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European Chemicals Agency (ECHA)
Committee for Socio-economic analysis (SEAC)

Report

Ballistic consequences of the change from lead to steel shot in shotgun sports shooting against clay targets

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Content

In case of uncertainty or doubt, the German version of this report shall prevail.

1 Inducement

By e-mail dated 31.05.2022, bpk consultancy gmbh was asked by the European Chemicals Agency (ECHA) whether they would be interested in writing a ballistic report on the subject of replacing lead with steel in the field of shot ammunition in sports shooting against clay targets. On 22.06.2022 we received the invitation to submit a bid. On 12.07.2022 bpk consultancy gmbh was awarded the contract.

2 Terms of Reference

ECHA's request for proposal was accompanied by a Terms of Reference (*Annex A – Technical Annex*), which described the background of the topic and the questions to be answered. The Terms of Reference are attached in the annex of this report (annex section A-1).

3 Basics

3.1 Ballistic calculations (explanations see annex A.2.1–A.2.4)

The answers to the questions posed are substantiated by the results of ballistic calculations carried out for the 2.41 mm lead shot cartridge and for different variants of steel shot cartridges. The results are summarised in a table in annex section A-3.

> The bases for the ballistic calculations were developed with extensive tests in the ballistic laboratory of the Swiss Defence Department on behalf of a Working Group of the *Comité Européen de Normalisation* (CEN) (see annex section A.2.3, page A-4). They were experimentally verified by an independent body.
>
> The transfer of the data measured with lead shot to steel shot is acceptable in the sense of comparative data, since steel balls normally have a smoother surface which, however, tends to stall earlier in the case of subsonic inflow, which increases the air resistance.

The calculations show the velocity of the shot cloud tip and in the area of the cloud end. This means that the corresponding energies, the flight times and the crosswind deflection are also known.

The calculated radial propagation velocities of the shot clouds are also based on the experimental results for the 2.41 mm shot cartridge and on physical considerations of the cause of the lateral motion. It is not taken into account that steel pellets transmit a greater momentum than lead pellets during the mutual impacts at the beginning of the cloud propagation. The cloud diameter for the steel pellets is therefore likely to be somewhat larger than the calculation indicates. However, this is irrelevant for the relative comparisons between the different steel shot variants.

3.2 Hit probability (explanations see annex section A.2.6, page A-6)

In order to determine the number of hits on a clay target, a core cloud was assumed which comprises 95 % of the shot, which is equally distributed over 72 % of the cross-sectional area (85 % of the diameter) of the shot cloud. It is also taken into account that the clay target moves forward a certain distance during the time it is swept by the shot cloud (fly-through time) and thus increases the hit area.

3.3 *Recoil (explanations see annex section A.2.7, page A-6)*

The effect of the shot on the shooter can physically only be assessed by the recoil energy. The mass (weight) of the weapon plays a role. An increase of the weapon mass by 10 % reduces the recoil energy by about 9.5 %. Within a narrow range, the shooter can decide for himself whether he wants to reduce the recoil with a heavier weapon. However, a significant reduction in recoil energy is not possible in this way. The weapons would become too heavy.

In this context, it may be of interest to note that shotguns are long guns with high recoil energies (> 17 J). This is mainly due to the large mass of the projectile. Army rifles (assault rifles) are in the range of 3-10 J and common hunting rifles (excluding those for big game hunting) are in the range of 6-15 J.

4 Parameters of the hit probability

When changing from lead shot to steel shot, it is expected that the probability of hitting the clay target will not change. It is therefore worthwhile to look at the ballistic parameters which influence the hitting of the target and which must reach very similar values with the steel shot as they do with the lead shot.

Energy is needed to break the target. Depending on the mass of the pellet, this requires a certain *velocity*.

The *flight time* of the shot cloud until it reaches the trajectory of the clay target determines the lead. Changing the flight time requires a new practice of the lead measures.

> The lead distance is the distance one has to aim in front of the moving target in order to hit it. It is the distance the target travels while the shot (the projectile) is on its trajectory.

The *deceleration* (decrease in velocity) of the shot pellets on the trajectory is decisive for the wind sensitivity. The faster the velocity of the pellet decreases, the more sensitive it is to wind. Smaller mass and higher velocity increase the deceleration.

The *radial velocity of propagation* determines the diameter of the shot cloud and thus the surface density of the pellets. It also determines the *opening angle of the cloud* from the shooter's point of view. A narrow opening angle reduces the probability of hitting the target, as the shot is more likely to miss.

With the *number of loaded pellets*, their areal density is influenced and thus also the probability of a hit. However, an increase in this number has a direct and clear effect on the recoil.

Recoil can also have an influence on the probability of a hit (although this is not physically measurable) if it creates in the shooter a certain imperceptible fear of the shot being fired.

5 Ballistician's thoughts on the change from lead to steel

If the material of a projectile is to be changed while keeping the ballistic properties as constant as possible, the same cross-sectional density (CSD) should be considered (see annex section A.2.2, page A-4). The steel pellet corresponding to a lead pellet has a greater mass and thus also greater energy in the target with exactly the same trajectory (including flight time and wind sensitivity). However, one accepts that the number of pellets is significantly reduced.

This could possibly be compensated for by the higher energy of the pellets, in that fewer hits could be necessary to break the target.

Choosing steel shot with a diameter of ≤ 3 mm and increasing the muzzle velocity to compensate for the greater deceleration is not sensible. The higher velocity leads to an even greater deceleration (the air resistance increases quadratically with the velocity), which means that the energy in the target is nevertheless low.

Example: A lead ball with a diameter of 2.41 mm and an initial velocity of 400 m/s has an energy of 0.84 J at 50 m. A steel ball of the same mass and diameter 2.7 mm would have to have an initial velocity of 650 m/s to have the same energy at 50 m as the lead ball. This would lead to a muzzle energy that none of the usual shotgun designs could withstand.

