of 70% visual threat and 30% acoustic threat using the E2 model (case C, top), for various rounds of military interest (50 BMG not shown due to scale).

The two mix proposed (case B or case C) are telling us essentially the same story.

At the weapon’s muzzle and short range, the predicted suppression distance of the 7.62 x 39 mm is higher than the predicted suppression distance of the 5.56 x 45 mm, which is higher than the predicted suppression distance of the 45 ACP (a result in-line with the Figure 50).

At 600 m, all those 3 rounds are delivering similar suppression effects and any predicted difference would be probably very difficult to demonstrate.
Whatever the range, those 3 rounds are producing a significantly smaller predicted suppression distance than the 7.62 x 51 mm, which in turn is delivering a significantly smaller suppression distance than the 338 Lapua Magnum, while everyone is dwarfed by the 12.7 x 99 mm (not shown due to scale).

At short range, the 6 mm SAW is slightly inferior to the 7.62 x 39 mm, then a close equivalent around 350-400 m, and superior at longer range (particularly around 600 m) to the extent of being a close equivalent to the 7.62 x 51 mm around 800 m.

While absolutely no hypothesis were made about the relative suppression distance of the 5.56 mm relatively to the suppression distance of the 7.62 mm, this model actually predicts that the 5.56 mm is delivering roughly half the suppression distance of the 7.62 mm at 150 m (58% for case B, 53% for case C), and that the suppressive effect of the 45 ACP (fired from a M1A1 SMG) is lower than that of the 5.56 mm (fired from the M16A1), results in total agreement with actual values measured during the several CDEC experimental studies named previously (see Figure 49).

“High Velocity Small Calibre” assault rifle cartridges (5.45 x 39 mm and 5.56 x 45 mm) could be expected to deliver only half the “90% suppression distance” (hence a quarter of the effective area) of the “full power” 7.62 mm (51 mm or 54 mm case length) at any engagement range.

At short range (up to 300 m), the 7.62 x 39 mm shows good suppression behaviour, delivering around 75% of the full-power 7.62 mm, significantly higher than both 5.45 mm (~50%) and 5.56 mm (~55%).

One could see the 5.56 mm NATO capability to deliver half the suppression distance of the 7.62 mm NATO for half the cartridge weight, or the 7.62 mm NATO capability to deliver one fifth of the suppression distance of the .50 BMG for one fifth the cartridge weight as a fair deal (at least weight neutral), but when the fire dispersion is important, bullets could fall short or long, so it’s not the miss distance (one dimension) that is the driving parameter, but the beaten area (two dimensions, see Figure 54).

Figure 54: Simple representation of a bullet threatened area.
In this representation, the distance D is the calculated suppression distance (90% level)\(^5\).

This area could be divided by the cartridge weight to obtain the specific suppression area for 1 kg of ammo (Figure 55).

![Figure 55: Specific suppression area of several military bullets as a function of the range.](image)

This intensive parameter (suppression area divided by ammo weight) is telling us a very different story about bullets “soft power” on the battlefield, compared with the more traditional “hitting power” approach.

At a distance of 200 m, the specific area suppressed by the 5.56 mm NATO is around 70 m\(^2\)/kg, compared with 120 m\(^2\)/kg for the “full power” 7.62 mm NATO so that means that in theory you could expect to expend 40% less ammunition weight to achieve the same suppression area using a 7.62 mm NATO MG than using a 5.56 mm NATO MG.

The “full power” 7.62 mm maintains this ~2 to 1 ratio up to 600 m (60 m\(^2\)/kg versus 30 m\(^2\)/kg) then the gap starts to increase and at 800 m the advantage of the 7.62 mm is now 5 to 1.

If you add the fact that since all gas-powered MGs have roughly the same rate of fire (so that in a given timeframe a 7.62 mm MG will fire twice as much ammunition weight than a 5.56 mm MG), at the end of the day (between 0 and 600 m) a “full power” 7.62 mm MG will achieve the same suppression effect as

\(^5\) Another possible methodology to evaluate this threatened area would be to consider that the threatened area in the horizontal plane is a function of the visual index only, and that the threatened area in the vertical plane is a function of the acoustic index only.

In this case, the set of hypothesis would be that a bullet with a visual index of 7.0 will have a horizontal suppression distance (90% level) of 1 m, and that a bullet with an acoustic index of 3.64 will have a vertical suppression distance (90% level) of 1 m. The total threatened area is the sum of both horizontal and vertical half-disc.
a 5.56 mm version, using only half the ammunition load and 4 times faster. At longer range the difference is even more balanced against the 5.56 mm.

While still highly speculative, this suppression criteria at least offers an explanation as to why, contrary to all predictions based on “hard power” (terminal ballistics) indicators, the 5.56 x 45 mm never managed to effectively replace the 7.62 x 51 mm (hence the current movement in western armies to reintroduce 7.62 mm LMG and DMR at the fire team level), and also the unexpected longevity of the 7.62 x 39 mm that is, despite unimpressive external and terminal ballistics, still so widely encountered on nearly every battlefield 40 years after its official replacement.

Another interesting point is that the 6 x 45 mm SAW, designed to deliver effective fire up to 800 m, seems to duplicate (at least on paper and using this criteria) the 7.62 mm NATO suppression effectiveness at this distance. While not a clear and definitive demonstration, this point sustains the view that the Relative Suppression Index, as defined previously, is a useful index if one wants to be able to replace the current 7.62 mm NATO without limiting itself to shortening the cartridge case by a half-inch.

Looking at the upper part of the scale, the .338 Lapua Magnum (or the ballistic equivalent .338 Norma Magnum), while not really a substitute for the mighty .50 BMG, seems to deliver significantly better performances than the current ubiquitous 7.62 mm GPMG to warrant significant interest if chambered in a lightweight MG, a kind of modern reincarnation of the pre-WWII experimental 9x66 mm MAS MG that used a 20 g bullet launched at 780 m/s.

We’ve seen that using a “conditional hit probability” (hit without being hit) seems to be a way to account for “incoming fire effects”, so the same approach could be used to calculate the “suppression probability”, then the “hit without being suppressed” conditional probability.

Using this methodology and the proposed miss distance for 90% suppression, we can compare the probability of hitting an IPSC target (direct hit) and the probability of hitting inside the “90% suppression circle” (achieving direct hit or suppression of the target, Figure 56).
Figure 56: Predicted hit probability of an IPSC target in the absence of incoming fire (blue curve), predicted suppression probability (red curves) for the 5.56 mm (dots and dash), 7.62 mm (solid), .338LM (dash) and predicted hit probability in battlefield conditions (“under fire”, black curves) against 5.56 mm, 7.62 mm and .338LM suppressive fire.

Computations were run using Applied Ballistics Analysis software, a “low confidence” scenario and a “worst case” of 25 MoA (~7.5 mils, 3 seconds target exposure time) extreme spread for the weapon system (as found in ORO-T-160).

The comparison of the blue curve and the black curves on Figure 56 is a vivid illustration of the military effect of, and interest in, suppressive fire, the hit probability (effectiveness) of opposing soldiers being drastically reduced.

At a range of ~200 m, the opposing force hit probability decreased from 23% (without suppressive fire) to 11% against 5.56 mm suppressive fire, or 3% against 7.62 mm suppressive fire and finally 0.3% against .338” Lapua Magnum suppressive fire.

Using a 10 MoA dispersion (5 seconds target exposure time) and the previous hypothesis, we obtain the following results (Figure 57).
Figure 57: Predicted hit probability of an IPSC target in the absence of incoming fire (blue curve), predicted suppression probability (red curves) for the 5.56 mm (dots and dash), 7.62 mm (solid), .338LM (dash) and predicted hit probability in battlefield conditions (“under fire”, black curves) against 5.56 mm, 7.62 mm and .338LM fire.

The reduction of fire dispersion from 25 MoA to 10 MoA do not change the general shape of the various curves, but tends to increase the “optimum engagement range”, from 200 m to 400 m (against 5.56 mm NATO suppressive fire), and from ~400 m to ~600 m against 7.62 mm NATO suppressive fire.

**Suppression requirements**

By construction, the RSI(90%) value of the 7.62 mm NATO bullet is 1.00 m at 150 m and the quoted effective range of this round against point target, when fired from a bipod, is generally 800 m which cover the full supersonic range of this round.

The calculated RSI(90%) value of this round at Mach 1.1 is 0.62 m and the area “suppressed” by a kilogram of 7.62 mm NATO ammunition is 50 m².

