Towards a "600 m" lightweight General Purpose Cartridge, v2015

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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.

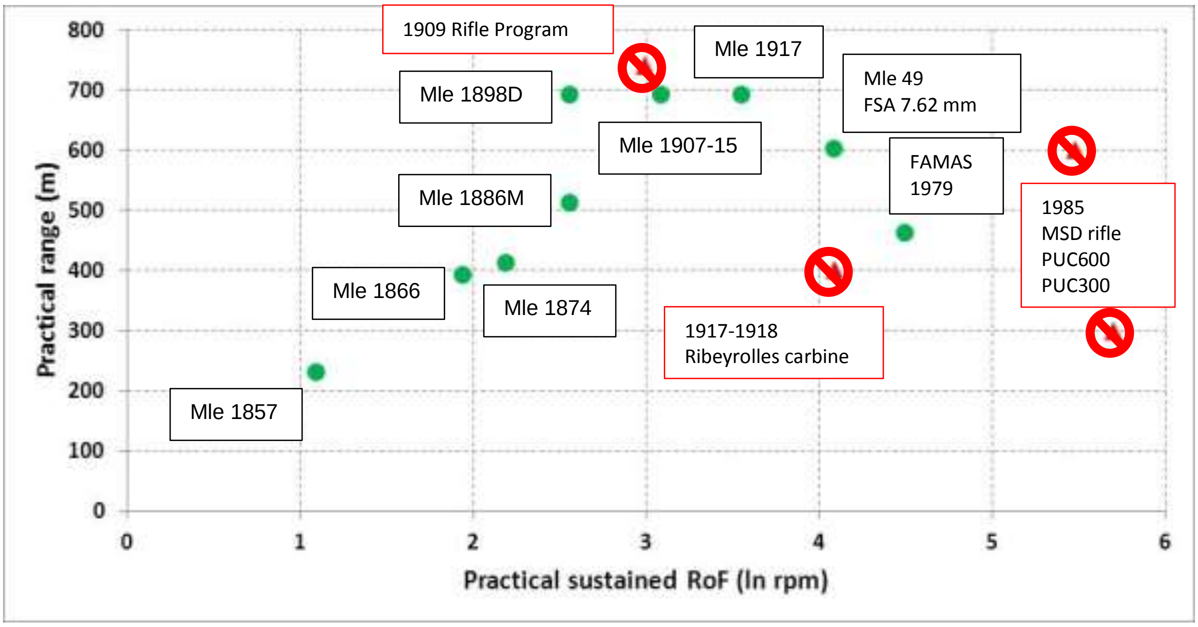


Figure 1: Evolution of the range and rate of fire of individual weapons used by the French army during the last 150 years

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].

Supersonic aerodynamics was an unknown field at this time and the development of the “balle D” was an iterative process; the final design was n°139.

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).

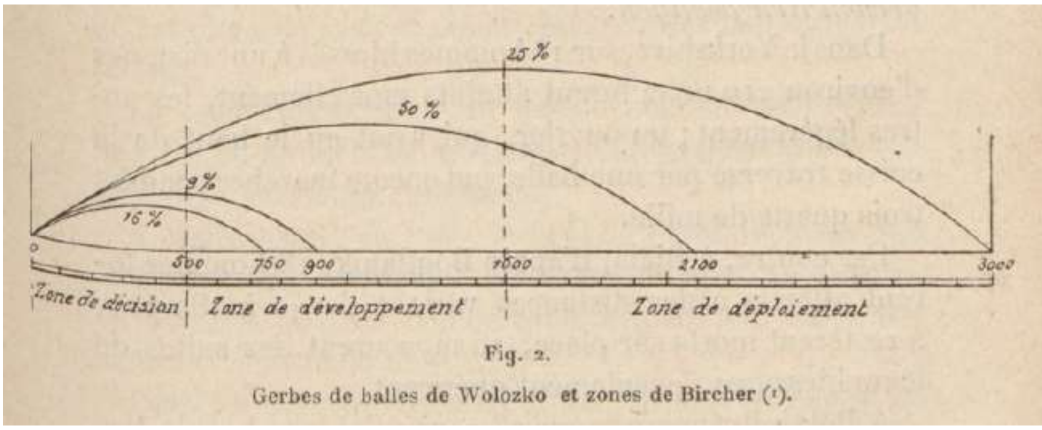


Fig. 2.
Gerbes de balles de Wolozko et zones de Bircher (1).

Figure 2: Engagement distances during the 1880-1900 period according to Wolozkoï and battlefield depth according to Bircher.

According to J.B.A. Bailey[iii], in the sixty years preceding 1914, artillery fire produced less than 10 percent of all battle casualties, the remaining 90 percent 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[iv],

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 (even before WWI) that artillery fire could produce as much as 40-50 percent of overall casualties in future conflicts [iv].

A first dead-end, the semi-automatic rifle program of 1909

In France, this trend toward more firepower, delivered at the longest possible range, should have reached its apex just before WWI with the 1909 rifle program[v].

The goal of this program was to 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 an emergency) with a box-magazine semi-auto rifle shooting a new ammunition that should have a 800 m point-blank range against a 1.6 m standing man. The minimum bullet diameter was set at 6.5 mm. Smaller diameter (6 mm) cartridges were also studied between 1890 and 1906 with muzzle velocities from 700 m/s (1895 STA cartridge, firing a 6.65 g copper bullet [x]) to 850 m/s (in 1899), and finally 900 m/s (in 1906) but discarded due to their inadequate long-range performance when the muzzle velocity was low, and dramatic accuracy reduction during sustained fire when the muzzle velocity was high enough.

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. After a lot of work on various

6.5 mm and 7 mm cartridges with different case capacities (body diameter of 12.5 mm and 13 mm, length around 59-61 mm) and geometries (shoulder angle up to 40° half-angle were tested), efforts were finally focused (but not before December 1913) on one 6.5 mm cartridge (~6.8 g steel-brass bullet, loaded with 4.1 g "*mel.107 ter*" powder) and one 7 mm cartridge (~7.6 g soft steel bullet, loaded with 3.6 g of "*mel. 105*" powder) [vi, x]. Both cartridges used a unusually large 13 mm body diameter (compared to 12 mm for the 8 mm Mauser line of cartridges and 12.6 mm for the Swiss GP11) and a length around 59 mm and 61 mm, with a case capacity in the vicinity of 4.5 cm^3 (69 gr of water).

The 1909 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 BN_3F powders[vi]), 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.

The semi-auto Meunier A6 rifle selected for service in 1913 was actually produced and used in limited numbers during WWI, but firing a more practical "downloaded" 7 x 56.95 mm cartridge (9 g "type 307" bullet and 3.2 g of powder) instead of the "high intensity" 7 x 59 mm (powder load of 3.6 g).

Like all bullets developed in France before WWI, the "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 1898 D.

In contrast to the Mle 1898 D, this bullet was not "monolithic" but used a soft-steel core like the "bi-métal" bullets developed by the "Ecole Normale de Tir" (E.N.T, more on this topic later), but in this case the steel core was fully enclosed (Figure 3) instead of having the tip exposed (Figure 5).

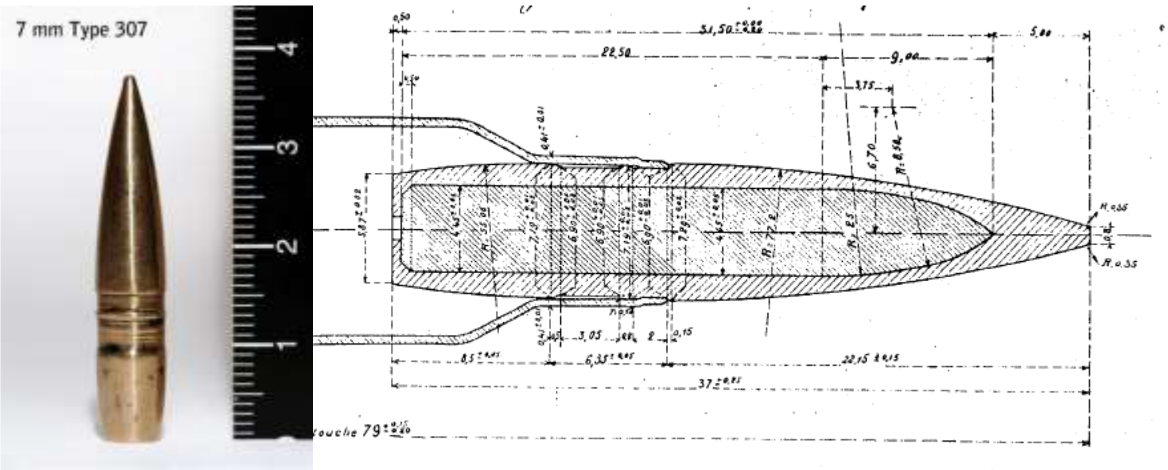


Figure 3: the final version of the "balle 307" used in the 7 x 56.95 mm cartridge for the Meunier A6 (*drawing on the right courtesy of J. Huon*).

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 between 2/3 of enemy casualties (when fire support was lacking), and sometimes 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 second 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 1886 P cartridge (weight 9.6 g[vii], length 32.5 mm, powder weight 0.90 g[viii]). Due to the long ogive of this bullet (24.5 mm, the same as the Mle 1898 D), the cartridge length was 59 mm.

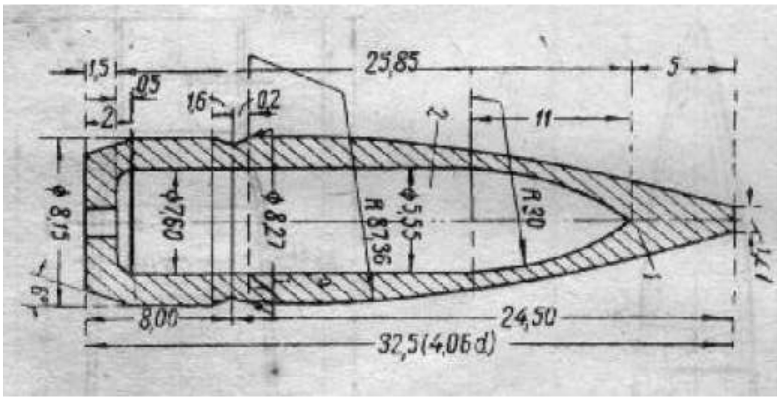


Figure 4: Drawing of the bullet for the 8 mm Mle 1886 P cartridge.

According to the French literature of this time[ix], 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 1898 D up to 600 m (a large change from previous WWI papers on the same topic[x] that asked for a 800 m "point blank" range, when just after WWI duplicating the external ballistics of old Mle 1886 M 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 G6 ballistic coefficient - BC - of .22), around ⅓ of the Mle 1886 P rifle ammunition that used the same bullet (and less than ¾ 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 440-450 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 (~675-700 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 third dead-end, the end of the first "lead-free" bullet

Since 1894 and the first studies by Captain Desaleux of 6 mm brass bullets followed by the adoption of the "balle D" in 1898, every bullet used in French experimental cartridges before WWI was made of cold-pressed brass, or cold-pressed brass with a soft steel core (called "bimétal" bullets and developed by the "Ecole Normale de Tir de Châlons"; in Figure 5, the 2 bullets on the left with exposed steel tips and the next with a fully enclosed steel core). Steel core bullets with steel jackets and homogeneous steel bullets were also tested (Figure 5, bullet n°4, 5 & 6 from the left), with less success.

Figure 5: Some French experimental bullets used during the 1909 program; Left from right: short 6.5 mm bimétal (length 32.5 mm, weight ~6.7 g); long 6.5 mm bimétal, (length 37 mm, weight ~7.6 g); 6.5 mm steel core, (length 36 mm, weight ~7.7 g); two 7 x 59 mm steel bullets (weight ~7.6 g) and two 7 x 56.95 mm Meunier bullets (*courtesy of Y. Etievant*).

Following external ballistics studies made in 1894 and 1895 with lathe turned bullets (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 exact shape is not known but some hypothesis could be made. The Swiss school of ballistics was highly regarded when the French army adopted the Mle 1886 cartridge with the "balle M" full metal jacket lead core bullet and the original cartridge closely followed the Swiss design of bore deep rifling and undersize bullet.

The (nominal) land-to-land diameter of the Mle 1886 bore was 8.00 mm, the groove-to-groove diameter was 8.30 mm (0.15 mm rifling, deeper than the 0.10 mm rifling used by the US and UK) and the bullet diameter was 8.15 mm.

Proper bore sealing was achieved by the limited bullet expansion occurring at launch, something that did not happened with a solid brass bullet so bore sealing was a challenge with the "balle D".

The bullet shank diameter could not be increased without reducing the case thickness around the neck, or increasing the chamber diameter and a 8.15 mm bullet shank diameter was retained.

The bullet length was 39.2 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 application.

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) 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.

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.

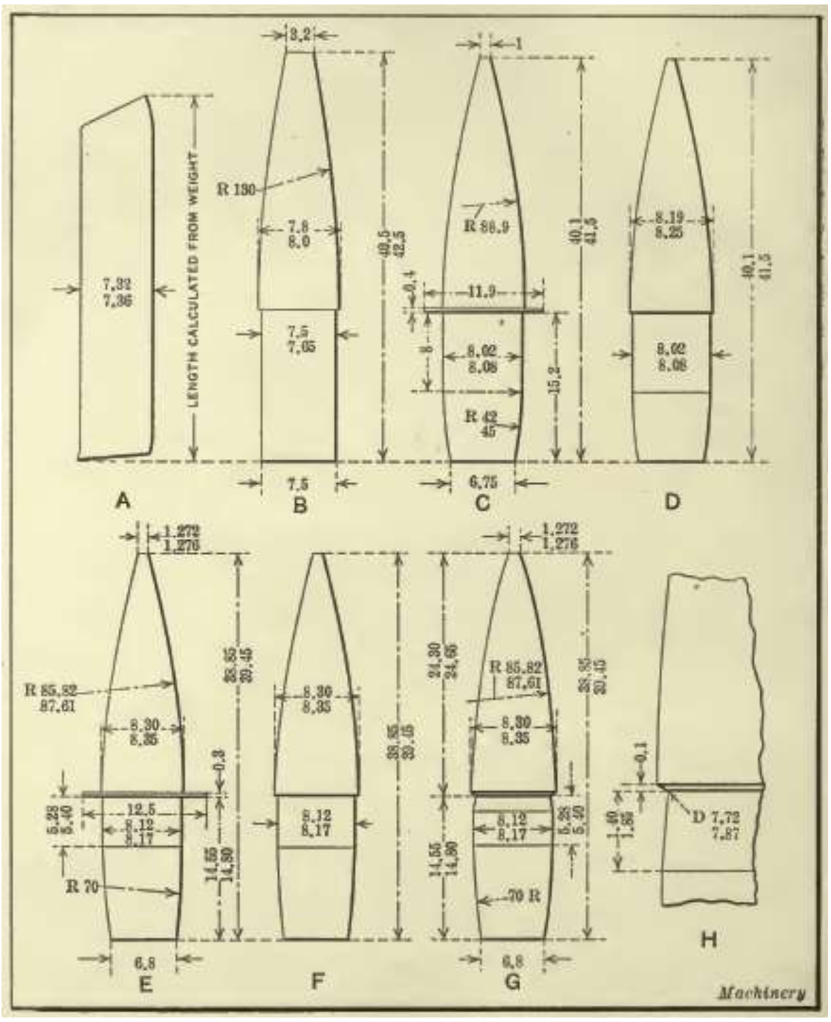


Figure 6: Sequence of operations for manufacturing the “balle D” (n°139)[xi]

The introduction of the Mle 1886 D cartridge (Mle 1886 cartridge loaded with Mle 1898 D bullet) greatly increased the ballistic performance of the “Lebel” rifle and was possible only because of the lucky combination of the long COAL and “short” case of the original Mle 1886 M cartridge, and of the tight 240 mm twist used.