If the ballistic properties are to be at least approximately maintained with the above-mentioned change of material, heavier steel balls should be used. The muzzle velocity should not be increased, but rather reduced in favour of a larger number of pellets.

6 Comments on points 1-6 of the order

6.1 Damage to the gun because of abrasion: The argument is that steel will damage the gun barrel because of its abrasive action.

It can be assumed that steel shot cartridges are designed with shot cups. This means that the pellets do not come into contact with the barrel wall and cannot damage the barrel.

6.2 Damage to the gun because of high pressure: To compensate for the lower density of steel pellets (leading to a faster deceleration after they leave the gun muzzle) powder charges need to be higher, leading to higher pressure when firing the shotgun.

With the appropriate choice of steel shot, the deceleration can be kept in the same order of magnitude as with lead shot. A higher muzzle velocity and thus a higher pressure in the gun is not necessary (see section 5, above).

6.3 Higher recoil and noise if steel shot is used: A higher powder charge in the case of steel will inevitably lead to a stronger recoil and a louder bang when firing the gun.

A higher powder charge would only be required in connection with light steel shot, but this is not sensible with reference to section 5, above.

6.4 Different pattern of steel shot vs. lead shot: The different mechanical properties of steel pellets will cause a difference in the spreading out after the pellets leave the gun, which may influence its hitting characteristics.

The lateral spread of the shot cloud (its radial velocity) has less to do with the mechanical properties of the shot than with the dynamic pressure of the air resistance to which the emerging shot package is subjected (see annex Section A.2.4, page A-5). The forces acting for a short time accelerate the shot to a (small!) radial velocity. Heavier shot is brought to a lower velocity than lighter shot. If steel shot is used that is heavier than the previously used lead shot, a slightly smaller cloud diameter is to be expected, which requires shooters to be somewhat more precise.

It should be borne in mind that by using barrel constrictions (chokes) at the muzzle (see annex section A.2.5, page A-6), the shooters can influence the diameter of the shot cloud themselves to a much greater extent than is done by the influence of the dynamic pressure of the air resistance at the muzzle.

6.5 Difference in ability to destroy a target: The lower density of steel shot will cause the pellets to lose velocity faster than in the case of lead shot hampering the shooter's ability to break a clay target upon impact.

This is correct if small, light steel shot is used. Steel shot with a diameter > 3 mm, whose mass is so large that it has a similar trajectory to the reference lead shot, has a higher energy on target than the lead shot. The higher energy could possibly compensate for the lower shot density, so that the probability of breakage of a target becomes approximately similar. (however, this can only be confirmed or disproved by practical shooting).

6.6 Less precision with steel: The lower density of steel is claimed to result in a higher sensitivity towards wind deflection. FITASC/ISSF argue that the precision achievable with steel gunshot decreases to an unacceptable level beyond 30 metres. However, SEAC found evidence that a competition clay target shooter can hit the target consistently even on a windy day and at long distances, although some adjustment to the shooting technique is needed.

This is only correct if steel shot with diameters of ≤ 3 mm is used. Larger steel shot has practically the same or less wind sensitivity. Furthermore, in Switzerland, when a new army weapon was introduced with over 30 % higher wind sensitivity, it was found that shooters quickly became accustomed to compensating accordingly for the greater windage.

7 Answers to the questions of SEAC (see order)

7.1 What can be said about the energy of steel shot vs lead shot as a function of muzzle speed and distance?

This depends on the choice of the steel shot diameter. If the diameter is ≤ 3 mm, a stronger decreasing energy curve is to be expected, if the diameter is > 3 mm, the energy curve is almost similar or even less decreasing than that of the 2.41 mm lead shot.

7.2 Given common distances in clay target shooting disciplines (about 55m), can steel shot be used effectively? From a scientific point, does patterning and energy upon impact provide for fair conditions in competitions?

The change to steel shot can be made in such a way that the ballistic flight properties of the shot cloud are practically the same as with lead shot. The smaller number of pellets and possibly a smaller diameter of the shot cloud have to be accepted. However, the shot has a greater energy on the target, which could at least partially compensate for the lack of pellets in terms of hit probability.

An increase in the number of pellets is possible with the disadvantage of a greater recoil.

Annex Section A.3, page A-8 contains tables which, in addition to all ballistic data, also list the approximate number of hits per target.

7.3 Is it sufficient to use a 2.7 mm steel pellet (with a higher powder charge) instead of a 2.4 mm lead pellet to compensate for ballistic behaviour?

No. The ballistic behaviour of steel balls is the same as that of 2.4 mm lead balls if the cross-sectional density (see annex section A.2.2, page A-4) of both is the same. This is the case with steel balls of diameter 3.43 mm. In practice, 3.25 mm steel balls would still show a very similar ballistic behaviour, 3.5 mm steel balls a slightly better one.

7.4 Or would a 3 mm pellet be more suited, and if so, would the use of such pellets present unacceptable problems for sports shooting as claimed by FITASC/ISSF?

A 3 mm or (as mentioned in answer 7.3) even better a 3.25 mm steel ball would in any case be more suitable. There are two problems to be mentioned here: one is the smaller number of pellets, which results in a lower pellet density in the target region, the other is the probably smaller diameter of the shot cloud, which demands a somewhat better precision from the shooter.

7.5 Regarding the pellet size, how should SEAC interpret the criticism raised by FITASC/ ISSF on the analysis presented in the proposed restriction that was underpinned by data from Remington?

In general, the analysis based on the Remington study suggests choosing heavier steel shot. This is at least partly consistent with the answers to questions 7.1-7.3 above and with the statements under section 5, above.