Longer effective ranges (1100 m and up to 1800 m when T&E mechanism is present) could be found in the context of tripod-mounted MGs (delivering high volume of fire) but those values are probably not relevant to LMGs and IWs fire.

For comparison purpose, the calculated RSI(90%) of the 6 x 45 mm SAW is 0.49 m at 600 m (50 m² per kg) and 0.42 m at 800 m (36 m² per kg), in essence delivering the same suppression effects as the 7.62 mm NATO at 800 m and 1000 m respectively, in a more compact and lighter package.
Given those results, it is safe to assume that a value close to 0.50 m is probably needed in the context of bipod-mounted LMGs or Individual Weapons, or a value of 50 m² per kg of ammo if one wants to properly take the opportunity to reduce unitary cartridge weight.

The chart below details the maximum distance at which the 7.62 mm NATO, the 6 mm SAW and the 5.56 mm NATO are achieving a RSI(90%) of 0.5 m or 50 m per kg of ammunition.

<table>
<thead>
<tr>
<th>RSI(90%)</th>
<th>0.5 m</th>
<th>50 m² per kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.62 mm NATO</td>
<td>~750 m</td>
<td>~700 m</td>
</tr>
<tr>
<td>6 mm SAW</td>
<td>~550 m</td>
<td>~550 m</td>
</tr>
<tr>
<td>5.56 mm NATO</td>
<td>~200 m</td>
<td>~350 m</td>
</tr>
</tbody>
</table>

The area of the IPSC target used by AB Analytics WEZ software for the evaluation of the hit probability is 2775 cm² (0.2775 m²), that's nearly the same area as a 0.30 m radius circle, so when the RSI(90%) falls below ~0.30 m, the 90% suppression probability and the hit probability are nearly equal and the interest for using a 90% suppression distance is lost, but for analysis of long range fire one could still choose a lower suppression probability (75% or even 50%) and use the bigger suppression radius.

For example, according to Figure 49 the radius of the 50% suppression probability seems to be around 5 to 6 times the radius of the 90% suppression probability, so between 1.5 m to 1.8 m (7 m² to 10 m per round) when the 90% suppression radius of a given round is falling below 0.3 m, probably effective enough from a military point of view for harassing fire, but very far from IWs, DMRs or LMGs fire application.
Part Three: Study of a 600 m lightweight round

With the realization that hand-held weapons could be used with a significant military effect (suppression) up to a much longer range (~600 m and up) than predicted by studies focusing only on hit probability, we will now “explore the design space” to try to found the “best” (or the least handicapping) combination of parameters.

The methodology used in this study is very similar to the one presented in CRC-307vi “A METHODOLOGY FOR SELECTING SMALL-ARMS ROUNDS TO MEET MILITARY REQUIREMENTS”, but with different design parameters.

Two “design space” will be explored, the first one with a 2.8” cartridge overall length (COAL) fired from a 508 mm (20”) barrel (rifle or MG), the second with a 2.26” COAL fired from a 406 mm (16”) barrel (carbine).

Technical requirements

The main requirements of a “600 m lightweight round” are:

- to be able to hit and defeat a protected soldier at 600 m (point target) and to deliver accurate and lethal fire up to 800 m (area target),
- to deliver suppressive effects as close as possible to current 7.62 mm NATO ball,
- to be as light as possible (as a general rule, low cartridge weight means low cartridge impulse AEBe, so impulse will be used as a weight surrogate).

2.8” COAL design space results

Bullet design

In the previous versions of this paper, 3 bullet lengths (4; 4.5 and 5 calibres) were investigated. Since the shortest bullet was neither an optimum, it was decided in this release to remove it and include a 5.5 calibres flat-base bullet that will benefit from the increased stability demonstrated by flat-base bullets compared with boat-tail bullets.

So, instead of a “short”, “medium” and “long” bullet, this study is using a “medium, boat-tail” (MBT), a “long, boat-tail” (LBT) and a “long, flat-base” (LFB) bullet design.

The boat-tail bullets featured a tangent-secant ogive with a length of 60% of the total bullet length, a shank with a length of 25% of the total bullet length, and a 7° boat-tail with a length of 15% of the total bullet length.

The flat-base bullet featured a tangent-secant ogive with a length of 65% of the total bullet length.
This balance of parameters ensured that the bullet centre of gravity (CoG) is supported by the barrel grooves during bullet in-bore travel, avoiding detrimental “in-bore yaw”. The expected i7 form factor of the MBT bullet is ~.93 (with a 2.7 calibres ogive height, slightly better than the 0.94 measured for the 7.5 mm Mle 1933D bullet with its tangent ogive of similar height) and ~.90 for both the LBT bullet (with a 3 calibres ogive height) and the LFB bullet (with a 3.6 calibres ogive height but no BT).

For the LFB bullet, this value is “valid” (see the warning below) only in the supersonic domain, as this design induces a very high drag in the subsonic domain due to the combination of flat-base and large (but stable) in-flight angle of attack.

The bullet density was set at 8.5 g/cm$^3$, a typical value for the common 70/30 brass. A further performance increase could be achieved by using a higher density brass (8.74 g/cm$^3$ for the 90/10 alloy used for the “balle D” bullet for example).

<table>
<thead>
<tr>
<th>Bore and bullet diameter</th>
<th>MBT</th>
<th>LBT</th>
<th>LFB</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight (g)</td>
<td>G7 BC</td>
<td>Weight (g)</td>
</tr>
<tr>
<td>5.56 mm (.224&quot;)</td>
<td>3.9</td>
<td>.18</td>
<td>4.4</td>
</tr>
<tr>
<td>6 mm (.243&quot;)</td>
<td>5.0</td>
<td>.20</td>
<td>5.5</td>
</tr>
<tr>
<td>6.35 mm (.257&quot;)</td>
<td>6.0</td>
<td>.21</td>
<td>6.6</td>
</tr>
<tr>
<td>6.5 mm (.264&quot;)</td>
<td>6.5</td>
<td>.22</td>
<td>7.1</td>
</tr>
<tr>
<td>6.8 mm (.277&quot;)</td>
<td>7.4</td>
<td>.23</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Finally, 5 bullet diameters (5.56 mm, 6 mm, 6.35 mm, 6.5 mm, 6.8 mm bore, 7 mm and 7.62 mm have been removed because they were found too heavy) and 5 case body diameters (9.6 mm, 10.2 mm, 10.7 mm, 11.2 mm and 12.0 mm) were considered.

So, for each bore diameter studied, 15 combinations were investigated but only the most appropriate will be presented.

The i7 form factors used in this study need a word of caution. They are based on the application of similarity laws (the same shape giving the same form factor), whatever the bullet diameter.
Unfortunately, those (widely used) non-dimensional relationships, while true when the boundary layer thickness and boundary layer transition are small compared to projectile size, could fail in the case of small-arms bullets.

For example, keeping a constant ratio between the meplat diameter and the bullet diameter (around 0.15) means that the “optimum” meplat diameter of a 7.62 mm bullet is ~1.2 mm, while the “optimum” meplat diameter for a 5.56 mm bullet is ~0.9 mm.

This reduction in meplat diameter should be considered with caution, because instead of a single attached bow shock, the small amount of bluntness provided by the meplat is producing an additional detached bow shock (Figure 59, left) at “low” Mach number (less than Mach 3). This bow wave structure (detached and attached shock) produces two interesting aerodynamics effects:

- A slight reduction of the total nose drag (due to the flow overexpansion after the strong bow shock, Figure 59, right),
- A faster transition of the boundary layer from laminar flow to turbulent flow, due to the favourable pressure gradient. This transition avoids early flow detachment on the bullet boat-tail (if present).

Figure 59: Effect of the bullet tip bluntness on the bow shock structure (left) and pressure distribution along the bullet nose profile (right) [vi].

The positive effect of a bullet meplat (for a given ogive height and given bullet length), while empirically known since the end of the XIX century, could be seen below.
The projectile used was the 7.5 mm Mle 1924C flat-base bullet. In its ordinary form the meplat diameter is 1.2 mm. During this test, the bullet tip was first rounded, then pointed with a 100°, 80°, 70° and 60° angle, in order to try to increase the bullet BC.

Each time, 5 bullets were fired with the measure of the velocity at 25 m, and the time needed to go from 24 m to 200 m.

![Figure 60: Ordinary Mle 1924C bullet tip, rounded and pointed versions.](image)

Contrary to what was expected, pointing the bullet actually decreased the BC instead of increasing it, from .359 (G1, .593 i1 FF) with the original tip, down to only .322 (G1, .660 i1 FF) for the most pointy type (60°), a pretty significant decrease when the original goal was to increase it.