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[x].

The bullet was manufactured from a 90/10 (copper and zinc) brass rod (diameter between 7.32 mm and 7.36 mm), with the addition of 0.4 % of lead and 0.4 % of tin[xii], 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[xiii], 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.

Another experience from WWI not forgotten by the French army was that using main components as specific as the cold-pressed brass bullet Mle 1898 D was not a good idea. Even if during the war, the *daily* production figure of this 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 1898 D in France was 6,812,894,087 rounds[xiv], 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 1886 M bullet, but only 2000 rounds with the Mle 1898 D 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[xv]), 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.

The final choice was to adopt the 7.5 x 54 mm, firing a 9 g lead core FMJ bullet (Mle 1924 C, Figure 7 left) 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 1933 D, Figure 7 middle) with a V_{25} of 694 m/s (closely following the external ballistics of the much revered Mle 1898 D bullet) for the MG devoted to the “artillery” role.

At the same time, the 8 mm 12.8 g Mle 1898 D was superseded by the 15 g Mle 1932 N (Figure 7 right) lead core bullet fired at 715 m/s muzzle velocity, providing even longer range and accuracy [xvi].

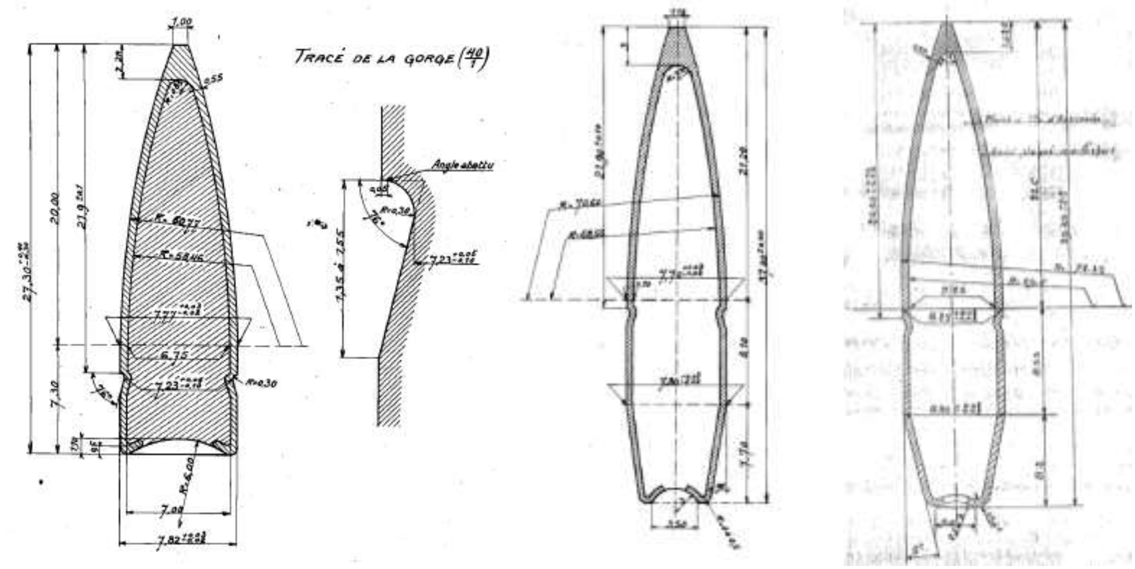


Figure 7: French military lead-core bullets developed after WWI (from left to right, 7.5 mm Mle 1924C, 7.5 mm Mle 1933D, 8 mm Mle 1932N).

From an external ballistics point of view, the performances of those bullets were pretty good (Figure 8).

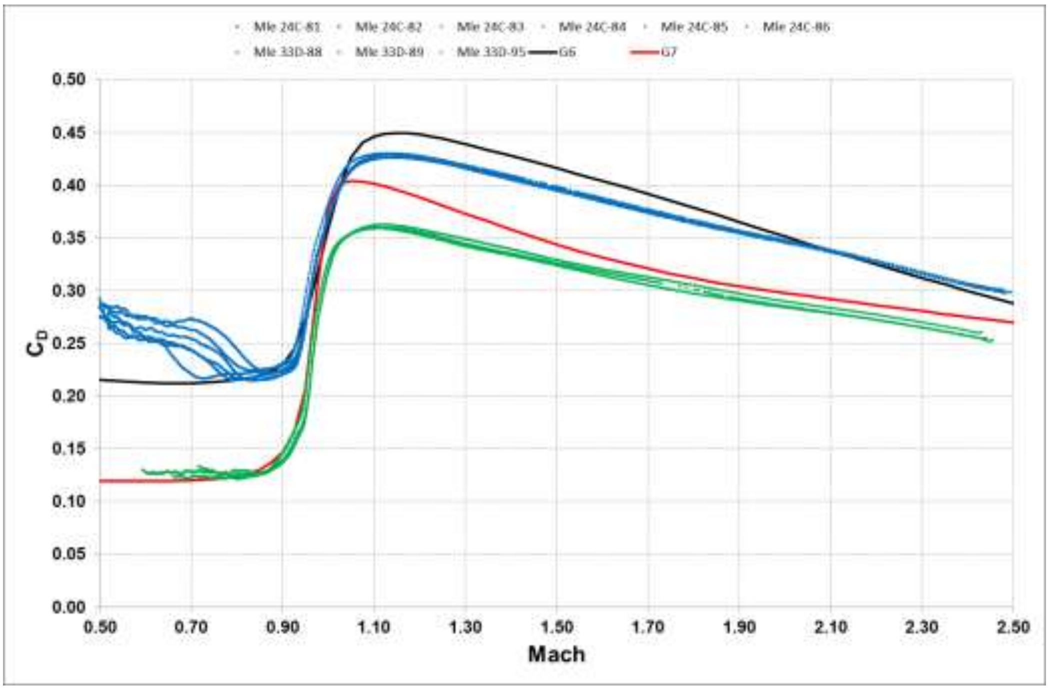


Figure 8: Drag curves of the Mle 1924 C bullet (blue), Mle 1933 D bullet (green), G6 model (black) and G7 model (red).

If the light Mle 1924 C 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 1.13 for a G7 BC of 0.188. 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. A small dynamic instability (precession) could be seen at Mach number below M0.8 but without much consequence.

Combined with a MV around 850 m/s (up to 870 m/s have been measured in FRF1 bolt action rifle for Mle 1929 C ammunition lots produced during the '70s and 840 m/s could be found in official firing reports for cartridges manufactured in 1963, 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 finally 797 m/s was measured when loaded with the heavy 11.8 g "Is" type precision bullet), this cartridge delivers performances similar to the .30-06" M2 or the 7.62 mm NATO.

Lower MV 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 secret, published velocities 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 1886 D and Mle 1886 N cartridges (instead of 701 m/s and 715 m/s).

Anyway, the 7.5 mm Mle 1929 C load delivered a flatter trajectory up to 800 m than the previous 8 mm Mle 1886 D, with less recoil and a case geometry more compatible with automatic loading, so the main requirements for a new small-arm ammo were fulfilled.

The heavy Mle 1933 D 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 AI 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 in a much more compact platform, using 50% less powder. Unfortunately, this bullet is now a collector 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".

Finally, the manufacture of the heavy Mle 1933 D bullet was stopped shortly after WWII and only the light Mle 1924 C 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 needed performances for both IW and MG, is not an optimal solution when balanced with “battlefield” logistics considerations.

Post WWII

The experience of infantry engagements during WWII and the Korean war (high intensity wars) was reviewed in the US and the famous “Hitchman” report[xvii] concluded that since most (~90 %) infantry engagements occured 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. The addition of a toxic agent to the bullet (to increase the lethality) was also proposed.

The parallel work[xviii] 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.

Hit probability rising as the “first and only” indicator of effectiveness

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 exemple, 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.

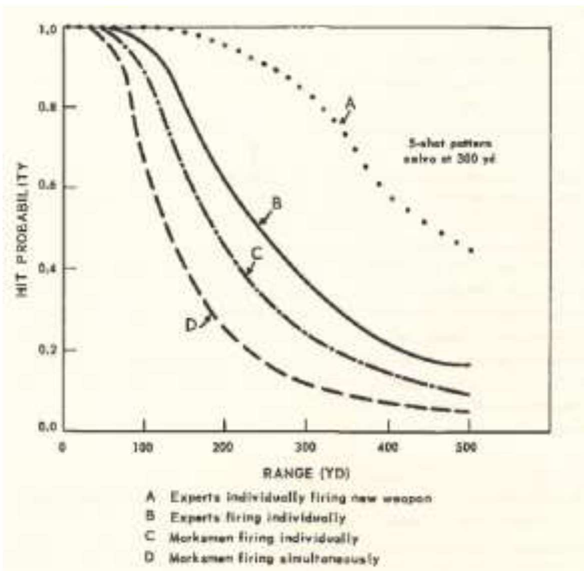


Figure 9: Marksmanship using the M1 rifle.

This report set the way to numerous studies that 1)- tried to evaluate the rifleman effectiveness under what was considered "realistic" stress conditions and 2)- tried to provide a technical answer to the perceived lack of effectiveness at range 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[xix] 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 topic.

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 mass 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 10: Small arms fire in a "high-density" context (left) versus small arms fire in a "low density" context (right).

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 ($p_{I/H}$) against unprotected target, or after defeating personal protections (but not intermediate barriers).

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

For example, a 28 gr / .177” diameter bullet launched at 950 m/s will have the same ToF to the 300 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”, without inducing too much recoil, so the shooter will also benefits from a better hit probability.

The total absence of suppression measurement and criteria was pinpointed in [xx]

“Because of the importance of suppression effectiveness, thorough testing of near miss perception is badly needed. Little or nothing is known on this subject a 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.”

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 Figure 11.

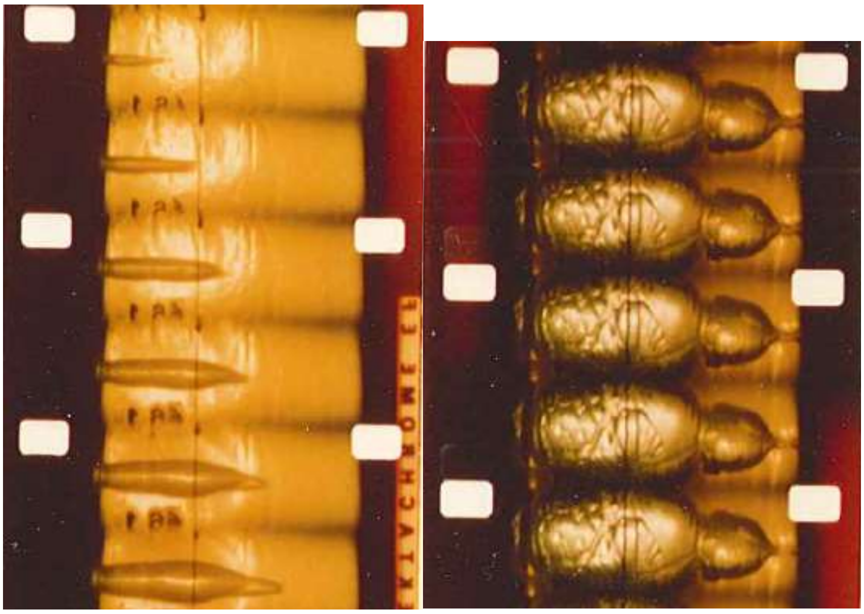


Figure 11: High speed film of 4.6 x 36 mm type 614 solid brass bullet impacting a 20 % ballistic gelatine bloc (15 x 17 x 38 cm), impact from the left side of the bloc. Left picture, bullet yawing inside the bloc; Right picture, maximum temporary cavity size.

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[xxi] 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 difference 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"*[xxii].

The same (inconclusive) result could be reached in the field of deer hunting. No difference in "killing power" was found between rifles in 6 mm, .25", 7 mm and .30" bore, or between "light and fast" and "heavy and slow" bullets. Deer shot with "heavy and slow" bullets travelled further on average than deer struck with "light and fast" bullets, but the final recovery rate was identical, probably due to the better blood trail left by deeper penetrating bullet.

Leaving the medical field for 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 criteria used to "scientifically" evaluate a 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 cavity in ballistic gelatine (Figure 12).

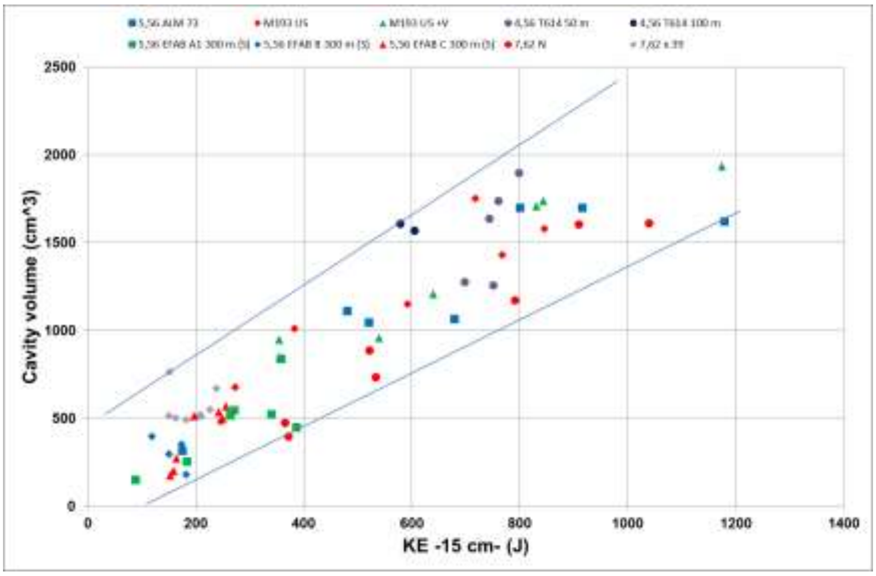


Figure 12: Relation between kinetic energy loss in the first 15 cm of uncalibrated ballistic gelatine and maximum temporary cavity.