The ballistic calculations described in the FITASC addendum of 04.05.2021 are based on a very simple calculation model and on drag data taken from the internet. According to the link provided, they are based on a known standard curve of the drag coefficient, which depends only on the Reynolds number (a number that characterises the viscosity of the air). At high velocities and large Reynolds numbers (> 30 000, in the case of shot pellets they are initially around 70 000) the influence of the viscosity becomes small and the drag is mainly determined by the ratio of the projectile velocity to the speed of sound (Mach number). Through the formation of supersonic shock waves and turbulent flow separation, energy is extracted from the projectile, which is not taken into account in the standard curve mentioned above. At the beginning, pellets fly at supersonic velocity, i.e. in the range in which the Mach number is decisive.

For this reason, ballistic institutes exclusively use drag functions which have been determined by measuring the velocity loss of the bullet during real shooting. In this way, all Mach and Reynolds number influences are automatically taken into account according to the velocity.

Our own calculations have shown that the velocities and energies given in the FITASC Addendum are too high. The same applies to the energy values in the analysis based on the Remington study. These too high values can easily be explained by the fact that the influence of the Mach number has not been taken into account.

The own calculations are based on *air drag measurements of shotgun clouds and of spheres*, which have been carried out in the ballistic laboratory of the Swiss Ministry of Defence.

In the recoil calculations, the FITASC Addendum uses the value 1 200 m/s for the outflow velocity of the powder gases (after the bullet has released the muzzle). This value is clearly too high.

The outflow velocity depends primarily on the pressure and density of the powder gases still prevailing in the barrel at that point in time.

Shotguns have a muzzle pressure of less than 100 bar (typically 70-80 bar). Using a formula derived from fluid mechanics to estimate the outflow velocity, which shows plausible results for different weapons, values in the order of 600-700 m/s are obtained for shotguns. The value chosen by FITASC is found for high-powered cannons with muzzle pressures of several 100 bar.

8 Summary

The change from lead to steel shot in sports shooting against clay targets has the greatest chance if, by choosing steel shot of the same or very similar cross-sectional density, the ballistic trajectory characteristics remain practically the same. Velocity, flight time and wind sensitivity hardly change, the energy in the target increases; it can rise to up to twice the value.

The disadvantage is that the number of pellets and thus the coverage in the target drops below half for the same load. This is counteracted by the higher energy of the pellets in the target, in that fewer hits may be required to break a clay target. However, the load (the number of pellets) can also be increased, which increases the mass of the projectile and thus also the recoil. This increase in recoil can be kept within limits by reducing the muzzle velocity at the same time as increasing the load.

The extent to which these approaches can lead to comparable hit probabilities must of course be tested in practice.

Der Berichterstatter:

Dr. Beat Kneubuehl

Annex

A.1 Original order (extract from Annex A – Technical Annex)

Background

On 24 March 2021, ECHA opened a consultation on a proposal to restrict the use of lead in outdoor shooting (incl. hunting and sports shooting) and fishing.[1] In this consultation various stakeholders submitted information raising questions about the suitability of alternative ammunition for sports shooting, and especially for trap and skeet shooting.

One recurring point raised by stakeholders is whether the differences in properties and performance between steel shot and lead shot are so significant that they will prevent general use of steel shot in sports shooting, which relates mainly to different variations of clay target shooting. In international competitions organised by FITASC[2] or ISSF[3] the use of lead shot is currently mandatory (as it is specified in the rules).

In the consultation on the proposed restriction many comments were received which made statements pro and contra this matter. Moreover, many reports about personal experiences have been reported in internet fora. Recently, a voluntary ban on the use of lead shot announced in the United Kingdom has generated a lot of comparative testing of alternative shot, both for hunting and clay target shooting. In general, these tests show that initial scepticism on steel gunshot gave rise to a more positive opinion after some experience with this type of shot was gained.

This matches experiences in other countries that have been using steel shot already for a longer time. However, data submitted by FITASC and ISSF to the consultation shows differences with regard to relevant aspects of ballistics and other parameters. The following key arguments have been identified by these federations as reasons for concluding that steel shot is not suitable for high-level sports shooting:

1. **Damage to the gun because of abrasion**: The argument is that steel will damage the gun barrel because of its abrasive action.
2. **Damage to the gun because of high pressure**: To compensate for the lower density of steel pellets (leading to a faster deceleration after they leave the gun muzzle) powder charges need to be higher, leading to higher pressure when firing the shotgun.
3. **Higher recoil and noise if steel shot is used**: A higher powder charge in the case of steel will inevitably lead to a stronger recoil and a louder bang when firing the gun. FITASC/ISSF presented numerical data on this and claim this will harm the health of the shooter and cause problems with permits of shooting ranges and is therefore not acceptable.

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[1] Submitted restrictions under consideration – ECHA (europa.eu)

[2] Fédération Internationale de Tir aux Armes Sportives de Chasse

[3] International Shooting Sport Federation

4. **Different pattern of steel shot vs. lead shot**: The different mechanical properties of steel pellets will cause a difference in the spreading out after the pellets leave the gun, which may influence its hitting characteristics.
5. **Difference in ability to destroy a target**: The lower density of steel shot will cause the pellets to lose velocity faster than in the case of lead shot hampering the shooter's ability to break a clay target upon impact.
6. **Less precision with steel**: The lower density of steel is claimed to result in a higher sensitivity towards wind deflection.[4] FITASC/ISSF argue that the precision achievable with steel gunshot decreases to an unacceptable level beyond 30 metres. However, SEAC found evidence[5] that a competition clay target shooter can hit the target consistently even on a windy day and at long distances, although some adjustment to the shooting technique is needed.

