Introduction to Ammunition and Basic Ballistics

SONORAN DESERT INSTITUTE

SCHOOL OF FIREARMS TECHNOLOGY

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Chapter 1 - Introduction, History, Projectiles: Parts and Types

Introduction to Ammunition and Basic Ballistics

Ammunition is as important to firearms as gasoline is to automobiles. Without ammunition, the firearm is simply an over-engineered blunt object. Ammunition is the fuel that drives the firearm and like fuel, there are many different types and grades. Understanding how a cartridge is designed to function, its performance, and how each of its components lead to its performance is extremely important on all levels of shooting sports, hunting, self-defense, and military use.

Understanding static parts and their function is only the beginning. Add a spark, heat, and pressure and things really get interesting. Ballistics is the science of the behavior of a cartridge

Figure 1: Various types of cartridges.

Front Row, left to right: .40 Smith & Wesson, .17 Hornady Mach II, .22 Long Rifle Stinger, .22 Long Rifle, .17 PMC Aguila, .380 ACP, .32 ACP, .32 Smith & Wesson, .25 ACP, .22 Short, .22 BB Cap.

Second Row, left to right: .44 Remington Magnum, .30 Carbine, .50 Action Express, .357 Smith & Wesson Magnum, .25-20 Winchester, 5.7x28mm FN, .17 Winchester Super Magnum, 12-Gauge 1¾ in. ⅞ oz. Slug, .44 Smith & Wesson Special, .45 Schofield, .38 Smith & Wesson Special, 7.62x25 Tokarev, .22 Winchester Magnum Rimfire, .17 Hornady Magnum Rimfire, 5mm Remington Rimfire Magnum, .45 ACP, .45 Auto Rim, 10mm Auto, .44 Russian, 9x19mm Parabellum, .38 Smith & Wesson.

Third Row, left to right: .35 Remington, .25-35 Winchester, 12-Gauge 2¾ in. 1 oz. Bean Bag, 12-Gauge 2¾ in. 1 oz. Slug, .22-250 Remington, .410 Bore 2½ in. #6 Birdshot, 20-Gauge 2½ in. #7.5 Birdshot, .460 Smith & Wesson Magnum, .450 Bushmaster, .50 Beowulf, .458 SOCOM, .375 Reaper, .300 AAC Blackout, 7.62x39mm, 6.8mm Remington Special Purpose Cartridge, .224 Valkyrie, 5.56x45mm NATO M855A1, 5.45x39mm, 12-Gauge 2¼ in. 00 Buckshot, .454 Casull.

Fourth Row, left to right: 12.7x108mm, .50 Browning Machine Gun M2, .408 Cheyenne Tactical, .338 Lapua Magnum, .300 Winchester Magnum, .458 Winchester Magnum, 7mm Dakota, .270 Winchester, .30-06 Springfield, 7.92x57mm Mauser, 7.5x55mm Swiss, 6.5x55mm Swedish Training Round, 7.62x54mmR, .303 British, 7.62x51mm NATO MK 319 MOD 0, .410 Bore 3 in. ¼ oz Slug, 12-Gauge 3 in. 00 Buckshot, .338 Marlin Express, .243 Winchester, .444 Marlin, .45-70 Government, .300 Savage.

and projectile inside the firearm, in flight and upon impact. Ballistics is divided into four basic categories based upon the environment the projectile is interacting with. The study of the cartridge and projectile inside the firearm is known as Interior/Internal Ballistics. The study of the projectile once it has exited the muzzle and cleared the muzzle "blast" is Intermediate/Transitional Ballistics. The study of the projectile "in flight" is known as Exterior Ballistics, while the study of the projectile upon impact of the target is known as Terminal Ballistics.

Throughout this book we will discuss the various parts of a cartridge, cartridge types, the firing sequence of a cartridge, and how the cartridge and projectile behave during and after discharge. We will also discuss the basic factors that affect ballistics and how to explain why certain features of a cartridge will affect the various ballistic types in very specific ways. Through an understanding of ammunition and basic ballistics, you will be able to choose the most appropriate cartridge for any situation and circumstance.

A BRIEF HISTORY

The history of the modern cartridge can be traced back to over 1,000 years ago to the Chinese and the invention of gunpowder (charcoal, saltpeter, and sulphur). They crafted makeshift "rockets" from tubes filled with gunpowder that featured metal spear tips. As technology and time progressed, someone realized that they could use gunpowder crammed into crude "firearms" to fling projectiles at their enemies. Once the technology began to spread west around the 13th century, the Arabs became the first people in recorded history to use "cannons" in battle.[1]

The cannon was scaled down to provide soldiers with the first portable firearms, in the form of the muzzleloader. Even as the technology of the muzzle loader progressed from the matchlock, to the wheel lock, to the flintlock, the basic design was still the same: a tube filled with gunpowder, capped by a projectile. It wasn't until the advent of two separate technologies in the 19th century that we start to see the groundwork for the modern cartridge: percussion caps and the breechloader. [2]

The percussion cap lead to what we now know as a primer, and the breechloading design allowed the use of a cartridge instead of separate

Figure 2: Some of the first modern metallic cartridge types.

From left to right: 5mm Pinfire (Circa 1840). The pinfire round was the first true self-contained metallic cartridge and the precursor to the modern cartridge.
.22 BB Cap (1845). The .22 BB Cap was the first rimfire cartridge and the predecessor to all modern, self-contained metallic cartridges.
.22 Short (1857). The .22 Short was the first American metallic cartridge and is the oldest cartridge still being manufactured to this day. The .22 Short was also developed for the first Smith & Wesson revolver. .44 Henry Rimfire (1860). The .44 Henry Rimfire was developed in conjunction with the Henry Model 1860 Repeating Rifle used during the American Civil War. The round and the rifle were the first successful examples of a repeating rifle and cartridge combination.
.45 Colt (1872). The .45 Colt was the original chambering for the Colt Single-Action Army, which was adopted by the United States Army in 1873. .44-40 Winchester (1873). The .44-40 Winchester was the first metallic centerfire cartridge manufactured by Winchester and was the original chambering for the Winchester 1873 rifle and carbine. The .44-40 and 1873 rifle became so popular that the rifle was touted as the "gun that won the west." 8x50mmR Lebel (1886). The 8mm Lebel was the first smokeless propellant cartridge to be manufactured and adopted by any country (France). .30-30 Winchester (1895). The .30-30 Winchester was the first non-military, smokeless, high-velocity bottleneck cartridge developed in the United States. The .30-30 Winchester was the first smokeless chambering for the Winchester Model 1894 and became one the most famous rifle/cartridge pairings. 7.92x57mm Mauser (8mm Mauser) (1905). The 8mm Mauser is the direct descendant of the first smokeless, rimless bottleneck cartridge, the Patrone 88/M88. The M88 evolved into the 8mm Mauser by necking the case up from .318 in. to .323"; everything else remained the same.

components. The first modern cartridge as we know it was a rimfire design introduced in 1859. About 10 years later, we saw the introduction of the first centerfire cartridge.[3]

The basic cartridge design hasn't deviated much from the first self-contained metallic cartridges of 150 years ago. While the materials are basically the same (lead, brass), the shape of the projectile and case and the composition of the propellant and priming compound have changed significantly. Performance in all aspects has also changed significantly, reaching distances that were once impossible. New case and projectile materials have been introduced and have found success with niche markets but have not replaced the originals. The modern cartridge also benefits from computer-aided design, computer-controlled manufacturing techniques, and state-of-the-art testing facilities.

Parts of a Cartridge

Depending on the design, there are three or more major parts or assemblies that come together to form a complete cartridge. These parts are the bullet or projectile, the case, propellant, and primer. The case houses the other components and, in most instances, is the only part that can be re-used. Some cartridges may feature a few more parts or combine two parts into an assembly. Sometimes, some of these parts are interchangeable with other cartridges while others are meant for specific applications. Understanding the features of these parts will help in the overall understanding of the science behind the ballistics of a certain cartridge.

PROJECTILES

A projectile is a generic term for an object that is propelled by an external force and continues to travel from its own momentum. When a cartridge is discharged, the object exiting the muzzle and flying through the air is the projectile. Depending on the type of cartridge, the projectile used may be a single bullet or multiple round balls (or combination of the two).

The major difference between a bullet and other forms of firearm projectiles is that the shape of a bullet requires it to be "stabilized" by the firearm before entering the open air. This stabilization comes from rotation imparted by the rifling inside the bore of certain firearms' barrels. Typically, bullets are fired from pistols and rifles, while shotguns with "smooth" bores fire round projectiles (balls) that do not require spin to stabilize in flight.

Consider a person throwing a football and a baseball. When a football is thrown properly, it will rotate around its center axis as it flies through the air to its intended target. A football that is thrown improperly will wobble and tumble through the air, rarely if ever hitting its target. Now think about someone throwing a baseball. Regardless of whether the baseball is spinning or not (such as a knuckle ball), it will always make it to its intended target without wobbling or tumbling.

Figure 3: Various components.

Figure 4: Various projectiles.

Like a football, a bullet is an elongated projectile that requires spin to stabilize it in flight. The basic bullet shape is a cylinder with either a round or pointed nose, depending on whether it is intended for a pistol or rifle, respectively(and is more or less aerodynamic). There is a point, however, that a bullet can be spun too fast, which may cause the bullet to fragment or separate prior to striking the target. Therefore, the appropriate spin to bullet weight and shape has some science to it.

Other projectiles used in modern firearm cartridges are often limited to smoothbore shotgun use. The general types of projectiles used in these cartridges are slugs, which are similar to bullets in shape and design but utilize a special feature to impart spin on themselves, and buckshot and birdshot, which are spheres of varying sizes. Like baseballs, buckshot and birdshot do not have to spin to stabilize in flight, which perfectly suits them for use in a non-rifled shotgun smoothbore.

PARTS OF A BULLET

Although the general bullet shape is a fairly standard design, there are many features of the modern bullet that allow it to perform well beyond what was capable even 100 years ago. As computer-aided modeling and simulated fluid dynamic software evolve, bullet designers are able to evolve the design of the bullet at a rate never seen before. Using powerful software, designers can rapidly change the shape of a bullet and simulate its travel both inside the bore and in various environmental conditions, without ever having to leave the comfort of their office.

Each feature of the modern bullet contributes to its overall performance and many features can be "stacked" to multiply its performance. The following are the various parts and features of a bullet.

- **Core –** The core of a bullet is its heart. The core is what makes up the basic size and shape of the bullet. The term core is typically used when the bullet utilizes a multi-piece construction: the core wrapped in an envelope. Solid construction bullets do not feature a core or envelope and are comprised of a single material throughout. The core and jacket will always be constructed of dissimilar materials, typically with a softer core and a harder coat. There are instances with

Figure 5: Various bullet cores.

military use where the core is made up of dual or multiple materials while still being covered with a metal jacket.

Depending on bullet type, the core (or solid bullet) may be formed in one of several ways: the bullet may be cast in a single operation, drawn from wire and swaged (pressure formed in a die) over multiple operations, machined from a solid billet with one or multiple operations, or (injection) molded from advanced composite materials. The core may also be mechanically "bonded" to the jacket through various methods. Bonding two or more different substances together can be thought of as welding the materials together.

- **Jacket** – The jacket is a protective metal covering, formed over the core and used to protect both the bullet and the bore of the firearm. Since the advent of modern, smokeless propellants, bullet velocities and chamber pressures became so great that soft, unprotected cores were deforming drastically and melting inside the bore. The answer was to cover the soft core with a harder material that would prevent it from deforming or melting and would protect the bore from a melted core.

  Depending on bullet type, the jacket may completely encompass the entire core, or only cover a small portion of it. The jacket may simply cover the core, allowing for more of a chance of separation upon impact of the target, or the jacket may be mechanically bonded (brazed, glued or swaged) to the core, creating less of a chance of separation upon impact. The jacket type is a huge factor in the bullet's terminal ballistic performance. The jacket material is also a considerable factor in its terminal performance.

  The concentricity of the jacket and the uniformity of the wall thickness is key to its exterior ballistic performance and its ability to stabilize. The typical forming process for a bullet jacket involves stamping out a round disc or biscuit

Figure 6a: Various solid projectiles.

Figure 6b: Solid brass projectiles.

from a sheet of material and forming a "cup" by drawing out the material with various shaped dies. The length of the cup is stretched until it is long enough to cover the core. The core is inserted into the jacket and another set of dies is used to shape the open end of the jacket and form a tip (or base) over the core.

- **Body/Bearing Surface –** The body (or bearing surface) is the cylindrical section of a bullet that contacts the bore and rifling as it passes through the barrel. The diameter of the body of a bullet closely matches the diameter of the bore of the firearm (from groove to groove) to within .0005 in. The tight body-to-bore fit seals the bore forward of the bullet from high pressure gas when the cartridge is discharged. As the bullet enters the bore, the rifling will engrave its pattern into the body of the bullet and begin to rotate it as it travels through the barrel. The length of the body and its relation to the tip and base of the bullet is critical to the stabilization of the bullet inside the bore and to its transitional ballistics as it leaves the muzzle-rifled slug. The rifling will not only react with the material in the bore, but when the bullet/projectile leaves the bore, air will pass through the rifling and impart resistance in the rifling that will cause the bullet/projectile to continue to spin.
- **Cannelure/Crimp Groove/Grease Ring –** The cannelure (or crimp groove/grease ring) is a channel formed as a ring around the body of a bullet. The cannelure serves many purposes depending

Figure 7: The body of a new bullet and the engraving of a bullet that was fired.

Figure 8: A rifle shotgun slug.

on the type of bullet it is being used on. With solid, cast bullets the groove serves as a grease ring to help lubricate the bullet as it travels through the bore. Solid cast bullets may feature several grease rings, with one ring being used as a crimp groove.

With jacketed and solid bullets, the cannelure acts as a crimp groove, allowing the case mouth to be pressed into it, securing the bullet in place and position. When used as a crimp groove, it prevents bullet setback during the loading cycle with semi-automatic firearms. If the action of the bullet being loaded into the chamber is too violent, the bullet may push back into the case when contacting the feed ramp. If the bullet is pushed too far back (typically ~.075 in.) and the cartridge is discharged, the pressure may spike and damage the firearm and possibly cause injury.

The cannelure is also used to "bond" the jacket to the core. When the cannelure is pressed into the jacket, the groove that is created displaces material on the core and secures the material below the groove together. The cannelure acts as a "belt" being cinched around a pair of pants to keep them from falling. Every cannelure is not meant to bond the two parts together; some cannelures are not deep enough. The cannelure allows the bullet forward of the groove to distort, while the area behind the bullet remains intact. Only bullets advertised as "bonded" utilize the cannelure for this purpose. The cannelure still also acts as a crimp groove in many instances. As a byproduct, the cannelure and crimp can affect the burn rate and pressure curve of the discharging cartridge on every bullet. Many manufactures and shooters believe that cannelures have a negative impact on the flight of the bullet/projectile as it may increase the turbulence in that area as the bullet/projectile passes through the air.

- **Shoulder** – The shoulder of the bullet is the area at the top edge of the bearing surface, just ahead of the cannelure. The shoulder is the transition between the cylindrical portion of the body and the curved or angled section of the front (or nose) of the bullet. When the bullet

Figure 9: Grease rings, crimp grooves, and a bullet with a bonded jacket.

Figure 10: Two shoulder types: smooth shoulders and sharp shoulders.

begins to enter the bore, the shoulder is the first point to contact the lead of the rifling. The shape of the shoulder will affect how the bullet enters the rifling. A smooth shoulder will allow the bullet to enter the rifling straighter, on a more consistent basis, and is less perceptible to cant caused by the bullet's seating depth. A sharp shoulder is more likely to cant as it enters the rifling.

- **Ogive** – The ogive of a bullet is the curved (or straight) area just ahead of the shoulder, up to the tip. The ogive shape is basically a circular arc (segment of a circle); ogives with smaller arcs (smaller circle) will form shorter, rounder noses, while larger arcs (larger circle) will form longer, pointed noses. The shape and length of the ogive will determine how suited the bullet is to defeating air resistance.

There are two basic ogive shapes, based on the size of the arc and its intersection with the bearing surface (shoulder). The two types are tangent and secant. A tangent ogive utilizes a smaller arc and a smooth transition to the bearing surface (the arc of the ogive flows into the body). Bullets with a tangent ogive will have a larger bearing surface and, in turn, more mass than a comparable bullet with a secant ogive. The tangent ogive is a feature of the original spitzer (spire) bullet, the first truly aerodynamic bullet design used in a modern cartridge.

A secant ogive utilizes a larger arc and a sharper transition to the bearing surface (the arc of the ogive flows beyond the body). Generally, a secant ogive will be more suited to defeating drag and other environmental factors but will be more susceptible to misalignment when engaging the rifling. A bullet with a secant ogive will have a shorter bearing surface and, in turn, less mass than a comparable bullet with a tangent ogive. The secant ogive is typically a design feature with

Figure 11a: Tangent ogive bullets.

Figure 11b: Secant ogive bullets.

Figure 11c: Hybrid ogive bullets.

Figure 12: Various sized meplats.

very low drag (VLD) and ultra-low drag (ULD) bullets, which are (currently) the pinnacle of aerodynamic bullet design.

Hybrid ogives provide the best of both worlds. A hybrid ogive utilizes a tangent arc just ahead of the shoulder, which transitions to a secant arc at the nose of the bullet. This allows the bullet to be very aerodynamic, while not being as finicky with seating depth and rifling engagement. A bullet with a hybrid ogive will have a longer bearing surface than a bullet with a secant ogive, and less mass than one with a tangent ogive.

- **Meplat –** The meplat is the point or tip of the nose of the bullet. The size of the meplat is directly related to the bullet's ability to cut through the air and contributes greatly to its terminal performance. A smaller meplat (a sharper point) will cut through the air (and target) better than a blunt (round or flat) meplat. Typically, pistol bullets will have a much larger meplat than long, pointed rifle bullets. The term applies to pointed, round, flat, and hollow bullet designs. Consistently shaped meplats (from bullet to bullet) will ensure the highest possible precision.

- **Boat Tail –** The boat tail of a bullet is the tapered area at the bottom that runs from the body to the base. The boat tail

Figure 13: Bullets featuring boat tail and rebated boat tail bases.

Figure 14: The heel of various bullets.

design serves two main intended purposes while providing incidental benefits. Unlike the flat-based bullet design that creates turbulent air behind the projectile, the boat tail design provides a transition that will smooth the flow of air behind the projectile. This will provide greater stability and better aerodynamics. The boat tail design is also intended to reduce drag on the projectile by reducing surface area from the bullet's body. As a side effect, the boat tail design can be used to shift the center of mass of the bullet, making it more stable in flight. The boat tail design decreases the bearing surface area, reducing the amount of strain on the bullet and the barrel. The boat tail design also increases accuracy and precision. The original spitzer design was the first bullet to utilize a boat tail.

A variation of the boat tail design, the rebated boat tail, utilizes a sharp (~90°) shoulder from the bearing surface to a boat tail with a reduced diameter at its junction with the shoulder. The rebated design creates a smoother, more uniform transition of muzzle gas behind the bullet, improving its transitional and external ballistics. The rebated boat tail design creates a better seal than the traditional boat tail, increasing bore life. The tapered design of the traditional boat tail allows gas to wedge itself between the boat tail and bore and escape ahead of the bullet. The sharp transition between the shoulder and bearing surface does not allow gas to force the bullet to cant inside the bore. The rebated design also offers increased accuracy and precision over similar bullets with a traditional boat tail.

- **Heel** – The heel of a bullet is the junction between the bearing surface (for flat base bullets) or boat tail and the base of

Figure 15: Different base styles.

Figure 15b: Rebated base bullets.

the bullet. The heel typically features a small radius regardless of base design. The radiused heel aids in the loading process, preventing any shaving as the bullet is seated in the case. The uniformity of the heel also contributes to the bullet's transitional ballistic performance by distributing muzzle gas around the base evenly.

- **Base** – The base of the bullet is the surface opposite the meplat: the bottom of the bullet. The majority of the force from expanding gas when a cartridge is discharged is focused primarily on the base. The shape of the base will dictate how thoroughly the bullet will seal the bore and how effectively it will divert gases at the muzzle. There are several different base designs including flat, dish, cup, hollow, and heel (or rebated).

The flat base is appropriately named as the base is flat, perpendicular 90° to the bullet's bearing surface. The dish base is slightly concave, while the cup base is much deeper. The hollow base provides the deepest cavern of the three. The dish, cup, and hollow bases are designed to expand (slightly for the dish, much greater for the hollow), sealing the bore (obturation) behind the bullet as it travels down the barrel. The dish, cup, and hollow bases also aid in bullet stabilization as they can be utilized to shift the center of mass of the bullet, enhancing its exterior ballistic performance.