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[xxiii].

The KE deposit model used during the ‘60s and ‘70s was later superseded by the EKE model that use 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)[xxiv]. While this model addresses some issues found in the previous KE model, others (like energy “consumed” by the bullet deformation or fragmentation and not transferred to the ballistic medium) are still unsolved.

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 13 for the “defence” criterion). This range is useful for discriminating high velocity fragments and FMJ handgun bullets, but it’s much more difficult to discriminate between rifle bullets.

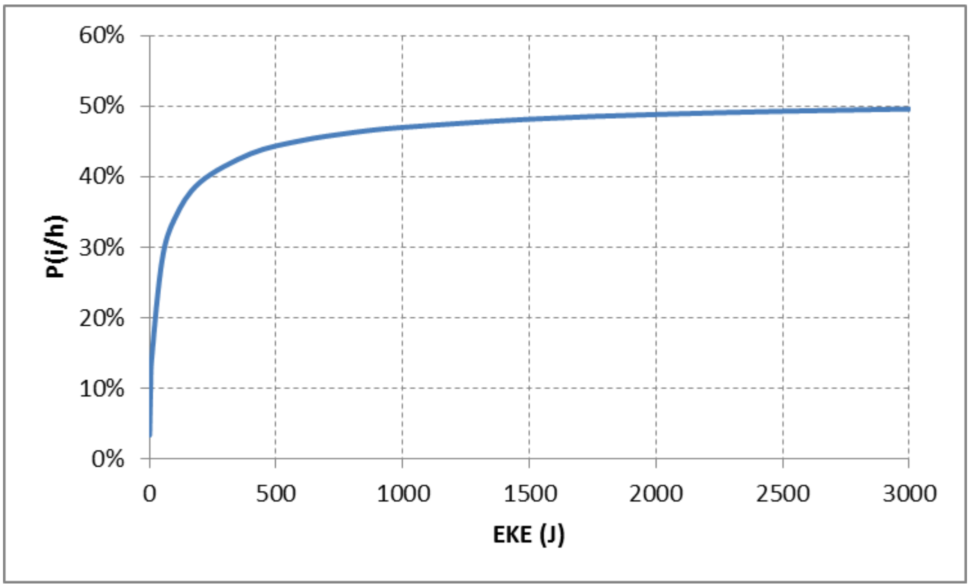


Figure 13: Relationship between EKE and P(i/h) for the "defence" case.

According to the "defence" criteria, a bullet delivering an EKE of 500 J (handgun power level) will have a $p_{(I/H)}$ 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 expansive bullets) is 50 % compared to 45 %, but this very small difference in effectiveness could be easily explained if one consider 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" class[xxv] (see Figure 14).

DISABILITY (FUNCTIONAL) GROUPS BASED ON EXTREMITY BEHAVIOR, AVAILABLE FOR ASSIGNMENT TO EXPERIMENTAL WOUNDS (WOUND CLASSES)

ARMS	LEGS		FUNCTIONAL (DISABILITY) GROUPS
- -	- -	=	I
CATEGORY A	Wounds having no effect on extremity function, no matter in what anatomical location the missile strikes		
- -	- +	=	II
- -	‡	=	III
- -	- ++	=	IV
‡	+ ++	=	XI
CATEGORY B	Lower extremity group		
- +	- -	=	VI
‡	- -	=	VII
- ++	- -	=	VIII
+ ++	‡	=	XIII
CATEGORY C	Upper extremity group		
- -	‡‡	=	V
‡‡	- -	=	IX
‡	‡	=	X
‡	‡‡	=	XII
‡‡	‡‡	=	XIV
- -	++ +	=	XV
- +	‡	=	XVI

KEY:

- = no effect

+ = loss of fine muscular coordination (weakness), with maintanance of coarse extremity function

++ = total loss of extremity function, both fine and coarse coordination

Figure 14: Extract of the sixteen disability groups, based on hits to extremities.

For example, in the above table a soldier “losing” both legs, but with no wounds to the arms, torso or head is classified as a “group V” disability class, and in the “defence” scenario (Figure 15) an incapacitation rating of 50 % is applied.

Gould's Disability Group	Percent Incapacitation			
	Assault	Defense	Reserve	Supply
I	0	0	0	0
II	50	25	75	25
III	75	25	100	50
IV	100	50	100	100
V	100	50	100	100
VI	50	25	75	25
VII	75	50	100	50
VIII	75	75	100	75
IX	100	100	100	100
X	75	75	100	75
XI	100	75	100	100
XII	100	75	100	100
XIII	100	100	100	100
XIV	100	100	100	100
XV	100	50	100	100
XVI	75	50	100	75

Figure 15: Incapacitation as a function of disability group and combat scenario.

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.

The work of M.L. Fackler[xxvi] leads 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 bloc. Contrary to models based on kinetic energy, this approach explains why hunting arrows (or a blow from a slashing weapon of sufficient size, as informally demonstrated by the infamous "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 rely 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 need to be done again.

So, with a methodology that do 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 and the wild development of high velocity "micro-calibres" (lower than 5 mm) and saboted flechettes during the '70s that promised significant ammunition weight reduction without a decrease of terminal performance.

Trying to define other criteria to evaluate small-arms fire 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 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[xxvii], 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 range 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 9).

Of course, “mean” values are only average and in particular events close to “ideal” shooting scenario, shots-to-casualty ratio around 30 per 1 were achieved. While this number (p_H ~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.

Police shooting that take place at very short range exhibits 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 (p_H ~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 exposition time and avoiding being hit is mandatory.

So, if we look back at Figure 9, 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 its target, this 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 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 16).

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.

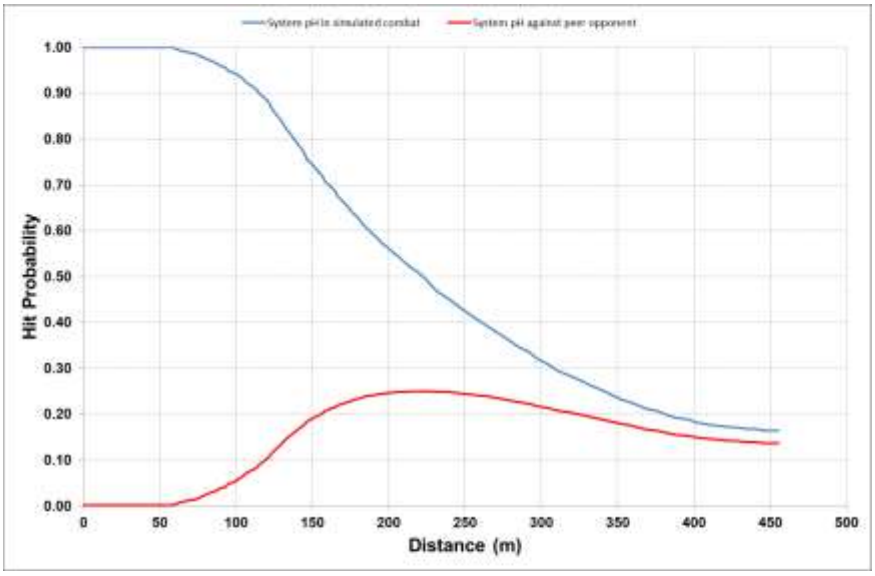


Figure 16: Hitting without being hit, survival first!

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 that mean that the "system" (mostly soldier) will behave way 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 from returning fire, the more different is 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[xxviii]).

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 test, "experts" scored significantly higher than "marksmen" (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 17), when “marksmen” scored only 2 hits (6 % hit probability, Figure 18).

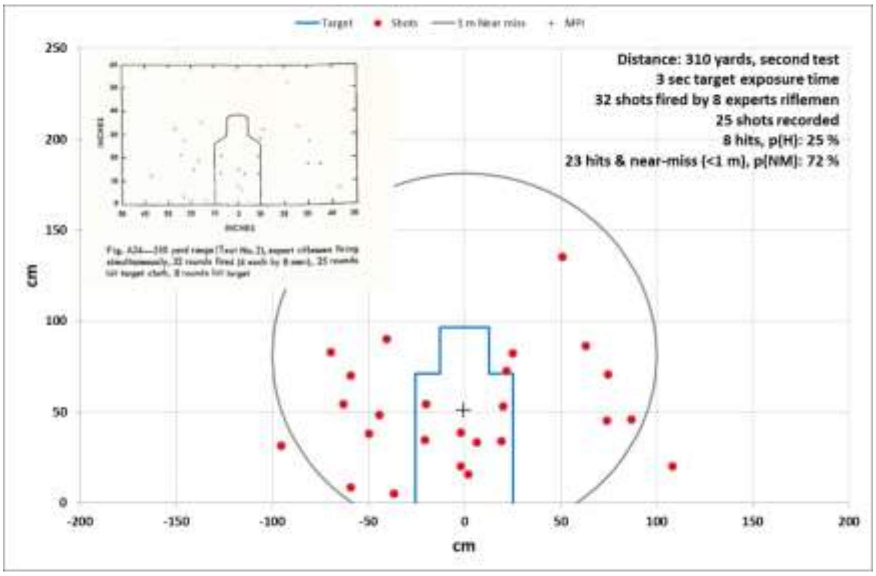


Figure 17: Dispersion measured for 8 “experts” riflemen shooting collectively.

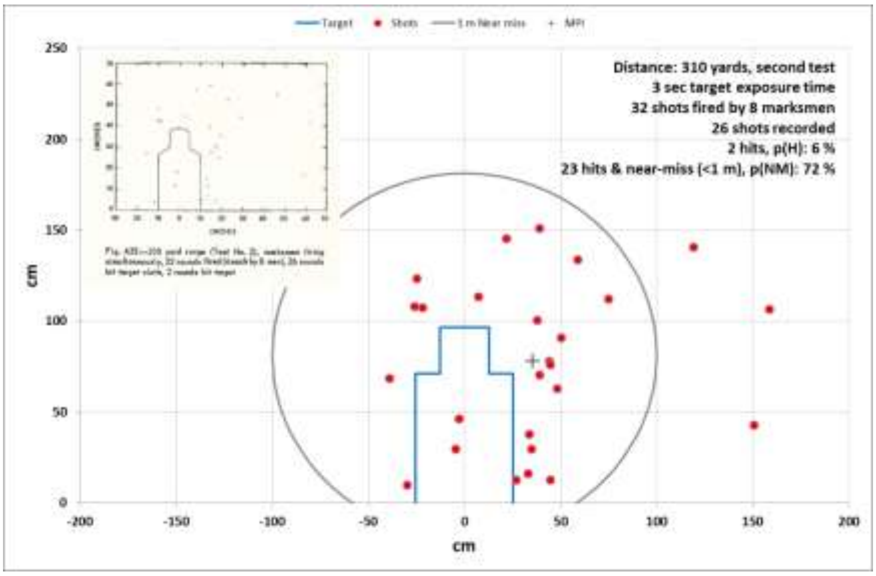


Figure 18: Dispersion measured for 8 “marksmen” shooting collectively.

During those test, a large cloth was used to record as many shots as possible (hits and near-miss), and it’s interesting to notice that in both case:

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

Anyway, up to now such “perfect” dispersion pattern was not 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 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 10, 3-shots bursts resulted in a mean dispersion of 4.6 mils (and a first shot dispersion of 6.1 mils), and informal off hand full-auto firing of a 5.45 mm AK-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 and 2.93 mils; “Sharpshooters”, mean dispersion between 2.12 and 3.67 mils; “Marksmen”, mean dispersion between 2.30 and 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 19).

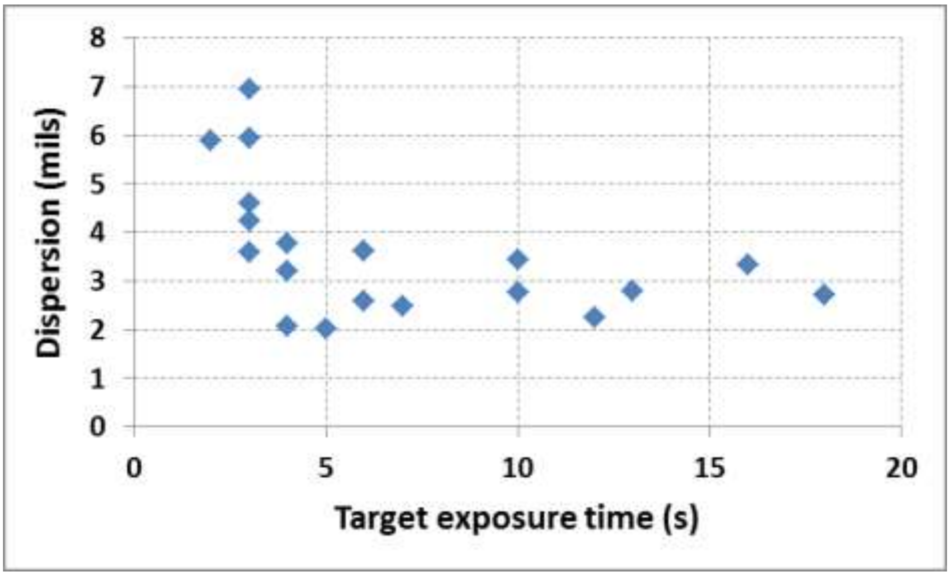


Figure 19: Hand-held weapons dispersion as a function of target exposure time, according to ORO-T-397.

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 (TRAINFIRE I was introduced in 1954, and TRAINFIRE II in 1957), from “bull’s-eyes” targets to “pop-up” targets.

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 when the exposure time was decreasing, up to 7 – 7.5 mils (24 MoA to 26 MoA).

For the same exposure time, the mean dispersion could 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.