Experimental results seem to indicate that the optimum meplat diameter (in mm) is a function of the bullet length (in mm), and (as a rule of thumb) follows this relationship:

\[
Meplat\ diameter = \sqrt{3.5 - (0.055 \cdot bullet\ length)}
\]

The longer the bullet, the smaller the “optimum” meplat diameter.

So, the previous hypothesis (bullet form factor independent of the bullet diameter) is probably not true for the “smallest and shortest” bullets found in this study. Results shown for the .224” diameter (short, medium and long bullets), the .243” diameter (short and medium bullets) and the .257”, .264”, .277” diameters (short bullet) are probably overestimated.
**Results, 5.56 mm bore diameter (.224")**

This bore diameter achieved a good balance between short range accuracy (until the advent of “small case” 6 mm, the .222 Remington was considered the most accurate cartridge ever created) and great success for hunting varmints at extended range (the .220 Swift and the .22-250 immediately comes to mind if one want a great varmint cartridge). Success on medium-size game is more debatable (to the extent that some states prohibit the use of this bore diameter for that task), but with properly constructed and “heavy” bullets (around 5 g) this bore proved to be a good performer.

![Bullet comparison](Figure 61: Main characteristics (600 m Combined Distance From Centre, 600 m Kinetic Energy, Relative Suppression Index at 600 m and Specific Threatened Area at 600 m) for various incarnations of a 5.56 x 51 mm loaded with the 77 gr 5.5 calibres LFB.)

From a trajectory point of view, most of the 5.56 mm considered here deliver very good performance up to 800 m, but at the cost of very high heat load (generally higher than 20 kJ/cm²).

600 m impact energy with the LFB bullet is sufficient when loaded below 20 kJ/cm² but the suppression capability is far from both 0.50 m RSI or 50 m²/kg objectives.
It is interesting to see that if “putting more horsepower” (using a bigger case and powder load) behind the LBT and LFB bullets (hence increasing the heat load) helped achieving a better RSI at 600 m, the specific threatened area is following an opposite trend due to the law of diminishing return.

So, it seems that given the hypothesis made in this study, there is no “solution space” for this bore diameter.

Allowing the use of even heavier lead-core bullets (like the current 80 gr to 90 gr OTM commercial offering) launched at “sedate” muzzle velocity (700 m/s to 750 m/s) from a long and nearly cylindrical case (~8 mm casehead diameter) will produce good RSI and specific threatened area, but internal ballistics will be sub-optimum.
Results, the 6 mm bore diameter (.243")

In civilian shooting circles, the various 6 mm used for precision shooting (sometimes up to 1000 yards / 914 m) earned a wide acceptance due to their balance of low recoil and very good long-range performance, using bullets of 105 grains to 115 gr (6.8 g to 7.45 g).

As seen previously, this bore was considered “optimal” by the French army at the end of the 19th century (using a 99 gr to 102 gr very long lead-free bullet) and more recently (during the ‘70s) by the US Army with a 105 gr lead-core bullet.

<table>
<thead>
<tr>
<th>MV (m/s)</th>
<th>ME (J)</th>
<th>Heat (kJ/cm²) [max. 20]</th>
<th>Impulse (N.s) [max. 8.5]</th>
<th>CDFFC (m) [max. 1.03]</th>
<th>KE (J) [min. 720]</th>
<th>RSI (m) [min. 0.50]</th>
<th>STA (m²/kg) [min 50]</th>
</tr>
</thead>
<tbody>
<tr>
<td>.38&quot;</td>
<td>808</td>
<td>14.7</td>
<td>6.9</td>
<td>0.92</td>
<td>776</td>
<td>0.47</td>
<td>49</td>
</tr>
<tr>
<td>.40&quot;</td>
<td>834</td>
<td>16.7</td>
<td>7.3</td>
<td>0.86</td>
<td>840</td>
<td>0.49</td>
<td>47</td>
</tr>
<tr>
<td>.42&quot;</td>
<td>857</td>
<td>18.6</td>
<td>7.7</td>
<td>0.81</td>
<td>900</td>
<td>0.50</td>
<td>46</td>
</tr>
<tr>
<td>.44&quot;</td>
<td>880</td>
<td>20.6</td>
<td>8.2</td>
<td>0.76</td>
<td>961</td>
<td>0.51</td>
<td>45</td>
</tr>
<tr>
<td>.47&quot;</td>
<td>911</td>
<td>24.1</td>
<td>8.8</td>
<td>0.71</td>
<td>1046</td>
<td>0.53</td>
<td>44</td>
</tr>
</tbody>
</table>

Figure 62: Main characteristics (600 m Combined Distance From Centre, 600 m Kinetic Energy, Relative Suppression Index at 600 m and Specific Threatened Area at 600 m) for various incarnations of a 6 x49 mm loaded with the 97 gr 5.5 calibres LFB.

Just like the 5.56 mm bore, the trajectory of the 6 mm bore is very good but contrary to the 5.56 mm, heat loads lower than 20 kJ/cm² are reached even with bullet kinetic energy in the range of 2100 J to 2400 J.

Retained kinetic energy at 600 m is sufficient with LBT and LFB bullets but adequate suppression effects (0.5 m RSI) are achieved only with the heaviest (97 gr) LFB bullet (5.5 calibres long).
Results, the 6.35 mm bore diameter (\( .257'' \))

Unlike the 6 mm, this number is a strict medium game getter, and a very successful one (the .250 Savage and the .25-06 come to mind). The main consequence is that standard barrel twists commercially available are too long to properly stabilize high BC lead-free bullets.

<table>
<thead>
<tr>
<th></th>
<th>.38&quot;</th>
<th>.40&quot;</th>
<th>.42&quot;</th>
<th>.44&quot;</th>
<th>.47&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV (m/s)</td>
<td>749</td>
<td>776</td>
<td>800</td>
<td>823</td>
<td>855</td>
</tr>
<tr>
<td>ME (J)</td>
<td>2074</td>
<td>2222</td>
<td>2364</td>
<td>2501</td>
<td>2697</td>
</tr>
<tr>
<td>Heat (kJ/cm²) [max. 20]</td>
<td>14.7</td>
<td>16.7</td>
<td>18.6</td>
<td>20.6</td>
<td>24.1</td>
</tr>
<tr>
<td>Impulse (N.s) [max. 8.5]</td>
<td>7.1</td>
<td>7.6</td>
<td>8.0</td>
<td>8.4</td>
<td>9.1</td>
</tr>
<tr>
<td>CDFC (m) [max. 1.03]</td>
<td>0.92</td>
<td>0.86</td>
<td>0.81</td>
<td>0.76</td>
<td>0.71</td>
</tr>
<tr>
<td>KE (J) [min. 776]</td>
<td>785</td>
<td>858</td>
<td>927</td>
<td>995</td>
<td>1093</td>
</tr>
<tr>
<td>RSI (m) [min. 0.50]</td>
<td>0.51</td>
<td>0.53</td>
<td>0.54</td>
<td>0.56</td>
<td>0.58</td>
</tr>
<tr>
<td>STA (m²/kg) [min 50]</td>
<td>53</td>
<td>53</td>
<td>53</td>
<td>52</td>
<td>51</td>
</tr>
</tbody>
</table>

Figure 63: Main characteristics (600 m Combined Distance From Centre, 600 m Kinetic Energy, Relative Suppression Index at 600 m and Specific Threatened Area at 600 m) for various incarnations of a 6.35 x48 mm loaded with the 114 gr 5.5 calibres LFB.

The lack of commercial offering of barrels with short twist and good Match bullets is unfortunate because the .257" bore seems to be the smallest bore that could approach the needed level of performance at 600 m with a 5 calibres (not shown) to 5.5 calibres long bullet (between 102 gr and 114 gr), while still offering good trajectory, reasonable heat load (~16 kJ/cm²) and impulse (below 8 N.s).
Results, the 6.5 mm bore diameter (.264")

The 6.5 mm, once strictly a “military number” (6.5 x 50 mm Japanese, 6.5 x 52 mm Italian, 6.5 x 53 mm R Dutch & Romanian, 6.5 x 54 mm Greek, 6.5 x 55 mm Swedish, 6.5 x 58 mm Portuguese and also the experimental French 6.5 mm for the Meunier A5 rifle and the Russian 6.5 mm for the Fedorov rifle) is now widely used by civilian shooters for 1000 yards / 914 m competitions (6.5 x 47 mm, 6.5 mm Creedmoor, .260 Remington and the semi-wildcat 6.5-284 Norma), delivering better performance than the 6 mm with less recoil than the 7 mm.