The heel (or rebated) base design serves a different purpose than other base designs. The heel base is designed for cartridges with case and bullet diameters that are the same. To be able to insert and crimp the bullet into the case, the base of the bullet needs to be slightly smaller than the diameter of the inside of the case. Unlike the rebated boat tail, the heel base does not taper but runs parallel with the bearing surface. The heel is inserted into the case and crimped right under the shoulder.

Figure 16a: Different types of polymer tips.

Figure 16b: Polymer-tipped projectile cross-sections.

- **Polymer/Ballistic Tip** – The polymer tip is a hard plastic or rubber insert used in the hollow cavity in the nose of some bullets. The insert serves different purposes, depending on its intent. With some designs, the polymer tip serves to increase the aerodynamics of a bullet with a flat or hollow nose. With other designs, the tip acts as a wedge, forcing the hollow cavity it rests in to expand outward upon impact of the target, causing the bullet to deform greatly. Some designs will serve to improve aerodynamics and enhance the bullet's ability to expand. Polymer tips are only used with some bullet designs and are not a feature of every bullet.

Other tip inserts include aluminum and titanium. Aluminum tips serve several functions. The tip shifts the bullet's center of mass and extends the length of the bullet's nose, both contributing to the bullet's aerodynamics. The tips are also utilized to defeat hard barriers and aid in the expansion/deformation of the bullet. The titanium tip is used in a much different manner. The titanium tip can be designed for defeating barriers and hard armor. Titanium can also be used for instant feedback in the form of flash and sparks when hitting another hard object. The titanium tip can also be used to aid in expansion and deformation.

Figure 16c: Expanded polymer tipped bullets.

Figure 17: Aluminum- and titanium-tipped bullets.

Figure 18: Gas checks. Photo courtesy of Shamus Sage, Sage's Outdoors. Used with permission.
www.sagesoutdoors.com/blog new-50-rifle-caliber-copper-gas-checks-are-in-the-testing-phase/

- **Gas Check** – A gas check is a small metal cup used on the base of some solid bullets used to seal (obturate) and protect the bore. Gas checks are only found on solid, soft (lead) bullets that are fired at supersonic speeds. The bullet features a rebated base, which is capped by a (pressed) gas check that is the same diameter as the bullet. When fired, the gas check expands, sealing the bore and protecting the soft bullet from the hot, high pressure gas. The gas check also protects the bore by reducing the amount of (soft) bearing surface. The gas check is typically found on bullets intended for magnum and some rifle cartridges.

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Types of Projectiles

There is no “magic bullet”— a projectile that can perfectly perform every task that is presented to it. With as many facets of shooting as there are, it may be an impossible task to design a single bullet (even over multiple calibers and weights) that could successfully perform for each purpose. This is the reason there are so many types of projectiles, with many variants of each, with many different weights, over a plethora of calibers. One caliber can use many different projectile types and weights for a variety of purposes and still not meet the need of every shooter. Understanding the various types of projectiles and their intended purposes will allow you to choose the correct cartridge for the task at hand. As William Cowper so aptly put it in his 1785 poem, *The Task*, "Variety is the spice of life."

Pistol and rifle bullets are measured in caliber (U.S. standard and metric) and by weight. Caliber is typically a measurement from groove to groove but may be measured from land to land. Weight is expressed in grains, which are equal to 1/7000 of a pound, 1/438 of an ounce, or 1/15 of a gram.

- **Ball** – The name “ball” is very misleading. Ball projectiles are not spherical at all; in fact, some are long and pointed (spitzer). The term ball applies to bullets with a round nose and meplat, jacketed or solid (monolithic). Both pistol and rifle bullets can be found in ball configurations. Ball ammunition is designed to be cheap and abundant, unlike hollow point, soft point, or one of the many specialty projectiles. The military almost exclusively uses ball ammunition, which also finds extensive use with civilians.

  Because of their design, ball projectiles are more likely to perforate (put a hole through) a target (most materials) than are other bullet types. Depending on the material the bullet impacts, there is often little to no deformation of the bullet. Often, the only marking found on recovered bullets are the engravings cut by the rifling. Ball ammunition is also more likely to ricochet off hard targets than other bullet types.

Figure 19: Recovered ball bullet from a dirt berm.

  Ball ammunition is also better suited for use in semi-automatic firearms. In fact, many semi-auto firearms are designed specifically for exclusive use of ball bullets. The round nose makes the perfect shape for use in magazines or to move across the feed ramp and into the chamber. The smooth nose design does not feature any edges that may hang up against the magazine or firearm, making ball bullets more reliable than other bullet shapes.

- **Full Metal Jacket (FMJ)/Total Metal Jacket (TMJ)/Complete Metal Jacket (CMJ)** – The full metal, total metal, or complete metal jacketed bullet is a variation of the ball round. The terms FMJ, TMJ, and CMJ are used to describe ball bullets, which are jacketed or covered. The FMJ utilizes a jacket that encompasses everything but the base of the bullet, while a TMJ covers the bullet

Figure 20: Various ball bullet types.

completely. CMJ bullets do not technically utilize a jacket; rather the solid, swaged core is coated (electroplated) with a very thin layer of copper. The benefits of jacketed or covered ball ammunition are that a jacketed bullet can be fired at higher velocities than its non-jacketed counterpart; a jacketed bullet will experience less deformation upon impact of certain targets than their non-jacketed counterparts (the CMJ is the exception); and jacketed and coated bullets are more popular than non-jacketed solid bullets.

- **Hollow Point** – The hollow point bullet is appropriately named because of the large cavity in the meplat of the bullet. The hollow point bullet is designed to limit penetration and prevent perforation. When a hollow point bullet contacts a soft target (animal or human), the hydraulic pressure created inside the cavity forces the material surrounding it outward, forcing the mouth of the opening to expand and roll over itself. As the bullet expands as it moves through the target, the increased surface area will

Figure 21: Different FMJ, TMJ, and CMJ bullets.

Figure 22a: Several different hollow point bullets.

Figure 22b: Various hollow point bullet cross-sections.

Figure 22c: Expanded hollow point bullets.

Figure 22d: Hollow point versus open tip projectiles.

dramatically slow the projectile. The bullet's expansion is what prevents it from perforating the target and possibly damaging or injuring (or worse) something behind it. When a hollow point bullet impacts any other material, it may fail to expand, or distort unexpectedly. Some materials may clog the cavity of the bullet and prevent it from expanding because of the lack of hydraulic force.

The hollow point bullet may be solid or jacketed. When solid hollow points expand (under hydraulic pressure) and the mouth rolls over, the recovered bullet may look like a mushroom. This is where the term "mushrooming" comes from. Jacketed hollow points typically feature a jacket that extends up to the mouth of the cavity, just short of it, or even extends into the cavity. The jacket may be solid, or it may be scored or prestressed so that upon impact the jacket will expand, split, and form "petals." These petals are devastating to soft tissue and create enough drag to stop the projectile inside the target. Some jacketed hollow point bullets utilize a jacket that is bonded to the core, which limits expansion but prevents the core and jacket from separating (which happens with non-bonded bullets).

The hollow point bullet is used almost exclusively by law enforcement and civilians for self-defense. The use of hollow point bullets by the military is prohibited by The Hague Convention. The hollow point's design makes it the perfect choice when over-penetration or perforation is a concern, especially with hunting and self-defense. Because of the increase in quality control and cost of manufacturing, hollow point ammunition is often two to three times more expensive than ball ammunition.

- **Soft Point** – The soft point is named so because of the exposed, malleable core that protrudes from the jacket at the nose of the bullet. With soft point bullets, the jacket will typically cover the base completely and extend upward, stopping just short of the tip. The core of the bullet will fill the jacket completely and protrude upward from the opening in the front of the jacket. The exposed core, protruding from the jacket, will form a semi-pointed/round/flat tip. The

Figure 23a: Various soft point bullets.

Figure 23b: Soft point bullet cross-sections.

Figure 23c: Expanded soft point bullet.

soft tip is designed to promote deformation and expansion. When the bullet impacts the target, the first point to hit is the soft tip. The tip will begin to deform and push back into the jacket, forcing the nose of the jacket to expand and deform. The soft point bullet is not as finicky as the hollow point bullet and will expand through a variety of conditions.

The soft point is designed to be more aerodynamic than a hollow point bullet and experiences greater expansion and deformation than a ball bullet. The soft point bullet will also penetrate deeper than a traditional hollow point. The rate of expansion is dependent on the alloy of the core, the velocity of the bullet upon impact, and the material that is being impacted. If the material is too soft, the soft point may not expand and perforate the target, similar to a round nose bullet.

- **Match** – Match bullets are manufactured to a much higher tolerance than other bullets. The core of the match bullet is much more consistent in the mixture of its alloying materials and is almost always swaged for the most uniform shape and weight. The jackets are also drawn with greater precision to ensure the most uniform wall thickness and concentricity

Figure 24: Various types of match bullets.

to the core. The machines used to manufacture match bullets are more precise and consistent than machines used to manufacture bulk ammunition. The quality control process involved in manufacturing match bullets is also more meticulous, sometimes featuring human interaction during every step of the process. In some cases, match bullets are also weighed, measured, and sorted for the utmost consistency between batches.

Match bullets are not limited to a particular style or type. Match bullets can be found in both pistol and rifle bullets, ball, hollow point, open tipped, tipped, and many other styles. Match bullets will typically utilize many features to make the bullet more aerodynamic, including various types of tips, long ogives, and boat tails. Match bullets are only the beginning to match ammunition. As is often the case, propellant and primer are all of a higher quality and manufactured more consistently.

- **Very Low Drag (VLD) –** Very low drag bullets are the current pinnacle of aerodynamic projectile design. They are designed to be extremely streamlined to overcome disruption from outside forces. The name very low drag indicates that the projectile will experience less air resistance than other projectiles of the same size and weight, with a less aerodynamic form. This means the VLD bullet can fly farther, maintain its velocity over a greater distance, and resist wind and atmospheric conditions better than any other projectile type.

  The typical VLD projectile is a jacketed (lead core), open tip (not hollow point), boat tail design. The VLD bullet tends to be very long and heavy for a bullet of its caliber, with a longer tapered or rebated boat tail, a short bearing surface, and a very long secant or hybrid ogive nose. The open tip design is used to shift the projectile's weight rearward, increasing its stability. The VLD projectile will be built to match standards and may sometimes feature a tip to further increase aerodynamics.

Figure 25: VLD bullets.

Figure 26: Various types of tipped bullets.

- **Tipped –** Tipped bullets utilize a specialized tip of varying materials for different purposes. The tip may be made from hard polymer, rubber, aluminum, steel, or titanium. Polymer-tipped bullets serve many purposes, including making flat or hollow point bullets more aerodynamic, assisting hollow point bullets in expansion, increasing the feeding reliability of hollow points, and making pointed (spitzer) bullets safe to load into lever-actions.

  The polymer tip turns flat and hollow point bullets into more of a spitzer shape, making them less susceptible to drag, allowing them to move faster and further. The polymer tip may also aid in (more consistent) expansion by acting as a wedge, driving into a cavity and forcing the core and jacket outward. It also makes the bullet expand more consistently through a variety of materials (wood, drywall, sheet metal, glass, heavy clothing) rather than just expanding from hydraulic pressure.

  Some hollow point bullets utilize a polymer tip with a round nose that aids in feeding with semi-automatic pistols. Because many semi-auto pistols are designed to use ball ammunition primarily, using hollow point bullets may cause malfunctions in the feeding cycle of operations. The ball tip eases the cartridge's transition up the feed ramp and into the chamber. The ball also acts as a wedge, aiding in more consistent expansion. With cartridges intended for lever-actions, the polymer tip allows the use of spitzer-style bullets without the risk of unintentional discharge. If a traditional spitzer bullet were used in a tubular magazine, a large enough shock (recoil) might cause the tip of one cartridge to strike the primer of the cartridge in front of it, setting off a dangerous chain reaction. Rubber tips are generally used with pistol bullets to aid with expansion.

- **Wadcutter –** The wadcutter bullet is designed primarily for use in target and bullseye competition. The basic wadcutter (full wadcutter) bullet features a completely flat nose. From the bearing surface, the shoulder turns 90° to the face. The sharp shoulder is designed to "punch" a perfectly round hole in a piece of paper. The idea behind the wadcutter design is that there is no way to dispute the score on the target because the holes are cut so precisely. Other bullet designs typically tear through paper, leaving torn or serrated holes.

Because of the shape of the wadcutter bullet, they are typically limited to subsonic velocities and distances of 25 yd. or less. Wadcutter bullets will also typically feature solid construction. The subsonic velocities will not distort solid, soft (lead) bullets and will not melt or foul the bore, which would happen if they were moving at supersonic speeds. There are jacketed wadcutter bullets that feature a jacket that extends half to three-quarters of the way up the bearing surface. These rounds can be fired at supersonic speeds and do not foul the bore as much as solid wadcutters. While the typical wadcutter design features a completely flat face, there are variants that feature small differences. Wadcutter bullet designs include target (small ring groove of the face of the bullet), hollow base, hollow point, beveled base (small bevel on the base that aids in loading the cartridge) and double-ended (a bevel on each end).

The wadcutter bullet is also not suited for use in anything other than revolvers. The shape of the bullet creates a feeding nightmare for magazine-fed, semiautomatic pistols. When the wadcutter is used in a revolver's cylinder, there are no issues as the cartridges do not undergo a "feeding cycle" as seen in semi-automatic firearms. With the typical wadcutter cartridge, the bullet is set back in the case so that the face of the bullet is flush with the case mouth. Some cartridges feature a bullet that is seated farther out.

Because of the shape of the bullet and the fact that they are typically "heavy" for a bullet of a specific caliber (there are no tapers, so there is more material and more mass), wadcutter bullets are sometimes used for hunting at close distances (loaded to supersonic velocities within ~50 yd.). The increased surface area on the nose of a wadcutter will impact the target harder than a similarly designed bullet with a spitzer point, which is more likely to perforate the target. The wadcutter bullet is more likely to deliver

Figure 27: Several different types of wadcutter bullets.

Figure 28: Various semi-wadcutter bullets.

all of its energy to a target rather than carrying its energy through the target. This is why the wadcutter bullet is also sometimes used for self-defense.

- **Semi-Wadcutter –** The semi-wadcutter (SWC) is similar to the wadcutter in purpose but differs dramatically in design. The semi-wadcutter bullet utilizes the sharp shoulder of the traditional wadcutter but features a nose similar to a ball round. The semi-wadcutter is designed to cut precise holes like the traditional wadcutter but features enhanced aerodynamics like a ball round. From the shoulder, the nose of the bullet is rebated (reduced diameter). The shape of the nose will vary greatly, depending on the bullet design. The various semi-wadcutter designs include button nose, conical, Keith/truncated, and round nose.

  The button nose semi-wadcutter features a small button-shaped nose that projects from the face of the wadcutter. The conical wadcutter features a sharp cone-shaped nose. The Keith or truncated conical wadcutter features a cone-shaped protrusion with its nose cut off. The nose of the truncated wadcutter is flat but there are also some hollow point versions. The round nose wadcutter features a nose similar to a ball round. The SWC may be fully or partially jacketed or may utilize a gas check.

  A benefit of the SWC over the traditional wadcutter is the enhanced reliability when feeding through semi-auto pistols. The nose on the SWC (specifically truncated and round) is designed to improve the cartridge's ability to travel through the breech (through the magazine, up the feed ramp, and into the chamber). The SWC also benefits from the aerodynamic advantage in the form of increased effective range (100+ yds). SWC bullets may also be fired at both subsonic and supersonic velocities. The semi-wadcutter is used in both revolvers and semi-automatic pistols.

- **Flat Nose/Truncated –** The flat nose or truncated bullet features a nose that is flat. Unlike the wadcutter or SWC, the flat nose/truncated bullet does not feature a sharp shoulder or rebated nose. The flat nose bullet serves the same purpose as the wadcutter and SWC bullet while displaying greater aerodynamics and enhanced reliability when feeding in semi-auto pistols. The main difference between the flat nose and truncated bullet is the shape of their ogives. The flat nose bullet features an ogive similar to a round nose bullet: an arc that extends from the bearing surface to the meplat. Unlike the round nose bullet, the meplat of the flat nose bullet is flat with a very sharp shoulder from the ogive to the meplat. The ogive on the truncated bullet is flat. From the bearing surface, the nose of the bullet is shaped like a cone with its tip cut off. The flat nose and truncated bullet may be solid or jacketed/semi-jacketed. Flat nose and truncated bullets are used primarily in semi-automatic pistols and in some rifles.

Figure 29: Flat nose and truncated bullets.

Chapter 2 - Projectiles: Military and Shotgun, Materials, Coatings, BC and SD

Military

Military projectiles typically consist of ball rifle and pistol bullets. However, militaries all around the world utilize specialty projectiles for a variety of reasons. Some of these specialty rounds are used to defeat armor (both hard and soft), identify trajectory and point of impact, ignite flammable materials, and explode or prevent penetration of hard targets. Special rounds include armor piercing (AP), tracer, incendiary, explosive, and frangible.

- **Armor Piercing (AP) –** The armor piercing cartridge, as its name implies, is used to perforate both soft and hard body armor and vehicle armor. Most AP bullets are constructed in a way similar to a standard ball round, with the exception of a steel (typically hardened) or tungsten (carbide) penetrator. The typical AP round features a core consisting of a steel or tungsten spike in front of or enveloped by a lead, aluminum, or tin/bismuth core encased by a full or partial jacket. Upon impact, the core and jacket will separate from the penetrator as it continues into or through the armor. The penetrator may be shaped like a cone in the nose of the bullet or may be spitzer-shaped centered in the core or a spike (or spikes) positioned in the rear of the core. Some AP bullets utilize a hollow point design, with the penetrator exposed in the cavity, while others utilize the penetrator as the tip.

  While most soft armor will stop almost all pistol calibers, they will not likely hold up against an AP pistol round or even a standard ball rifle round. Most AP is designed to defeat hard body armor and vehicle armor. A typical ball rifle round will fragment upon impacting hard armor, while an AP rifle round will often punch right through, leaving a hole that looks like it was laser cut. AP bullets can be used in pistols and rifles, but there are also penetrator slugs for use in shotguns.

- **Tracer –** Tracer bullets are used to identify trajectories when shooting at night. Tracers produce a bright flash that creates a trail behind the bullet. Tracers are primarily used with machine guns where the firing rate is high and aiming is often accomplished by watching point

Figure 1: Various armor piercing rounds.
From left to right (pairs)- .50 BMG M2 AP, .30-06 Springfield M2 AP, 7.62x51mm NATO M61 (T29), 7.62x51mm NATO M80 A1, Norinco 7.62x39mm AP, 5.56x45mm M855A1, 5.45x39mm 7N6, 5.56x45mm NATO M855, 7.65mm Browing AP.

Figure 2: Various tracer bullets.

of impact. In this application, tracers are often loaded every third to tenth round. When fired, the tracer will provide a visual reference of the approximation of impact of the shot stream. When discharging at a high enough rate, it may appear as if the individual tracers are a continuous stream.

Upon discharge, as the propellant ignites inside of the case, it will also ignite chemicals compressed in the base of the bullet. The bullet often features a deep cup or hollow base but remains a primarily jacketed ball design. The color of the tracer will depend on the chemicals used, which are typically magnesium, phosphorus, and another chemical that burns a specific color. The most popular tracer colors are red (from strontium nitrate in the compound) and green (from barium nitrate in the compound), but other colors can also be found.

Figure 3: Tracer fire. Photo Courtesy of Wikipedia.

The benefit of the tracer round is also its downfall. The bright light of the tracer round can be seen from every angle. While the tracer is providing the shooter a visual reference, it is also providing the enemy with the shooter's position.

The tracer round can also be used for training purposes. The tracer can be used to help new shooters understand trajectory and teach point of aim and point of impact at various distances. The tracer round can also be used to show how ricochet affects the bullet's trajectory.

Although tracer rounds are available for civilian use in most states (check your local and state laws and regulations

Figure 4a: High explosive incendiary bullets.

regarding tracer use), the use of the tracer round can be dangerous in irresponsible hands. Many fires have been created by tracers fired into environments that may catch fire. Tracers should not be fired into dry grass or dead trees and are banned for use in most indoor ranges.