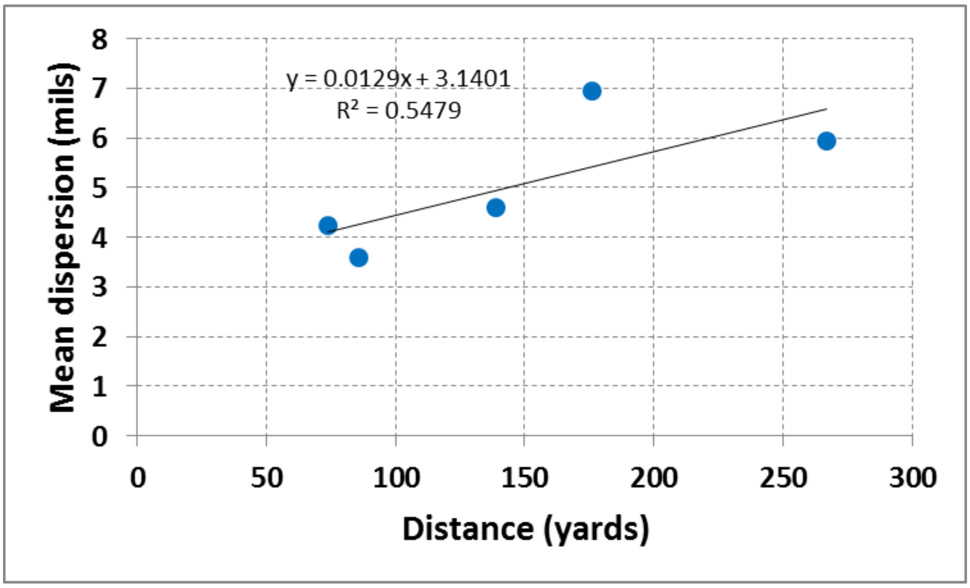


Figure 20: Slight increase of the measured mean dispersion as a function of the target distance, for E-type targets and 3 s exposure time.

So, there is a wide difference between the way we evaluate small-arms hit probability and "real-life" results which seem ranging from 0.3 % to 3 %, even at fairly close range.

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 exemple:

- 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.

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.

The most commonly found criterion for suppression is that any bullet striking at a distance less than 1 m (or 3 ft.) than its intended target will have a suppressive effect, regardless of the bullet mass, diameter or energy.

Using this methodology, we can them compare the probability of hitting an IPSC target (direct hit) and the probability of hitting a 1 m radius circle (achieving direct hit or suppression of the target).

Computations were run using Applied Ballistics Analysis software, a “low confidence” scenario and a “worst case” of 25.8 MoA (7.5 mils) extreme spread for the weapon system (as found in ORO-T-160).

Due to the very large dispersion used, the external ballistics of the simulated .30-06 M2 round and the “low confidence” settings did not play a significant role in this evaluation.

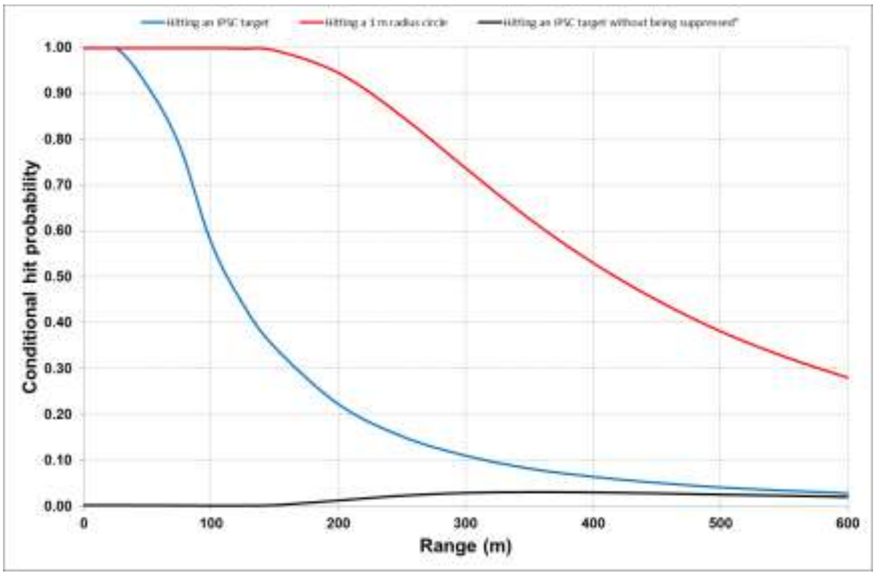


Figure 21: Predicted hit probability of an IPSC target in the absence of incoming fire (blue curve), predicted suppression probability (red curve) and predicted hit probability in battlefield conditions (“under fire”, black curve).

The comparison of the blue curve and the black curve on Figure 21 is a vivid illustration of the military effect and interest of suppressive fire, the hit probability (effectiveness) of opposing soldiers being drastically reduced.

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 find in [xxix]. In this 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.

Acoustic index.

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, but the difference between the M16 and the M60 could be considered significant ("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 comparison of the M60 and the M16 (+0.39) reached ICI of 0.38).
- 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).

Since the sound produced by a bullet in-flight is a dissipative mechanism, from a theoretical point of view it's probably better to try to correlate bullet "loudness" to instantaneous kinetic energy loss, than to remaining kinetic energy.

Air drag being the physical source of bullet velocity loss (and energy loss), we will try to correlate this parameter with bullet loudness.

While lacking the distinctive supersonic "crack" of all other rounds tested, the subsonic .45 ACP was rated higher than the hyper-velocity XM645 flechette round in the acoustic signature test, so the whole drag will be taken into account, and not only the "wave drag" (lead shock) of supersonic bullet.

On this subject, while highly supersonic, flechettes are so small that the induced shockwave is of very limited amplitude.

"A test of miss distance measurement for flechettes was conducted by USAIB, but no formal report was published. The shock wave was so weak that it could not be detected at distances greater than 5 ft. As a result, the Infantry Board microphones could not record flechette miss distances. Similar difficulties can be expected using the CDEC method to measure flechette miss distances." [xx]

Drag is the product of air density, bullet reference area, drag coefficient and bullet velocity squared. Air density being an external parameter, we will keep only the bullet reference area (diameter squared), the velocity (squared) and the drag coefficient.

From a physiological point of view (and since we are dealing with acoustic response), using a logarithm scale seems relevant. The fact that the.50 BMG round did not distort the evaluation scale support this idea.

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

$$Ln(C_D.(d.V)^2 + 1)$$

With *d*, the bullet diameter (in m), *V* the local velocity (in m/s) and C_D, the drag coefficient relative to the local velocity.

The resulting parameter is the instantaneous volume (m^3/s) displaced by the bullet travel.

Results for the projectile tested.

Projectile	Acoustic index (at 150 m)	Relative Acoustic Index (at 150 m)
XM645	1.0	0.41
.45 ACP	1.0	0.42
.223 Remington M193	2.1	0.85
7.62 x 39 mm	2.2	0.89
7.62 x 51 mm	2.5	1.0
.50 BMG	3.4	1.4

This proposed formula captured all the experimental results except maybe the fact that the XM645 should have been rated lower than 0.41 (.45 ACP = 0.42), but the exact external ballistics of this round is not well documented. In order to achieve a rough estimate, a muzzle velocity of 1300 m/s and a drag curve computed for the XM144 flechette were used.

Visual index (impact signature experiments).

Again, live fire test 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 scale" compared to other weapons that it was not possible to found a statistical 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 to use momentum (in N.s) instead for building a Relative Visual Index (RVI).

Results for the projectile tested.

Projectile	Visual Index (at 150 m)	Relative Visual Index (at 150 m)
.223 Remington M193	2.7	0.41
.45 ACP	3.6	0.51
7.62 x 39 mm	4.6	0.66
7.62 x 51 mm	7.0	1.0
.50 BMG	35	5.0

If the acoustic signature of the .50 BMG bullet was “only” 40 % 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.

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 [xxix].

The proposed Relative Suppression Index (RSI) was arbitrarily built giving a slightly better rating for the visual signature than for the acoustic signature (60 % and 40 % relative weight respectively), but any other combination could be examined.

Figure 22 shows the RSI of several military rounds (5.45 mm, 5.56 mm, 7.62 x 39 mm, 7.62 x 51 mm, 7.62 x 54 mm R and .338 Lapua Magnum) as a function of the distance between shooter and target (not the target miss distance). Included also is the experimental 6 x 45 mm SAW (solid black curve) and a 6.5 mm (doted black curve) using a 6.8 g VLD bullet delivering a ME of 2500 J from a 22” barrel (same barrel length than the 7.62 x 51 mm).

The .50 BMG which have a RSI higher than 3 at the muzzle, and higher than 5 at 800 m, is not shown due to scale.

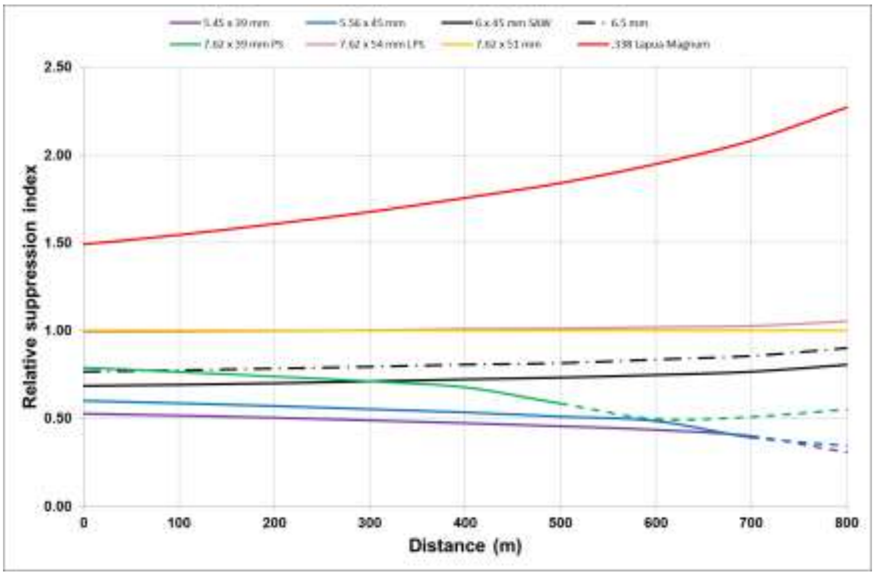


Figure 22: Composite Relative Suppression Index (7.62 x 51 mm = 1.00 at all distance).

At a range of 600 m, both current 5.56 x 45 mm and 7.62 x 39 mm could be expected to deliver only half the suppression index of the "full power" 7.62 mm (51 mm or 54 mm case length).

The experimental 6 x 45 mm SAW, developed for an effective range of at least 600 m, is scoring much better (75 % at 600 m and 81 % at 800 m), and the 6.5 mm is expected to reach 84 % at 600 m, and up to 90 % at 800 m.

At shorter range (up to 300 m), the 7.62 x 39 mm is showing 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 (55-60 %).

Unfortunately, if this scale could be used to compare probable "suppression effectiveness" of two different rounds, results up to now do not answer the basic question of "what is the maximum – or average - distance at which a given bullet will be considered dangerous and could be expected to suppress".

With the realization that hand-held weapons could be used with a significant military effect (suppression) up to a much longer range than predicted by studies focusing only on hit probability, what would be the effective range needed for an Individual Weapon, without completely forgetting the fact that low ammunition weight and low recoil are also needed.

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. s

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 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[xxx].

Studies with the .223 Remington round started in 1963 in France and finally led to the adoption of the “hesitation locked” FAMAS F1 (without a 3-shot burst device in 1977, and with a 3-shot burst device 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[xxxi] 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 SC2 target).

Due to its very fast extraction cycle (~1200 rpm cyclic) and heavy weight, 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).

A fourth 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 1979-1982 NATO small-calibre review.

The evaluation of the G11 rifle was stopped just after performing the cook-off test, so when the experimental FAMAS MSD ("Munitions Sans Douilles", caseless ammunition) rifle program was launched in 1985 it was decided to incorporate a kind of active cooling to the gun chamber, enabling a maximum chamber-wall temperature of 130°C after firing 150 rounds in less than 1 minute.

Two ammunition families were studied, the first one ("PUC600" or demonstrator n°1) around a 600 m range requirement (firing a saboted 5.56 mm 3.6 g PPA bullet, with a tungsten carbide front insert), and the second ("PUC300" or demonstrator n°2) based around a 300 m range requirement (firing a saboted 4 mm, 1.30 g brass, or 2.61 g tungsten bullet). In both cases, a muzzle velocity higher than 1200 m/s (in a 450 mm barrel) was expected due to the heavy powder load for the calibre (2.4 g for the PUC300, which was the only one "fully" developed, Figure 23).

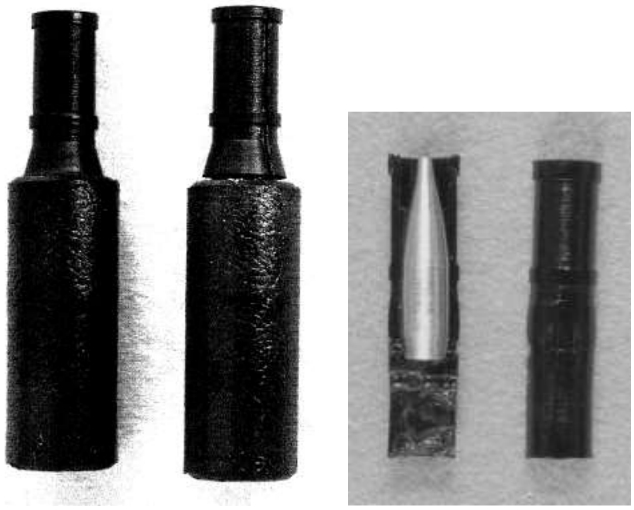


Figure 23: The PUC300 saboted & caseless ammunition (left), and its bullet and sabot (right)

Unfortunately, trying to solve at the same time the problems of caseless ammunition, electric ignition, saboted bullets and active cooling (even only in the form of an advanced heat sink) proved to be a real technical challenge and the study was stopped in ~1995 after the evaluation of the demonstrator n°2 (PUC300).

Compared with the M193, the “PUC300” round used a lighter bullet (1.77 g lead bullet used for the internal ballistics tests vs. 3.56 g) with the same SD (157 lbs/in²) launched at a higher velocity (~1200 m/s vs. ~970 m/s), but needed a relatively heavy powder load (2.4 g vs. 1.8 g) and finally demonstrated a very low propulsive efficiency (<15 %) compared with conventional brass-case, full-calibre, ammunition.

A fifth 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) was intended to combine grenade launcher (for long range engagements) and a “kinetic energy” system for engaging targets at shorter range [viii].

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

Figure 24: Ergonomic demonstrator of the PAPOP concept 1, 30 mm grenade launcher and 7.62 mm rifle.

Demonstrator C1 combined a “side-by-side” 20 shots 7.62 mm NATO rifle (using beefed-up FAMAS mechanism) and a 5 shots 30 mm medium velocity HE grenade (157 g at 225 m/s) with 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.

Figure 25: Ergonomic demonstrator of the PAPOP concept 2, 25 mm grenade launcher and 5.56 mm rifle.

Demonstrator C2 combined an “over-and-under” 30 shots 5.56 mm NATO rifle (using FAMAS mechanism) and a 2-shots 25 mm medium velocity HE grenade (135 g at 150 m/s) with 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.