![Graph showing characteristics of 6.5 mm bullets](image)

The 6.5 mm, once strictly a “military number” (6.5 x 50 mm Japanese, 6.5 x 52 mm Italian, 6.5 x 53 mm R Dutch & Romanian, 6.5 x 54 mm Greek, 6.5 x 55 mm Swedish, 6.5 x 58 mm Portuguese and also the experimental French 6.5 mm for the Meunier A5 rifle and the Russian 6.5 mm for the Fedorov rifle) is now widely used by civilian shooters for 1000 yards / 914 m competitions (6.5 x 47 mm, 6.5 mm Creedmoor, .260 Remington and the semi-wildcat 6.5-284 Norma), delivering better performance than the 6 mm with less recoil than the 7 mm.

![Graph showing characteristics of 6.5 mm bullets](image)

This bore diameter enables a wide choice of solutions with both MBT (6.5 g), LBT (7.1 g) and LFB (8.0 g) bullets, the best results (trajectory and energy) being achieved with the LBT bullet.

The LFB bullet (8 g) seems a little too heavy for optimum results, delivering more energy, RSI and specific threatened area than necessary at impulse level 0.2 N.s higher than with the LBT bullet.
At the lower end of the solution space, a body diameter of 10.2 mm (case capacity of 2.65 cm$^3$) will allow the firing the 7.1 g bullet at a calculated MV of ~810 m/s from a 508 mm barrel (ME ~2300 J).

At the higher end of the solution space a body diameter of 11.2 mm (in the same class as the 6.5 mm Japanese, 6.5 mm Italian or 6.5 mm Greek, with a case capacity of ~3.1 cm$^3$) will allow a calculated MV of 860 m/s from the same barrel length (ME ~2650 J).

Interestingly, the biggest case (12.0 mm case head) corresponds almost exactly to the commercial .260 Remington, and real world results indicate that although this cartridge easily outperforms the 7.62 mm NATO at long range, the reduction of recoil and ammunition weight will be minimal.
Results, the 6.8 mm bore diameter (.277")

Like the .257", this number is also mostly used for hunting and hence lacks a commercial offering of short barrel twist and long Match bullets, but at least very good low drag hunting bullets are available.

<table>
<thead>
<tr>
<th>MV (m/s)</th>
<th>.38&quot;</th>
<th>.40&quot;</th>
<th>.42&quot;</th>
<th>.44&quot;</th>
<th>.47&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>789</td>
<td>817</td>
<td>843</td>
<td>867</td>
<td>900</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ME (J)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2298</td>
<td>2464</td>
<td>2623</td>
<td>2775</td>
<td>2994</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat (kJ/cm²) [max. 20]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.4</td>
<td>13.0</td>
<td>14.6</td>
<td>16.3</td>
<td>19.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Impulse (N.s) [max. 8.5]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.7</td>
<td>8.2</td>
<td>8.7</td>
<td>9.2</td>
<td>9.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CDFC (m) [max. 1.03]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.05</td>
<td>0.97</td>
<td>0.90</td>
<td>0.85</td>
<td>0.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>KE (J) [min. 858]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>738</td>
<td>809</td>
<td>880</td>
<td>946</td>
<td>1041</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RSI (m) [min. 0.50]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.53</td>
<td>0.55</td>
<td>0.56</td>
<td>0.58</td>
<td>0.59</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STA (m²/kg) [min 50]</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>54</td>
<td>53</td>
<td>53</td>
<td>52</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 65: Main characteristics (600 m Combined Distance From Centre, 600 m Kinetic Energy, Relative Suppression Index at 600 m and Specific Threatened Area at 600 m) for various incarnations of a 6.8 x52 mm loaded with the 114 gr 4.5 calibres MBT.

Minimum threshold values for trajectory, retained energy and suppression effects are easily met with moderate heat load, with all bullets (7.4 g, 8.2 g, and 9.1 g) and case diameters of 10.7 mm and 11.2 mm to provide the muzzle velocity required (muzzle energy between 2620 J and 2775 J).
**Discussion**

In the beginning of this chapter, we have seen that the technical requirements of a 600 m GP round could be limited to only 4 parameters, one related to the trajectory (hit probability or near miss), one related to the impact energy (terminal effectiveness), and two related to suppression characteristics (90% suppression distance and specific threatened area) that are more or less equivalent for a given cartridge technology.

Those 3 parameters should be evaluated in regard to the heat load (muzzle report, practical rate of fire and system life) and impulse (weapon recoil and cartridge weight).

**Trajectory**

If we draw the 800 m CDFC as a function of the round heat load, we obtain the following result.

![Figure 66: 800 m “Combined Distance From Centre” as a function of the cartridge heat load (selected bullets).](image)

It’s easy to see why “small-calibre, high velocity” cartridges sparked so much interest, because on paper they could deliver reduced time of flight to target and a great increase of the hit probability against a moving target at unknown range.

But within the 20 kJ/cm² limit, the best trajectory for a given heat load is given by the 6 mm, 6.35 mm and 6.5 mm loaded with a “long” bullet (LFB or LBT) or the 6.8 mm and 7 mm loaded with a MBT bullet.

As could be seen, in .224”, .243”, .257” and .264” diameter, the “long” bullet is delivering the best results, while for the .277”, .284” and the .308”, the “medium” bullet is better for the envisioned 600 m to 800 m range due to the higher muzzle velocity.
Retained energy

Looking at the retained energy at 600 m as a function of the cartridge impulse (Figure 67), we see that below 7.2 N.s, the 6 mm bore (using the 5.5 g LBT bullet) delivers more energy for a given impulse value than the other combinations considered.

Between 7.5 N.s and 9.2 N.s, the 6 mm is superseded by the 6.5 mm bore (using the 7.1 g LBT bullet) then for impulse higher than 9.2 N.s the 6.5 mm is superseded by the 7 mm.

![Figure 67: 600 m impact energy as a function of the cartridge impulse.](image)

The .257” and .277”, while not represented on this graph for ease of reading, are very close to the .264” curve and represent local “optimum” between 7.2 N.s and 7.8 N.s (for the .257”) and between 8.5 N.s and 9.2 N.s (for the .277”).

Suppression

If trajectory (as a function of cartridge heat load) and retained energy (as a function of cartridge impulse) show the existence of an “optimum” calibre choice as a function of the range of heat load and impulse (high heat load and low impulse favour the 6 mm, low heat load and high impulse favour the 7 mm, the 6.5 mm being in between), suppression seems to be an extensive value and clearly favoured the “bigger is better” approach.

Similar to trajectory and retained energy, calculated suppression index also shows a significant advantage for “long” bullets at a range of 600 m (Figure 68) for bore diameter below 6.5 mm. For the 6.8 mm and 7 mm, the “medium” bullet will deliver sufficient terminal effects with less weight.
The smallest bore that could reach the 0.5 m threshold (with a 5 calibres lead free bullet) is the 6.35 mm. The 6.5 mm (using a “long” bullet) and 6.8 mm (using a “medium” bullet) deliver very similar results.

If around 8 N.s (impulse), the 6.5 mm showed superior external ballistics and retained energy, it seems that the larger bullet diameter and increased bullet weight of the 7 mm would deliver better suppression effects, close to those of the 7.62 mm M80 for heat load around 15 kJ/m².

Due to the good external ballistics of the 6.5 mm (that reduces fire dispersion due to range errors and wind drift), the effective difference between the 6.5 mm and 7 mm is small, as seen in Figure 69 comparing the suppression probability of a “long” 6.5 mm bullet delivering 2500 J at the muzzle and a “medium” 7 mm bullet delivering 2650 J at the muzzle (using AB Analytics WEZ software in a “low confidence” scenario and a system dispersion of 25 MoA, as found in ORO-T-160).

Figure 68: Calculated 90% suppression distance as a function of the cartridge heat load, 600 m range.
Figure 69: Expected suppression probability of the 5.56 mm NATO, a generic 6.5 mm (2500 J), a generic 7 mm (2650 J) and the 7.62 mm NATO.

Technical solutions
The smallest combination of parameters that fills the “solution space” combines the 6.35 mm bore and a ~10.2 mm case head similar to the Russian 5.45 x 39 mm (but 48 mm long), firing the LFB bullet.