- **Incendiary** – The modern incendiary round is designed to cause ignition of a target that contains flammable materials, such as a gas tank. Similar to a tracer, incendiary bullets use a chemical (typically phosphorus and magnesium) in the nose of the bullet that ignites upon impact. The incendiary will typically perforate the intended target, igniting its contents as it passes through. Early incendiary bullets were similar to tracer bullets because they would ignite upon firing, limiting their use to a few hundred yards. The incendiary bullet may also feature a penetrator, like with armor piercing incendiary (API) rounds that are designed for harder targets. The incendiary round can be found with pistols, rifles, and shotguns.

- **Explosive** – Explosive rounds are used for exactly what their name implies: to explode. The explosive projectile is designed to explode on impact or slightly thereafter. The explosive cartridge utilizes an incendiary compound in the nose of the bullet, followed by a high explosive (HE) compound located in a hollow cavity behind the incendiary. Upon impact, the incendiary will ignite the HE and cause the projectile to explode into many pieces. Some HE rounds may feature a penetrator that will continue through the cavity the HE round has just created. These rounds are known as high explosive incendiary armor piercing (HEIAP). HE rounds are typically reserved for large rifle calibers, like the 50 BMG, but can be found in smaller rifle and pistol rounds.

- **Frangible** – The frangible projectile is designed as a training round to prevent ricochet or shrapnel. The frangible bullet is designed to disintegrate or crumble when impacting a hard target. It is constructed from powdered metal (typically copper) that is either compressed or compressed and sintered. Sintering brings the individual grains of metal powder to a temperature just short of melting. This creates a (weak) bond between the grains. The frangible may

Figure 4b: Incendiary slug.

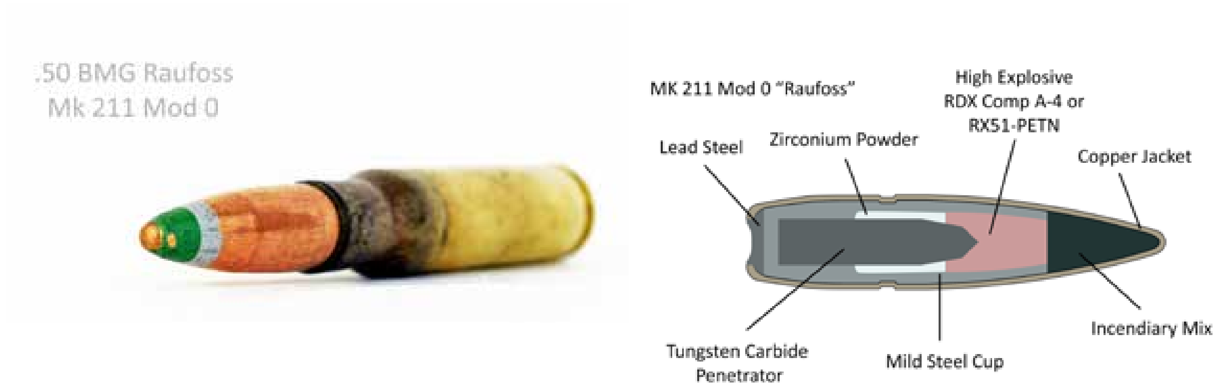

Figure 5a & 5b: Explosive projectiles.

also be composed of metal powder that is mixed either with a glue or polymer and molded. When impacting a hard target, the individual grains or small chunks will break apart, preventing penetration, perforation, or ricochet. The frangible is used inside of "shoot houses" when practicing tactics in confined spaces. It allows the shooter to train in a simulated house without fear of shooting into another room. Frangible rounds are also used for shooting steel targets at close range, which has become a fairly new practice in modern tactical training.

One major con with frangible bullets is there is a chance with compressed, non-sintered rounds that they can break up in the bore and become jammed. Newer designs utilize a solid jacket over a compressed metal core to help prevent break-up in the bore. The jacket does make the frangible perform similar to a ball round on soft targets but will still break up when impacting a hard target. This makes some frangible rounds candidates for use as home or self-defense rounds. Frangible bullets (projectiles) can be found in pistol, rifle, and shotgun cartridges.

Figure 6: Various frangible projectiles.

Shotgun Projectiles

Shotgun projectiles can vary more than any other projectile type, but there are three major variances: slugs, buckshot, and birdshot. Buckshot and birdshot consist of small balls of varying sizes. Because of their smoothbore design, shotguns are also capable of firing many other objects outside of their standard load, including less lethal, explosive, and armor piercing projectiles. The various projectiles that can be fired through a smoothbore shotgun make it the most versatile platform ever. Shotgun projectiles are used for everything from hunting and self-defense to sport/competition and law enforcement/military use. To understand the capabilities of shotgun ammunition, there are many places in Africa where the shotgun is known as the "poor man's elephant gun," although it would not be the preferred method (or the smartest).

Shotgun ammunition is not expressed in caliber or bore size like pistol and rifle cartridges. Shotgun ammunition is expressed in the gauge of the bore. Gauge is a measurement of the number of bore diameter lead balls that can be made from one pound of lead, which has nothing to do with the projectiles used. Shotgun projectiles are measured by the size of a single pellet and the total weight of all the projectiles in the case. Weight is almost always expressed in ounces.

WADS AND CUPS

Before we discuss shotgun projectiles, we need to touch on wads and cups. Wads and cups are not technically projectiles, even though they are projected from the firearm. Wads and cups are used to protect the propellant and the projectiles inside the case and when discharging.

The wad is used to separate the propellant from the projectile and act as a buffer during discharge. When the cartridge is loaded, the powder is loaded into the case and capped with a wad. The wad prevents the propellant from mixing with the birdshot or buckshot and acts as a "filler," taking up any empty space inside the hull. The wad also acts as a cushion and seal during discharge, preventing the shock of the propellant gas expanding from damaging the projectiles. The expanding gas works (primarily) against the wad, driving the projectiles through the bore. Depending on the load, there may only be a single wad or a few stacked up. With slug loads, the wad sits over the propellant and below the slug. With buckshot or birdshot loads, the

Figure 7: Various shotgun projectiles.

Figure 8a: Various wads and cups.

wad sits above the propellant and below the cup. The wad may be made from compressed paper/fiber, felt, or plastic. Wads made of plastic are also known as gas seals. With some shot shell designs, there may be an additional wad in front of the shot to prevent it from falling out of the front of the case.

The cup is used to hold the projectiles together inside the case and bore and release them when exiting the bore. During discharge, the wad will drive the cup through the bore, while the cup holds the birdshot or buckshot (or another projectile) together in a tight cluster. This cluster is called the shot string. The cup can be used to control the expansion or restriction of the shot string. The cup also protects the buckshot and birdshot from deforming while firing. Any shot that is not completely round will destabilize during flight and cause the shot string to expand dramatically. The cup also protects the bore from the projectiles and prevents excessive fouling in the bore. When the cup exits the muzzle, the air resistance will slow the cup dramatically (as if it had its own parachute) and the projectiles will continue ahead. Cups are typically made from plastic and often feature slits around their body, forming sections. When exiting the muzzle, the drag exerted against the cup will cause the body to split and the sections to expand outward, forming petals that create a huge amount of air resistance. Only shot shells loaded with buckshot and birdshot utilize a cup; they are not used with slugs.

Modern shot shells utilize a combination wad/cup. The one-piece design features a wad/gas seal at its base, a buffer or "crush zone" above the base, and a cup on top of the buffer. The wad/gas seal is still used to contain the propellant and seal the bore from expanding gas and the cup is still used to contain and protect the

Figure 8b: Various wads and cups.

shot. The buffer acts as a cushion between the wad/gas seal and cup and also serves as a spacer, filling any empty space inside the hull. When discharged, the wad will drive forward before the cup begins to move. The buffer will crush and absorb some of the energy from the wad. The buffer is used to protect the shot from deforming upon discharge. The design of the buffer will vary greatly by manufacturer, which will change how each crush zone compresses.

- **Slug** – The slug is like a round nose bullet that is used in smoothbore shotguns. Unlike the bullet, the slug is typically the same size as the bore or slightly smaller (~.001" – .0005"). Because shotgun loads are typically very low pressure (~11,000 psi) and the wad/gas seal obturates to seal the bore, the slug does not need to expand (but may slightly). Also, unlike traditional round nose bullets, the slug will feature hollow construction, centering most of its mass toward the nose of the slug. There are slugs that are designed for use with smoothbores, chokes, and rifled bores. The slug manufacturer will often recommend the barrel or choke that should be used. The primary use for slugs is hunting at short ranges, where the use of rifles is not allowed. Some slug designs are also meant for self-defense.

Figure 9: Brenneke slugs.

There are several different slug designs, but they can all be grouped into two main categories: full bore and sabot. Full bore slugs are appropriately named because the diameter of their bearing surface is the same as the bore. Of all of the full bore slug variances, the Brenneke and Foster slugs are the most popular.

The Brenneke slug is the original modern shotgun slug. Before the Brenneke slug, smoothbore shotguns fired cylinder diameter round balls. The need arose for a more accurate, stable projectile. Introduced in 1898, the Brenneke slug was the first projectile with a more traditional bullet shape to be used in smoothbore shotguns. The original Brenneke design features solid construction, "fins" around the circumference of the bearing surface, and a paper/fiber wad that is attached to the base of the slug.

The solid design of the Brenneke slug does not provide much stabilization and the fins do not impart very much rotation as the slug moves through the bore. From the bearing surface to the nose of the slug there is a sharp (~90°) shoulder that transitions to a short, rebated round nose similar to a SWC. The wad is attached to the base to shift the weight of the slug forward, increasing its stabilization in flight. If there is any disturbance in flight, the air resistance around the projectile will act upon the lighter tail and "push" it in line with the slug's trajectory. The wad also serves to seal the bore upon discharge. The fins are designed to reduce the amount of bearing surface, reducing friction and increasing velocity. In flight, air resistance does act upon the fins, imparting a very slow rotation on the projectile. The Brenneke slug is used in smoothbore shotguns and with most choke types. The Brenneke slug has an effective range of about 75 yd.

- ***Foster slugs*** feature some of the characteristics of the Brenneke slug but are a newer, improved design. The foster slug features more of a ball bullet shape, with a round nose that extends from the bearing surface and tangent ogive. The bearing surface of a Foster slug is "rifled" and the base is hollow. The design of the Foster slug (with its hollow base) pushes all of the mass to the front of the bullet, eliminating the need for the wad base. Once a Foster slug leaves the barrel, the wad quickly falls off from air resistance. The Foster slug may or may not feature grooves along its bearing surface. Although the rifling is only designed to reduce friction by removing surface area from the body of the slug, the rifling will impart a small amount of rotation on the slug, providing slightly more stability than a non-rifled slug. The Foster slug is used in smoothbore shotguns and with some choke types. The Foster slug has an effective range of about 75 – 100 yd.
- ***Sabot slugs*** differ greatly from full bore slugs. Sabot slugs are more similar to a rifle bullet than to a pistol bullet. The sabot slug utilizes a jacket that acts as a vehicle for the slug inside the bore. The sabot is similar to the combination wad/cup, except the walls of the "cup" are much thicker. The thicker walls on the sabot require a bullet that is a much smaller diameter than the bore. Twelve-gauge Brenneke and Foster slugs typically measure around .729 in. – .730 in. (12-gauge bore diameter is around .729 in. – .730 in.), while a 12-gauge sabot slug measures between approximately .450 in. and .630in.

The sabot slug is designed for use exclusively with shotguns that utilize a rifled barrel. During discharge, the sabot (not the bullet) will engage the rifling. As the sabot travels through the bore, the rifling will impart rotation on the sabot, which in turn, imparts rotation on the bullet. Upon exiting the muzzle, the sabot will fall away due to air resistance while the bullet will continue ahead, stable from the rotation.

The sabot slug can be found in a variety of styles. Because the sabot protects the bore from the projectile, sabot slugs can be found with solid construction (with a variety of material), jacketed, hollow point, and tipped. The sabot may be constructed from plastic or paper. The sabot slug is designed for use only with rifled barrels. When used in smoothbore shotguns, they do not receive the required stabilization

Figure 10: Foster slugs.

Figure 11: Sabot slugs.

Figure 12: Wad slugs.

Figure 13: Plumbata slugs.

and accuracy suffers. The sabot slug has an effective range of 200+ yd.

Wad slugs are similar to the sabot slug with the exception that the slug itself is more like a smooth (non-rifled) Foster. The name suggests that a wad slug is similar to a Brenneke slug with the wad attached to the base, but the wad slug utilizes the combination wad/cup. In fact, standard buckshot/birdshot cups can be used. The slug itself features a deep hollow base that is reinforced by a rib that runs the diameter of the bottom of the cavity in the base. The rib prevents the slug from expanding too much and creating unnecessary strain on the wad during discharge. The wad slug also features more of a ball nose. The diameter of the wad slug is also much closer to the bore than a sabot slug, usually measuring around .690 in. for a .729 in. 12-gauge barrel.

The wad slug is designed for use with smoothbore shotguns but can also be used in rifled barrels. The rifled barrel will impart rotation onto the wad, but because its wall thickness is much thinner than a sabot slug, the wad may become damaged. The wad slug makes reloading slugs easier as it utilizes a standard wad/cup and can be used with various crimps. The wad slug has an effective range of about 75 yd.

Plumbata slugs are similar to Foster-style slugs but function similar to a Brenneke. The plumbata slug is typically rifled and hollow like a Foster slug but utilizes a wad that fits inside the hollow base. Working on a similar principle to the Brenneke slug, the plumbata slug utilizes a lightweight wad as a tail to help stabilize it in flight. The plumbata's wad features a wad/gas seal for its base, followed by a buffer zone and finally a nose that fits inside the slug's base. When exiting the muzzle, the wad does not fall away from the slug, but continues with it, stabilizing its flight. It is not until impact that the wad separates from the slug.

There is a variance of the plumbata that features a sabot/wad combination. The sabot is designed to break away from the slug, leaving the wad attached to its base. The sabot/plumbata is designed for use in rifled barrels. The plumbata slug has an effective range of about 75 – 100 yd.

SHOT

Shot is a term used to describe shotgun projectiles that consist of a cluster of (sometimes very small) spheres. Shot may range in size from very tiny balls to large balls the size of a 9mm bullet. Shot size is expressed with numbers and letters: the larger the number, the smaller the shot pellet. A #12 pellet of birdshot measures around .05 in., while a 000 (pronounced triple aught) pellet of buckshot measures around .36 in. As shot size increases, fewer pellets can be loaded into the hull. In a 1 oz. load, approximately 2,000 #12 pellets will be loaded, while only six 000 pellets will fit. Because of the wide range of sizes and loads of shot, it is one of the most versatile projectiles available.

Shot can be divided into two basic categories: bird and buck. As their name implies, bird shot is typically used for hunting birds, while buckshot is used for hunting deer and other game. Shot can also vary in the alloy of its composition. Softer shot or "chilled" shot features a higher lead content than "magnum" shot, which features a higher antimony (an alloying metal used to make shot harder) composition. Some types of shot (both bird and buck) may be plated (not jacketed) with a harder metal. Because of the range in size of shot, there is typically a size for any type of game that may be encountered. Shot is also used for competition, self-defense, law enforcement, and military use. (See Tables 1 and 2.)

BIRDSHOT

Of the types of shot, birdshot utilizes the smallest sized pellets. Birdshot sizes run from #12 (.05 in.) to F (.22 in.). Because of its small size, birdshot is best suited for hunting birds, snakes, small mammals and pests. Birdshot in sizes 12, 11, and 10 are referred to as snake/pest/dust shot because of its extensive use on nuisance animals. As shot size increases, the size of the animal that can be humanely dispatched increases. Shot sizes #9 – #7 are used for most bird hunting and some small game: doves, pigeons, grouse, quail, partridge, rabbits. Sizes #9 – #7 are also used for sporting purposes: trap, skeet, and sporting clays. Sizes #6 – #4 are best suited for larger birds such as turkey. Sizes #3 – T are used for water fowl such as ducks and geese and are also suited for many varmints, including coyotes, fox, cougar, and bobcats. Pest shot has an effective range of about 10 yd. (max), while

Figure 14: Various types of shot.

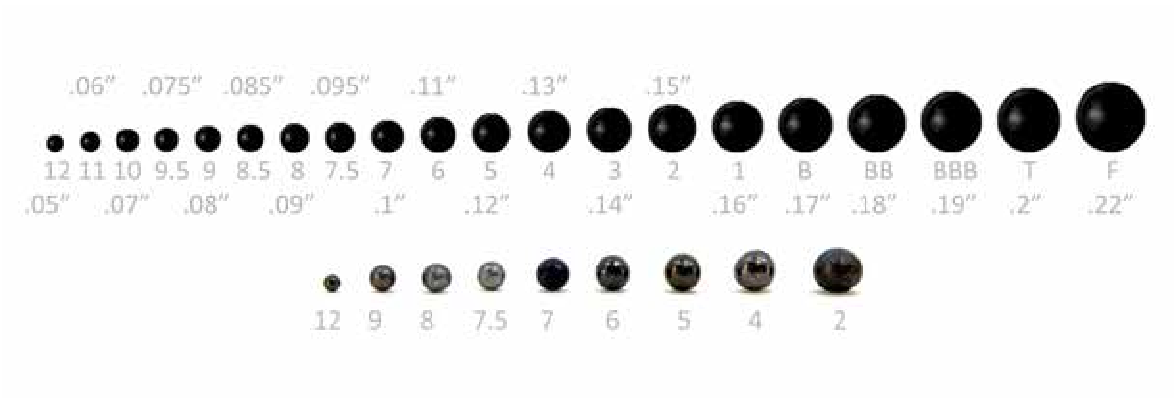

Figure 15: Various types of birdshot.

medium sized shot is around 40 yd., and sizes #3 – T can reach 50 – 60 yd.

Birdshot is also well suited for home defense. One of the greatest considerations when choosing home defense ammunition (or any defensive ammo) is over-penetration. Walls inside of a home typically consist of wood framing, sheet rock walls, and some insulation. There may also be some wire and plumbing. Most rifle and handgun bullets will perforate through at least one complete wall, endangering anyone in the other room. Slugs and buckshot will produce the same results. Many of those same cartridges will perforate several walls, including exterior walls (with the added layers from siding, stucco, or brick) and continue into another dwelling.

The small size and low mass of birdshot makes it a good choice for use inside of the home. Shot in sizes #7.5, #7, and #6 are the best balance of shot size and weight (~1.5 grains per pellet), and pellet count. The #7.5 shot will typically only perforate a single layer drywall, becoming stuck in the second layer on the opposite side. The shot may perforate the second wall but will not typically have enough energy to cause life threatening injury. If the shot were to perforate one complete wall, it would not make it through a second. The energy and penetration from the shot may not be enough to completely incapacitate an intruder, but the tradeoff is the safety of other family and friends inside the home (and anyone outside of the home).

BUCKSHOT

Buckshot is much larger than birdshot, ranging from #4 (.24 in.) to 000 (.36 in.). Because of its larger size, buckshot is suited for small and large game. Buckshot is used to harvest everything from varmints to elk. The #4 – #3 buckshot is useful for large birds, such as geese, and small to medium varmints. With #2 and #1 buck, you begin to get into medium game territory, pronghorn, and deer within ~40 yd. Buckshot in sizes 0 (aught), 00 (double aught) and 000 (triple aught) is used for medium to large game. Single aught is good for medium game such as pronghorn, ram, and coyote. Between double aught and triple aught you can harvest several types of big game, including deer, caribou, and most bears (black, grizzly, polar, and brown).

Figure 16: Various types of buckshot.

Buckshot is not a responsible choice for home or self-defense (except for some of the smaller calibers) because of its larger size, pellet count, mass, and energy. Most buckshot will perforate several walls inside a home and continue outside. Even if you hit your intended target, there is still risk of perforation into other rooms. Buckshot's primary purpose is hunting medium to large game and is (often) too powerful for most other tasks. Buckshot, typically 00 and 000, has also found extensive use with military and law enforcement.

SHOT BUFFER

Shot buffer is used with some birdshot and buckshot loads, as well as with some hollow base slugs. The shot buffer is used to protect the shot inside the hull and during its travel through the bore. The buffer material will cushion the pellets during discharge, preventing pellet deformation by preventing them from contacting each other. When exiting the muzzle, the buffer will fall away with the wad. The buffer material is typically made of tiny polymer (polyethylene or polypropylene) spheres that are usually white but may be dyed to suit the manufacturer's needs.

SELF-DEFENSE SHOTSHELL PROJECTILES

Although we have established that most buckshot and slugs are not very suitable for self- or home defense, specialty loads have been developed by mixed slugs and shot of various sizes. Some of these specialty loads may feature a few

Figure 17: Shot buffer material.