Figure 26: Ergonomic demonstrator of the PAPOP concept 3, 35 mm grenade launcher.

Demonstrator n°3 was a 5 shots 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 radius of air-bursting grenades was also found to be very small (between 14 m^2 against unprotected standing target, and 4 m^2 against protected prone target in the 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 %[xxxii]. 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.

During the same timescale, infantry fire changed from collective fire aimed at compact columns manoeuvring in the open, to individual fire aimed at a single fleeting target using the maximum concealment and cover.

Under these engagement conditions, the hit probability of infantry fire was found sufficient up to 100 yards, and very low at ranges longer than 300 yards.

In order to increase the efficiency of the infantryman's individual fire at long range, the concept of "controlled pattern dispersion" (ideally, 5 shots in a diamond pattern) was first introduced but for proper execution needed to use a "low recoil" cartridge.

The adoption of the 5.56 mm in the M16A1 was seen as a first step in this direction, but battlefield experience revealed that the recoil of the 5.56 mm round was not low enough for achieving "controlled dispersion" at ranges higher than 50 m, and most western armies have recently come back to semi-auto firing only.

Further reduction of the recoil impulse (like the .17 SBR among other experimental diminutive cartridges) was not so successful due to the concomitant reduction of terminal effectiveness, the Russian 5.45 x 39 mm being probably the best balance of reduced recoil and useful lethality.

Up to now, it seems that the closest practical realisation of the concept of "controlled pattern dispersion" is the G11 "3 shot burst" free-recoil system (at 2200 rpm) and the AN-94 "accelerated double-tap" (2 shot burst at 1800 rpm), two systems that have not achieved wide acceptance due to the mechanical complexity involved and have yet to demonstrate tactical interest compared to semi-auto firing.

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 reducing the warhead effectiveness.

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.

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.

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.

Part Two: Study of a 600 m lightweight round

The methodology used in this study is very similar to the one presented in CRC-307[xxxiii] "A METHODOLOGY FOR SELECTING SMALL-ARMS ROUNDS TO MEET MILITARY REQUIREMENTS", but with different design parameters:

- A slightly shorter barrel (508 mm vs. 560 mm),
- The case capacity is defined by the maximum volume of existing 7.62 x 51 mm ammunition and covers only the "Medium / Short", "Typical Medium" and "Medium / Long" case volume of CRC-307,
- The use of lead-free bullets (that limits the bullet weight to "Typical Light", "Medium / Light" and "Typical Medium" weight class of CRC-307),
- A better form factor (between .91 and .97 in this study, depending on the bullet length, instead of ~.99 for all bullets used in CRC-307),
- A different requirement for the energy needed to produce a lethal wound (82 J vs. 100 foot-pounds; 135 J in CRC-307).

Technical requirements

The main requirement of a "600 m lightweight round" is to be as light as possible, but still 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).

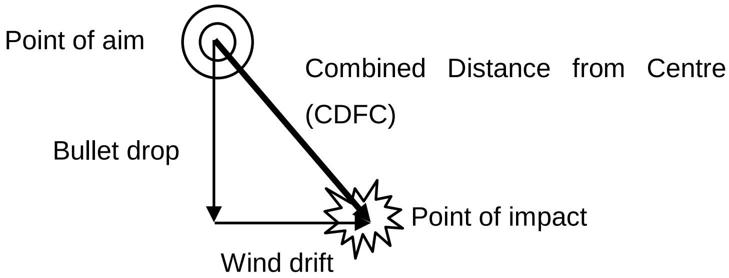
The protection generally considered on the battlefield is the 3.5 mm NATO steel plate. The impact energy needed to perforate such plate is a function of the bullet diameter (to the power 3/2). Better protection (NIJ level III & IV) is available today, but those levels, tailored to stop full-power rifle lead-core FMJ and steel-core armour piercing bullets respectively, are defeated by bullets with tungsten carbide inserts.

The energy needed to inflict a lethal wound is more debatable and a commonly found value of 82 J was selected for this study.

Bore & bullet diameter	Energy needed to defeat the 3.5 mm plate	Energy needed to produce a lethal wound	Total energy required at 600 m
5.56 mm (5.69 mm)	565 J	82 J	647 J
6 mm (6.21 mm)	638 J	82 J	720 J
6.5 mm (6.71 mm)	722 J	82 J	804 J
7 mm (7.21 mm)	806 J	82 J	888 J
7.62 mm (7.82 mm)	910 J	82 J	992 J

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.

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 $\frac{1}{2}.g.(ToF)^2$ (with *g* the gravitational constant, and *ToF* the time of flight to the target), and the Didion formula for wind drift (Y) is $W.(ToF - \frac{X}{V0})$, with *W* the wind speed and $\frac{X}{V0}$ the time of flight in vacuum conditions.

Since *g* equals 9.81 m/s², then *g/2* 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 $\left[ToF^4 + (ToF - \frac{X}{V0})^2\right]^{\left(\frac{1}{2}\right)}$

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.

The thermal problem

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 flux (wasted heat divided by bore diameter) for both rounds is around 15.5 kJ/cm².

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 cm^3 (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 % and is equal to a thermal load of 9960 J (33 % more than the current 7.62 mm M80 ball) and a thermal flux of 24.5 kJ/cm² (60 % higher).

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.

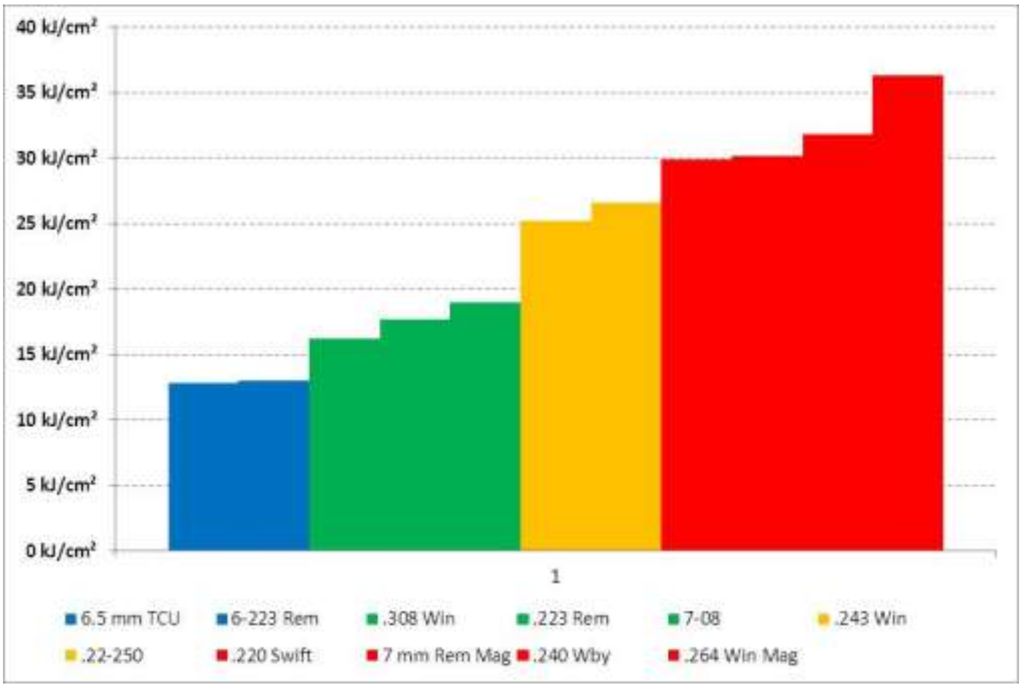


Figure 27: Thermal flux for different civilian cartridges.

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 flux.

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.

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 flux lower than 20 kJ/cm² is a safer bet (and closer to 15 kJ/cm² even better).

Cartridge and bullet design

All of the cartridges investigated here with the "Powley computer" are loaded to the same overall length (71.1 mm), the same pressure (48 000 CUP – 330 MPa) and results are given in a 508 mm barrel.

This cartridge overall length (COAL) was selected because previous investigations (see part 1) have shown that the COAL of the 5.56 x 45 mm (57.4 mm) was not sufficient to fulfil the energy and trajectory requirements with "heavy metal"-free bullets, and given the limited difference in weight between some 5.56 mm and 7.62 mm rifles (for example, 3.545 kg "dry" for the 5.56 mm FN SCAR-L with a 14.5" barrel and 3.621 kg "dry" for the 7.62 mm FN SCAR-H with a 16" barrel) there is little reason to choose an "intermediate" action length between the "micro-action" 5.56 mm and "short action" 7.62 mm.

3 bullet lengths were investigated, a "short" bullet (4 calibres long), a "medium" bullet (4½ calibres long) and a "long" bullet (5 calibres long). All 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.

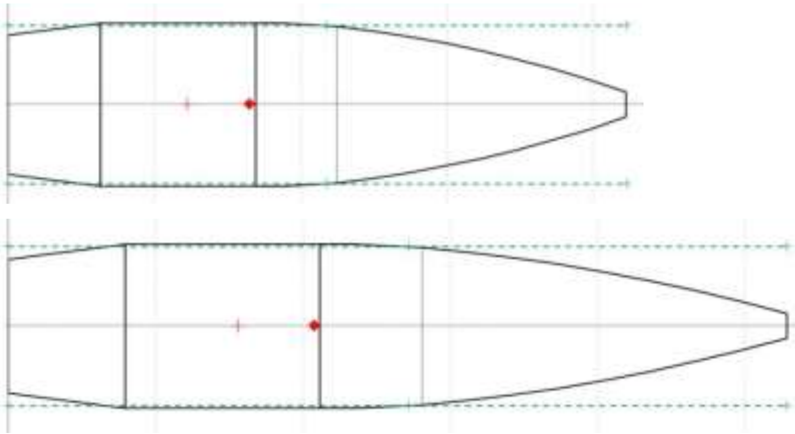


Figure 28: example of the general shape of "short" (4 calibres) and "long" (5 calibres) bullets: their centres of gravity are indicated by the red dots

This balance of parameters ensured that the bullet centre of gravity (CoG) was supported by the barrel grooves during bullet in-bore travel, avoiding detrimental "in-bore yaw". The expected i7 form factor of the "short" bullet with its 2.4 calibres ogive height is ~.98 (a slight improvement compared to the ~1.12 of the M80 bullet), ~.93 for the "medium" bullet (with a 2.7 calibres ogive height) and ~.90 for the "long" bullet (with a 3 calibres ogive height).

A longer bullet (5½ calibres long with a 3.3 calibres ogive height) would enable an even better shape and a heavier bullet, but the barrel twist required for gyroscopic stability would be unusually (and maybe impractically) short, so the maximum length used in this study is 5 calibres.

The bullet density was set at 8.5 g/cm^3 (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).

Finally, 5 bullet diameters (5.56 mm, 6 mm, 6.5 mm, 7 mm and 7.62 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, covering case capacities from 2.36 cm^3 to 3.89 cm^3.

Bore diameter	Short bullet		Medium bullet		Long bullet	
	Weight (g)	G7 BC	Weight (g)	G7 BC	Weight (g)	G7 BC
5.56 mm	3.6	.16	3.9	.18	4.4	.21
6 mm	4.4	.17	5.0	.20	5.5	.23
6.5 mm	5.8	.19	6.5	.22	7.1	.25
7 mm	7.1	.20	8.1	.24	9.0	.27
7.62 mm	9.5	.22	10.4	.26	11.7	.30

So, for each bore diameter studied, 15 combinations were investigated.

Results, 5.56 mm bore diameter

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

600 m impact energy is not so impressive, but the extrapolation of the “long bullet” curve (.21 G7 BC) to 20 kJ/cm² shows that the 4.4 g bullet with a muzzle velocity of ~950 m/s is close to the minimum requirement, but also that this bore diameter would benefit from a heavier bullet launched at a reduced velocity.

Pushing the bullet length to 5½ calibres should give us the desired result, with a 4.7 g bullet that could be launched at a MV around 905 m/s from a 508 mm barrel (according to the Powley computer).

The calculated 600 m impact energy of such a very long bullet is close to 670 J and the 800 m CDFC should be 1.68 m. Expected impulse and heat flux are 6.4 N.s and 18.2 kJ cm², respectively. Unfortunately this bullet would need a very short twist (150 mm) for proper stabilisation, so in the limits of the design parameters of this study there is no “solution space” for this bore diameter.

While this combination (small case volume and very long bullet) delivers probably very good performance from a “cartridge weight” point of view, when loaded to the same heat flux or to the same impulse, the shorter 6.5 mm “5 calibre” bullet will deliver the same 800 m CDFC, or the same 600 m impact energy, respectively.

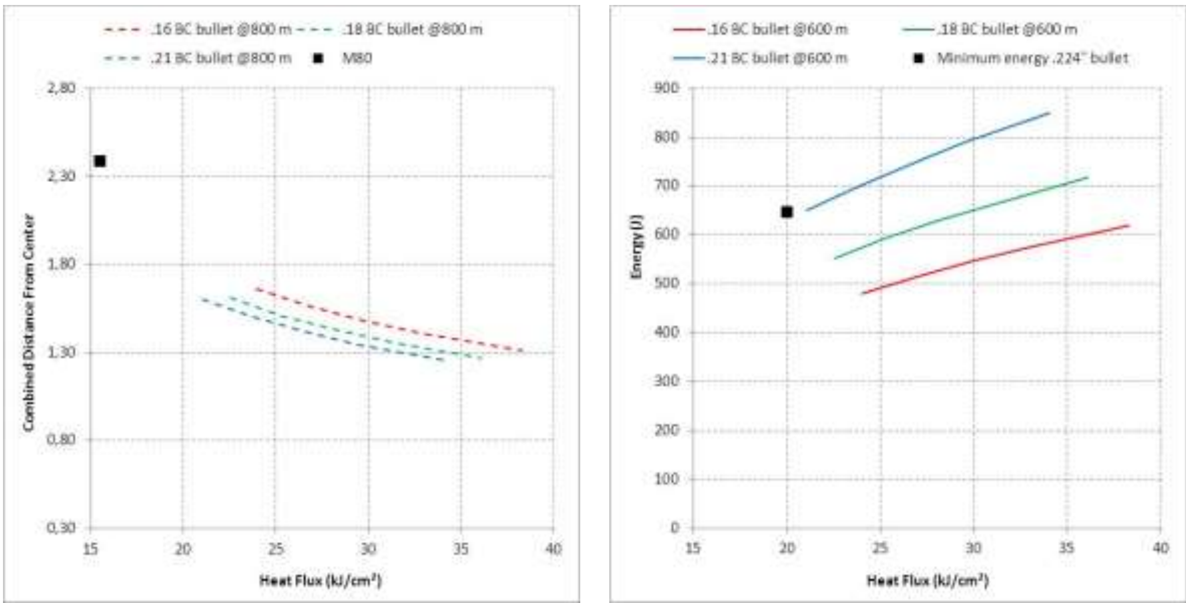
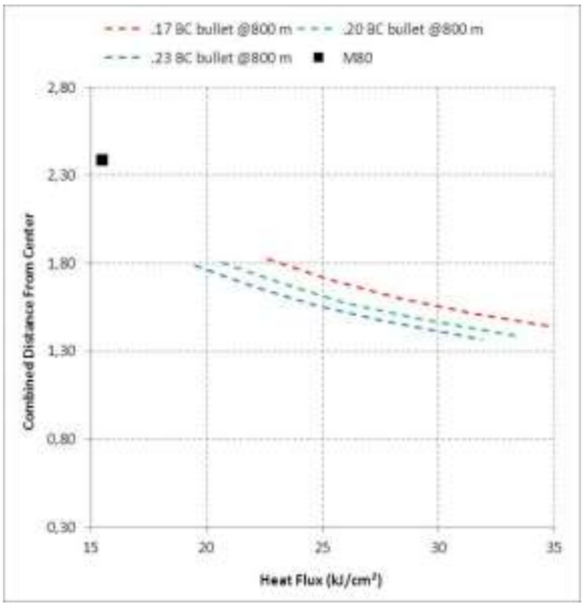


Figure 29: 800 m CDFC (left) and 600 m impact energy (right) for the 5.56 mm bore.