The calculated MV of 780 m/s from a 508 mm long barrel (2200 J) would give an impact energy of 808 J (776 J minimum) with a heat load of 14.9 kJ/cm² (20 kJ/cm² maximum). The remaining velocity at 600 m would be around 490 m/s.

Figure 70: Simplified drawing of the 6.35 x 48 mm (courtesy M.J. Nordhaus).
The expected cartridge weight is around 16.8 g for the conventional brass version (11.8 g for a fully developed composite case version, using a short brass head and a polymer body), making it the lightest combination meeting all requirements.

With a RSI(90%) of 0.53 m at 600 m, the specific suppressed area for a brass version is around 53 m²/kg, nearly as effective per kg of ammo as the current 7.62 mm NATO (60 m²/kg at 600 m and 50 m²/kg at 700 m), and a very good 75 m²/kg for a composite case version.

Unfortunately, this combination will also require to use i)- a custom case and ii)- a custom .257” barrel with a twist short enough to stabilize the L/D=5.5 long bullet.

If the lack of cases, barrels and Match bullets in this diameter is too much of a problem, two (nearly equivalent) solutions exist, using the widely available .30 Remington case and a “long” 6.5 mm bullet (7.1 g), or a “medium” 6.8 mm bullet (7.4 g).

The 6.5 mm variant will allow a MV around 830 m/s (ME ~2500 J, powder load 2.07 g), the duplication of the 7.62 mm NATO retained energy between 600 m and 1200 m, a better trajectory and a 600 m impact velocity of 500 m/s. This round will weight around 18.3 g for a conventional brass case version (1.5 g more than the .257” version), and 12.8 g for a composite case version.

The 6.8 mm variant will allow a slightly higher MV (around 845 m/s, ME ~2650 J, powder load 2.14 g, 600 m impact velocity of 490 m/s) and a weight around 18.8 g for a brass case version (2 g more than the .257” version), and 13.1 g for a composite case version.

Figure 71: Simplified drawing of the 6.5 x 50 mm (top) and 6.8 x 51 mm (bottom) (courtesy M.J. Nordhaus).
Given the very similar performance achieved, the choice between a 7.1 g “long” 6.5 mm bullet and a 7.4 g “medium” 6.8 mm bullet is a matter of personal preference and access to available hardware.

While significantly heavier than the 5.56 mm NATO in a brass case configuration, the expected suppressive effect of those two rounds is also significantly larger so the suppressed area per round and per kg of ammo is significantly higher (equivalent to the 7.62 mm NATO).

**2.26” COAL design space results**

**Bullet design**
Due to the demonstrated interest of the “longest possible” bullet, only two bullet lengths were investigated, a “medium” bullet (4½ calibres long) and a “long” bullet (5 calibres long). The shape was the same as used in the 2.8” COAL case, but instead of solid brass the bullets were composed of a steel arrow and a brass shoe, so the density was lower than 8.5 g/cm³, reducing bullet weight and BC accordingly.

<table>
<thead>
<tr>
<th>Bore and bullet diameter</th>
<th>Medium bullet</th>
<th>Long bullet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight (g)</td>
<td>G7 BC</td>
</tr>
<tr>
<td>5.56 mm (.224&quot;)</td>
<td>3.8</td>
<td>.17</td>
</tr>
<tr>
<td>6 mm (.243&quot;)</td>
<td>4.7</td>
<td>.185</td>
</tr>
<tr>
<td>6.35 mm (.257&quot;)</td>
<td>5.6</td>
<td>.195</td>
</tr>
</tbody>
</table>

Finally, 3 bullet diameters (5.56 mm, 6 mm and 6.35 mm bore diameter) and 5 case body diameters (9.6 mm, 10.2 mm, 10.7 mm, 11.2 mm and 12.0 mm) were considered.

So, for each bore diameter studied, 10 combinations were investigated.

Compared to the 2.8” COAL, the muzzle velocity of the 2.26” COAL was still evaluated with the Powley computer but with a 16” barrel length (carbine).
Results, the 5.56 mm bore diameter (.224")
Due to the more efficient bullet construction, the required trajectory and retained energy are easily achieved with heat loads lower than 20 kJ/cm², but this bore diameter still fail to deliver the level of suppressive effects needed at 600 m.

Figure 72: 800 m CDFC (left), 600 m energy (centre) and 600 m RSI (right) of the 5.56 mm bore.

The weight reduction from 4.4 g (2.8" COAL) to 4.1 g (2.26" COAL) and subsequent reduction of BC moderately reduced the RSI(90%) at 600 m, from 0.39 m (with a heat load of 21.1 kJ/cm²) to only 0.34 m (with a heat load of 19.9 kJ/cm²), a ~25% reduction in the suppressed area per round.
Results, the 6 mm bore diameter (.243")

Compared to the 2.8" COAL case, the reduced muzzle energy allows all combinations to stay below 20 kJ/cm², but only the rounds with case heads larger than 10.7 mm could deliver the needed bullet trajectory to 800 m. Suppression effects are markedly improved but the minimum level of 0.4 m is achieved only with the “long” bullet loaded in something close to the 6 mm BR case (12.0 mm casehead).

Figure 73: 800 m CDFC (left), 600 m energy (centre) and 600 m RSI (right) of the 6 mm bore.

The weight reduction from 5.5 g (2.8” COAL) to 5.2 g (2.26” COAL) and subsequent reduction of BC reduced the RSI(90%) at 600 m, from 0.46 m (with a heat load of 18.4 kJ/cm²) to slightly below 0.40 m (with a heat load of 17.7 kJ/cm²), a ~25 % reduction in the suppressed area per round.
Results, the 6.35 mm bore diameter (.257")

While all combinations are delivering a comfortable level of retained energy, only the 11.2 mm and 12 mm cases allow a sufficient case capacity to drive the "medium" and "long" bullets fast enough to achieve a trajectory flat enough. While still lower than required, suppression effects at least reach the minimum level of 0.4 m, but the 0.5 m threshold is out of touch.

Figure 74: 800 m CDFC (left), 600 m energy (centre) and 600 m RSI (right) of the 6.35 mm bore.

The weight reduction from 6.6 g (2.8" COAL) to 6.2 g (2.26" COAL) and subsequent reduction of BC reduced the RSI(90%) at 600 m, from 0.48 m (with a heat load of 14.9 kJ/cm²) to 0.44 m (with a heat load of 14.6 kJ/cm²).
**Technical solutions**

The use of a more effective bullet structure greatly reduce the required muzzle energy and the 2.26” COAL limits accompanying heat loads of the smaller calibres (.224” and .243”), increasing the “solution space”, but unfortunately the slight reduction of bullet weight (and BC), combined with the reduction of the barrel length (16” instead of 20”), have a negative effect on the suppression potential.

The balance between trajectory, retained energy and suppression requirements is not easy to reach. The 6 mm bore shows good trajectory and retained energy but low suppression (according to the RSI factor, the most powerful 6 mm combination studied, a 6 mm BR equivalent, could barely duplicate at 600 m what the 7.62 mm NATO is delivering at 1000 m), while the 6.35 mm bore is soon restricted by its arcing trajectory (not enough muzzle velocity, except for the biggest case). Maybe a diameter in between (~6.2 mm?) could help, but before trying to develop something totally new let’s have a deeper look at the various 6 mm and 6.35 mm solutions available.

The 0.5 m threshold needed to duplicate the 700 m 7.62 mm NATO suppressive effects is never reached, but a 0.4 m “closest equivalent” is met with the .257” bore, and is closely approached with the 3 “biggest” 6 mm, one based on a shortened 6.8 mm SPC case (6 mm SPC wildcat equivalent), one based on the 7.62 x 39 mm case (6 mm PPC or 6 mm AR equivalent), and the biggest one based on the “fat” Bench Rest case (6 mm BR equivalent).

For the 6 mm bore, the predicted muzzle velocity of the 5.2 g bullet is 817 m/s; 835 m/s and 859 m/s respectively, the remaining velocity at 600 m is 447 m/s, 461 m/s and 478 m/s respectively. The RSI(90%) of those 3 cartridges at 600 m is very close (0.37 m; 0.39 m and 0.40 m) and the lightest one (using the SPC case) is also the one delivering the highest specific suppressed area (27 m²/kg, expected cartridge weight of 14.1 g for a brass case version).

With the 6.35 mm, the smallest combination of parameters that approach the “solution space” combines the 6.2 g “long” bullet and a necked-down Russian 7.62 x 39 mm case slightly shortened. The calculated MV of 780 m/s from a 406 mm long barrel (1900 J) would give impact energy of 600 J with a very low heat load of 12.6 kJ/cm² (20 kJ/cm² maximum). The predicted remaining velocity at 600 m is 440 m/s, but with modern powder and a slightly higher chamber Maximum Average Pressure a velocity of 450 m/s could be safely achieved.