Figure 18: Specialty self-defense projectiles.

smaller (under #1) buckshot pellets, followed by a slug that is typically half of its normal weight. Other designs may use small, stacked disks (similar to a nickel) followed by larger birdshot (B and above). Others may utilize a mixture of a few smaller buck and several larger birdshot (B and above) pellets. Limiting the number of larger projectiles and increasing the number of smaller projectiles will increase the likelihood of a hit, while still providing more energy than small projectiles alone. It will also prevent the likelihood of over-penetration and perforation. The smaller birdshot will not likely penetrate more than a wall, and the smaller number of larger projectiles limits the chance of one of hitting something unexpected in another room.

Outside of the specialty rounds that are available, there is also a category of less-lethal options. These projectiles are designed to cause injury and pain, but they will not (typically) penetrate let alone perforate. These less-lethal projectiles are often shaped like slugs or buckshot but are made from a very dense rubber. Upon impact, these projectiles will often bounce off of the intended target, leaving large welts and bruising. There are also "bean bag" projectiles that are filled with birdshot-sized rubber pellets.

The reason these projectiles are called less-lethal and not non-lethal is there is still a chance for severe injury or worse. Less-lethal rounds are designed to be fired below the target's neck. If fired at the head, the impact may be enough to kill instead of injure. The greatest downside to less-lethal projectiles is that if the attacker is not incapacitated, they can continue to attack. Less-lethal rounds may even be illegal to use for self-defense in some areas. Less-lethal rounds are employed mostly by law enforcement and the Department of Corrections.

Figure 19: Less-lethal projectiles.

Figure 20.

OTHER SHOTSHELL PROJECTILES

There are also many "non-standard" projectiles used in smoothbore shotguns. These projectiles are not used for sport or self-defense and are considered novelties (not to say they could not cause injury or be lethal). These projectiles include (but are not limited to) bolo, flechette, flamethrower, flashbang, and rock salt. The bolo rounds consist of two to three larger balls (larger than 000 buck) connected by a braided metal wire. The flechette round utilizes dozens of small metal "darts" or tiny arrows. The flamethrower rounds utilize phosphorous and magnesium to create a huge stream of flame and spark.

12-Gauge Shotshell[a]		
Size	**Diameter in Inches**	**Pellets per Ounce (Average)**
Lead Birdshot:		
12	.05”	2,385
11	.06”	1,250
10	.07”	1,040
9.5	.075”	688
9	.08”	585
8.5	.085”	497
8	.09”	410
7.5	.095”	350
7	.1”	300
6	.11”	225
5	.12”	170
4	.13”	135
2	.15”	90
BB	.18”	50
Steel Birdshot:		
8	.09”	577
7.5	.095”	490
7	.1”	420
6	.11”	317
5	.12”	247
4	.13”	192
3	.14”	154
2	.15”	125
1	.16”	103
B	.17”	86
BB	.18”	72
BBB	.19”	61
T	.2”	53
F	.22”	40
Buckshot:		
4	.24”	22
3	.25”	19
2	.27”	15
1	.3”	11
0	.32”	9
00	.33”	8
000	.36”	6
Slug:		
Foster/Brenneke	.729”	1

[a]American National Standard Voluntary Industry Performance Standards for Pressure and Velocity of Shotshell Ammunition for the Use of Commercial Manufacturers. (n.d.). Retrieved October 4, 2018, from www.SAAMI.org saami.org/wp-content/uploads/2018/01/Z299-2_ANSI-SAAMI_Shotshell.pdf#page=8

Table 1. 12-Gauge Shotshell

12-Gauge Shotshell Uses* [b,c]	
Game: †	**Projectile**:
Moose,ǂ Bisonǂ, Elkǂ	1 oz Slug (including sabot slugs) or Heavier
Bear: Grizzly,† Polar,† Brownǂ	1 oz Slug (including sabot slugs) or Heavier, 00, 00 Buckshot
Caribou, Deer, Black Bear	000, 00, Buckshot
Pronghorn, Mountain Goat, Ram	00, 0, 1, 2 Buckshot
Geese, Fox, Bobcat, Coyote	4, 3 Buckshot F, T, BBB, BB, B Birdshot
Turkey, Duck, Rabbit	B, 1, 2, 3, 4, 5, 6, 7 Birdshot
Doves, Pigeons, Grouse, Quail, Partridge	9, 8, 7 Birdshot
Snake, Pests	12, 11, 10 Birdshot
Sporting/Competition:	
Action Shooting (3 Gun)	Slug (when allowed)
Trap, Skeet, Sporting Clays, Cowboy Action	9, 8, 7 Birdshot
Military/LE:	000, 00 Buckshot
Self Defense: §	9, 8, 7.5, 7, 6 Birdshot

* Make certain to research state and local hunting laws for specific use of different projectiles on various animals.

† Some areas will only allow shotguns because of range restrictions. Some areas do not allow certain calibers or projectiles.

ǂ Within 30 – 40 yd.

§ Within 5 – 10 yd.

b Shot Sizes. (n.d.). Retrieved October 4, 2018, from www.rivermenrodandgunclub.com/shot-size-chart--recommendations.html

c Browning, Chris. (n.d.). Shotgun Shell Sizes: Comparison Chart and Commonly Used Terms. Retrieved October 4, 2018, from "gunnewsdaily.com/shotgun-shell-sizes-comparison-chart-terms/

Table 2. 12-Gauge Shotshell Uses.

Projectile Materials

Projectile materials will vary almost as much as bullet types. The materials used are very important in all aspects of the projectile's ballistics. It is important to understand how each material affects the overall performance of the round. Most bullets will use more than one material, while others will be made of one solid piece.

- **Lead –** Lead is a very soft, dense, and heavy metal used in most projectiles. It makes the perfect projectile material because of its properties. Lead is much denser and, in turn, has more mass per area than most other metals. This contributes to the projectile's momentum and energy. The malleability of lead leads to its deformation when impacting most targets and helps with energy transfer.

  Lead can be found in nearly pure (99.9 percent) form, which is known as "soft" lead, or in a variety of alloys, which are known as "hard" lead. The compound used and the ratio of the alloy will change how the lead performs throughout the firing cycle. Alloying metals are tin or antimony. Tin or antimony can be blended into lead from 1 percent to 30 percent of total mass and a tin-antimony blend can go as high as 35.5 percent (23 percent antimony, 12.5 percent tin). As the percentage of alloying metal increases, so will the hardness of the lead.

  Lead is widely used for projectiles or as a component of a projectile. It is used for solid bullets and as a core for jacketed bullets. Lead is also primarily used with bird- and buckshot as well as with slugs. Most military rounds also contain lead as the core. The lead used in pistol and rifle bullets is either cast (melted and poured into a mold) or swaged (formed by hydraulic pressure and dies).

  Slugs and buckshot are either cast or swaged, while birdshot is formed by air. Larger sizes of birdshot are sometimes swaged, while most birdshot is formed by pouring molten lead or lead alloy over a sieve (a metal sheet with many small holes or a fine grate) in a shot tower. A shot tower is a multi-story building with holes that are aligned on each level to allow the shot to fall through. The drops of lead will fall 30+ ft. (about three stories) through the hole in each level, into a pool of water. As the molten lead falls, air resistance acts upon the drop, causing the surface tension of the lead to form spheres. The spheres are then sorted by size and non-round pellets are discarded.

Figure 21: Lead in various forms.

Figure 22: Copper in various forms.

Pure lead is often too soft for most applications, except if it is jacketed. Most lead used in projectiles is alloyed with at least 1 percent tin or antimony. The average alloy contains at least 4 percent tin or antimony (or a mixture of both). Projectiles produced with this alloy are either cast or swaged, solid or jacketed. Most slugs, buckshot, and birdshot are also composed of ~96 percent lead with a 4 percent tin/antimony mix. Soft lead projectiles will often deform too much inside the bore and create a huge amount of fouling. If soft lead is used, it is with projectiles intended to be fired subsonic, with very low chamber pressure. If the lead alloy features too much tin or antimony, the bullet will be too hard and brittle and may shatter upon discharge.

WARNING

Lead is a toxic element that is known to cause cancer and other issues. Whenever handling lead, either in raw form or as solid lead bullets or shot, make certain to wash your hands before eating or touching your face or mouth. Not only must you be mindful of handling cartridges and bullets, you must also take caution when cleaning firearms. Wash your hands with cold water to prevent your pores from opening and inviting lead in.

- **Copper –** Copper is a semi-soft, malleable metal that is harder and less dense than lead. The use of copper in projectiles is the primary contributor to the modern bullet design. Without the copper jacket, lead bullets would not be able to handle the pressure and reach the velocities of the modern jacketed bullet. Copper is also the perfect "middle-man," protecting the soft lead core and the bore. While copper is harder than lead (preventing the pressure inside the bore from deforming the bullet), it is also softer than steel and prevents excessive lead buildup in the grooves of the rifling.

  Copper is found in pure form in jackets, solid projectiles,* pressed or sintered (heated powder or granules to make a solid) cores, or as plating. Copper jackets and gas checks are typically drawn out using a hydraulic press and a series of dies. Solid copper bullets are either swaged or turned on a lathe. Copper cores are typically constructed from copper powder that has either been compressed or sintered and may feature a copper jacket. Sometimes, the copper powder is mixed with another metal powder such as tin or zinc. Copper may also be used as plating over a steel jacket.

Figure 23: Brass in various forms

The steel jacket may be too hard for the bore and cause excessive wear. Copper is applied in a very thin coat that prevents the steel of the jacket contacting the bore. Copper plating is typically found on pistol bullets and bird- and buckshot.

Copper solid projectiles (as well as other materials) are quickly becoming popular as many state and local governments push legislation to ban the use of toxic lead projectiles. Copper (as well as other materials) is considered environmentally friendly for use when hunting.

**The ATF considers some solid copper handgun bullets to be armor piercing, making them illegal in some areas. Please review local, state, and federal laws for the legality of solid copper projectiles.*

- **Brass** – Brass is an alloy of copper that is harder and slightly lighter than pure copper. It is composed of roughly 60 percent copper and 40 percent zinc. Brass can be found in solid* (monolithic) projectiles and as a jacket or gas check. Because brass is harder and less malleable than copper or lead, it is mostly used for bullets intended for large and dangerous game. Brass projectiles will penetrate deeper and deform less than a bullet with the same design of a different material, which makes them very well suited for animals with thick hides. Brass projectiles are almost always turned, while jackets and gas checks are drawn. Like copper, the use of brass is growing in an attempt to replace lead.

**The ATF considers some solid brass handgun bullets to be armor piercing, making them illegal in some areas. Please review local, state, and federal laws for the legality of solid brass projectiles.*

- **Steel** – Steel is an alloy of iron, carbon, and a few other trace elements. Steel is harder but lighter than brass, copper, and lead. It is found as a jacket material and as a penetrator for AP bullets. When

Figure 24: Steel in various forms.

used as a jacket, steel should be plated to help protect the bore and preserve barrel life. When used as a penetrator, the steel may be in an annealed form (slow air cooled) or hardened. Hardened penetrators undergo further processing where the projectile is quenched (rapidly cooled in liquid) and then undergoes tempering (raised to a controlled temperature to stabilize the structure of the metal). Steel jackets are drawn and composed of a very soft form of annealed steel. Contrary to popular belief, the steel used in projectile jackets are generally softer than the steel used for barrels. Because of this, accelerated wear may be seen as it is harder than copper; however, it will still take time to wear down the rifling in the bore.

- **Aluminum** – Aluminum is a lightweight metal that is fairly malleable and about as hard as brass. It is used for projectile tips and cores. The tips and cores may either be swaged, cast, or turned. Aluminum tips are used to shift the weight of the bullet, elongate its form, and improve its aerodynamics. As a core material, aluminum is not used to add momentum to the projectile, but rather to limit the projectile's penetration and perforation by removing mass. These lightweight bullets move much faster than traditional lead or copper projectiles but are affected more by air and environmental factors. Aluminum is also used with gas checks. Aluminum is not used for solids or as a jacket because it can cause severe fouling or galling in the bore.

- **Tin** – Tin is an alloying metal that is lighter than brass and copper and slightly harder than lead. It is found mostly mixed with lead, but as the push to replace lead continues, tin may be alloyed with other metals. Tin is also alloyed with copper to form the brass used in some solid bullets. Tin can be found as a core material, utilizing a copper jacket, but can only be found in a few examples.

- **Nickel** – Nickel is a metal that is almost as heavy as copper, and almost as hard as some steels. It is found primarily as plating. Nickel is used to prevent corrosion and is used on copper jackets and solid copper bullets. Because nickel is as hard as or only slightly harder than steel, there is little to no worry of excessive barrel wear because of the limited use as a coating. Nickel plating can be found on pistol and rifle bullets as well as on some bird- and buckshot. Nickel-plated buck- and

Figure 25: Aluminum tipped and core bullets.

Figure 26: A tin core bullet.

Figure 27: Nickel plated bullets and plated shot.

birdshot consists of a base coating of copper followed by the nickel plating.

- **Zinc** – Zinc is a metal that is nearly as heavy as tin and as hard as aluminum. It can be found as a core material or as plating. When used as a core material, the zinc is always jacketed by copper to protect both the bullet and bore. Zinc is also used as a plating on bullets that utilize a steel jacket. The zinc is used to preserve barrel life and prevent excessive wear.

- **Bismuth** – Bismuth is a metal that is nearly as dense as lead but is slightly harder. Bismuth is quickly becoming one of the major replacements for lead because it is environmentally safe and features similar properties to lead. Bismuth is mostly found as an alloy with both birdshot and buckshot. It is also beginning to appear as a core material in solid form and as a powdered metal core in frangibles. Bismuth is typically alloyed with tin at a ratio of around 9:1.

- **Antimony** – Antimony is an alloying metal that is lighter than zinc and as hard as brass. It is typically only found as an alloying compound of lead. Antimony may also be mixed with tin in various lead alloys.

- **Tungsten** – Tungsten is a very hard, very heavy metal. It is found as a penetrator in armor piercing bullets and as a material for some buckshot and birdshot. Because tungsten is so hard, the only way to process it into penetrators or shot is to sinter it. Tungsten powder is compressed into a spike or ball and heated until the grains of powder fuse together. While tungsten may be hard, tungsten carbide is an alloy that is much harder. The carbon, along with various heat treats, quenches, and temperings, creates a crystalline structure in the alloy's atoms, which makes it extremely hard, but also brittle. Tungsten carbide is used in applications where standard tungsten may not penetrate hard armor.

Figure 28: Zinc core rifle and pistol bullets.

Figure 29: A tungsten penetrator.

- **Titanium –** Titanium is a lightweight metal that is harder than steel. It can be found as a specialized bullet tip that can be used for several different purposes. The tip is typically turned and then swaged into a core. Like tungsten, titanium can be alloyed to change the way it performs under various conditions.
- **Metal Composite –** Metal composite is a hybrid material that utilizes some type of metal powder and a binder. Depending on the composition of the composite, the projectile may perform like a solid or frangible. The metal powder is typically copper, though other powders or blends are used. The binder is typically an adhesive, but epoxies and polymer blends are also used. The metal composite projectile may be mixed with a binder and compressed until cured, or it may be injection molded. The metal composite bullet may also be constructed as a solid or as a core that is jacketed.

COATINGS

On top of all the various materials that compose a projectile, some may use additional coatings to enhance their performance in certain aspects. Coatings are used to protect the bullet or bore from fouling, wear, and corrosion. Other coatings are used to reduce the amount of friction the bullet experiences while in the bore.

Some coatings, like copper and zinc, are used to protect the bore from the bullet. Bullets that feature a steel jacket are typically plated with a

Figure 30: A titanium tipped bullet

Figure 31: Metal composite bullet.

Figure 32: Copper, zinc, and nickel plated bullets.

thin layer of copper or zinc to shield the bore from the jacket. Nickel is used on copper jacketed or copper solid bullets for corrosion resistance or aesthetic appeal.

Black oxide is more of a surface conversion than a coating and does not add any thickness to the material. Although black oxide is more of an aesthetic coating, it does have a few benefits. Only copper jacketed or solid copper projectiles can be coated. Black oxide does not increase wear on the bore while reducing fouling. Black oxide also provides corrosion resistance similar to nickel without the increase in diameter.

Polymer is used as more of a protective coating than a performance coating. Polymer is used on cast lead bullets to protect the bore from the core. The polymer coating allows lead pistol bullets to be fired at greater velocities (1,300 fps – 1,500 fps), with some coatings allowing lead rifle bullets to be fired to as high as 2,700 fps. Polymer coated bullets not only protect the bore from fouling, they almost provide a cleaning or polishing attribute, leaving the bore surprisingly clean after firing many rounds.

The polymer coating is applied to cast bullets before they are sized. The coating is typically a two-part mixture that the bullets are tumbled in and then baked to cure. Because of the material thickness added, once the bullets have been cast, they are coated and then sized to their final dimension. The polymer coating can also be used for aesthetic purposes. Polymer coatings come in a plethora of colors, including metallic flakes and pearls.

There are other coatings designed to enhance a projectile's interior/internal ballistics. Such coatings are designed to reduce friction inside the bore, which increases velocity and barrel life.

Figure 33: Black oxide coated bullets.

Properties of Materials Found in Projectiles		
Material	**Weight** *(pounds per cubic foot)*[d]	**Hardness** *(Mohs Scale)*[e]
Lead	707.96	1.5
Copper	559.87	3
Brass	535.68	3
Steel	490	4 – 4.5
Aluminum	168.48	2.5 – 3
Tin	455.67	1.5
Nickel	555.72	4
Zinc	445.30	2.5
Bismuth	611	2 – 2.5
Antimony	419.99	3 – 4
Tungsten/Carbide	1204.41	7.5/8.5 – 9
Titanium	283.39	6
Metal Composite	N/A	N/A

[d] *Coyote Steel. (n.d.). Weights of Various Metals in Pounds per Cubic Foot. Retrieved October 16, 2018, from www.coyotesteel.com/assets/img/PDFs/weightspercubicfoot.pdf*

[e] *E] Jewelry Notes "The MOHs Scale of Hardness for Metals: Why is it Important" www.jewelrynotes.com/the-mohs-scale-of-hardness-for-metals-why-it-is-important/ (Accessed 10/16/2018)*

Table 3. Properties of materials found in projectiles.

These coatings are typically a dry film (non-liquid) lubricant that is applied to the projectile by tumbling. The most popular coatings for projectiles are molybdenum disulfide (MoS2/moly), tungsten disulfide (WS2), and hexagonal boron nitride (HBN).

Lubricants are measured by how "slick" they make a surface. This measurement is expressed in a coefficient of friction (COF) number. The lower the number the "slicker" the coating. Moly has a COF of around .1 – .3,[1] while WS2 comes in around .03 – .07,[2] and HBN around .15 – .7.[3] All three lubricants can be applied through tumbling; the coating is peened into the surface via impact with the projectile. Moly is one of the original dry lubricants used on projectiles, with

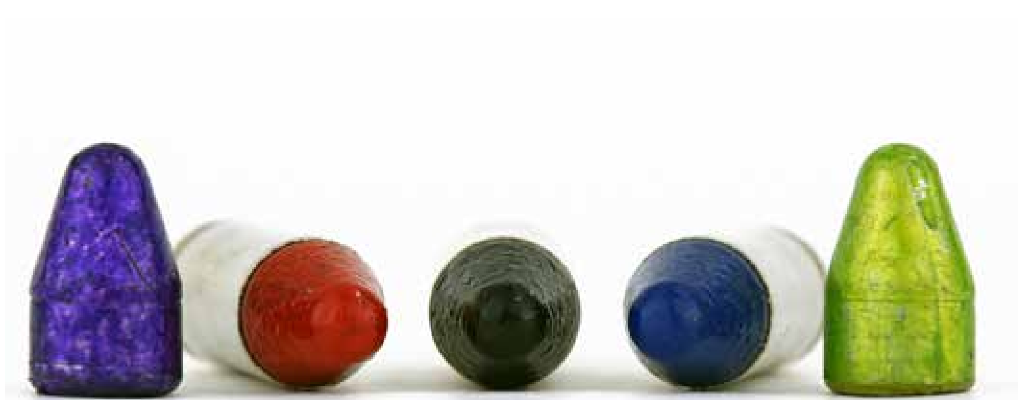

Figure 34: Polymer coated bullets.

many factories utilizing the technology in production ammunition. WS2 and HBN are fairly new for use on projectiles. While moly is one of the most widely used lubricants, its application also requires that it be sealed (with wax) to prevent the coating from rubbing off during handling. WS2 and HBN do not experience this issue. Once the coating is embedded into the surface it is difficult to remove. All three coatings can also be used to treat the bore of the firearm, further increasing the projectile's capabilities.