Results, the 6 mm bore diameter

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 to 7.45 g).



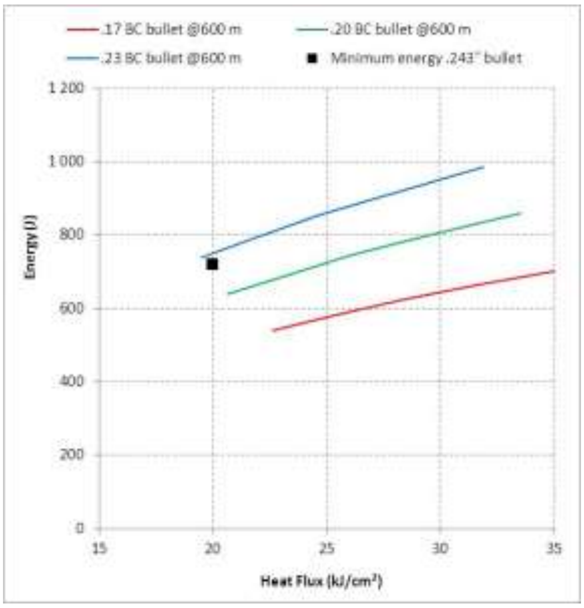


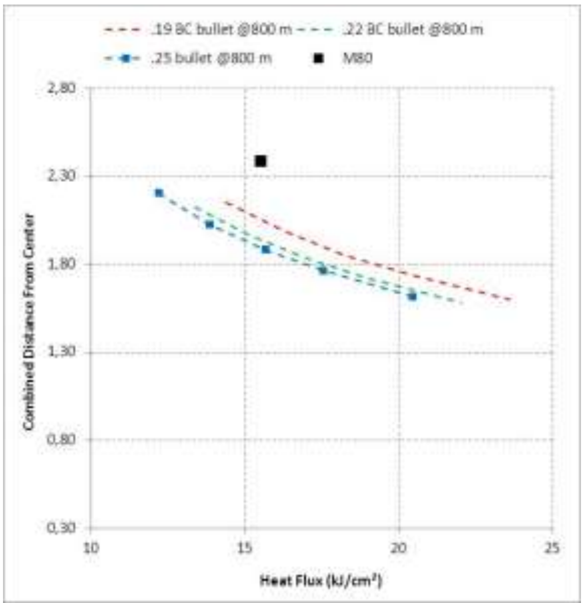
Figure 30: 800 m CDFC (left) and 600 m impact energy (right) for the 6 mm bore.

Unfortunately, the heaviest bullet studied here weighs in at 85 gr (5.5 g) and it can be seen that just like the 5.56 mm bore, the 6 mm would benefit from a longer and heavier bullet.

But unlike the 5.56 mm bore, there is at least one combination of parameters that fills the “solution space” using the 85 gr “long” bullet and what is essentially a commercial 5.6 x 50 mm case necked up to 6 mm. The calculated MV of 880 m/s from a 508 mm long barrel would give an impact energy of 739 J (720 J minimum) with a heat flux of 19.5 kJ/cm² (20 kJ/cm² maximum). Anyway, any change in the various parameters (shorter barrel or reduced BC due to increased production tolerance or the addition of a bullet groove) will decrease performance below the minimum specified values.

Results, the 6.5 mm bore diameter

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.



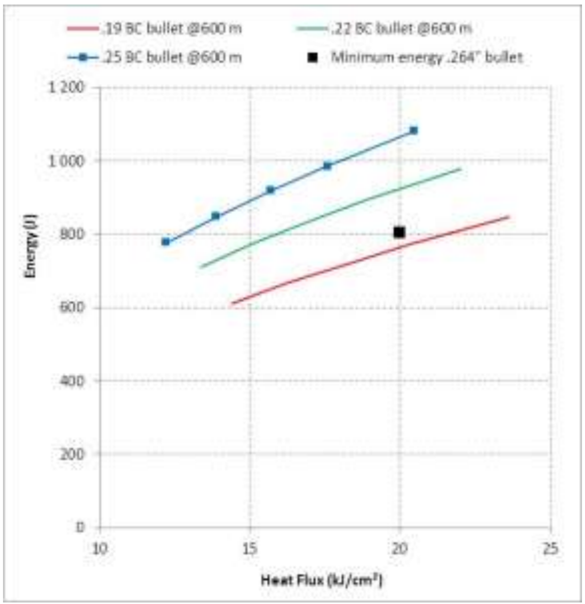


Figure 31: 800 m CDFC (left) and 600 m impact energy (right) for the 6.5 mm bore.

As can be seen in Figure 31, this bore diameter enables a wide choice of solutions with both “medium” (6.5 g) and “long” (7.1 g) bullets, the best results (trajectory and energy) being achieved with the “long” bullet.

At the lower end of the solution space, a 51 mm long case with a body diameter of 10.2 mm (~5.45 x 39 mm Russian case elongated to 51 mm, capacity of 2.65 cm^3) will allow a calculated MV of 810 m/s firing the 7.1 g bullet from a 508 mm barrel.

At the higher end of the solution space a 51 mm long case with 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.

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 x 51 mm at long range, the reduction of recoil and ammunition weight will be minimal.

Results, the 7 mm bore diameter

Ever since the introduction of the 7 mm Mauser in 1892, this bore diameter has enjoyed a very good reputation both as a civilian round and as a military round.

This bore diameter was selected prior to WWI by both the French (7 x 59 mm) and UK (.276 Enfield) to replace the 8 mm Mle 1886 and .303 British respectively (with equal lack of success in both cases), and more importantly by the US before WWII for the .276 Pedersen and by the UK just after WWII for the .280 British.

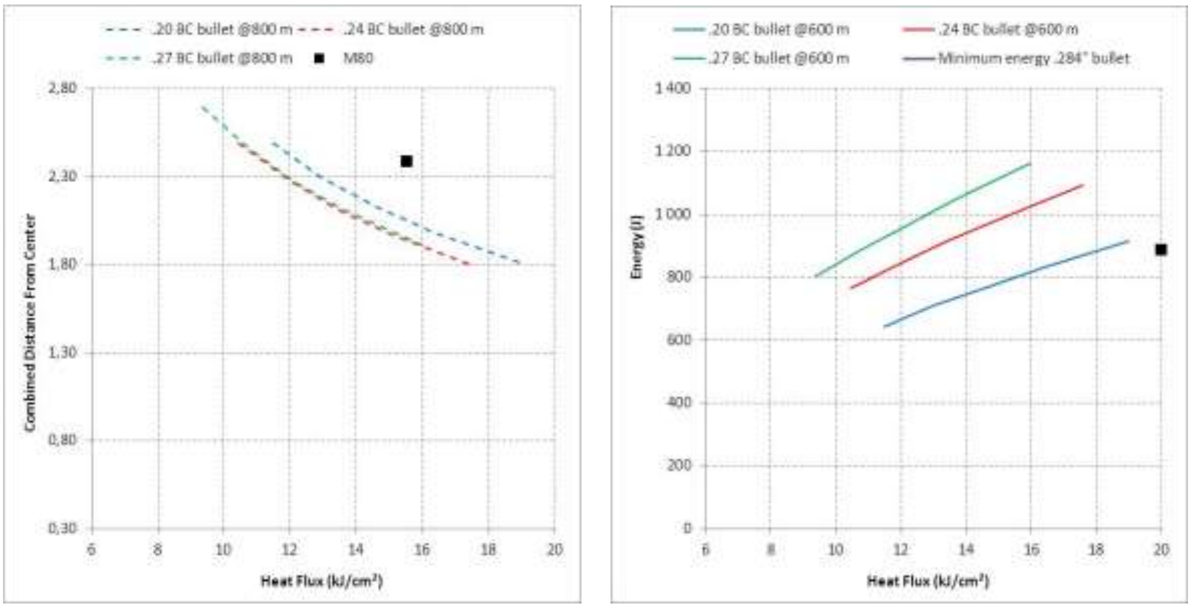


Figure 32: 800 m CDFC (left) and 600 m impact energy (right) for the 7 mm bore.

As could be seen, the "solution space" for this diameter is wide and every bullet / case combination produces a heat flux lower than 20 kJ/cm².

From a trajectory point of view, the "long" bullet (9.0 g) does not deliver a better trajectory up to 800 m than the "medium" (8.4 g) bullet, but the 600 m retained energy is higher due to the weight.

Here again, case diameters of 10.7 mm and 11.2 mm with a capacity of 3.1 ±0.1 cm^3 are enough to provide the muzzle velocity required.

With both "medium" and "long" bullets, this bore diameter delivers very good performance (high retained energy, good trajectory and minimum heat flux) but also represents the "high end" of the game, with a round weight probably very close to the 24 g of the M80 round.

Results, the 7.62 mm bore diameter

This diameter seems to be one of the most used for military applications, delivering universally appreciated terminal results but with mostly inefficient external ballistics (the 600 m impact energy of the M80 bullet is only 1/3 of its muzzle energy), too much weight (24 g per round) and too much recoil (11.6 N.s).

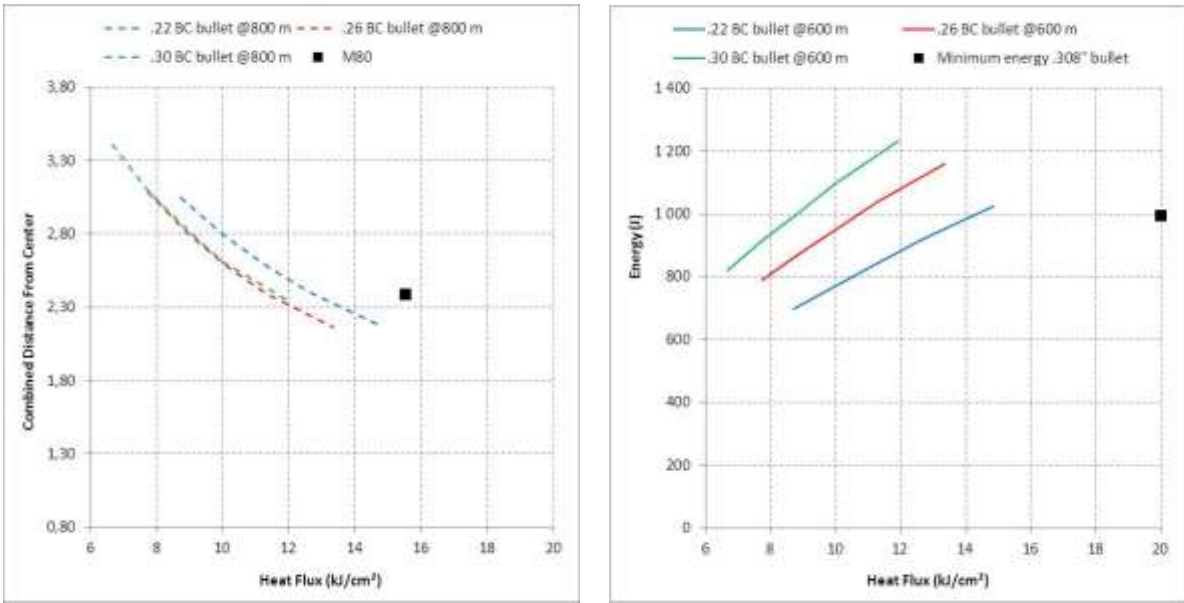


Figure 33: 800 m CDFC (left) and 600 m impact energy (right) for the 7.62 mm bore.

Due to the choice of design parameters aimed toward a lighter round than the M80 (maximum length and largest body case diameter equalling the 7.62 x 51 mm M80), the solution space for the 7.62 mm bore is very limited.

Only the largest case body diameter (12.0 mm) allows the required powder load needed to drive the "short" (9.5 g) and "medium" (10.4 g) bullets at sufficient muzzle velocity (830 m/s and 778 m/s, respectively) to achieve the required trajectory at 600 m and 800 m.

Compared to the M80, increasing the projectile weight (and BC) increases the impact energy, reduces the needed powder load and the heat flux but does not improve the trajectory nor the cartridge weight or the recoil.

In order to reduce the cartridge weight and recoil, we need to find a way to reduce the bullet weight while increasing its BC.

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 3 parameters, one related to the trajectory (hit probability), one related to the impact energy (terminal effectiveness), and one related to the heat flux (muzzle report, practical rate of fire and system life).