![Figure 75: Simplified drawing of the 6.35 x 38 mm (courtesy M.J. Nordhaus).](image-url)
The expected cartridge weight is around 15.7 g, making it significantly lighter than the 2.8” COAL technical solutions, but with a RSI(90%) of 0.43 m, the expected specific suppression area is only 27 m²/kg, a slight improvement over the 21 kg/m² of the 5.56 mm NATO but no better than the lightest 6 mm described previously (based on the SPC case) and still very far from the 50 m²/kg of the 7.62 mm NATO.

It seems that with this current set of parameters (2.26” COAL, 16” barrel and lead-free bullet), it’s impossible to find a technical solution that could replace both 5.56 mm and 7.62 mm NATO.

**Cartridge design conclusion**

It is no surprise that the best results in this study were obtained with the 6.35 mm, 6.5 mm and 6.8 mm bores with a COAL of 2.8”.

The 6.35 mm and 6.5 mm need a “long” bullet (7.4 g LFB and 7.1 g LBT respectively) to achieve the best results and could be considered the lightest technical solutions, since they will deliver the highest impact energy at 600 m for impulse value below 8.5 N.s.

The 6.8 mm and the 7 mm are probably best used with the “medium” bullet (7.4 g and 8.1 g respectively). Those two bores will deliver the highest impact energy at 600 m for impulse value above 8.5 N.s and also good suppression capability, but with recoil a little higher than with the 6.35 mm and the 6.5 mm bore.

The “optimum” case capacity for both bore diameters is in the vicinity of 2.9 – 3.1 cm³, with predicted muzzle energy of 2500 – 2700 J out of a 508 mm barrel.

For example, a 51 mm long case with a body diameter of 10.7 mm (essentially the full-length .30 Remington case necked down to 6.5 mm, case capacity of 2.9 cm³), firing the “long” 7.1 g bullet at a calculated MV of 835 m/s, will allow (compared to the current 7.62 x 51 mm M80):

- a lighter round (19 g vs. 24 g) using existing technologies and a brass case,
- a reduced recoil (8.3 N.s vs. 11.6 N.s), due to the reduced bullet weight and powder load,
- a better trajectory at all distances (less bullet drop and 25% less wind drift),
- the same bullet sectional density and higher impact velocity at all ranges, giving better tactical penetration,
- the same impact energy at 600 m and up,
- Equivalent suppression capability per kg of ammo (brass version) and significantly better capability with a lightweight case,
- longer supersonic range (1000 m vs. 800 m).
Those findings are very similar to those obtained in the CRC 307 study.

Of course, if one was to adopt a new round, it would be highly advisable that this new round case geometry should allow (from the beginning) the easy use of a light polymer (or composite) case.

A polymer case (with a light alloy case head) could:

- be tailored so that case capacity exactly fits the powder load and avoids free volume, decreasing shot-to-shot dispersion and improving internal ballistics,
- reduce the heat transfer from the cartridge to the chamber due to their low heat conductivity,
- reduce the weight of a given round by ~30-35% compared to conventional brass cased ammunition.

The cartridge described above, with a composite case and a slightly greater body diameter (~11.2 mm) to account for the internal volume loss due to the polymer body, is expected to be no heavier than the current 5.56 x 45 mm SS-109.
Part Four: And now? Current development

Due to the urgent need to replace the ageing FAMAS F1 assault rifle (produced between 1979 and 1989), the French army has decided to keep the 5.56 mm NATO round for the AIF (Arme Individuelle Future) and supplement it with two 7.62 mm weapons, the DMR “FPSA” (Fusil de Précision Semi-Automatique) and the LMG “FM 7.62” (Fusil Mitrailleur 7.62) for “medium to long-range” (400 – 800 m) fire support.

This mix of 5.56 mm and 7.62 mm weapons is expected to remain in service at least up to 2040.

The current limitations of the 7.62 x 51 mm M80 round (weight and recoil) are well known and a small-scale study (supported by the “Mission Innovation Participative” of the French MoD) was launched to find a way to improve this round for dismounted infantry operations.

Experimental validation of previous findings

As stated before, the key point for improving small-arms ammunition performance is to reduce the bullet drag compared with current designs. Reducing the drag will enable, for a given impact energy at a given distance, a reduction in the required muzzle energy, hence reductions in the powder load, bullet weight, ammunition weight and recoil.

Several bullet shapes were investigated and Doppler radar was used to check the actual bullet drag when fired from real small-arms (Figure 76).

Figure 76: Doppler radar measurement of seven shots recorded with the best supersonic shape tested, compared with the G7 drag curve (form factor = 1).
The best shape was found to closely follow the G7 curve (in the supersonic domain) with an i7 form factor of 0.79, a 30% reduction of drag compared to current 7.62 mm M80 bullet (i7 form factor of 1.12).

The long boat-tail of this bullet impaired its dynamic stability below Mach 0.80 but this phenomenon did not degrade significantly the accuracy at long range.

Unfortunately, this bullet was also very long (L/D ~5.4 calibres) and was found unstable when fired in “cold” conditions (-40°C), so this design was not usable for a “general purpose” bullet and further test focused on L/D close to 5.

Due to the availability of a large number of weapons already chambered for several 6.5 mm wildcats ranging from the small 6.5 mm TCU (case capacity of ~2.1 cm³), to the massively overbore 6.5-300 Winchester Magnum (case capacity of 5.35 cm³), this bore diameter was selected for running some additional experimental validation and two lots of 6.5 mm bullets were manufactured, keeping the same proportions as the previous bullet in a more compact shape.

![Figure 77: Example of manufactured bullets (left, 6.8 g “hybrid” ogive, right 7.5 g tangent ogive)](image)

Three bullet nose-shapes and brass grades were tested:

- A deeply grooved, hybrid nose, boat-tail, “light” one (6.8 g) with a high zinc content (common machining brass with 3% lead),
- A deeply grooved, tangent nose, boat-tail, “heavy” one (7.5 g) with a low zinc content (lead content < 0.1%),
- A deeply grooved, hybrid nose, flat-base, “light” one (6.7 g) with a high zinc content (lead content < 0.1%).

Those bullets were loaded in various weapons, with different MV:
Very good results were achieved with a compressed powder load of ~1.8 g and the 6.5 mm TCU case. Due to the limited number of available bullets no effort was made to test different type of powders, loading densities and bullet jump.

The reloading process was limited to basically removing the bullet and powder from a 5.56 mm military round, expanding the case neck to the correct diameter, putting back the original powder load (minus a fraction of a gram to account for the extra bullet intrusion due to the long boat-tail) and seating a new 6.5 mm bullet on top of that.

With this powder load, the best results were achieved with the 6.8 g bullet. The accuracy of this load was found to be very good, with typical 3 shot groups smaller than 1 minute of angle (MoA) at 300 m (Figure 78).

![Figure 78: Typical groups at 100 m (left) and 300 m (right) with the 6.8 g bullet (0.6 MoA).](image)

Typical powder loads were around 1.50-1.55 g for the wildcat 6.5-357" (.357 Magnum case necked down to .264"), around 1.75-1.80 g for the wildcat 6.5 mm TCU, around 2.40 g for the .260 Remington and 4.10 g for the .264 Winchester Magnum.

A Doppler radar was used to track bullets during ~12 s of flight, covering between 2450 m and 3300 m of horizontal range (flat-fire shooting conditions) depending on bullet type and muzzle velocity.
I7 form factor for the 105 gr HBT and 103 gr HFB are shown in Figure 79 and Figure 80, along with the G7 BC (rounded to nearest 0.005) found in 5 velocity bands (below Mach 0.8; between Mach 0.8 and 0.95; between Mach 0.95 and Mach 1.5; between Mach 1.5 and Mach 2.5, and higher than Mach 2.5 if significant results were found). The drag penalty for flat-base bullet in the subsonic domain is obvious.

Figure 79: Drag curve for the 105 gr Hybrid Boat Tail and fitting of the G7 and G1 curves in the supersonic domain.

Figure 80: Drag curve for the 103 gr Hybrid Flat Base and fitting of the G7 curve in the supersonic domain.
"Improved" bullet (I-HFB and I-TBT) were slightly modified for increasing bullet flight stability.