BALLISTIC COEFFICIENT

A projectile's exterior ballistic performance can be quite accurately predicted with its ballistic coefficient (BC) and a few other factors (velocity, mass, atmospheric conditions). Ballistic coefficient is a measure of a projectile's ability to defeat air resistance and environmental factors. The higher the number the greater the projectile's ability to cut through the air.

To cut through any material, there are a couple of basic requirements: the cutting instrument needs to be sharp and there needs to be a sufficient amount of energy/mass from/within the cutting instrument. If the bullet is the cutting instrument and the medium is air, then the bullet needs to be sharp and heavy to efficiently cut through the air. Streamlined, heavy bullets will have a greater BC than blunt, light bullets. A heavy projectile will cut through the air better than a light projectile but not as well as a heavy, streamlined projectile.

Projectiles with a greater BC will have a flatter trajectory and maintain their velocity over a greater distance. They will also have a greater effective range. A high BC projectile will be able to deliver more energy farther down range than a low BC projectile because they will retain more of their energy while in flight. Projectiles with a high BC will resist changes in trajectory from wind, altitude, and temperature better than lower BC bullets.

The idea sounds simple but when you begin to introduce all factors involved, BC can become quite confusing. Mass and general shape are not the only factors to consider when calculating a projectile's BC. Other factors include the diameter of the projectile, velocity, and its shape in relation to a standardized form (form factor),

Figure 35: A projectile with a high ballistic coefficient next to a projectile with a low BC.

including the shape of its ogive, tip, length of body, and base. Although there are several factors that compose a projectile's BC, they can be grouped into two major factors: sectional density and form factor. In the most basic terms, BC is a ratio of the projectile's section density to its form factor (BC = sectional density/form factor).

SECTIONAL DENSITY

Section density (SD) is a ratio of a projectile's mass to its diameter. The higher the SD number, the greater the projectile's mass is in relation to its diameter. A greater mass to diameter ratio is beneficial for one purpose: penetration, regardless of medium.

When talking about SD in relation to BC, air is the medium being penetrated. A projectile with a high SD features a smaller cross-section compared to its mass, focusing drag onto a smaller area on the front of the projectile. A projectile with a high SD will experience less drag because there is less surface area to act against and more momentum behind it. Projectiles with a low SD will experience drag more because of the greater frontal area and lack of momentum from reduced mass. Sectional density does not take shape or velocity into account, so with all things being equal (caliber and mass), a spire point projectile will have the same SD as a blunt, round nose projectile.

While SD is a factor when calculating BC, sectional density can also be useful when selecting a projectile for hunting. When discussing SD in relation to hunting, the projectile is measured on its ability to penetrate flesh. Like with air, a higher SD will penetrate better than a low SD. Section density numbers can be used to determine a projectile's ability to dispatch various sized game. For example, a section density of .180 and below is suited for small game, an SD between .200 and .240 is good for medium game (deer), an SD between .270 and .290 is suited for large game (elk), and .300+ is needed for large, thick-skinned and dangerous game (bear, moose), regardless of caliber.[4]

Sectional density can also be used to determine a projectile's ability to penetrate armor and barriers. A projectile with a high SD alone will not automatically become AP, but a bullet with a high SD that is constructed like an armor piercing round will perform much better than a similar projectile with a low SD. With AP projectiles, construction is more important than SD, but a high sectional density will increase the AP bullet's penetration capabilities.

The advantage of using a smaller caliber projectile with a high SD versus a larger caliber, heavy projectile is the reduced recoil, because it takes less energy/force to make a lighter projectile move. We know that "for every action, there is an equal and opposite reaction", which means that the same force that is exerted on the rear end of the projectile to begin its movement will also be exerted on the breech/bolt face of the firearm. This rearward force causes felt recoil. Thus, a lighter projectile will cause the operator to experience less felt recoil. Therefore, if you can choose a projectile that recoils less and provides more penetration, the decision seems obvious.

A projectile's sectional density is more important to BC than its shape because the mass of the projectile will allow the projectile to retain more of its energy when counteracted by forces like gravity, air resitance, and wind. This relates to Newton's first law which summarizes that an object will not change its motion unless another force is great enough to alter that objects motion. Therefore, it will take more energy to alter the motion of a projectile that has more density (mass). Form does contribute to a projectile's BC, but changes in form will only incrementally change its ballistic coefficient; changes in SD will affect it more dramatically.

For example purposes, we will use three different projectiles. Because all factors are known, you can see how they relate and affect each other. The projectiles we will use are:*

- 9x19mm NATO – .355 diameter, 115 grains (weight), .130 SD, .155 BC between 900 and 1,300 fps, .839 G1 FF.

- 5.56x45mm NATO – .224 diameter, 77 grains, .219 SD, .372 BC 3000+ fps, .591 G1 FF.
- .308 Winchester – .308 diameter, 168 grains, .253 SD, .462 BC 2,600+ fps .548 G1 FF.

**All three projectiles' data gathered from SierraBullets.com. All three BCs are related to the G1 form factor. The pistol round is a standard ball (FMJ), the two rifle rounds are open tip, jacketed boat tail (HPBT Matchking).*

Calculating SD is fairly simple. All you need is the projectile's weight in grains and its diameter. SD is calculated by dividing the projectile's mass (M) by its diameter (D) squared (D x D), multiplied by the constant 7,000.* Sectional density is expressed in pounds per inch, squared (lb. in.^2). The formula is as follows:[5]

SD lb. in.^2 = M (grains)/7,000* x (D x D)

SD – sectional density in pounds per inch squared

M – mass in grains

D – bullet diameter

***Constant 1 lb. = 7,000 grains**

9x19mm NATO –115 (M)/(.355 x .355) (D) x 7,000 = SD

115/.126† x 7,000 = SD

115/882 = SD

.130† = SD

5.56x45mm NATO –77/(.224 x .224) x 7,000 = SD

77/.050† x 7,000 = SD

77/350 = SD

.220 = SD

.308 Winchester –168/(.308 x .308) x 7,000 = SD

168/.095† x 7,000 = SD

168/665 = SD

.253† = SD

†*Rounded to three digits after the decimal.*

The Sectional Density Chart on page 63 shows a selection of the most popular cartridges and their sectional densities for various projectile weights. Some of the results are surprising when considering that some very powerful cartridges do not penetrate as well as cartridges with smaller diameter projectiles and less mass. It is easy to see from this chart why SD plays such a big role in a projectile's BC. Many of the calibers that have a high SD will also typically have a very high BC.

FORM FACTOR

The form factor (FF) of a bullet is a measurement of how well its form will overcome drag compared to a standardized model of a projectile. Form factor measures how streamlined the shape of a specific bullet is (regardless of mass) in comparison to a standardized bullet shape. While measuring a projectile's SD is fairly easy and only requires a calculator, form factor is much more difficult to measure. Form factor requires measurement of a projectile's drag, which is specific to each projectile.

The standardized models, "G" models or Gavre functions, are projectile designs that have been extensively tested to calculate the amount of drag their shape experiences. The basic specification for the standardized projectile is that it weighs 1 lb. and is 1 in. in diameter. Each specific G model will vary in shape and length, with some specializing in varying velocity ranges. There are 11 different forms used for a variety of projectile shapes, with one being more suited to artillery than small arms, and only two that have been adopted as industry standard: G1 and

Figure 36: A projectile with a low SD versus a projectile with a high SD.

G7. The form used for artillery projectiles is the G2, and the remainders are the G5, G6, G8, GI, GL, GS, GC and RA-4.

The value of each standardized form factor is 1, but each form factor value is not equal to each other. A G1 form factor of 1 is not equal to a G7 form factor of 1. The value of each form factor is equal to one unit of drag against that specific projectile form. The form factor number will change for a specific projectile when compared to the different shapes of the G models. This is why a projectile's G1 and G7 form and BC numbers will differ greatly.

For example, let's compare two theoretical projectiles to the G1 drag model. Let's say that Projectile I is more aerodynamic than the G1 model, while Projectile II is less aerodynamic. Projectile I's form factor (FF) may equal .950. Projectile II's FF may equal 1.050. What these numbers mean is that Projectile I experiences 95 percent (or 5 percent less) of the drag than the G1 projectile experiences, while Projectile II experiences 105 percent (or 5 percent more) drag.

Now, let's take the same two projectiles and compare them to the G7 form factor, which is more aerodynamic than the G1. Both projectiles will have a 1+ FF because neither is more aerodynamic than the standard form. This is why G1 BC numbers will always be higher than G7 BC numbers.

For decades, the G1 form was the standard upon which all small arm BC calculations were based. The G1 was one of the first standardized models used for ballistic calculations and so was widely adopted by the ballistic community. 1 in. diameter, flat-based, semi-pointed bullet. The G1 projectile is 3.26 calibers long (3.26 in.) with a 1.96-caliber (1.96 in.) body, and a 1.32-caliber (1.32 in.) nose with a 2-caliber (2 in.) tangent ogive. The G1 form factor is also known as the Ingalls form factor and is nearly identical to the GI form factor.

The G7 form factor has gained much favor in the last decade. The form of the G7 projectile is closer to the modern spitzer and VLD style bullets, with a longer profile and boat tail. The G7 form

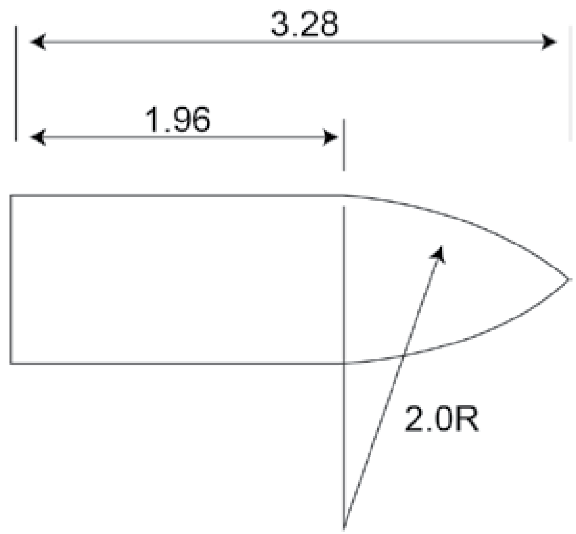

Figure 37: G1 form factor.

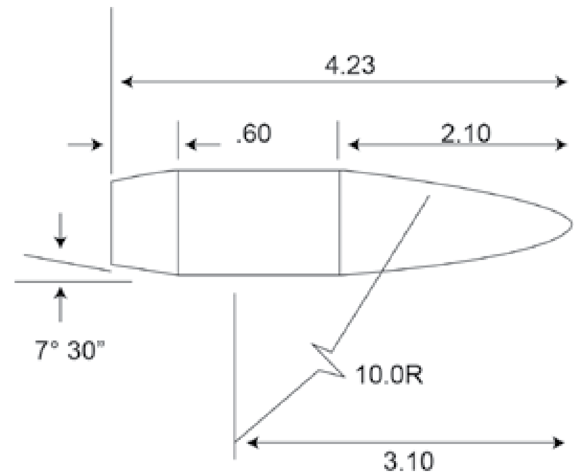

Figure 38: G7 form factor.

is a 1 lb., 1 in. diameter, flat-based, semi-pointed bullet. The G1 projectile is 3.26 calibers long (3.26 in.) with a 1.96-caliber (1.96 in.) body, and a 1.32-caliber (1.32 in.) nose with a 2-caliber (2 in.) tangent ogive.

It is easy to see from these figures why the G1 form factor produces high BCs for boat tail spitzer bullets. The modern spitzer has superior aerodynamics compared to the blunt point, flat base G1 projectile, but only marginal performance when compared to the streamlined G7.

The remaining form factors are used for various other types of projectiles, including artillery, cylindrical (wadcutter), round ball (buck/birdshot) and rimfire. Other form factors include the following: [6]

- **G2** – A long, conical nose, banded artillery projectile. The G2 projectile is 5.19 calibers long with a .5-caliber, 6° boat tail. The G2 form factor is typically not used to calculate FF for small arms projectiles. Also known as the Aberdeen J projectile.
- **G5** – A short boat tail, semi-pointed projectile. The G5 projectile is 4.29 calibers long, with a .49-caliber, 7° boat tail, and a 2.1-caliber nose with a 6.19-caliber blunt tangent ogive.
- **G6** – A flat base, spitzer style projectile. The G6 projectile is 4.81 calibers long, with a 2.53-caliber nose and a 6.99-caliber secant ogive.
- **G8** – A flat base, spitzer style projectile. The G8 projectile is 3.64 calibers long, with a 2.18-caliber long nose and a 10-caliber secant ogive. Similar to the G6 model with a longer nose.
- **GI** – Basically a G1 form factor.
- **GC** – A blunt nose (wadcutter) projectile. The GC projectile is 3 calibers long. The GC form factor mirrors that of the G1 projectile below 1,200 fps.
- **GS** – A sphere. The GS projectile is a 9⁄16 in. ball projectile. Smaller or larger spheres will have an identical form factor.
- **GL** – A long, round nose lead projectile (ball). The GL form factor mirrors that of the G1 below 1,400 fps.

- **RA-4** – .22 Long Rifle Rimfire. Mirrors the G1 below 1,400 FPS.

Although it may be very difficult measuring a projectile's form factor if BC is unknown, when BC *is* known, the calculation is fairly simple. All that is needed is the projectile's BC and SD (both of which manufacturers typically provide). The formula is as follows:[7]

FF = SD/BC

FF – form factor

SD – sectional density

BC – ballistic coefficient

9x19mm NATO –.130 (SD)/.155 (BC) = FF

.839† = G1 FF

5.56x45mm NATO –.220/.372 = FF

.591† = G1 FF

.308 Winchester –.253/.462 = FF

.548† = G1 FF

†*Rounded to three digits after the decimal.*

In a perfect world all projectiles would have a BC of 1.0 or higher, meaning that the projectile would perform as well as the selected

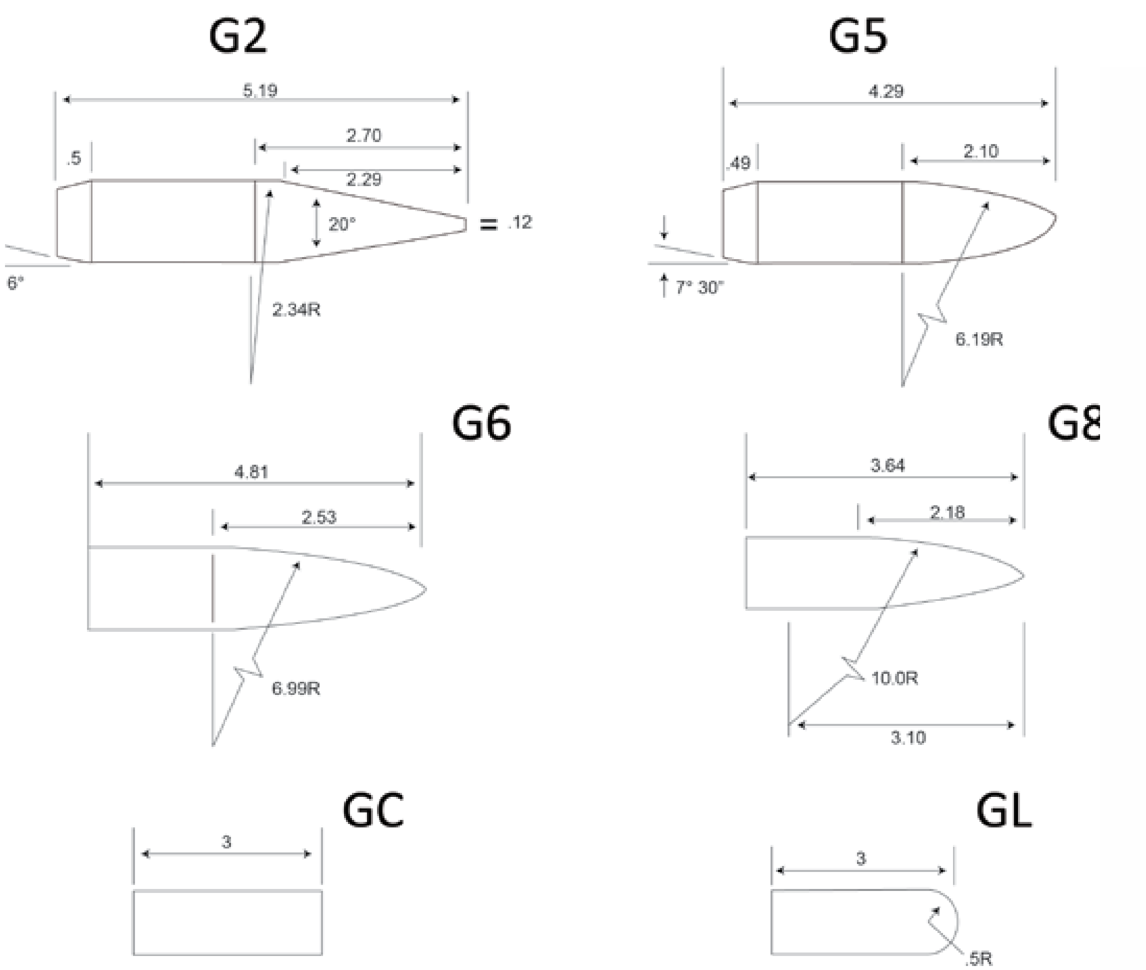

Figure 39: Other form factors.

standardized projectile. Since this is the real world, there is a finite number of projectiles used by civilians that have a BC that even approaches 1.0. Most projectiles average a G1 BC of around .250 – .350, while VLD bullets will average between .500 and .700. One of the only projectiles to reach a G1 BC higher than 1.0 is the 50 Browning Machine Gun (BMG) with a BC 1.05. This is a massive projectile compared to other small arm projectiles; the 50 BMG is .5 in. in diameter and weighs in at 750 grains or 1.71 oz. The mass and diameter of the 50 BMG contribute to an SD of .429, which by itself is very impressive. Add a very streamlined body and you get an extremely high-performance projectile. A high SD and a low form factor will contribute to a high BC projectile.

If you know both sectional density and the projectile's form factor (related to a specific G model), calculating BC is simple.

BC G? = SD / FF

BC – ballistic coefficient of a specific G model

SD – sectional density

FF – form factor

9x19mm NATO –.130 (SD)/.839 (FF) = G1 BC

.155† = G1 BC

5.56x45mm NATO –.219/.591 = G1 BC

.371† = G1 BC

.308 Winchester –.253/ 548 = G1 BC

.462† = G1 BC

†*Rounded to three digits after the decimal.*

Luckily for us, manufacturers typically list the BC of all the projectiles they manufacture. It is almost impossible for the average person to calculate a specific projectile's BC (specifically form factor) without very sophisticated and expensive testing equipment (Doppler radar and specialized, environmentally controlled facilities). Even if we were able to calculate a projectile's specific BC in a controlled environment, the ballistic coefficient would change under different conditions, such as altitude, temperature, humidity, and barometric pressure. Even fired into an environment where all conditions are

Figure 40: Various projectile BCs. All BCs in G1.

From left to right: .510 dia. 750 grains 1.050 BC, .338 dia. 300 grains .736 BC, .308 dia. 212 grains .673 BC, .308 dia. 168 grains.490 BC, .257 dia. 115 grains .483 BC, .257 dia. 115 grains .453 BC, .224 dia. 77 grains .420 BC, .224 dia. 73 grains .398 BC, .308 dia. 150 grains .215 BC, .451 dia. 230 grains .175 BC, .223 dia. 40 grains .138 BC, .224 dia. 31 grains .115 BC, .355 90 grains .112 BC, .730 dia. 437.5 grains .090 BC, .410 dia. 109.4 grains .060 BC.

known and accounted for, the BC of a projectile will change as its velocity changes.

Now that you have a basic understanding of ballistic coefficient, what does it actually mean? How can this be applied to real world shooting? If you are shooting a pistol or are within about 100 yd., BC does not really apply. With pistol cartridges that are used between 25 and 50 yd., the projectile is not in flight long enough for a high BC to make a difference. If you are shooting beyond 100 yd., BC doesn't really come into play until about 200 yd. Beyond 200 yd., BC plays a huge role because projectiles with a high BC will have a flatter trajectory and maintain higher velocities and energy over a greater distance. This means that you can shoot farther with a high BC bullet than with a low BC bullet in the same firearm. High BC projectiles effectively extend the effective range of most firearms (that have the proper twist rate to stabilize them). Projectiles with high BCs can benefit hunters, target shooters, long-range shooters, and military/LE personnel.