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

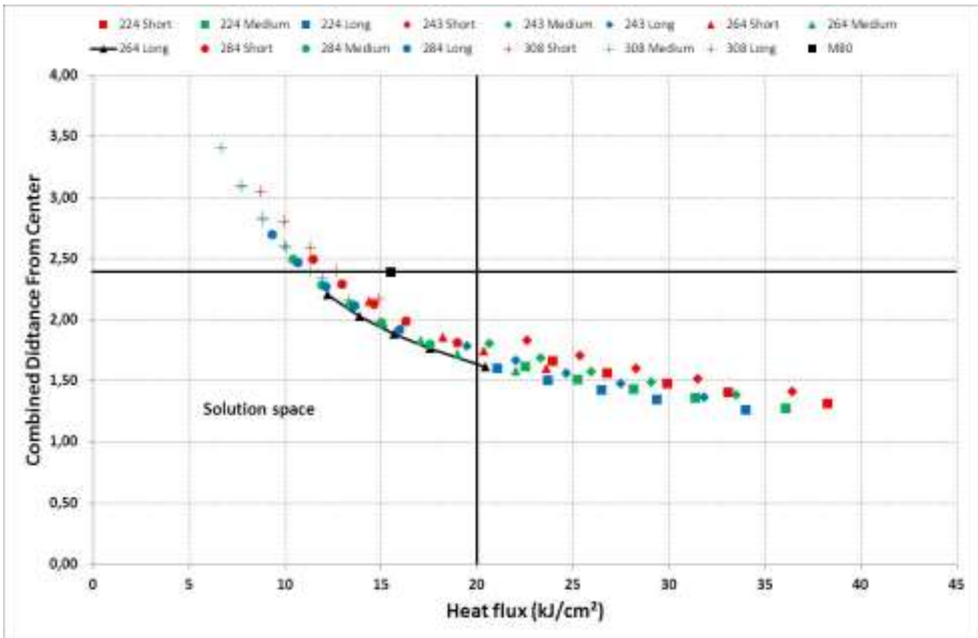


Figure 34: 800 m Combined Distance From Centre as a function of the cartridge heat flux.

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 flux is given by the 6.5 mm bore loaded with the 7.1 g "long" bullet, followed by the 7 mm bore loaded with the 8.4 g "medium" bullet, then again the 6.5 mm loaded with the 6.5 g "medium" bullet, then by the 7 mm bore loaded with the 9.0 g "long" bullet (in that order, but the difference between those 4 combination is very small).

If we narrow our choice to those two bore diameter, we could see that for a given impulse (recoil), the 6.5 mm delivers better trajectory up to 800 m than the 7 mm (Figure 35), a fact well-known by the long-range civilian shooter crowd.

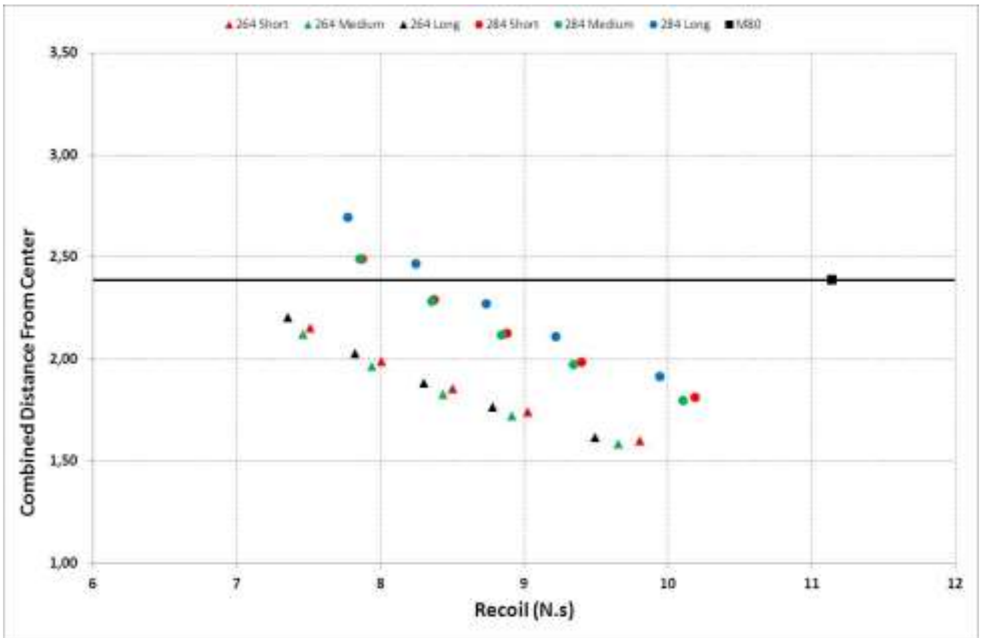


Figure 35: 800 m Combined Distance from Centre as a function of the cartridge impulse.

Now, if we look at the retained energy at 600 m as a function of the cartridge impulse (Figure 36), we could see that the 6.5 mm bore 7.1 g "long" bullet delivers more energy for a given impulse value (for impulse value <9.2 N.s) than the other combinations, the 7 mm bore 9.0 g "long" bullet being better when the impulse is higher than 9.2 N.s.

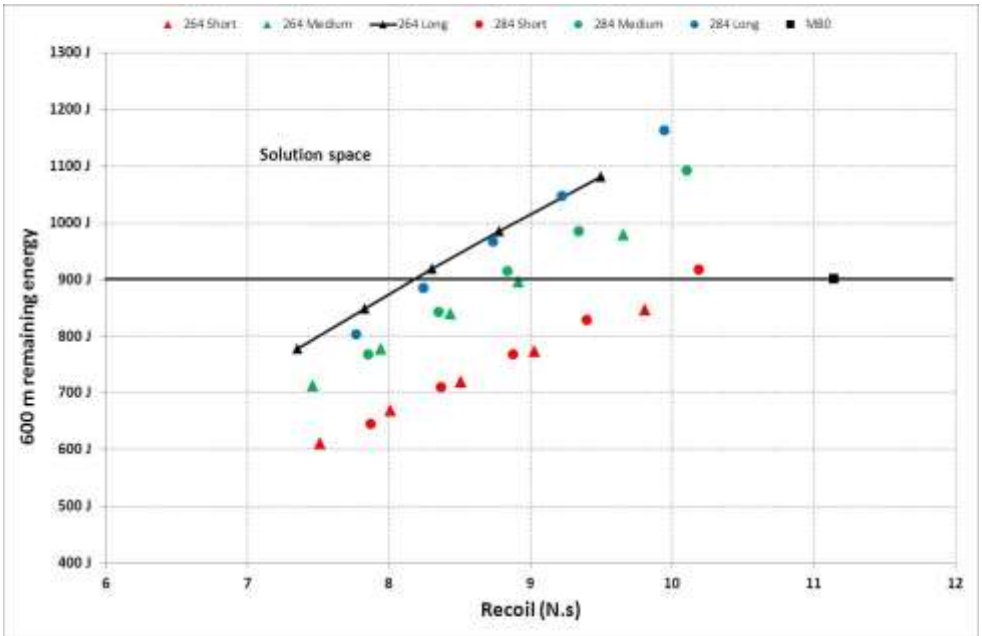


Figure 36: 600 m impact energy as a function of the cartridge impulse.

If the 600 m impact energy is drawn as a function of the heat flux (Figure 37), the 7 mm shows a marked reduction of the cartridge heat flux for a given 600 m energy, compared to the 6.5 mm bore, even if due to its smaller diameter the 6.5 mm will need less impact energy to perforate the 3.5 mm steel plate.

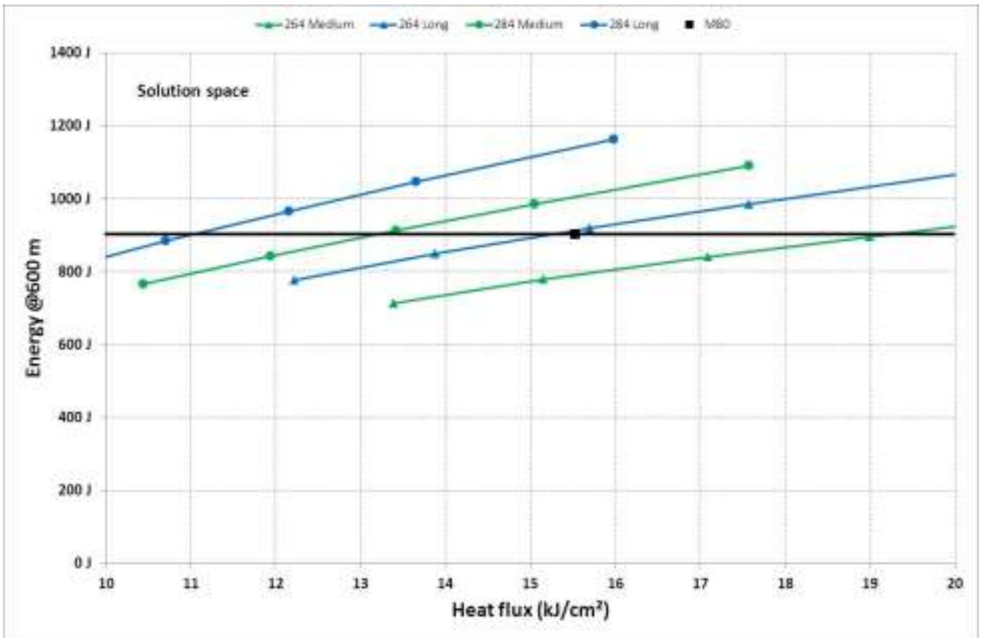


Figure 37: 600 m impact energy as a function of the cartridge heat flux.

Cartridge design conclusion

It is no surprise that the best results in this study were obtained with the 6.5 mm and the 7 mm bore. Although not studied here, it is clear that the .270" / 6.8 mm calibre would be equally effective if designed using the same parameters.

The 6.5 mm will need a “long” (7.1 g) bullet to achieve the best results and could be considered as the lightest technical solution, since for a given impulse and heat flux it will deliver the highest impact energy at 600 m and the best trajectory up to 800 m.

The 7 mm could be used with both the “medium” (8.4 g) and the “long” (9.0 g) bullet, the last one being probably the heaviest technical solution boundary. Those two combinations will deliver the highest impact energy at 600 m for a given heat flux, but with recoil a little higher than the 6.5 mm bore “long” bullet combination.

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 cm^3), 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,
- 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 Three: 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 “AIF-P” (Arme Individuelle Future de Précision) and the LMG “FM 7.62” (Fusil Mitrailleur 7.62) for “long-range” (600 – 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 38).

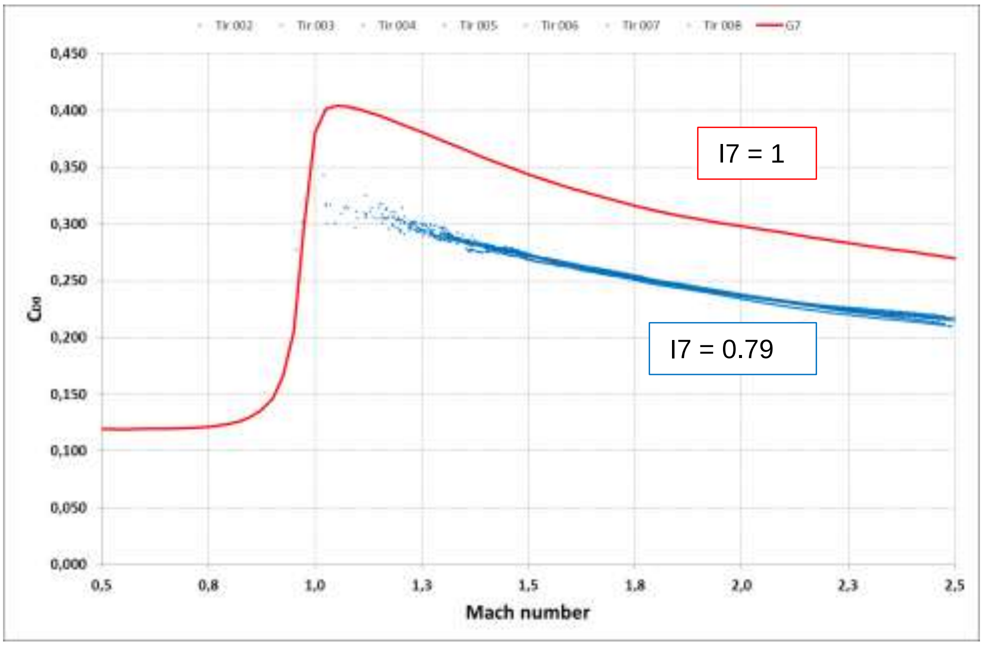


Figure 38: Doppler radar measurement of seven shots recorded with the best shape tested, compared with the G7 drag curve (form factor = 1).

The best shape was found to closely follow the G7 curve (in the supersonic domain) with an i7 form factor of .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 around Mach 1 (shot-to-shot drag variation increase below Mach 1.2) but this phenomenon did not degrade significantly the accuracy at long range.

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 cm^3), to the massively overbore 6.5-300 Winchester Magnum (case capacity of 5.35 cm^3), 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 39: Example of manufactured bullets (left, 6.8 g “hybrid” ogive, right 7.5 g tangent ogive)

Three bullet nose-shape and brass grade were tested:

- A deeply grooved, hybrid nose, boat-tail, “light” one (6.8 g) with a high zinc content,
- A deeply grooved, tangent nose, boat-tail, “heavy” one (7.5 g) with a low zinc content,
- A deeply grooved, hybrid nose, flat-base, “light” one (6.7 g) with a high zinc content and lead-free.

Those bullets were loaded in various weapons, with different MV:

	6.5-357”	6.5 mm TCU	.260 Rem	.264 WM
103 HFB	797 m/s	848 m/s	912 m/s	1093 m/s
105 HBT	-	850 m/s	-	-
115 TBT	-	801 m/s	-	1046 m/s

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 40).

Figure 40: Typical groups at 100 m (left) and 300 m (right) with the 6.8 g bullet (0.6 MoA).

Typical powder load was 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.

Drag curves for the 105 gr HBT, 115 gr TBT and 103 gr HFB are shown in Figure 41, Figure 42 and Figure 43, along with 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).

As shown in Figure 41, the G1 model is so "rounded" between Mach 0.95 and Mach 1.5 that fitting this model to real curves (even the one of the flat base bullet) will not give good results in this Mach range.

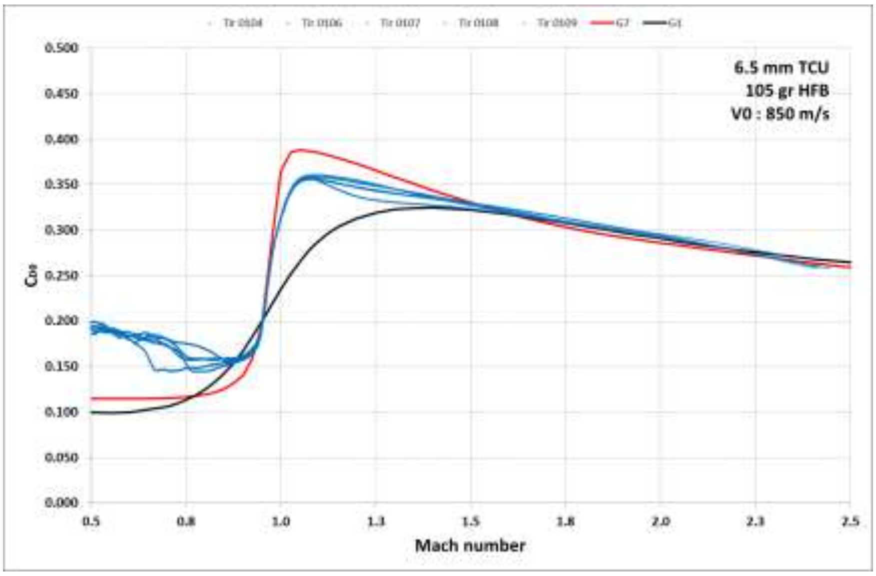


Figure 41: Drag curve for the 105 gr Hybrid Boat Tail and fitting of the G7 and G1 curves in the supersonic domain.