It could be seen that for a given bullet length, flat-base design could be very competitive in the supersonic domain and down to Mach 0.95, but for very long range performances (around 2 km and up) a boat-tail bullet will deliver significantly lower time of flight when loaded to the same muzzle energy.

<table>
<thead>
<tr>
<th></th>
<th>Static stability</th>
<th>M&lt;0.80</th>
<th>0.80&lt;M&lt;0.95</th>
<th>0.95&lt;M&lt;1.50</th>
<th>1.50&lt;M&lt;2.50</th>
<th>2.50&lt;M&lt;3.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>103 HFB</td>
<td>1.6</td>
<td>0.085</td>
<td>0.140</td>
<td>0.225</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>103 I-HFB</td>
<td>1.7</td>
<td>0.085</td>
<td>0.140</td>
<td>0.230</td>
<td>0.240</td>
<td>0.250</td>
</tr>
<tr>
<td>105 HBT</td>
<td>1.4</td>
<td>0.165</td>
<td>0.165</td>
<td>0.235</td>
<td>0.225</td>
<td></td>
</tr>
<tr>
<td>115 TBT</td>
<td>1.3</td>
<td>0.150</td>
<td>0.150</td>
<td>0.240</td>
<td>0.230</td>
<td></td>
</tr>
<tr>
<td>115 I-TBT</td>
<td>1.4</td>
<td>0.150</td>
<td>0.150</td>
<td>0.255</td>
<td>0.245</td>
<td>0.245</td>
</tr>
</tbody>
</table>

Local conditions: pressure 1013 hPa; temperature 9.6°C; RH 100%.

Tactical penetration was evaluated at a distance of 200 m against a brick wall, a concrete masonry unit (CMU) and autoclaved aerated concrete (AAC) (Figure 81) in comparison with 7.62 x 51 mm ball, both bullets having the same impact velocity at 200 m (around 700 m/s).
Penetration in all media was identical or better with the 6.5 mm bullet (105 HBT) than with the 7.62 mm bullet.

Due to range limitations, it was not possible to evaluate tactical penetration at 400 m and 600 m, but it is thought that the 6.5 mm solid bullet, with a sectional density close to the 7.62 mm FMJ and a higher impact velocity due to a lower drag, will show at least the same level of performance.

Even if this study was far from being exhaustive (only ~700 bullets were manufactured and fired for the determination of the accuracy, ballistic coefficients and tactical penetration), those experimental results showed that the overall performance of the 7.62 x 51 mm ball ammunition could be duplicated in a much smaller and lighter package, the degree of the size reduction being a function of the weapon’s barrel length.

For example, the 103 gr HFB bullet fired from a 6.5 mm TCU case in a 28” barrel delivered equal retained energy between ~650 m and ~950 m and a better trajectory as the 7.62 mm DM41 ball (24-25 g cartridge) when fired from a 22” barrel, with a cartridge weight slightly less than 15 g (6.7 g bullet, 1.8 g powder load and 6.2 g for the case and primer). An extreme case (but quite impractical) was the small 6.5-357” cartridge (~13 g cartridge, 57.4 mm COAL) delivering (from a 28” barrel) the same energy as the 7.62 mm DM41 when fired from a 16” barrel, between 650 m and 950 m.
Given a cost of brass case small-arms ammunition around 0.02 € per gram (~0.25 € for the 5.56 mm NATO, ~0.50 € for the 7.62 mm NATO) and the expected service life of 15,000 rounds for an IW and around 60,000 rounds for a MG, a 15 g cartridge will present a cost increase of 750 € per IW, and a cost reduction of 12,000 € per MG (cost neutral for 16 IWs per MG). A 17 g cartridge will present a cost increase of 1,350 € per IW, and a cost reduction of 9,600 € per MG (cost neutral for 7 IWs per MG).

An improved 7.62 x 51 mm load, the 7.62 x 43 mm “neckless”

This “improved” round should be as light as possible, with reduced recoil, but more importantly should be compatible with existing weapons.

In addition to the requirements found in the Multi Calibre MOPI, the bullet needs to be stable in the 305 mm twist used in the NATO nominated L7A2 MG (and in most 7.62 mm NATO weapons).

The lower bound of bullet weight is 8.4 g and minimum energy is 2756 J at 24 m (810 m/s) from a 22” (560 mm) barrel.

The objective, to reduce both cartridge weight and recoil without reducing the terminal effects, leads to the reduction of the bullet and powder load weight and at the same time an increase of the bullet BC, and also the ability to use a much lighter cartridge case.

This could be achieved using a bullet with a much lower form factor than the ~1.1 (i7) form factor of the current M80 bullet, and with the replacement of the brass case with a composite case (polymer body and light alloy case head).

The geometry of the 7.62 x 51 mm cartridge puts a strict limit on the maximum ogive height (2.5 calibres), and the geometry of a “bottle shaped” cartridge neck is a perfect example of a concentration of mechanical constraints, which makes the manufacture of a reliable polymer case body difficult.

So, the basic idea of the “neck less” ammunition was to simply forget about the cartridge neck and make the mechanical link between the bullet and the case in the case shoulder area (Figure 82).

Figure 82: Sketch of a “neckless” 7.62 x 43 mm round in a conventional 7.62 x 51 mm chamber.
This design was successfully tried 30 years ago by the AAI Corporation for 20 mm and 25 mm medium calibre ammunition \[^{viii}\], but unfortunately the reduction in the case capacity did not allow the required muzzle velocity to be achieved.

![Figure 83: Example of AAI Corporation 25 mm ammunition (1973 manufacture) with neckless composite case (left), a 6.5 mm neckless round based on the 7.62 x 51 mm case (centre) and a 6.5 mm CT (showing the reduced volume of the CT round compared to more conventional case, courtesy of Textron Systems Unmanned Systems).](image)

The reduction in the case capacity will limit the muzzle velocity and muzzle energy, but will also enable a large increase in the ogive height and a reduction in the bullet drag.

The manufacturing process for neckless ammunition will be also different from that for conventional ammunition.

The polymer case body will be over-moulded directly onto the bullet shank for a good mechanical link between the bullet cannelure and the case body.

The powder will be loaded from the rear of the case (with loose powder or with a pre-compressed block) then the case will be closed with the light alloy base supporting a conventional primer.

Of course, this choice is not without drawbacks:

- The case capacity is severely reduced, hence a lower muzzle energy.
- The “bullet jump” (freebore) is significantly lengthened and could reduce accuracy.
- The “light and long” bullet still needs to be properly stabilized by the 305 mm twist.
In order to minimize those points, it is expected than:

- Even with a large reduction in case capacity (due to the shorter case and thicker walls), the composite case internal volume would be perfectly suited for a 2.2 - 2.4 g powder load (compared to 2.9 – 3.0 g for the M80 load) which (as found in part 2) would be sufficient for proper 600 m performances.
- The bullet weight is reduced from 9.5 g to 8.5 g but the improvement in the form factor in the supersonic domain would be enough to actually increase the overall bullet ballistic coefficient, enabling a supersonic range a little higher than 800 m in standard OACI atmosphere.
- The choice of bullet nose shape and centre of gravity (CoG) would enable the “self-centring” of the bullet and minimize in-bore yaw.
- The bullet’s flat base would reduce sensitivity to flow dissymmetry at the gun’s muzzle and improve the accuracy compared with a boat-tailed bullet. This geometry also improves significantly the bullet gyroscopic and dynamic stability in all flight regimes. The drag in the subsonic regime is increased but this effect would be significant only at very long range (higher than 1500 m).

A few hundreds of a 130 gr flat (and hollow) base bullet with a length of 33.5 mm and a nose of 23.5 mm were manufactured and fired from 7.62 x 51 mm weapons. The powder load was changed in order to cover a range of MV between 770 m/s and 850 m/s.
**External ballistics results**

The climate of the test-range did not allow for truly "low temperature" investigations, but shots were fired at a low MV (770 m/s) to slightly reduce the gyroscopic stability and evaluate a kind or "worst case" scenario.

![Graph](image)

**Figure 84**: Drag curve for the 130 gr Hybrid Flat Base and fitting of the G6 and G7 curves in the supersonic domain.

The measured G7 BC from Mach 0.95 up to Mach 2.5 was 0.198 (i7 form factor of 0.99), lower than expected but still similar to current M80 ball (0.197).

The static muzzle stability was higher than 1.90 even in very cold conditions (−40°C), so the in-flight stability is very good.

Common to every flat base bullet, a small precession phenomenon could be seen at low Mach number (<0.80).