Sectional Density (SD) by Cartridge			
Cartridge	Diameter (in Inches)	Weight (in Grains)	SD
.22 Long Rifle	.223	40	.115
.380 ACP	.355	90	.102
9x19mm NATO	.355	115	.130
.40 Smith & Wesson	.400	165	.147
.45 ACP	.451	230	.161
5.7x28 FN	.224	31	.088
.22 Hornet	.224	40	.113
.44 Remington Magnum	.429	240	.186
5.56x45 NATO	.224	55	.156
5.56x45 NATO	.224	62	.176
5.56x45 NATO	.224	77	.220
.300 Blackout	.308	110	.165
.300 Whisper	.308	220	.331
7.62x39	.311	124	.183
6.5mm Grendel	.264	130	.267
6.8 SPC	.277	130	.242
30-30 Winchester	.308	150	.226
.243 Winchester	.243	75	.181
45-70 Government	.458	300	.204
6.5 Creedmoor	.264	120	.246
6.5x55 Swede	.264	139	.285
.308 Winchester	.308	168	.253
.257 Weatherby Magnum	.257	100	.216
30-06 Springfield	.308	200	.301
300 Winchester Magnum	.308	190	.286
.358 Winchester	.358	225	.251
.338 Lapua Magnum	.338	300	.375
.416 Rigby	.416	400	.330
.450 Bushmaster	.452	250	.175
.50 Browning Machine Gun	.510	750	.412
.410 Bore (Slug)	.410	109.4 (¼ ounce)	.092
12-Gauge (Slug)	.729	437.5 (1 ounce)	.117

Table 4. Sectional density (SD) by cartridge.

Ballistic Coefficient (BC) by Cartridge		
Cartridge	Weight (in Grains)	Average Ballistic Coefficient (G1)
.22 Long Rifle	40	.138
.380 ACP	90	.112
9x19mm NATO	115	.158
.40 Smith & Wesson	165	.131
.45 ACP	230	.172
5.7x28 FN	31	.115
.22 Hornet	40	.132
.44 Remington Magnum	240	.185
5.56x45 NATO	55	.237
5.56x45 NATO	62	.233
5.56x45 NATO	77	.396
.300 Blackout	110	.155
.300 Whisper	220	.467
7.62x39	124	.265
6.5mm Grendel	130	.461
6.8 SPC	130	.403
30-30 Winchester	150	.215
.243 Winchester	75	.221
45-70 Government	300	.192
6.5 Creedmoor	120	.389
6.5x55 Swede	139	.465
.308 Winchester	168	.499
.257 Weatherby Magnum	100	.357
30-06 Springfield	200	.613
300 Winchester Magnum	190	.533
.358 Winchester	225	.377
.338 Lapua Magnum	300	.768
.416 Rigby	400	.319
.450 Bushmaster	250	.210
.50 Browning Machine Gun	750	1.05
.410 Bore (Slug)	109.4 (¼ ounce)	.060
12-Gauge (Slug)	437.5 (1 ounce)	.090

Table 5. Ballistic Coefficient (BC) by cartridge.

Chapter 3 - Cases: Parts of a Case, How Cases are Formed

Figure 1: Various cartridge cases.

Cases

The case is the central component to any cartridge: it is the housing for all of the other pieces. The cartridge case is utilized to contain part of the immense pressure that is created when a cartridge is discharged, when it is held stable by the chamber. The case is also the only part of a cartridge that can typically be re-used. Upon discharge, the case must expand to seal the chamber and prevent gas blowback from the breech of the firearm and contract once chamber pressure has dropped so that it may be extracted. This means that the case must be strong enough to contain the extreme pressure, pliable enough to stretch and expand to seal the chamber, ductile enough to contract back to nearly it's original shape and soft (malleable) enough to do it repeatedly without cracking or splitting. The case will contract back slightly when it has experienced a slight cooling. This happens very quickly to the observer, however, a case should contract or extraction of the case would become very difficult, depending on the condition of the chamber. Pistol and rifle cartridge cases may be referred to as "brass," while shotshell cases may be referred to as "hulls."

There are many different case types and styles with various features for a variety of chambers. There are also several different materials that are used and coatings that are applied. Cases can be grouped into two main categories, with many styles for each. The case may also be used for identification purposes. The case features markings that provide different information about the cartridge, but if the markings are missing or unknown, the dimensions of the case will also provide information about the caliber. While a single projectile can be used with different cases, each case is specific to a caliber and is (typically) never interchangeable.

Parts of a Case

The general cartridge case design is basically a cylindrical container with provisions for the primer and extractor. The case design will vary with the type of firearm it is intended for and for its proposed purpose. Some features are universal to every case and some are unique to only a single type. The various parts and features of a cartridge case include the following:

- **Body** – The body of a cartridge case is a cylindrical tube that features one end that is partially capped. The hollow of the body houses the propellant and part of the projectile. Depending on cartridge type, the body will either transition to the case shoulder or mouth. In the opposite direction, the body will extend downward into the case rim or the extractor groove. At the bottom of the hollow, the body transitions into the web and the flash hole. The body may feature (semi) straight walls or walls that taper toward the mouth. The body may also feature a cannelure around its circumference used to control projectile seating depth.

Almost every cartridge case (with the exception of many rimfire cases and a few centerfire cases) will feature some taper; even "straight wall" cases will taper slightly. The taper helps the case to release from the chamber after discharge, aiding in its extraction. The greater the taper, the easier it will extract. The tradeoff to enhanced extraction is magazine design. When heavily tapered cases are stacked, the stack begins to curve. The magazine design must account for this curvature, which may cause issues with reliability. The taper will vary by caliber and type of case but will range from .14° for a "straight-walled" case (e.g. 10mm Auto) to 2.7° for a heavily tapered case (e.g. 7.62x39).

Depending on the caliber, type of case, manufacturer, and location of measurement, the wall thickness of the body will vary between .010 in. and .060+ in. Typically, the wall thickness will be thinner near the case mouth and taper so that it is thicker near the case head. If the case is reloaded, the walls will begin to thin out as the case is forced to repeatedly stretch. Because the external

Figure 2: Various case bodies.

Figure 3: How case taper affects magazine design.

dimensions of the case are restricted by very tight tolerances, much of the variation in wall thickness is internal. Variations in wall thickness between cartridges will lead to variations in case volume and pressure levels.

With pistol and rifle cartridges, the entire cartridge is typically a single piece with many features. With modern non-metallic shotshell cartridges, the body is a separate component that is mechanically bonded to the case head. Because

Figure 4: Various wall thicknesses. From left to right: .50 BMG, .410 Bore 3 in., .30-06 Springfield, .30-06 Springfield (steel case), 12 Gauge 2¾ in., .30-30 Winchester, .308 Winchester (steel case), .45 Long Colt, 10mm Auto, .25 ACP, .22 Long Rifle.

Figure 5: Shotshell body length before and after discharge.

most shotshell hulls are polymer, the body is molded to the case head, which is a different material. With most shotshells, the crimp is also part of the body. When fired, the crimp will unroll or unfold and reveal the full length of the cartridge body.

- **Shoulder** – The shoulder is a tapered area above the body used to transition from the neck to the body. It is used to provide a smooth transition from the case neck to the case body, which is a larger diameter. The shoulder also provides a smooth transition for the high pressure moving from the inside of the body, through the case neck and through the bore. The shoulder is a feature of the over-bore or bottleneck cartridge, which features a body that is a larger diameter than the neck and the bullet. The angle of the shoulder will vary with caliber but is typically anywhere from 5° to 40º, with the average shoulder angle of about

Figure 6: Various shoulder angles. From left to right: .408 CheyTac, .338 Lapua Magnum, .257 Weatherby Magnum, .270 Winchester, .30-06 Springfield, 7.5x55 Swiss, 7.62x54mmR, .30-30 Winchester, .35 Remington, 6.8 Remington SPC, .22 Hornet, .300 AAC Blackout, 5.7x28mm FN, 5mm Remington Magnum, 7.62x25mm Tokarev.

Figure 7: Various case necks.

23°. A sharp shoulder (~40°) will allow for more case capacity than a steep (~5°) shoulder. A steep shoulder will provide a smoother transition for propellant gases.

With some calibers, the shoulder also acts as a point for the cartridge to headspace against if the shoulder has a sharp enough angle (~15°+) and is wide enough. When the cartridge is chambered, a point halfway between the top and bottom of the shoulder will bottom out against the chamber wall. When the chamber is locked, the breech face will sandwich the cartridge between the shoulder and the cartridge head. If the shoulder does not sit in the correct location, the cartridge may not fit or it may be too loose in the chamber.

- **Neck –** The neck is the part of a bottleneck cartridge case that places tension on the bullet, preventing it from moving unintentionally. The neck also supports and aligns the bullet to the bore. On a bottleneck cartridge, the neck is ahead of the shoulder, just before the mouth.

  Depending on the cartridge type, the crimp may be applied to the neck. Some cartridges do not utilize a crimp, but the friction on the bullet created by the neck is enough to keep the projectile in place. The length of the neck depends on the caliber, recoil, and whether it was designed for longer or shorter projectiles. As with cartridges designed to fire longer, high SD bullets are typically designed with longer necks to support the round. Cartridges designed to fire short projectiles will have a shorter neck. Typically, the neck will be around 1 caliber long (equal to the diameter of the projectile) for heavy recoiling cartridges, while lighter recoil cartridges may feature a neck length 80 percent – 90 percent of a caliber.

- **Mouth –** The mouth is the part of the cartridge case where the projectile is inserted. It is the hole in the front of the case. Depending on the caliber, the mouth may be ahead of the neck or atop the body. Also, depending on caliber, the mouth may be crimped, headspaced against, or simply be an opening.

  When the case mouth is utilized for crimping, the mouth is rolled into a cannelure or crimp groove located on the projectile (roll crimp). With some shotshells, the mouth is folded over the front of the projectiles. When the mouth is

Figure 8: Various case mouths.

Figure 9: Case cannelures.

utilized for headspace, the mouth of the cartridge will bottom out against a ledge inside the chamber and the cartridge will be sandwiched by the breech face/slide. When the mouth is used for headspace it cannot also utilize a roll crimp. The crimp changes the length of the case and it will not headspace correctly.

- **Cannelure –** The cartridge case cannelure is an indented ring or channel along the body or neck. The cannelure serves to prevent the bullet from being pushed back (setback) into the case during the feeding step or with hard recoil. The cannelure forms a small ledge inside the case that prevents the bullet from entering beyond a specific point. The cannelure may also add additional friction, strengthening the crimp on the projectile.

Excessive setback can lead to a catastrophic pressure spike that could destroy the firearm and cause injury. Bullet setback as little as .010 in. can be dangerous with some loads. Even if a crimp was not satisfactory, the cannelure would stop any rearward movement of the bullet as it impacts the feed ramp of the firearm. A cannelure is often found with high power pistol cartridges and cases intended for self-defense ammunition designed for autoloaders.

- **Web –** The web is the area between the body and the case head on the inside of the case; it is the bottom of the hollow part of the case. The web almost completely seals the bottom of the inside of the case with the exception of a small hole (or holes) that is centrally located in the web. The web tends to be much thicker than any other part of the case (with the exception of maybe the head), so that it can withstand the immense amount of pressure inside the case. Upon discharge, the web will experience chamber pressure equal to the case walls and projectile. The web also separates the inside of the body from the primer pocket.

Figures 10: Various case web and flash style holes.

Figure 11: Parts of a case head.

- **Flash Hole –** The flash hole is the opening in the center of the web. The flash hole provides an orifice from the primer pocket into the case body. Upon discharge, embers from the primer travel through the flash hole and onto the propellant. There is no "standard" flash hole size, but most manufacturers will utilize a hole .080 in. in diameter for pistol and rifle cartridges. The flash hole may range from about .070 in. to .085 in., with some examples as small as .050 in. and as large as .100 in. Shotshells utilize a flash hole that is around .180 in. for almost every shotgun caliber. The .50 BMG utilizes a flash hole around .135 in.

  Some cartridge designs utilize two smaller flash holes that are located around the center of the web. These smaller flash holes measure around .040 in. each. The size of the flash hole will vary by the manufacturer, caliber of the cartridge, case material, and size of the primer used (small/large). The size of the flash hole

Figure 12: Shotshell case heads.

may also vary from case to case because of manufacturing tolerances.

- **Head –** The case head is the base of the cartridge. Although the case head is only a feature of the cartridge case, the head has several of its own features. The head contains the primer pocket and is comprised partly of the rim and, if applicable, the extractor groove. The case head also bears the cartridge markings or "headstamp." Regardless of cartridge type or caliber, the "face" of the head will always be the cartridge's second point for headspace. The front of the cartridge case will headspace against a point inside the chamber, while the head of the case will headspace against the bolt/breech face/slide.

  With shotshells, the head is typically a separate piece from the body. The body is molded to the head, which extends partly up the body. There are two basic head lengths, referred to as "high-brass" and "low-brass." The size of the head will usually depend on the type of load, not the pressure of the load, which is a common myth. Buckshot and slug loads will typically feature a head that extends further up (high) the case body, while low-pressure, "target," or birdshot loads will typically have shorter (low) heads.

- **Primer Pocket –** The primer pocket is a hollow cavity in the center of the head of a centerfire cartridge. It is utilized to house the primer. The primer pocket shares the web with the body and utilizes the flash hole to transfer embers from the primer onto the propellant. Depending on case and primer type, the primer pocket may also feature a part of the primer: the anvil.

  Some cases and primer pocket designs utilize an integral anvil in the primer pocket and feature two smaller flash holes. The cases are known as "Berdan" style, while cases with a single flash hole and no anvil are known as "Boxer" style. The two types are not interchangeable. Regardless of style, the primer pocket is typically the same size or slightly smaller (~.002 in.) than the primer, so that the primer can be pressed into place and secured by a friction fit.

  The Boxer primer pocket's size will vary by cartridge type and caliber. There are four primer pocket sizes: small pistol/rifle (~.1735 in. diameter x ~.120 in. deep), large pistol (~.2095 in. diameter x ~.120 deep), large rifle (~.2095 diameter x .129 in. deep), and shotshell (~.241 in. diameter x ~.299 in. deep).[1] Although small pistol and rifle pockets are the same size, the primers are not interchangeable.

Figure 13: Various primer pockets. From left to right: (Boxer) small pistol, large pistol, small rifle, large rifle, .50 BMG, shotshell, (Berdan) small pistol, large pistol, small rifle, large rifle.

Figure 14: Various rim types.

There is a fifth primer pocket size, but it is specific to the .50 BMG. The .50 BMG primer pocket is ~.315 in. in diameter and ~.216 in. deep.

The Berdan primer pocket is also found in four basic sizes: small pistol 4506/4521 (~.176 in. diameter x ~.092 in. deep), large pistol 5005 (~.196 in. diameter x ~.092 deep), small rifle 4520 (~.176 in. diameter x .082 in. deep), and large rifle. It is with the large rifle where things get a bit confusing. There are five variations of the large rifle Berdan primer, which means five different pocket

Figure 15: Various cartridges being extracted.

Figure 16: With some cartridges that headspace against the rim, shorter cartridges can be safely fired that share the same caliber. For example, a firearm chambered for the .460 S&W can also safely fire the .454 Casull, .45 Colt and .45 S&W. A 12-gauge shotgun chambered for 3 in. shells can also fire 2¾ in., 2¼ in. and 1¾ in. shells safely. ****Make certain to read the specific firearms owner's manual or contact the manufacturer to verify exactly what calibers the specific firearm is designed to shoot.*** *From left to right: .460 Smith and Wesson Magnum, .454 Casull, .45 Long Colt, .45 Smith and Wesson/Schofield, 12-Gauge- 1¾ in., 2¼ in., 2¾ in., 3".*

sizes: (5608) ~.216 in. diameter x .112 in. deep, (5620) ~.216 in. diameter x ~.102 in. deep, (6000) ~.249 in. diameter x .112 in. deep, (6504) ~.253 in. diameter x .092 in. deep, and (6507) ~.253 in. diameter x ~.135 in. deep.[2]

- **Rim** – The cartridge case rim is a flange or lip that is located around the case head. The rim's size will vary greatly with cartridge type and intended firearm. The rim serves one main purpose but may also be used for secondary purposes. The primary purpose of the rim is to provide a point of contact for the extractor to remove the empty cartridge case from the chamber after firing. The secondary function of the case rim for some cartridges is headspacing. Another function of the rim for some cartridges is to provide a housing for the priming compound.

  The size of the rim will depend on the type of cartridge and the firearm the cartridge is intended for. There are four basic rim types: rimmed, semi-rimmed, rimless, and rebated rim. Rimmed cartridges feature a pronounced rim that is larger in diameter than the case body, while the semi-rimmed case features a rim that is only slightly larger than the case's body. The rimless case features a rim that is the same diameter as the case body, while the rebated rim case utilizes a rim that is smaller in diameter than the case body.

  Outside of the other possible uses for the rim, extraction (ejection for revolvers) is the primary purpose for every cartridge type. The extractor's claw will grab the rim of the cartridge and, as the action moves rearward (either manually or automatically), the empty (or new) cartridge case will be pulled from the chamber. With revolvers, the ejector will push against the rim, driving the cases from the chamber.

  The case rim can also be used for headspace. The top of the rim will bottom out against a recessed ledge along the chamber face of the barrel (or cylinder), while the bottom of the case head will rest against the breech face/bolt. This arrangement is used only with rimmed and semi-rimmed cases, as rimless and

Figure 17: Rimfire cartridge rims. From left to right (pairs): .22 Winchester Magnum Rimfire, .17 Hornady Magnum Rimfire, .22 Long Rifle, .22 Short.

rebated rim cartridges do not have a large enough rim. Headspacing against the rim allows for variation in case length, permitting use of multiple calibers in a single firearm platform.

With certain case types, the rim serves as a housing for priming compound. Rimfire cartridges utilize a case that uses a rim that doubles as a primer, is used for headspace, and is used for extraction. The inside of the case head and rim is hollow, and priming compound is packed around the inside of the lip. When impacted by the firing pin/striker, the hollow rim will crush the priming material between the walls of the rim and cause it to ignite.

- **Extractor Groove –** The extractor groove is a channel cut into the case body, directly above the case rim. It is designed to provide a relief for the extractor's claw. The extractor groove is found on almost every case type except for most rimmed cases. The extractor groove is not needed on a rimmed case because the rim is already a sufficient diameter to allow the extractor to grab the case. Every other case rim type (semi-rimmed, rimless, and rebated rim) requires an extractor groove to allow the extractor's claw to properly engage the case rim because of their reduced diameter.
- **Belt –** The belt of a case is a raised band along the bottom of the body, just above

Figure 18: Various extractor grooves.

Figure 19: Various belted cases.

Figure 20a: Various headstamps. From left to right: Aguila 12-Gauge, Barrett .50 BMG, Lapua .338 Lapua Magnum, Hornady .458 Winchester Magnum, Federal Cartridge (FC) .308 Winchester, Southern Ballistic Research (SBR) .458 SOCOM, Winchester .40 Smith & Wesson, Armscor Philippines (AP) .22 TCM, Remington-Peters (R-P) .22 Hornet.

the extractor groove. Only cartridges designated as "belted" or "belted magnum" will feature a belt. The belt is designed to provide a "shoulder" to headspace against for large caliber cartridges that do not have a large enough shoulder or cannot headspace against the case mouth.

- There is often some confusion about the purpose of the belt. Some claim the belt is used to strengthen "magnum" cases near the case head. While the added material may slightly increase the case's strength in that specific area, the belt is only designed to provide a point for headspace.

- **Headstamp –** The headstamp is a marking or series of markings that are used to identify the cartridge. The markings may consist of letters, numbers, symbols, or other images. The headstamp markings typically include caliber, manufacturer (sometimes only of the case), location, date of manufacture, features of the cartridge, and lot or batch number. Headstamp markings can be divided

Figure 20b: Military headstamps. From left to right: Lake City (LC) .50 BMG, NATO Lake City 7.62x51mm, NATO Lake City 5.56x45mm, Dornach (D) Altdorf (A) May (5) 1981 (81) 7.5x55mm Swiss, 1980 (8) Export (0) AB Norma Projektilfabrik Amotfors (027) 6.5x55 Swede, Igman Zavod Ad Konjic (Igman Factory at Konjic IK) 1977 7.62x39mm, Plant 21 Romania (21) 1955 (55) 7.62x25mm Tokarev.