In this context, SEAC understands that steel gunshots lose speed and impact energy faster than lead pellets. Compensation is sought by using higher velocities (through larger powder charges) and a larger pellet size. However, some specific questions have come up in the discussions of the SEAC:

- What can be said about the energy of steel shot vs lead shot as a function of muzzle speed and distance?
- Given common distances in clay target shooting disciplines (about 55m), can steel shot be used effectively? From a scientific point, does patterning and energy upon impact provide for fair conditions in competitions?
- Is it sufficient to use a 2.7mm steel pellet (with a higher powder charge) instead of a 2.4mm lead pellet to compensate for ballistic behaviour?
- Or would a 3mm pellet be more suited, and if so, would the use of such pellets present unacceptable problems for sports shooting as claimed by FITASC/ISSF?
- Regarding the pellet size, how should SEAC interpret the criticism raised by FITASC/ISSF on the analysis presented in the proposed restriction that was underpinned by data from Remington?

Objectives

The objective of this service contract is to provide SEAC with independent expert advice. To this end, the expert will scrutinise each of the key points listed above and provide i) a judgement on the plausibility of the concerns raised, and ii) to the extent the concerns are warranted, a view on whether limitations could be addressed, e.g. by adjustments of technical equipment, shooting technique, etc.

[4] https://www.knsa.nl/de-knsa/accommodaties/schieten-met-loodhagel-op-kleiduiven/

[5] https://www.youtube.com/watch?v=Nl1DLfzOzk8&t=240s

A.2 Ballistic basics

A.2.1 The aerodynamic drag coefficient c_D

In aerodynamics, forces are always related to the so-called stagnation pressure. This is the pressure exerted by a flow against a very large flat plate. The real resistance experienced by a body in the flow is related to the stagnation pressure resistance. The ratio is the aerodynamic drag coefficient:

$$c_D = \frac{F_{Real}}{F_{Stagn}} = \frac{F_{Real}}{\frac{1}{2} \cdot \rho \cdot v^2 \cdot A}$$

A means a reference area, in ballistics usually the cross-sectional area of the projectile in the direction of motion.

A.2.2 The cross-sectional density (CSD) and the deceleration

The air drag of a projectile is calculated in fluid dynamics by means of the following relationship:

$$F_{real} = c_D \cdot \left(\frac{1}{2} \cdot \rho \cdot v^2 \right) \cdot A$$

The bracket represents the stagnation pressure of the air flow, c_D stands for the drag coefficient, which is given exclusively by the shape of the projectile and A is the cross-sectional area of the projectile in the direction of flight.

For two projectiles to follow exactly the same trajectory, they must have the same velocity profile, i.e., they must have the same deceleration. The deceleration **a** result from the relationship "resistance (force) equals mass times deceleration".

$$a = \frac{F}{m} = c_D \cdot \left(\frac{1}{2} \cdot \rho \cdot v^2 \right) \cdot \frac{A}{m} = c_D \cdot \left(\frac{1}{2} \cdot \rho \cdot v^2 \right) \cdot \frac{1}{q}$$

Where q = m/A means the cross-sectional density (CSD).

If two projectiles have *the same drag coefficient, the same cross-sectional density and the same initial velocity*, they always have the same deceleration and thus always the same velocity; their trajectories are thus identical. It can be shown that the wind deflections are then also identical.

A.2.3 Trajectory calculation of the shot cloud

The trajectory calculations for the shot cloud are based on extensive experiments carried out in the ballistics laboratory of the Swiss Ministry of Defence in the first decade of this century (2004–2006) on behalf of a working group of the Comité Européen de Normalisation (CEN).

In these tests, 2.41 mm lead shot clouds as well as 2.61 and 2.85 mm steel shot clouds were shot along a measuring distance of up to 50 m via 6 pairs of light barriers and the delay of the first and the last pellet were measured. The velocity was determined by analysing the signals recorded by the light screens. For physical reasons, the frontmost pellet at the tip had to be measured. To determine the velocity at the end of the cloud, the last autocorrelated signals were searched for and defined as end velocity, knowing that there are a certain number of pellets that pass the light screen outside the measuring field.

From the measured decelerations, drag coefficients for the tip and end of the shot cloud could be determined, with which the trajectory of the tip and end of the cloud can be calculated. Due to the strong change of the cross-sectional density at the cloud opening, the drag coefficients depend on the muzzle velocity. The 2.41-mm lead shot was measured with the cylindrical and the full choke barrel, both with the muzzle velocities 380 and 420 m/s. In addition, the 2.61 mm and 2.85 mm steel shot were measured from the cylindrical barrel. The corresponding c_D functions are available. Since these are basically only dependent on the shape of the projectile, they can also be used for other materials and in a certain range also for other shot diameters. The results of the calculations were subsequently confirmed experimentally in tests by the CEN working group mentioned above.

A.2.4 The radial velocity of the shot cloud

When the shot package leaves the muzzle of the shotgun, air resistance causes a stagnation pressure to act on the front of the shot package. Since the pellets are no longer guided laterally, they are pushed apart by this pressure and receive a velocity component transverse to the direction of flight due to the effect of the force. The stagnation pressure does not depend on the load, but only on the muzzle velocity. The transverse velocity, on the other hand, depends on the mass of the pellet; heavy pellets are accelerated to a lower velocity than light pellets with the same force. This process only lasts a very short time, because when the cloud opens, the pellets are flowed around all sides and the lateral force disappears.

This velocity in radial direction is subsequently influenced by mutual contact and by other disturbances (shot cups, wads). After about 5 m, the shot cloud has expanded so much that most of the pellets fly individually. The radial velocity is maintained from then on, as the air resistance of the transverse motion is negligible due to the small amount of radial velocity. Other forces that could accelerate or decelerate the pellet are absent. The radial expansion of the shot cloud is thus proportional to the flight time from a distance of about 5 m and thus progressive with distance.

In the above-mentioned investigation, the radial velocity of the 2.41 mm lead shot cloud from the cylindrical barrel was measured to be 8 m/s. As explained above, it will decrease with increasing mass of the shot pellet. According to literature, the radial velocity of 3.5 mm shot is reduced by about 25 % compared to 2.5 mm shot. Since the (radial) accelerations are inversely proportional to the masses, the transverse velocities can also be roughly estimated for steel shot. For the ballistic assessment of the flight characteristics of steel shot, such estimated values based on physical considerations are important, even if they only provide approximate data. The radial extension of the shot cloud plays a decisive role in the hit probability.