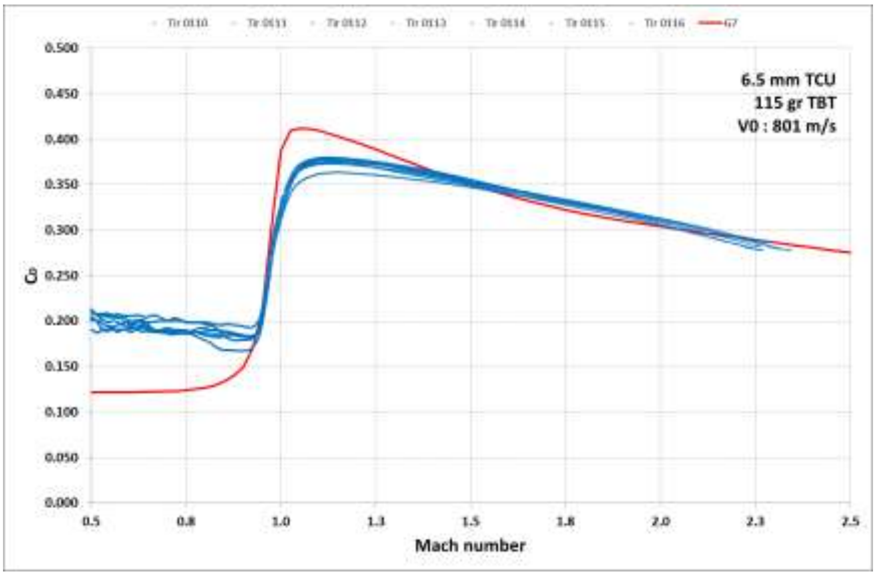


Figure 42: Drag curve for the 115 gr Tangent Boat Tail and fitting of the G7 curve in the supersonic domain.

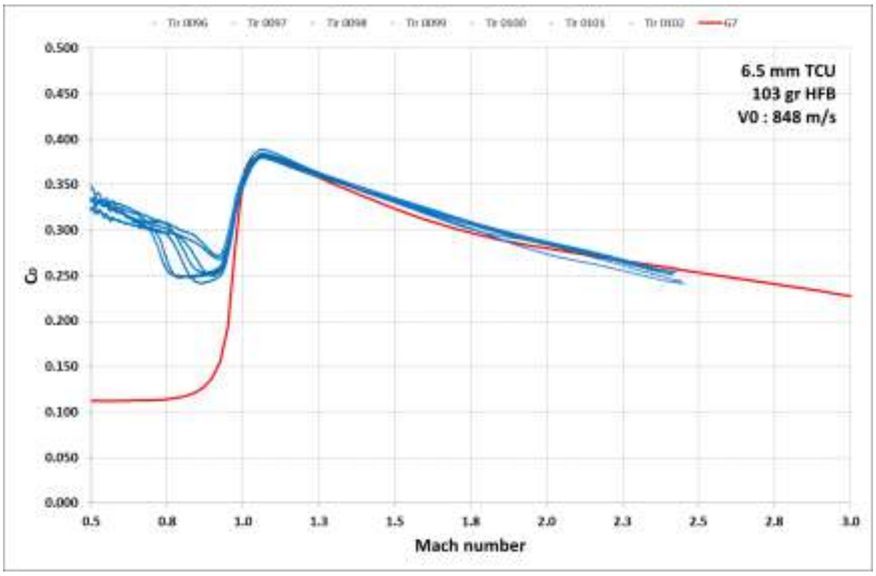


Figure 43: Drag curve for the 103 gr Hybrid Flat Base and fitting of the G7 curve in the supersonic domain.

	Static stability At launch	M<0.80	0.80<M<0.95	0.95<M<1.50	1.50<M<2.50	2.50<M<3.50
103 HFB	1.6	0.085	0.140	0.225	0.225	
103 I-HFB	*1.7*	*0.085*	*0.140*	*0.230*	*0.240*	*0.250*
105 HBT	1.4	0.165	0.165	0.235	0.225	
115 TBT	1.3	0.150	0.150	0.240	0.230	
115 I-TBT	*1.4*	*0.150*	*0.150*	*0.255*	*0.245*	*0.245*

"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.

	Muzzle velocity (m/s)	Muzzle energy (J)	ToF to 1000 m (s)	ToF to 1500 m (s)	ToF to 2000 m (s)	ToF to 2500 m (s)
103 gr HBF	1093	3986	1.35	2.70	4.87	8.50
115 gr TBT	1046	4076	1.46	2.88	4.75	7.15
419 gr SBT	855	9924	1.47	2.53	3.91	5.59
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 44) in comparison with 7.62 x 51 mm ball, both bullets having the same impact velocity at 200 m (around 700 m/s).

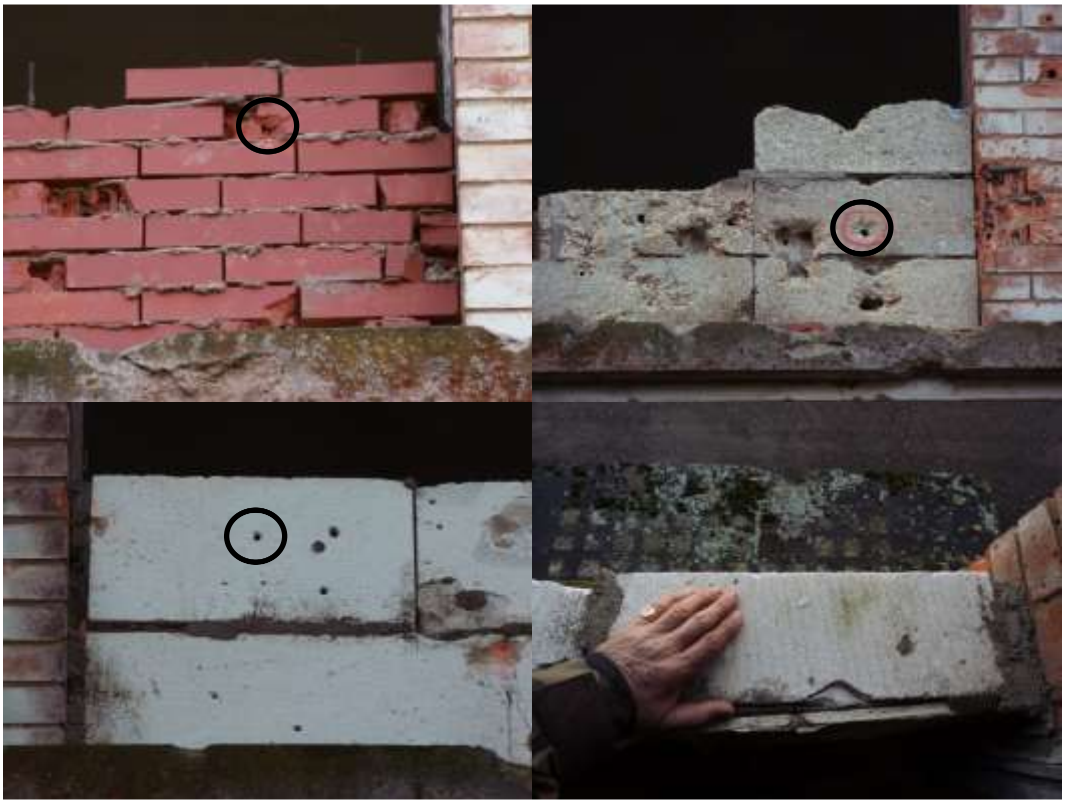


Figure 44: Targets used for tactical penetration evaluation.

Penetration in all media was identical or better with the 6.5 mm bullet 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 package.

While not completely fair due to the use of a compressed powder load (unsuitable for military use) and a slightly longer than usual 580 mm barrel, the 6.5 mm TCU cartridge weighed less than 15 g with its 6.8 g bullet, delivering better performance than the 7.62 mm M80 ball with only 75 % of its recoil and 60 % of its weight.

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 45).

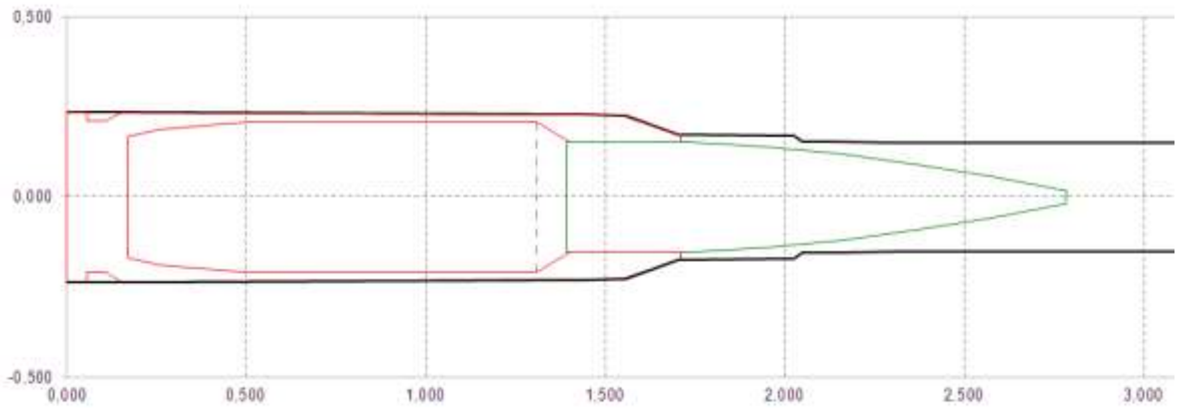


Figure 45: Sketch of a "neckless" 7.62 x 43 mm round in a conventional 7.62 x 51 mm chamber.

This design was successfully tried 30 years ago by the AAI Corporation for 20 mm and 25 mm medium calibre ammunition[xxxiv], but unfortunately the reduction in the case capacity did not allow the required muzzle velocity to be achieved.

Figure 46: Example of AAI Corporation 25 mm ammunition (1973 manufacture) with neckless composite case (left), and a 6.5 mm version based on the 7.62 x 51 mm case.

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).

In order to validate those points, a 130 gr flat (and hollow) base bullet with a length of 33.5 mm and a nose of 23.5 mm was manufactured and fired from 7.62 x 51 mm weapons.

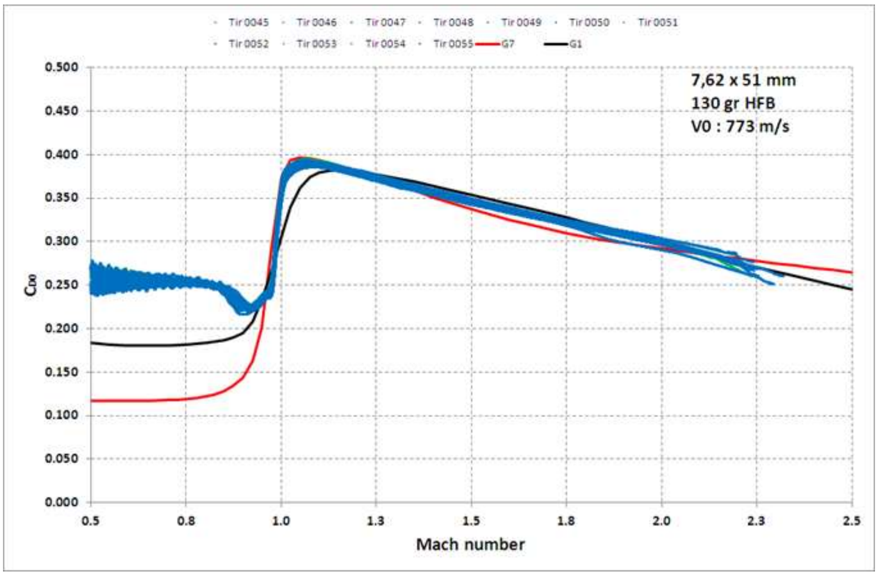


Figure 47: Drag curve for the 130 gr Hybrid Flat Base and fitting of the G1 and G7 curves in the supersonic domain.

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.

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.

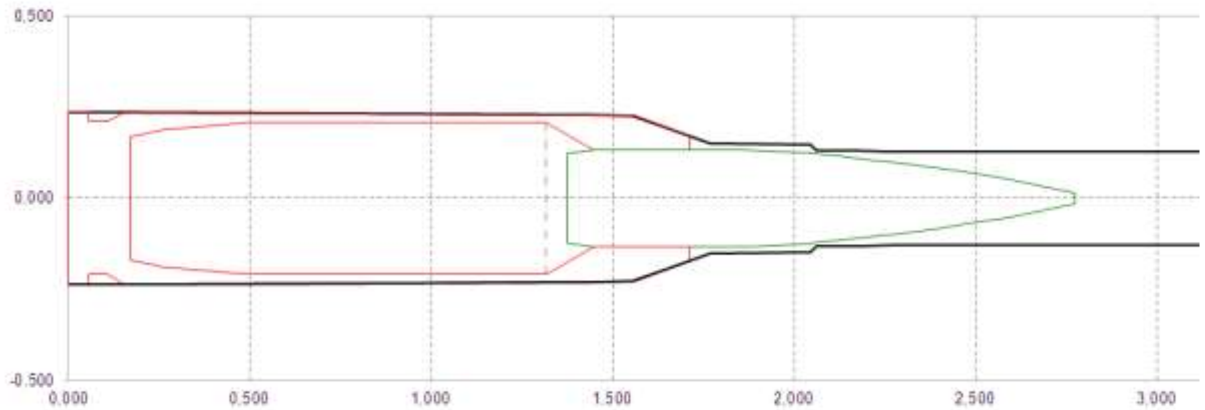


Figure 48: Sketch of a "neck less" 6.5 x 43 mm round in a conventional .260" Remington chamber.

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).

[i] « Etude sur les armes de chasse », Revue d'Artillerie, octobre 1896, p.156.
[ii] « L'Artillerie de terre en France pendant un siècle. Histoire technique (1816-1919) », T1, p.368.
[iii] "Field artillery and firepower", (2004) Naval Institute Press, ISBN 1-59114-029-3.
[iv] « Notes sur les effets vulnérants des nouvelles armes », Revue d'Artillerie, septembre 1901.
[v] « Fusil automatique », Revue d'Infanterie, janvier 1910, pp.97-99.
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