Contrary to most 6.5 mm bullets tested, the shank of this bullet was not so deeply grooved and the drag coefficient at low Mach number was around 0.25, compared to ~0.30 for grooved flat base bullets (inducing bigger precession in the process, probably due to the thicker boundary layer and bigger Magnus effect) or ~0.20 for grooved boat tail bullets.
Terminal ballistics results

Bullets were fired into “Permagel” and NATO 20% gelatine blocs, at various MV. In the whole range of impact velocity tested, the behaviour of the bullet remains constant.

The internal trajectory is curved and the bullet exits a 25 cm x 25 cm x 50 cm bloc from its lateral faces, without fragmenting and with minor deformations (Figure 85).

![Figure 85: the 130 gr HFB bullet after impacting a “Permagel” block.](image)

After impacting a 30 cm x 30 cm x 30 cm gelatine block with an initial yaw angle less than 0.5°, the bullet is reaching 90° yaw after ~23 cm (or 30 bullet diameters, Figure 86).

![Figure 86: The 130HFB bullet impacting a 20% gelatine block, i) initial trajectory inside the block, ii) bullet, at full yaw, iii) maximum temporary cavity after ~4 ms and iv) permanent cavity.](image)
The future?

The previous results obtained with a brass 6.5 mm bullet showed that it was possible to “easily” duplicate the 7.62 x 51 mm ball terminal performance with a bullet weight around 7 g, and at the same time achieving better hit probability (see part 2), so it was decided to investigate a 6.5 mm version of the 7.62 x 43 mm “neckless” ammunition which could be used in existing guns chambered for the 260 Remington round.

Figure 87: Sketch of a “neck less” 6.5 x 43 mm round in a conventional .260" Remington chamber.

Compared with the current 7.62 x 51 mm ball ammunition, this round is expected to show reduced recoil (25% less) and an improved trajectory (30% less wind drift and 10% less ToF to 600 m), both factors leading to an increase in the hit probability, an extended supersonic range (up to 1 km) and reduced weight (45% less, making this round just 5% heavier than the current 5.56 mm).

While this design enables a quick conversion of weapons chambered for the 7.62 x 51 mm with just the change of the barrel, a longer case (45-47 mm) with a reduced body diameter (10.7 – 11.2 mm instead of 12 mm) would probably be a better choice for a general purpose cartridge (allowing for 25-round magazines instead of 20 rounds with the 12 mm case head).
Appendix A: Characteristics of historical cartridges

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>8 mm Lebel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>Mle 1886M</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>8.3</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>8.15</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>30</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>15.0</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>1.55 (est.)</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>74.3</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>29.5</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>630</td>
</tr>
<tr>
<td>ME (J)</td>
<td>2980</td>
</tr>
</tbody>
</table>

Figure 88: The 8 mm Lebel with the original Mle1886M bullet, the Mle 1898D bullet, the n°405 bullet that should have been adopted in 1914 and the Mle 1932N.

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>6 mm APX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>N°30</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>6.28</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>6.24</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>34.4 (5.51)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>6.60</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>0.82 (est.)</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>84.4</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>22.0</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>878</td>
</tr>
<tr>
<td>ME (J)</td>
<td>2540</td>
</tr>
</tbody>
</table>

Figure 89: The 6 x 60 mm with the n°30 bullet as proposed for adoption around 1900.
### Cartridge Specifications

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>6.5 x 61 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>N°123</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>6.75</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>6.73</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>36.0 (5.35)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>7.5</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>0.96 (est.)</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>80.8</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>22.6</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>979</td>
</tr>
<tr>
<td>ME (J)</td>
<td>3570</td>
</tr>
</tbody>
</table>

**Figure 90:** The 6.5 x 61 mm with the N°123 bullet as tried in 1912.

---

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>7 mm Meunier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>Type 307</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>7.30</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>7.29</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>37.0 (5.07)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>9.05</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>0.97 (est.)</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>79.0</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>23.9</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>856</td>
</tr>
<tr>
<td>ME (J)</td>
<td>3320</td>
</tr>
</tbody>
</table>

**Figure 91:** The 7 mm Meunier with the N°307 bullet as used in 1916.
| Cartridge            | 7.5 mm Mle 1929  
<table>
<thead>
<tr>
<th></th>
<th>7.5 x 54 mm MAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>Mle 1924C</td>
</tr>
<tr>
<td></td>
<td>Mle 1933D</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>7.82</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>7.80</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>27.3 (3.5)</td>
</tr>
<tr>
<td></td>
<td>37.0 (4.74)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>9.05</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>1.14</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>76.1</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>23</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>840</td>
</tr>
<tr>
<td>ME (J)</td>
<td>3370</td>
</tr>
</tbody>
</table>

Figure 92: The steel case 7.5 x 54 mm with the Mle 1924C and 1933D bullets.

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>8 mm Ribeyrolles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>8 mm AP</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>8.30</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>8.32</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>32.5 (3.91)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>9.6</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td></td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>59</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>20.4</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>~500</td>
</tr>
<tr>
<td>ME (J)</td>
<td>1200</td>
</tr>
</tbody>
</table>

Figure 93: “best guess” estimates of the 8 mm Ribeyrolles with the “P” bullet, no data provided for the 600 m range due to unknown bullet behaviour in the subsonic domain.
Figure 94: The 7.62 x 51 mm Mle 1961 (steel case) and the 5.56 x 45 mm F1A (*: velocity measured from the FAMAS F1 with ammunition lot produced during the '80s, ammunition lots produced in the '70s were hotter).

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>5.56 x 45</th>
<th>7.62 x 51</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet</td>
<td>F1A</td>
<td>Mle 1961</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>5.71</td>
<td>7.82</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>5.71</td>
<td>7.84</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>19.4 (3.40)</td>
<td>29.5 (3.77)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>3.5</td>
<td>9.55</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>1.22</td>
<td>1.04</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>56.2</td>
<td>71.1</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>11</td>
<td>22.5</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>959*</td>
<td>840</td>
</tr>
<tr>
<td>ME (J)</td>
<td>1610</td>
<td>3370</td>
</tr>
</tbody>
</table>

Figure 95: The experimental 5.56 mm MSD (caseless).

<table>
<thead>
<tr>
<th>Cartridge</th>
<th>5.56 mm MSD / PUC300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet type</td>
<td>NA</td>
</tr>
<tr>
<td>G2G diameter (mm)</td>
<td>5.71</td>
</tr>
<tr>
<td>Bullet diameter (mm)</td>
<td>4.0</td>
</tr>
<tr>
<td>Bullet length (mm)</td>
<td>16.4 (4.10)</td>
</tr>
<tr>
<td>Bullet weight (g)</td>
<td>1.3</td>
</tr>
<tr>
<td>Bullet i7 FF (M&gt;1.2)</td>
<td>1.01 (est.)</td>
</tr>
<tr>
<td>Cart. length (mm)</td>
<td>39.4</td>
</tr>
<tr>
<td>Cart. Weight (g)</td>
<td>4.2</td>
</tr>
<tr>
<td>MV (m/s)</td>
<td>1200</td>
</tr>
<tr>
<td>ME (J)</td>
<td>936</td>
</tr>
</tbody>
</table>
Appendix B: Performances of historical cartridges

CB G7 (supersonic domain)

600 m Kinetic Energy (J)
Appendix C: References

5. "Rapport sur deux fusils de 6 mm établis par la Section Technique de l'Artillerie", Ecole Normale de Tir, 30 novembre 1896.
10. "La culture physique", n°156, juillet 1911, p.419.
19. "Examen de cartouches Mle 1924 C ayant donné lieu à incidents dans les corps de troupe", question n°304, PV n°14, le 6 novembre 1934.
20. "Tables de tir de la cartouche de 8mm Mle 1932 N", question n°461, Camp de La Courtine, le 29 Février 1940.
27. "Optimisation de la cartouche de 5,56 mm", STAT 10/75 A416.
34. "SOUS LE FEU, Réflexions sur le comportement au combat", LCL Goya, Cahiers de la réflexion doctrinale.
42. "Provisional Probabilities of Incapacitation by a Calibre 0.30 Rifle Bullet, Ball M2", BRL-R-949.
“Criteria for Incapacitating Soldiers with Fragments and Flechettes”, BRL-R-1269.

“Effects of small-arms on the human body”, M.L. Fackler.

“Small Arms & Cannons”, C.J. Marchant Smith & P.R. Haslam, Royal Military College of Science, Shrivenham, UK.


“20mm AMR – New Use for Unused Ammo”, Dave Armstrong - SOF Weapons Section Crane Division, Naval Surface Warfare Center.