A.2.5 The influence of the choke

The radial velocity of the shot cloud can be controlled via the so-called choke bore (choke). This is a (conical) constriction of the barrel at the muzzle of the shotgun. The cone (in the sub-millimetre range) gives the outer shot a velocity component directed against the barrel axis, which partially compensates for the outward component generated by the dynamic stagnation pressure. This reduces the overall radial velocity of the shot cloud, which in turn reduces its diameter. The result is a higher hit density of the shot.

There are a number of different degrees of barrel constriction, which are designated ¼-, ½-, ¾- and full choke, among others. In the study described in A.2.3, the radial velocity of a shot from a full choke barrel was also measured. It was 4 m/s, half that of the cylindrical barrel.

In order to show the influence of the choke bore, examples with full choke were calculated in this study. Smaller chokes lie between the results of the two groups of results, cylindrical barrel and barrel with full choke.

A.2.6 The number of hits per clay target

By means of the radial velocity of the shot cloud, its diameter can be calculated as a function of the distance. Since this velocity refers to the outermost shot, only a core cloud of 85 % of the total diameter (72% of the cross-sectional area) can be considered for the determination of the hits.

For the decisive shadow area of a clay target, the value 44 cm^2 was found in the documents of an earlier investigation. If one considers the process of hitting dynamically, the clay target moves forward by a certain distance during the time it is in the shot cloud, which is also to be counted as part of the possible hitting area. This distance is calculated from the passage time of the cloud at a certain distance and the velocity of the clay target, which can be assumed to be 20 m/s.

> Thus, the clay target in the 2.41 mm lead shot cloud moves forward by 48 cm at a distance of 40 m, thus increasing the actual hitting area.

Within the core cloud, a uniform distribution of 95 % of the total number of pellets is assumed. The hit density determined in this way, together with the hit area described above, provides the average number of hits per clay target.

A.2.7 The evaluation of the recoil

When the shot is fired, the projectile and the powder gases flowing after it receive a certain momentum in the direction of firing, which is balanced by an equally large momentum in the opposite direction. This counter-momentum is called *recoil momentum*. It is the direct cause of the mechanical forces acting on the shooter during firing.

The recoil momentum consists of the *projectile momentum* (pellet package including wad or shot cup) and the momentum of the powder gases flowing out of the muzzle – the *after-shot momentum*. The velocity of the powder gases flowing out of the muzzle is 600-700 m/s for shotguns.

As a result of the recoil momentum, the weapon begins to move with a certain velocity against the direction of shooting. It thus possesses kinetic energy, which in this context is called *recoil energy*. Since recoil energy is a measure of the working capacity of the moving weapon, it is the only measurable quantity with which recoil can be objectively assessed.

> The recoil momentum is not sufficient for an assessment. With heavy weapons, shooters find the recoil much more pleasant than with light weapons, although the recoil momentum is the same.

The recoil energy is calculated from the square of the recoil momentum divided by twice the mass of the weapon.

A.3 Comparison of ballistic data of lead and steel shot

A.3.1 On the validity and accuracy of the following ballistic calculations

The following pages contain the results of trajectory calculations of various steel shot clouds, which can be compared with each other and with the 2.41 mm lead shot. Each table comprises three pages. The following information on validity and accuracy must be considered.

The first column in Tables A.3.3 and A.3.5 concern 2.41 mm lead shot with muzzle velocity (v_0) 420 m/s and are based on measured data (mean values of five to seven shots). The external ballistic values have already been validated by shooting tests. They are likely to be close to the real behaviour of the shot cloud.

The drag coefficients of the 2.41 mm lead shot with v_0 400 m/s (comparison cartridge) were obtained by interpolation from the coefficients with v_0 420 and 380 m/s. An experimental verification did not (yet) take place. However, the tabulated trajectory data are plausible.

The trajectories of the steel shot were calculated with the measured drag coefficients of the 2.85 mm steel shotshell and corresponding initial values (calibre, mass, v_0). The data obtained can be used well to compare the influences of the parameters. The extent to which they correspond to reality can only be determined through experiments.

In the measurement method described in section A.2.3, it was accepted that a certain number of straggler pellets would escape the measurement. The end velocities are therefore rather too high, the calculated cloud lengths too short. From a ballistic point of view, these "lost" pellets hardly play a role because of their low energy.

The radial spread of the shot clouds is based on measurements for the lead shot. For the steel shot, the mass-dependent assumption described in section A.2.4 has been applied. Since all variants were calculated in the same way, a relative comparison of the data is still possible.

A.3.2 Notes on noteworthy points in the tables

The lines of interest for shooting against clay targets – the average energy of a pellet and the number of hits on the clay target – are highlighted in green.

Table A.3.3 shows that an increase in velocity with the 2.7 mm and the 3 mm steel shot results in a small increase in energy at 30 m, but at 40 m it is already lost. The higher number of hits on the clay target can be explained by the shorter flight time, which results in a smaller cloud diameter and thus a higher pellet density.

Table A.3.4 shows, in addition to the comparison cartridge (24 g, v_0 400 m/s), variants of the 3.25 and 3.5 mm steel shot with larger payloads and v_0 380 m/s. This allows the number of pellets to be increased without an excessive increase in recoil.

Table A.3.5 presents the results with a full choke barrel. The number of hits on the clay target increases greatly, but at the expense of a small cloud diameter, which requires much more precise shooting.