Figure 20c: Rimfire headstamps. From left to right: Henry-Winchester (H) .22 BB Cap, Remington (Rem) .22 Short, Aguila (A) .17 PMC Aguila, Hornady (H) .17 Hornady Mach II, CCI (C) .22 Long Rifle Stinger, Remington Arms Co./Union Metallic Cartridge Company (U) 5mm Remington Magnum, Winchester (W) .17 Hornady Magnum Rimfire, Winchester (W) .17 Winchester Super Magnum.

Figure 21: Modified cases. The .375 Reaper case is made by shortening and "necking" up the 7.62x51mm NATO case. The .300 AAC Blackout case is a shortened and necked up 5.56x45mm NATO case.

into two categories: civilian and military. Civilian headstamps will typically feature manufacturer and caliber information, while military headstamps will feature manufacturer/location, date of manufacturer, cartridge features or lot/batch number. Often, the information on the headstamp will be abbreviated so that it can fit on the head of the cartridge. Rimfire cartridges will typically only feature a single marking in the center of the head.

There are some exceptions where the cartridge caliber does not match the headstamp. When a cartridge is modified from one caliber to another, as with wildcat cartridges, the headstamp is not modified. The headstamp will display the old caliber while the cartridge may not be interchangeable. Identifying these cartridges may require measurement and reference to available drawings.

HOW CASES ARE FORMED

Regardless of caliber, case type, or features, forming cases is fairly standard. The major exception would be shotshell cases. All brass cartridge cases and the heads of shotshells begin life as processed, rolled brass (typically 70 percent copper, 30 percent zinc) sheet or "coil." From raw material to finished case requires varying processes and several operations in multiple machines. The steps between manufacturers will vary slightly but the overall process is very similar. Steel and aluminum cases are also formed in a similar manner.[3,4,5]

Figure 22: Brass cups. Photo courtesy of Peterson Cartridge.

Figure 23: Cups after the 3rd draw and trim. Photo courtesy of Peterson Cartridge.

Figure 24: Turned head. Photo courtesy of Peterson Cartridge.

Depending on manufacturer, the sheets or coils may be cut down into thinner strips. The sheets or strips are fed into a machine that stamps out small blanks. Heavy duty carbide dies and hydraulic pressure are used to form the blanks. The blanks will vary but typically consist of either a disk or cup. If a disk is stamped, it is then formed into a cup in a subsequent process. Some machines are capable of stamping a disk and forming a cup in a single process. Most machines will stamp out several disks or cups in a single pass.

The cups are very bulky compared to the final case. The base and walls are much thicker than the finished product, which allows the material to be drawn out or stretched. The mouth of the cup is also very rough from the initial stamping and will need to be addressed at a later step.

At this point, the brass may begin to "work harden" from the processing, which will make the brass hard and brittle. To alleviate the residual stress, the cases are put through an annealing process, which stabilizes the grain structure of the material and brings it back into a malleable state. Although the annealing process softens the brass so it can be worked again, it also introduces oxidizers into the material's surface. These oxidizers leave a very hard surface on the brass that can be harmful to the dies, so it must be removed. The cups are run through a machine that will tumble and clean them, removing the thin layer of oxidation. Moving forward, the cup may be annealed between each process depending on the manufacturer's procedure.

The next step is for the cups to be drawn out. The cup will pass through a series of carbide dies that will begin to expand and lengthen it. This step is often referred to as the "1st draw." After the 1st draw, the cup will be slightly longer and feature thinner walls. The base of the cup may also be slightly radiused. The cup will then go into another annealing treatment, followed by tumbling and cleaning.

Once the cups have been annealed, tumbled, and cleaned, they will go into a second drawing process. The 2nd draw is similar to the first in that the case is stretched farther. Like the 1st draw, the 2nd draw also introduces stresses and hardness into the material that must be relieved. The cup will go through another annealing, followed by tumbling and cleaning.

After the 2nd draw, anneal, and cleaning, the cups will go into a 3rd draw process. By now, the case will typically be drawn to nearly its final diameter and wall thickness (it may be slightly undersized in diameter). The drawing process has stretched the cup beyond the final length of the finished case and requires the extra material to be trimmed. The extra material is often removed in a process known as "pinch" trimming. The cup is trimmed to, or nearly to, its final length.

After the 3rd draw and trim, the cup is cleaned once more. The trimmed cup moves on to the "header" where the case head, primer pocket, rim, and headstamp are all formed over various processes. A fitted die is inserted into the mouth of the cup to hold it as other dies are "rammed" into the base. Depending on the manufacturer and caliber, the head may be formed in a single operation or over several stampings. If multiple dies are used, one die will typically flatten the face of the head and form the primer pocket and rim. A second die, featuring a raised mirror image of the headstamp, will strike the head once more, refining the face and imprinting it with the headstamp marking. With rimfire rounds, the head, rim, and headstamp are often formed in a single operation. After forming the head, the rimfire cartridge is typically ready for priming.

Once the headstamp and primer pocket have been formed, the case will move on to the head turning process. During the head turning step (which may be a single or several processes), the rim is cut to its final diameter and thickness and, if applicable, the extractor groove is cut. A single cutter or multiple profile cutters are used

Figure 25: Various stages of taper, neck, and shoulder forming. Photo courtesy of Peterson Cartridge.

to cut the rim while the case is spun in a type of vertical lathe. Once the head has been fully turned, the cases are annealed, tumbled, and cleaned once more. Rimfire cartridges do not undergo the head turning process. With belted cartridges, the belt is typically formed with the rest of the rim and extractor groove.

After head turning, the process will vary slightly depending on the manufacturer and case type. With some pistol cases, the next steps are typically to punch out the flash hole, perform the final trim, and finally taper the case. With some rifle cases, the next steps include several tapers, followed by a final trim and chamfer. Finally, the flash hole is punched.

With pistol cases, the unfinished case will move to a machine that uses a hydraulic punch to cut the flash hole out of the primer pocket. The press will punch a hole from the primer pocket, through the web, and into the body of the case. This process may be referred to as "venting."

Typically, the next step for pistol cases is the final trim. The case is trimmed one last time to bring it to its final overall length. This is a very important step for some pistol cases because they headspace against the case mouth. The final trim will ensure that these cases headspace correctly.

After being trimmed to size, the case may need to be tapered. Up to this point the body of the case is straight. Depending on the degree of taper, this may be done over a single or several processes. During the final tapering step, the case mouth may also receive a slight flare in preparation for accepting a bullet. Once the case is finished, it will undergo a final tumble and clean.

With rifle cases, the next step after head turning is tapering. The average rifle case features a bottleneck design. In addition to the taper, the neck and shoulder of the case are formed during the tapering process. The taper, neck, and shoulder are typically formed over two to three processes. Each progressive step tapers the case and forms the shoulder and neck slightly so as not to overwork or work harden it. The cases may also go through several annealing treatments between tapering steps. For rifle cases, the tapering process is as important as the final trim for pistol cases because many rifle cases headspace against the shoulder.

After tapering and forming the shoulder and neck, rifle cases go to final trim. The neck of the case is trimmed to the case's final overall length. The neck is typically trimmed by turning it, which also allows the inside of the mouth to be chamfered. The chamfer eases the bullet's seating when the cartridge is loaded.

After final trim and chamfer, the rifle case will move to the "venter," where the flash hole is pierced. From the venter, the case may go through another annealing process, but this time only the neck and shoulder are softened. The case is finished once it has been tumbled and cleaned one final time.

The forming process for shotshell cases varies greatly from other case types.[6,7] The forming of the case head is similar to traditional brass (or steel or aluminum) cases, but that's where the similarities end. The case head and body are made during different operations and joined later in the manufacturing process.

The case head is formed in a similar manner to pistol and rifle brass. The head begins life as a sheet or strip of brass or steel from which blank disks or cups are formed. The head will move through several draw, anneal, and tumble and clean processes, as well as receive a headstamp, primer pocket, and flash hole.

Manufacturing the body of a shotshell will vary based on the material being used. Shotshell bodies are manufactured from two basic materials: plastic and paper. Plastic shotshell hulls begin life as colored high-density polyethylene pellets. The pellets are fed into an extruder, where they are melted and forced through a die, forming a plastic tube. At this point, the tube features very heavy walls and is one continuous piece that spans over 100 ft. as it passes through various machines.

As the tube progresses from the first machine, it will pass through a series of furnaces, mandrels, and cooling baths, which will bring the tube into a pliable state, stretching and cooling it several times. After each pass through a furnace, the heavy walled tube will pass through a machine that will draw out the tube, bringing its internal diameter (ID) and outer diameter (OD) closer to its finished size. By the last heat and stretch cycle, the case body will reach its final dimensions. Once the tube has reached its final ID and OD, the tube will be cut to size in the final machine. These tube blanks will be moved on to another machine that will join the body to the head.

Paper shotshells begin life as a large roll of paper. The paper is cut into strips, which are fed into another machine and made into smaller rolls. The smaller rolls are fed into a machine that cuts the paper into smaller (12 in.) pieces that are rolled into tubes. The paper pieces are rolled around a mandrel and combined with some type of glue or binder. The newly formed tubes are removed from the mandrel and placed into an area where they can dry and cure.

The dried, cured tubes move on to a machine that lubricates and sizes them to their final ID and OD. The tubes are cured once more before moving on to the next step. The tubes are moved to another machine where they are cut down to their final length (2¾ in. – 3 in.). The tubes will then move on to a machine where they are treated once more by soaking them in pressurized, melted wax. From the wax bath, the tubes will need to cure one more time before being joined to the case head.[8]

Regardless of material, once the body is complete and cut to size, it is ready to be joined to the case head. Depending on the manufacturer, this may occur in one of several ways. The head and body may be joined by some mechanical means, be it friction-locked, wedged, molded, or bonded with adhesive. Once the head and body are joined, the case is ready to load.

Chapter 4 - Cases Part 2: Types of Cases, Materials and Coatings

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Types of Cases

Now that there is a basic understanding of case features and construction, we can discuss case types. The case type will vary with its intended purpose and the firearm it is designed for. The case shape and features will vary based on the type of action it is designed to function with.

RIMFIRE

The rimfire case is a simplistic design that combines a cartridge case with priming compound. The rimfire cartridge was the first successful design for a widely accepted/commercial self-contained cartridge. The rimfire case utilizes a hollow rim that accommodates a priming compound. When the case rim is crushed, the priming compound located in the rim will ignite, in turn igniting the propellant in the body of the case. Because of the design of the rimfire cartridge, rimfire cases are typically not reloadable. The rimfire case is designed to work primarily with pistols and rifles.

Originally, the rimfire cartridge case (and black powder) was utilized by a large variety of calibers. Rimfire cases could be found in everything from tiny .17 and .22 caliber cartridges, to large .40 and .50 caliber cartridges. The introduction of both smokeless propellant and centerfire cases made the large caliber rimfire cartridge obsolete. Smokeless propellant pushed chamber pressure to a level beyond the rimfire cartridge case's capacity with larger caliber cartridges. The thin walls of the rimfire case are not typically designed to withstand chamber pressure beyond 26,000 psi (the .17 Winchester Super Magnum is the exception with 33,000 psi).[1] If the rimfire case was designed to accommodate higher pressure, the rim would be too thick to try to reliably crush. Rimfire cases and cartridges are still in current use and production, but are limited to smaller calibers such as the .17 and .22.

CENTERFIRE

The centerfire case utilizes a primer that is a separate part from the case. This allows the case to feature thicker walls to contain greater pressure, while still utilizing a thinner primer cup. The centerfire design also allows the spent case to be reloaded (with most examples). There are centerfire cases that are designed to work with pistols, rifles, and shotguns.

The centerfire design is utilized with a variety of case types and can be scaled to function with a plethora of calibers. The centerfire design can be found in pistol, rifle, and shotgun cases in

Figure 1: Various rimfire cases. From left to right: .22 BB/CB, .22 Short, .22 Long Rifle, .17 PMC Aguila, .17 Hornady Mach II, .22 Long Rifle Stinger, 5mm Remington Magnum, .17 Hornady Magnum Rimfire, .22 Winchester Magnum Rimfire, .17 Winchester Super Magnum.

Figure 2: Various centerfire cases. From left to right: .25 ACP (semi-rimmed, straight wall), .357 SIG (rimless, bottleneck), .45 ACP (rimless, straight wall), .22 TCM (rimless, bottleneck), HK 4.6x30mm (rimless, bottleneck), .50 Action Express (rebated rim, straight wall), .17 Remington Fireball (rimless, bottleneck), .243 Winchester Super Short Magnum (rimless, bottleneck), 6.8mm Remington SPC (rimless, bottleneck), .25-35 Winchester (rimmed, bottleneck), .444 Marlin (semi-rimmed, straight wall), 7.92x57mm Mauser (rimless, bottleneck), 20-Gauge 2.5 in. (rimmed, straight wall), .410 Bore 2.5 in. (rimmed, straight wall), .257 Weatherby Magnum (rimless, belted bottleneck), 12-Gauge 3 in. (rimmed, straight wall), .338 Lapua Magnum (rimless, bottleneck), .458 Lott (rimless, belted straight wall), .408 CheyTac (rimless, bottleneck), 12.7x108mm (rimless, bottleneck).

calibers ranging from .17 caliber to the 20mm cannon (20x102mm) cartridge. The centerfire case design will vary depending on the application it is intended for. The thicker walls of the centerfire case are perfectly suited for smokeless propellant and higher chamber pressure.

Depending on the application, centerfire cases can withstand chamber pressures as high as 65,000 psi (8mm Remington Magnum).[2] Centerfire shotshell cases are designed for fairly low pressure, with some of the higher-pressure cartridges barely reaching 14,000 psi (3.5 in. 12-gauge).[3] Centerfire pistol cases range greatly, with some of the higher-pressure cartridges reaching 65,000 psi (460 Smith & Wesson Magnum/454 Casull).[4] Most pistol cases are designed to withstand pressures in the 20,000 – 30,000 psi range. Most centerfire rifle cases are designed to withstand chamber pressure in the 40,000 – 50,000 psi range.

Unlike the rimfire case, which features a fairly standard design regardless of its intended purpose, the centerfire case will vary with many different features. Centerfire cases can be grouped into four basic types based on the rim design. These cases can be classified even further based on the design of the body. The four basic centerfire case types include:

- **Rimmed** – Rimmed cases feature a rim that is significantly larger in diameter than the case body. The first centerfire cases were all rimmed and remained so for quite some time. The rimmed centerfire case design provides a place for the cartridge to headspace against and a point of contact to remove the spent case from the chamber. With certain actions like lever and pump guns, the rim is used to control feeding into the action.

  Rimmed cases were originally used with single-shot firearms, such as the break- and single-shot bolt-actions. As the development of the repeating action arose, the rimmed case was adopted by the lever-actions and revolvers, as well as pump-actions and repeating bolt-actions

Figure 3a: Various rimmed cases. From left to right: .32 Smith & Wesson, .44 Smith & Wesson Special, .44 Remington Magnum, .17 Hornet, .22 Hornet, .454 Casull, .460 Smith & Wesson Magnum, 8x50mmR Lebel, .45-70 Government, 7.62x54mmR, .303 British, .348 Winchester.

later on. The rimmed case has found great success with these action types and is still in use and production to this day. Almost every modern revolver, lever-action, break-action, and single-shot firearm still utilizes a rimmed cartridge.

Although the rimmed case has found success with many action types, it is limited in use to manual repeating actions and fixed, tubular magazines and revolver cylinders. The rimmed case has found little to no success with semi-automatic actions and detachable magazines. The greatest issue arises when rimmed cartridges are stacked in a box magazine. The first issue is that the cases can only be arranged in a "single stack." Staggering rimmed cases can cause feeding malfunctions. The rims do not allow the cases to sit flat against each other and may cause a condition known as "rim lock." Rim lock occurs when the rim of the top case in a magazine is located behind the rim of the case below it. When the top round is stripped from the magazine, it's rim hits the rim of the round below it and causes the top round to seize in the magazine. Rimfire rounds suffer the same issue when used in vertical magazines.

- **Rimless** – Rimless cases feature a rim that is the same diameter as the case body**.** The lack of rim makes the rimless case better suited for

Figure 3b: Rimmed case cross-sections. From left to right (pairs): .38 Smith & Wesson Special, .357 Smith & Wesson Magnum, .44-40 Winchester, .45 Colt, .30-30 Winchester.

Figure 4a: Various rimless cases. From left to right: .380 ACP, .40 Smith & Wesson, 7.62x25mm Tokarev, 10mm Auto, .300 AAC Blackout, .224 Valkyrie, .17 Remington, .308 Winchester, .270 Winchester, .338 Lapua Magnum, .50 BMG.

semi-automatic applications. Rimless cases can be stacked in single or multiple staggered columns, around the inside of a drum, and connected in the links of a belt. Unlike rimmed cases, the only purpose for the rim on a rimless case is to extract it from the chamber. The lack of rim also requires the case to utilize an extractor groove so that the extractor has ample space to engage the rim.

The modern semi-automatic and automatic firearm would not be possible if it were not for the rimless case. The vast majority of semi-automatic and automatic firearms as well as most feeding devices are designed to work with the rimless case. There are also many examples of single-shot and manual repeating actions being chambered for rimless cartridges. Even revolvers can be retrofitted to use rimless cases (which would

Figure 4b: Rimless case cross-sections. From left to right (pairs): 9x19mm Parabellum, .45 ACP, .22 TCM, .223 Remington, .30-06 Springfield.

Figure 5: Various semi-rimmed cases. From left to right (pairs): .25 ACP, .32 ACP, .338 Marlin Express, .308 Marlin Express, .444 Marlin.

otherwise drop through the cylinder) by using a specialty case holder known as a "moon clip." Rimless cases are utilized almost exclusively by pistols and rifles.

- **Semi-Rimmed** – Semi-rimmed cases feature a rim that is only slightly larger in diameter than the body of the case. The semi-rimmed case was designed as a solution to the issues of feeding rimmed cartridges before the introduction of the rimless case. The small rim requires an extractor groove to allow for clearance for the extractor. The rim may still be used for headspace with some straight-walled pistol cases (.25 ACP and .32 ACP), while the rim may only be used for extraction with bottleneck rifle cases (.308 Marlin and .338 Marlin) that headspace against the shoulder. Although the rimless case design quickly replaced the semi-rimmed case, there are still many current production cartridges, including .25 ACP, .32 ACP, .38 Super, .308 Marlin, .338 Marlin, .444 Marlin and .500 Smith & Wesson Magnum. The semi-rimmed case does not suffer the same fate as rimmed cartridges in semi-automatics because of the marginal size of the rim, and the small bevel on the edge of the rim allows the top case to ride over the rim of the bottom case.

- **Rebated Rim** – Rebated rim cases feature a rim that is smaller in diameter than the body of the case. The rebated rim case is intended to provide more case capacity in a cartridge that would

Figure 6: Rebated rim cases. From left to right (pairs): .50 Action Express, .458 SOCOM, .50 Beowulf, .450 Bushmaster.

Figure 7a: Straight-walled cases with a slight taper.

Outside of the type of rim the case features, the shape of the body can be utilized to categorize the case type. There are four basic body shapes:

- **Straight Wall** – The term "straight-walled" is often used to identify cases that are not bottleneck, belted, or heavily tapered. Although many cases that are classified as straight-walled truly feature straight (parallel) walls, there are many examples that feature a very slight taper. Cases like the .44 Remington Magnum, .380 ACP and 10mm Auto are all considered straight wall cases even though they all feature a slight taper (.04°, .12°, and .14° respectively). All shotshell cases and almost all rimfire cases (except the .22 Winchester rimfire with a .12° taper) are designed with true straight walls. Non-shotshell, non-rimfire cases include .25 Auto, .32 Smith & Wesson, .38 Special, .357 Magnum, .45 Colt, .454 Casull and .460 Smith & Wesson Magnum.

Most straight wall cases are also rimmed. This is mostly a result of the manufacturing process at the time of the case's introduction because tapered cases could

otherwise be too large for a given firearm. The rebated rim design allows a larger capacity/caliber case to be used in a firearm chambered for a smaller caliber without having to modify the action or bolt face (the barrel is typically the only part that needs to be replaced). An example of the rebated case design is the .50 Action Express, which shares a smaller diameter rim with the .44 Magnum. This allows a firearm like the Desert Eagle to swap caliber from .50 AE to .44 Magnum with a simple barrel and magazine swap. Recently, the rebated rim case has found a resurgence with the AR-style rifle platform, allowing larger chamberings like the .450 Bushmaster, .458 SOCOM and .50 Beowulf while still utilizing bolt heads from smaller calibers (the 50 Beowulf and 7.62x39 share the same rim diameter of .445 in.).