A.3.3 Comparison of 2.41 mm lead shot with 2.7 and 3 mm steel shot

Comparative table 2.41 mm lead shot to 2.7 and 3 mm steel shot

Cylindric barrel

Exposed clay target area 0.0044 m^2 Core cloud-Ø 0.85

Clay target velocity 20 m/s Effective pellets 0.95

Ballistics		Lead shot		Steel shot			
		2.41 mm	2.41 mm	2.7 mm	2.7 mm	3 mm	3 mm
Pellet mass	[g]	0.081	0.081	0.0804	0.0804	0.11	0.11
CSD of a pellet	[g/mm^2]	0.01819	0.01776	0.01404	0.01404	0.01556	0.01556
Muzzle velocity	[m/s]	**420**	**400**	**400**	**420**	**400**	**420**
Cartridge load	[g]	**24**	**24**	**24**	**24**	**28**	**24**
Number of pellets	[-]	296	296	299	299	255	218
Distance 30 m							
Velocity of the first pellet	[m/s]	203	198	171	173	183	186
Energy of the first pellet	[J]	1.67	1.59	1.18	1.20	1.84	1.90
Velocity at the end of the cloud	[m/s]	184	181	154	155	166	168
Pellet energy at the end	[J]	1.37	1.33	0.95	0.97	1.52	1.55
Flight time of the cloud centre	[s]	0.113	0.117	0.129	0.126	0.124	0.12
Fly-by time	[ms]	12	11	13	15	12	13
Mean velocity of the cloud	[m/s]	193	190	163	164	174	177
Mean pellet energy	[J]	1.52	1.46	1.07	1.09	1.68	1.73
Length of the cloud	[m]	2.2	2.1	2.2	2.4	2.1	2.3
Radial velocity	[m/s]	8.0	8.0	8.0	8.0	7.2	7.2
Diameter of the cloud	[m]	1.8	1.9	2.1	2.0	1.8	1.7
Opening angle	[°]	1.5	1.5	1.7	1.6	1.5	1.4
Number of pellets on clay target	[-]	2.32	1.96	1.83	2.24	1.42	2.03
Wind deflection (3 m/s crosswind)	[m]	0.12	0.12	0.16	0.16	0.14	0.14

Ballistics		Lead shot		Steel shot			
		2.41 mm	2.41 mm	2.7 mm	2.7 mm	3 mm	3 mm
Distance 40 m							
Velocity of the first pellet	[m/s]	166	164	135	136	148	149
Energy of the first pellet	[J]	1.12	1.09	0.73	0.74	1.2	1.22
Velocity at the end of the cloud	[m/s]	149	148	120	119	132	132
Pellet energy at the end	[J]	0.90	0.89	0.58	0.57	0.96	0.96
Flight time of the cloud centre	[s]	0.172	0.177	0.2	0.196	0.189	0.184
Fly-by time	[ms]	21	20	26	29	23	25
Mean velocity of the cloud	[m/s]	158	156	127	128	140	140
Mean pellet energy	[J]	1.01	0.99	0.66	0.66	1.08	1.09
Length of the cloud	[m]	3.3	3.1	3.3	3.6	3.1	3.5
Radial velocity	[m/s]	8.0	8.0	8.0	8.0	7.2	7.2
Diameter of the cloud	[m]	2.8	2.8	3.2	3.1	2.7	2.6
Opening angle	[°]	1.7	1.7	1.9	1.9	1.6	1.6
Number of pellets on clay target	[-]	1.47	1.42	1.36	1.59	1.47	1.45
Wind deflection (3 m/s crosswind)	[m]	0.23	0.23	0.3	0.3	0.26	0.26
Distance 50 m							
Velocity of the first pellet	[m/s]	136	136	106	106	119	119
Energy of the first pellet	[J]	0.75	0.75	0.45	0.45	0.78	0.78
Velocity at the end of the cloud	[m/s]	121	121	93	92	105	104
Pellet energy at the end	[J]	0.59	0.59	0.35	0.34	0.61	0.59
Flight time of the cloud centre	[s]	0.244	0.249	0.29	0.287	0.270	0.266
Fly-by time	[ms]	36	34	47	52	39	44
Mean velocity of the cloud	[m/s]	129	140	100	99	112	112
Mean pellet energy	[J]	0.67	0.67	0.4	0.40	0.70	0.69

Ballistics		**Lead shot**		**Steel shot**			
		2.41 mm	**2.41 mm**	**2.7 mm**	**2.7 mm**	**3 mm**	**3 mm**
Length of the cloud	[m]	4.5	4.2	4.5	4.9	4.3	4.7
Radial velocity	[m/s]	8.0	8.0	8.0	8.0	7.2	7.2
Diameter of the cloud	[m]	3.9	4.0	4.6	4.6	3.9	3.8
Opening angle	[°]	1.9	1.9	2.2	2.2	1.9	1.9
Number of pellets on clay target	[-]	1.20	1.08	1.10	1.21	1.11	1.09
Wind deflection (3 m/s crosswind)	[m]	0.37	0.37	0.49	0.50	0.43	0.43

Recoil		**Lead shot**		**Steel shot**			
		2.41 mm	**2.41 mm**	**2.7 mm**	**2.7 mm**	**3 mm**	**3 mm**
Powder charge	[g]	1.6	1.5	1.6	1.5	1.5	1.5
Exhaust velocity	[m/s]	660	660	660	660	660	660
Pellet mass	[g]	0.175	0.081	0.11	0.0804	0.0804	0.0804
Cartridge load	[g]	**24**	**24**	**24**	**24**	**24**	**24**
Wad	[g]	2.5	2.5	2.5	2.5	2.5	2.5
Weapon mass	[kg]	3.6	3.6	3.6	3.6	3.6	3.6
Recoil momentum	[Ns]	11.7	11.1	11.7	11.1	11.1	11.6
Recoil energy	[J]	18.9	17.1	18.9	17.1	17.1	18.8

A.3.4 Comparison of 2.41 mm lead shot with 3.25 and 3.5 mm steel shot

Comparative table 2.41 mm lead shot to 3.25 and 3.5 mm steel shot

Cylindric barrel

Exposed clay target area	0.0044 m^2	Core cloud-Ø	0.85
Clay target velocity	20 m/s	Effective pellets	0.95

Ballistics		Lead shot	Steel shot				
		2.41 mm	3.25 mm	3.25 mm	3.5 mm	3.5 mm	3.5 mm
Pellet mass	[g]	0.081	0.14	0.14	0.175	0.175	0.175
CSD of a pellet	[g/mm^2]	0.01778	0.01688	0.01688	0.01819	0.01819	0.01819
Muzzle velocity	[m/s]	**400**	**400**	**380**	**380**	**400**	**380**
Cartridge load	[g]	**24**	**24**	**28**	**26**	**24**	**28**
Number of pellets	[-]	296	171	200	149	137	160
Distance 30 m							
Velocity of the first pellet	[m/s]	198	205	190	200	214	200
Energy of the first pellet	[J]	1.59	2.94	2.53	3.50	4.01	3.50
Velocity at the end of the cloud	[m/s]	181	184	167	176	193	176
Pellet energy at the end	[J]	1.33	2.37	1.95	2.71	3.26	2.71
Flight time of the cloud centre	[s]	0.117	0.114	0.123	0.119	0.111	0.119
Fly-by time	[ms]	11	15	16	15	13	15
Mean velocity of the cloud	[m/s]	190	194	179	188	203	188
Mean pellet energy	[J]	1.46	2.66	2.24	3.11	3.64	3.11
Length of the cloud	[m]	2.1	2.7	2.8	2.65	2.7	2.65
Radial velocity	[m/s]	8.0	6.75	6.75	6.4	6.4	6.4
Diameter of the cloud	[m]	1.9	1.5	1.7	1.5	1.4	1.5
Opening angle	[°]	1.5	1.2	1.4	1.2	1.1	1.2
Number of pellets on clay target	[-]	1.96	2.28	2.18	1.98	1.88	2.13
Wind deflection (3 m/s crosswind)	[m]	0.12	0.11	0.13	0.12	0.1	0.12

Ballistics		Lead shot	Steel shot				
		2.41 mm	3.25 mm	3.25 mm	3.5 mm	3.5 mm	3.5 mm
Distance 40 m							
Velocity of the first pellet	[m/s]	164	169	156	166	178	166
Energy of the first pellet	[J]	1.09	2.00	1.70	2.41	2.77	2.41
Velocity at the end of the cloud	[m/s]	148	150	133	143	159	143
Pellet energy at the end	[J]	0.89	1.58	1.24	1.79	2.21	1.79
Flight time of the cloud centre	[s]	0.177	0.172	0.186	0.179	0.166	0.179
Fly-by time	[ms]	20	25	29	27	23	27
Mean velocity of the cloud	[m/s]	156	159	145	154	169	154
Mean pellet energy	[J]	0.99	1.79	1.47	2.1	2.49	2.1
Length of the cloud	[m]	3.1	3.9	4.2	4.0	3.8	4.0
Radial velocity	[m/s]	8.0	6.75	6.75	6.4	6.4	6.4
Diameter of the cloud	[m]	2.8	2.3	2.5	2.3	2.1	2.3
Opening angle	[°]	1.7	1.4	1.5	1.4	1.3	1.4
Number of pellets on clay target	[-]	1.42	1.46	1.63	1.35	1.31	1.45
Wind deflection (3 m/s crosswind)	[m]	0.23	0.22	0.24	0.22	0.2	0.22
Distance 50 m							
Velocity of the first pellet	[m/s]	136	139	128	138	149	138
Energy of the first pellet	[J]	0.75	1.35	1.15	1.67	1.94	1.67
Velocity at the end of the cloud	[m/s]	121	122	106	116	131	116
Pellet energy at the end	[J]	0.59	1.04	0.79	1.18	1.50	1.18
Flight time of the cloud centre	[s]	0.249	0.243	0.264	0.252	0.233	0.252
Fly-by time	[ms]	34	40	52	46	37	46
Mean velocity of the cloud	[m/s]	140	131	127	127	140	127
Mean pellet energy	[J]	0.67	1.2	0.97	1.43	1.72	1.43

Ballistics		Lead shot	Steel shot				
		2.41 mm	3.25 mm	3.25 mm	3.5 mm	3.5 mm	3.5 mm
Length of the cloud	[m]	4.2	5.1	5.9	5.7	5.0	5.7
Radial velocity	[m/s]	8.0	6.75	6.75	6.4	6.4	6.4
Diameter of the cloud	[m]	4.0	3.3	3.6	3.2	3.0	3.2
Opening angle	[°]	1.9	1.6	1.8	1.6	1.5	1.6
Number of pellets on clay target	[-]	1.08	1.06	1.32	1.12	0.96	1.20
Wind deflection (3 m/s crosswind)	[m]	0.37	0.35	0.39	0.36	0.32	0.36

Recoil		Lead shot	Steel shot				
		2.41 mm	3.25 mm	3.25 mm	3.5 mm	3.5 mm	3.5 mm
Powder charge	[g]	1.5	1.5	1.6	1.5	1.5	1.6
Exhaust velocity	[m/s]	660	660	660	660	660	660
Pellet mass	[g]	0.081	0.175	0.175	0.175	0.175	0.18
Cartridge load	[g]	**24**	**24**	**28**	**26**	**24**	**28**
Wad	[g]	2.5	2.5	2.5	2.5	2.5	2.5
Weapon mass	[kg]	3.6	3.6	3.6	3.6	3.6	3.6
Recoil momentum	[Ns]	11.1	11.1	12.1	11.3	11.1	12.1
Recoil energy	[J]	17.1	17.1	20.4	17.8	17.1	20.4

A.3.5 Comparison 2.41 mm lead shot with steel shot from a full choke barrel

Comparative table 2.41 mm lead shot to steel shot

Fullchoke

Exposed clay target area	0.0044 m^2	Core cloud-Ø	0.85
Clay target velocity	20 m/s	Effective pellets	0.95

Ballistics		**Lead shot**		**Steel shot**			
		2.41 mm	**2.41 mm**	**2.7 mm**	**3 mm**	**3.25 mm**	**3.5 mm**
Pellet mass	[g]	0.081	0.081	0.0804	0.11	0.14	0.175
CSD of a pellet	[g/mm^2]	0.01776	0.01776	0.01404	0.01556	0.01688	0.01819
Muzzle velocity	[m/s]	**420**	**400**	**400**	**400**	**400**	**400**
Cartridge load	[g]	**24**	**24**	**24**	**24**	**24**	**24**
Number of pellets	[-]	296	296	299	218	171	137
Distance 30 m							
Velocity of the first pellet	[m/s]	212	208	177	191	202	211
Energy of the first pellet	[J]	1.82	1.75	1.26	2.01	2.86	3.90
Velocity at the end of the cloud	[m/s]	190	184	156	169	179	185
Pellet energy at the end	[J]	1.46	1.37	0.98	1.57	2.24	2.99
Flight time of the cloud centre	[s]	0.110	0.113	0.125	0.119	0.115	0.112
Fly-by time	[ms]	17	18	22	20	18	19
Mean velocity of the cloud	[m/s]	201	196	167	180	190	198
Mean pellet energy	[J]	1.64	1.56	1.12	1.79	2.55	3.45
Length of the cloud	[m]	3.3	3.5	3.5	3.5	3.5	3.7
Radial velocity	[m/s]	4.0	4.0	4.0	3.6	3.4	3.0
Diameter of the cloud	[m]	0.9	0.9	1.0	0.9	0.8	0.7
Opening angle	[°]	0.7	0.7	0.8	0.7	0.6	0.6
Number of pellets on clay target	[-]	12.05	12.60	12.11	10.09	9.21	10.06
Wind deflection (3 m/s crosswind)	[m]	0.11	0.11	0.15	0.13	0.12	0.11

Ballistics		Lead shot		Steel shot			
		2.41 mm	2.41 mm	2.7 mm	3 mm	3.25 mm	3.5 mm
Distance 40 m							
Velocity of the first pellet	[m/s]	173	170	138	152	163	173
Energy of the first pellet	[J]	1.21	1.17	0.77	1.27	1.86	2.62
Velocity at the end of the cloud	[m/s]	155	150	121	133	143	150
Pellet energy at the end	[J]	0.97	0.91	0.59	0.97	1.43	1.97
Flight time of the cloud centre	[s]	0.166	0.171	0.194	0.183	0.175	0.17
Fly-by time	[ms]	27	30	38	35	31	32
Mean velocity of the cloud	[m/s]	164	160	129	143	159	161
Mean pellet energy	[J]	1.09	1.04	0.68	1.12	1.65	2.3
Length of the cloud	[m]	4.4	4.7	4.8	4.8	4.7	5.0
Radial velocity	[m/s]	4.0	4.0	4.0	3.6	3.4	3.0
Diameter of the cloud	[m]	1.3	1.4	1.6	1.3	1.2	1.0
Opening angle	[°]	0.8	0.9	1.0	0.8	0.7	0.6
Number of pellets on clay target	[-]	7.94	8.42	7.55	7.75	6.42	6.29
Wind deflection (3 m/s crosswind)	[m]	0.21	0.21	0.28	0.25	0.22	0.20
Distance 50 m							
Velocity of the first pellet	[m/s]	141	140	107	122	133	143
Energy of the first pellet	[J]	0.81	0.79	0.46	0.82	1.24	1.79
Velocity at the end of the cloud	[m/s]	126	122	93	105	116	123
Pellet energy at the end	[J]	0.64	0.60	0.35	0.61	0.94	1.32
Flight time of the cloud centre	[s]	0.235	0.241	0.284	0.256	0.249	0.239
Fly-by time	[ms]	42	47	65	45	51	50
Mean velocity of the cloud	[m/s]	140	131	100	114	131	140
Mean pellet energy	[J]	0.73	0.7	0.41	0.72	1.09	1.56

Ballistics		Lead shot		Steel shot			
		2.41 mm	2.41 mm	2.7 mm	3 mm	3.25 mm	3.5 mm
Length of the cloud	[m]	5.4	6.0	6.3	6.2	6.1	6.5
Radial velocity	[m/s]	4.0	4.0	4.0	3.6	3.4	3.0
Diameter of the cloud	[m]	1.9	1.9	2.3	1.8	1.7	1.4
Opening angle	[°]	0.9	0.9	1.1	0.9	0.8	0.7
Number of pellets on clay target	[-]	6.41	5.79	5.95	5.06	4.98	5.04
Wind deflection (3 m/s crosswind)	[m]	0.34	0.34	0.47	0.41	0.37	0.34

Recoil		Lead shot		Steel shot			
		2.41 mm	2.41 mm	2.7 mm	3 mm	3.25 mm	3.5 mm
Powder charge	[g]	1.6	1.5	1.5	1.5	1.5	1.5
Exhaust velocity	[m/s]	660	660	660	660	660	660
Pellet mass	[g]	0.081	0.081	0.0945	0.11	0.14	0.175
Cartridge load	[g]	**24**	**24**	**24**	**24**	**24**	**24**
Wad	[g]	2.5	2.5	2.5	2.5	2.5	2.5
Weapon mass	[kg]	3.6	3.6	3.6	3.6	3.6	3.6
Recoil momentum	[Ns]	11.7	11.1	11.1	11.1	11.1	11.1
Recoil energy	[J]	18.9	17.1	17.1	17.1	17.1	17.1