Figure 7b: Straight wall rimfire and shotshell cases. From left to right: .22 Short, .22 Long Rifle, .410 Bore, 20-Gauge, 12-Gauge.

Figure 7c: True straight wall cases. From left to right: .25 ACP, .32 Smith & Wesson, .38 Smith & Wesson Special, .357 Smith & Wesson Magnum, .45 Long Colt, .454 Casull, .460 Smith & Wesson Magnum.

not be manufactured reliably. Most cases intended for revolvers are also straight-walled. Straight wall cases are less likely to experience "setback," which is a condition where the case backs out of the cylinder during recoil, causing the action to seize. Straight-walled cases help to alleviate this issue with the increase in friction the case experiences with the walls of the chamber.

- **Tapered –** The tapered case design features a body that is larger near its base and narrower near the case mouth. The tapered case design was developed to assist in case extraction. The tapered case is less likely to stick in the chamber than a straight-walled case because the tapered shape will experience less friction when exiting the chamber. Unlike a straight-walled case that will drag the length of the case as it is pulled from the chamber, the taper case will release

Figure 8: Tapered cases. From left to right: .223 Remington, 9x19mm Parabellum, .22 Hornet, .300 H&H Magnum, .22-250 Remington, .250 Savage, .348 Winchester, 7.62x39mm.

almost immediately, depending on the degree of taper.

Cases that were originally designed to be made from steel will typically feature a greater taper. Steel will not contract as much as brass after firing, so the case design must account for the added friction. Cases that are made of steel but were not originally designed so may experience a greater chance of sticking in the chamber because of the lack of a sufficient taper.

Case taper may be slight, like the .223 Remington/5.56x45mm NATO and its 1° tapered body. One of the most heavily tapered cases is the 7.62x39 with a 2.7° taper. Other tapered cases include the 9x19mm Parabellum (1.14º), .22 Hornet (1.58º), .300 H&H Magnum (1.92º), .22-250 Remington and .250-3000 Savage (2.3º) and the .348 Winchester (2.46º).

- **Bottleneck –** The bottleneck case design features a body of a larger dimension than the diameter of the projectile. The diameter of the body will taper (the shoulder) down to the neck, which provides greater case capacity for a given caliber. The bottleneck case is also known as an "overbore" design, meaning the case volume is greater in relation to the bore diameter. The bottleneck case is designed for high pressure, high velocity cartridges over a vast range of calibers. The bottleneck design revolutionized small arm ballistics by providing flatter trajectories than anything before it.

  With all things being equal (caliber, bullet weight, and case length), a bottleneck design will produce higher velocities than a straight-walled or tapered case because of the increase in case volume. Bottleneck cases are not limited to rifle calibers either; there are many pistols that are chambered for high velocity bottleneck cartridges. The body of the bottleneck case will almost always feature a slight taper (1° – 2°) leading up to the shoulder to assist with extraction because most bottleneck cases are quite long. The bottleneck design can be found in rimfire, rimmed, semi-rimmed, rebated rim, and belted cases in calibers from .17 to .50.

  The design of the bottleneck case will vary by caliber. The case may feature a body that is much larger than the neck diameter, like with the .223 Winchester

Figure 9a: Bottleneck cases. From left to right: .17 PMC Aguila, .32 NAA, .357 SIG, .400 Corbon, HK 4.6x30mm, .300 AAC Blackout, .375 Reaper, .224 Valkyrie, .223 Winchester Super Short Magnum (WSSM), .243 WSSM, .25 WSSM, .17 Remington, .338 Marlin Express, .35 Remington, .303 British, .270 Winchester, .338 Lapua Magnum, .300 Weatherby Magnum, .375 H&H Magnum.

Figure 9b: Bottleneck case cross-sections. From left to right (pairs): 7.62x25 Tokarev, 5.7x28mm FN, .458 SOCOM, .22-250 Remington, .308 Winchester, 7.92x57mm Mauser, .300 Winchester Magnum, .50 BMG.

Super Short Magnum (WSSM), .243 WSSM and .25 WSSM, or the body may only be slightly larger, like with the .300 AAC Blackout, .375 Reaper and .35 Remington. Other bottleneck designs include the .50 Browning machine gun (rimless), .300 Winchester Magnum (belted), .303 British (rimmed), .338 Marlin (semi-rimmed), .458 SOCOM (rebated rim), 5.7x28mm FN (rimless rifle/pistol), 7.62x25 Tokarev (rimless pistol) and the .17 Aguila (rimfire).

- **Belted** – The belted case design features a band of material above the extractor groove used to headspace against. The belted case is often associated with high power, "magnum" cartridges, with the misunderstanding being that the belt adds significant strength to the case. The only purpose of the belt is for headspace. Although all belted cartridges are very powerful, there are more powerful cartridges that do not utilize a belt.

  The belt was introduced as a design feature for large caliber, straight wall (non-bottleneck) cases where headspacing off of the case mouth would be too dangerous. The fear was that the straight-walled case mouth could slip forward of the ledge inside the chamber and cause an excessive headspace issue. The belted case can now be found in both tapered and bottleneck cartridges. Belted bottleneck cases will still headspace against the belt. One of the original belted cartridges, the .375 Holland & Holland, became the parent case for many others, including the .458 Lott, .300 Weatherby Magnum, .300 Winchester Magnum, .257 Weatherby Magnum, .450 Marlin, and 6.6mm Remington Magnum.

Figure 10a: Belted cases. From left to right: .450 Marlin, 6.5mm Remington Magnum, .300 H&H Magnum, .300 Weatherby Magnum, .458 Lott, .375 H&H Magnum.

Figure 10b: Belted case cross-sections. From left to right (pairs): .458 Winchester Magnum, .257 Weatherby Magnum, .300 Winchester Magnum.

CASE CAPACITY

Case capacity is a measure of the volume inside the case's body, from the web to the mouth. A case with greater capacity can hold more propellant and produce more energy. Case capacity is measured in grains of water, which gives an accurate measure of the total volume inside the case but does not represent the amount of propellant the case will hold. Some of the case volume is consumed by the projectile and in the case of shotshells, wads and fillers. The remaining volume is not filled completely with propellant; there is typically a small amount of "air space" or empty space to allow for room for expanding propellant gas.

Case capacity can be affected by several factors. Assuming various cases utilize the same caliber projectile, bottleneck cases will have a greater capacity than tapered cases, which have a greater capacity than straight-walled cases. Cases of the same caliber may feature slightly different capacities because of variations between different manufacturers. Even inconsistencies between case wall thickness in cases from the same manufacturer can affect capacity. Brass designed for military use will often feature thicker walls. Because of the dimensional restrictions on the outside of the case, the added material is typically internal, meaning less case capacity.

Inconsistencies in case capacity can have an adverse effect on chamber pressure, pressure curve, velocity, and precision. For example, two cases with the exact same bullet weight, seating depth, and propellant charge, but with different capacities, will produce different results. The case with the smaller internal volume will experience a greater peak chamber pressure with a pressure spike sooner in the pressure curve, as well as produce higher velocities. The case with the greater internal volume will experience a lower peak chamber pressure, with a pressure spike farther along the curve and producing lower velocities. The reason for this is the propellant gas will lose pressure the more it expands; a greater internal volume will allow the gas to expand more.

Figure 11a: Various case capacities. From left to right: 7.65mm Browning Short 60 grain AP, .22 Long Rifle 36 grain hollow point, 9x19mm Parabellum 50 grain hollow point, .357 SIG 125 grain CMJ, .45 ACP 138 grain frangible, .17 Hornady Magnum Rimfire 17 grain hollow point, 5.7x28mm FN 40 grain polymer tipped, .458 SOCOM 335 grain hollow point, .300 AAC Blackout 110 grain polymer tipped (Supersonic), .300 AAC Blackout 212 grain polymer tipped (Subsonic), 5.56x45 NATO 62 grain AP, 12 Gauge 2¾ in. 1¼ oz. #6 Birdshot, .444 Marlin 225 grain hollow point, .410 Bore 3 in. ¼ oz. slug, 7.62x51mm NATO 155 grain AP, .257 Weatherby Magnum 115 grain OTM, .458 Winchester Magnum 500 grain FMJ, .50 BMG 750 grain aluminum tipped.

Figure 11b: Case capacity of commercial versus military brass.

Figure 12: Brass cartridge cases.

Case Materials

Cartridge cases are typically made from brass but can be found in a variety of different materials. Materials are chosen for their performance, attributes, workability, availability, or cost. Some cartridges may even use multiple materials to form the case. The various materials include:

- **Brass** – Brass is the most common material used in the construction of cartridge cases (and shotshell case heads), for several different reasons. Brass (in conjunction with a steel chamber) is capable of withstanding chamber pressures as high as 65,000 psi, providing great strength without being brittle. Brass is ductile enough to withstand the plastic (permanent) deformation the case undergoes when the cartridge is discharged and also exhibits elastic (temporary) deformation to a small degree when the expanded case contracts to nearly its original size. Brass will expand to seal the chamber and contract slightly to aid in extraction. The malleability of brass makes it very easy to work, turning flat disks into cases through a series of drawing steps. This is the reason the first metallic cartridges were all made from brass. Brass is also softer than steel. The soft brass case will not scratch or otherwise damage the steel chamber or extractor. Brass will not rust, but it may tarnish and, in severe instances, corrode.

Brass (Boxer primed) cases are also the only case type that are reloadable. The malleability of brass allows for multiple resizing and discharging cycles without compromising the integrity of the case. One of only a few drawbacks of brass is that it will work-harden after a few (to several, depending on caliber) reloads. Often, the work-hardening can be alleviated by annealing the brass. The brass case will eventually go through enough discharging and reloading cycles that the case walls will become too thin and fail or the case will become too brittle and crack.

A few downsides to the brass case are cost and heat. Brass-cased ammunition is typically more expensive per round than steel- and aluminum-cased ammunition. Although the manufacturing process is fairly similar, the cost of raw materials is much higher. The price of the case will also go up with the quality of the case. Mass produced, military, and bulk cases will cost less than cases manufactured with tighter tolerances.

Brass is also a very good thermal conductor.[5] During discharge, some of the energy from the expanding propellant will be transferred to the case in the form of heat. The case acts as a heat exchanger, transferring heat from the discharging cartridge to the chamber of the firearm. The exchange of heat is not an issue when only firing a few rounds per minute. The issue arises during sustained fire, rapid fire, and automatic fire. Excessive heat in the chamber can cause premature wear on the throat of the barrel. With some closed-bolt machine guns, excessive heat in the chamber can lead to a condition known as "cook off," where the round in the chamber is heated to the point where the propellant in the case will automatically ignite (auto-ignition) without the primer being struck.

- **Steel –** Steel has been used as a viable substitute for brass for over 75 years. The primary reasons steel would be used for cartridge cases instead of brass are cost and availability. Steel is more cost effective as a raw material for case manufacturing and is more likely to be available during war time resource shortages. This

Figure 13: Steel cartridge cases. From left to right (pairs): .380 ACP, 9x19mm Parabellum, 7.62x39mm, 5.45x39mm, 5.56x45mm NATO, .308 Winchester.

was especially true of European and Asian countries during WWI, WWII, and later, where brass was too expensive or not available.

As a case material, steel is stronger than brass, which makes it more than capable of withstanding extreme chamber pressure. Steel will experience more plastic deformation than brass as the case expands to seal the chamber, but will exhibit less elastic deformation as it will not contract as much as a brass case. Because steel is harder than brass and does not contract as much as a brass case, steel cases may create more wear on the extractor during extraction than a brass case would. The wear from steel is greater with cases that were not originally designed to be made from steel, like the .223 Remington or the .45 ACP. Steel does not conduct heat nearly as efficiently as brass, causing the case to stay hotter (and in turn, expanded) longer than a brass case.

While the manufacturing process for steel cases almost mirrors brass, steel will wear drawing dies more than brass. While steel may not be as easily workable as brass, the use of a very mild (low carbon) steel ensures it will not be overly hard or brittle. Steel cases also cannot typically be reloaded because they are manufactured by European and Asian countries where Berdan primer is primarily utilized. Many indoor ranges do not allow steel-cased ammunition because the range cannot sell the cases as scrap or reload them for resale. Unlike brass, steel will rust and corrode. This is why the majority of manufacturers will plate or coat the case to protect it from the elements. Steel case coatings include brass, copper, lacquer, and polymer. These coatings also protect the chamber from the steel case.

Figure 14: Aluminum cartridge cases.

- **Aluminum** – Aluminum is also used as a cost-effective substitute for brass. The cost of raw materials for aluminum cases is much lower than brass cases and does not fluctuate as much with market changes. Aluminum also has the benefit of being much lighter than brass, weighing only about a third as much. This may not seem like an advantage for the average civilian firearm owner, but for police and military applications, where they must carry several pounds of gear and ammunition, the weight savings really makes a difference.

  The downsides of the aluminum case are several. First, aluminum is not as strong as brass or steel.[6] Aluminum has a lower yield strength than other case materials and is not nearly as ductile. When an aluminum cartridge is fired, the case will expand to seal the chamber but will not contract as much as brass or steel. This is why aluminum cases are reserved for low pressure pistol applications. Another reason why aluminum is not used for high pressure or rifle applications is because of its relatively low melting point compared to brass or steel.[7] The stress from firing also makes the case weak and brittle, which prevents aluminum cases

Figure 15: Polymer hybrid cases.

from being reloadable. Aluminum does feature the benefit of not rusting, is fairly corrosion resistant, and does not require any additional coatings.

- **Hybrid-Metal/Polymer/Composite –** A hybrid cartridge case utilizes two dissimilar materials in its construction. The hybrid cartridge case design is not some "cutting edge" or "futuristic" concept. In fact, the hybrid case has been around for almost 150 years in the form of the paper shotshell.[8] The paper shotshell utilizes a paper (tube) body and a brass head. The modern version of the hybrid case, the plastic shotshell, has been around since the early 1960s. Like the paper shell, the plastic shell utilizes a plastic (low density polyethylene LDPE/high density polyethylene HDPE) tube body and a brass (or brass plated steel) head. The body may be joined to the head mechanically, bonded to the head with adhesive, or molded to the head during the injection molding process.

Although the hybrid plastic case has found great success with shotshells, which are fairly low pressure, hybrid rifle and pistol cases have not. Over the past few decades, many companies have tried to bring a polymer hybrid case to fruition with little to no success. The biggest issue with plastic cases has always been the type of polymer used. Either the material was too soft and could not contain the pressure or would melt, or the material was too hard and brittle, causing cases to crack or split. Within the past few years, many companies have introduced polymer cased ammunition in an attempt to evolve the traditional metallic cartridge. Advances in material and manufacturing have made the polymer hybrid case viable, but much of the concept's stigma has followed through with these new designs. Like the shotshell, polymer-cased ammunition also utilizes a polymer/composite body and a metallic head.

While many of the companies producing hybrid polymer casings are only filling military and law enforcement contracts, a couple have begun sales to the civilian market. Much of the advantage of the polymer hybrid case is not realized by the civilian market. For military and LE, the advantages are many. The greatest advantage of the polymer hybrid case is weight savings.[9] The polymer cartridge weighs between 30 percent and 40 percent less than a traditional brass cartridge, which means soldiers can carry more ammunition or more gear. The weight savings is also advantageous for vehicle and aircraft mounted weapons, allowing them to carry more ammunition or conserve fuel from the reduced mass. The weight savings is also beneficial when transporting pallets of ammunition to the battlefield, allowing more ammo to be carried or less fuel wasted.

Other claimed advantages of polymer hybrid ammunition include signature reduction (heat and flash), increased accuracy and precision, corrosion resistance and recyclability. Unlike a brass case, which acts as a heat sink or heat exchanger, the polymer hybrid case acts as an insulator.[10] Instead of the burning propellant transferring energy (in the form of heat) to the case, the insulating properties of the polymer case allow the propellant to burn more efficiently. The body of the polymer hybrid case can also be manufactured more consistently to a tighter tolerance than a brass or other metal case. This means the internal volume and neck tension is more consistent from case to case. An efficient, consistent burn rate coupled with a more consistent case manufacturing process will lead to more consistent velocities, which will lead to greater precision. Another advantage of the polymer case manufacturing process and the ability to control internal volume is that case volume can be reduced for subsonic loads, removing unneeded empty space.

The polymer/composite hybrid case also has the benefit of being rust and corrosion proof. This means cartridges can be stored for a greater amount of time without worry of degrading (as long as the metal head of the case is properly coated). Polymer hybrid cases can also be dyed to help identify the type of bullet/load being used (ball, tracer, AP). Some cases can even be recycled, making the polymer hybrid case environmentally friendly.

Another type of hybrid case has been introduced recently: the metal-metal hybrid. The metal hybrid case, like the polymer hybrid pistol/rifle case, has been a bit of an obscurity in the past that never really went mainstream. Previous incarnations featured a two-piece brass

Figure 16: Metal hybrid cases.

body and steel head that screwed together.[11] Other designs have been introduced for military use or have undergone military trial to replace brass-cased ammunition, but none have been adopted yet.[12] Recently, one design has begun to gain ground in the race to replace brass. [13]

Utilizing a nickel/stainless alloy body and a nickel plated aluminum case head provides many actual and some claimed benefits over the traditional brass case. First, is weight savings and strength. The use of aluminum allows for a lighter case, while the alloy body provides greater strength than brass or steel. The manufacturing technique also allows for a case with greater capacity at a cost less than or comparable to bulk brass. Because nickel and stainless do not conduct heat as much as brass, the case and chamber stay cooler, and the propellant is burned more efficiently.

Case Coatings

Case coatings are used primarily to prevent cases from rusting, corroding, or tarnishing. Coatings can also be used to improve feeding and extraction. Steel cases are primarily coated, but coatings can also be found on brass (or hybrid) cases. The various case coatings include:

- **Lacquer/Polymer –** Lacquer and polymer are both used on steel cases to protect the case from rust and corrosion. Originally, steel cases were coated with lacquer, which is a natural resin mixed with alcohol. Polymer was introduced as an alternative to lacquer and has nearly replaced lacquer in popularity. There are situations where both lacquer and polymer case coatings will "gum up" a hot chamber and cause cases to stick. The issue arises because steel cases will not expand as much as brass and will allow a small amount of gas blowback past the case into the chamber. When the firearm is neglected, the carbon buildup will cause cases to stick. Additionally, the case can heat up to the point where the lacquer melts and adheres to the chamber walls. Over time, these layers will build up and will make feeding, chambering, and extracting more difficult. This is especially true of cartridges that were not originally designed to be manufactured from steel (like the .223 Remington).
- **Nickel/Copper/Brass –** Nickel, copper, and brass are all used to plate brass and steel cases. Nickel is primarily used on brass cases, while copper and brass are used on steel. Nickel is used as more of a performance case coating on brass. Nickel is used to prevent brass cases from tarnishing or corroding as well as to make the cases "slicker." Nickel has a lower coefficient of friction than brass, which makes the cases feed and eject more easily. Nickel plated brass cases also feature the advantage of still being reloadable. Brass and copper are used to plate steel cases to prevent them from rusting or corroding.

Figure 17: Lacquer and polymer coated steel cases.

- **Black Oxide –** Black oxide is a surface conversion coating used on brass cases. Black oxide is used primarily as an aesthetic coating or for marketing hype, but also provides some corrosion resistance. Unlike lacquer/polymer, nickel, or copper/brass, black oxide does not add any material thickness to the case.

Figure 18: Nickel plated brass cases.

Figure 19: Copper and brass plated steel cases.

Figure 20: Black oxide coated cases.

NOTES

NOTES

Chapter 5 - Propellants: History, Type, Burn Rate and Charges

Figure 1a: Smokeless powder.

Propellant

Propellant is the fuel or "energy" of the cartridge. When the propellant is burned, the solid fuel is converted into rapidly expanding gas (sublimation). This high pressure gas forces the projectile from the case and through the bore of the firearm. Depending on the cartridge, the propellant can produce high pressure gas ranging from 12,000 to 65,000 psi, driving a projectile between 700 and 4,000+ fps.

Modern smokeless propellant is often misidentified as gunpowder or "black" powder. Although both modern black powder and smokeless propellant are used in some current production firearms and cartridges, they differ significantly. Modern smokeless propellant and gunpowder are not the same and are often not interchangeable. The major difference between smokeless and black powder is that black powder will burn at the same rate whether confined or not.

Figure 1b: Smokeless propellant.

Smokeless propellant will only burn at a high rate when confined and pressurized.[1] Smokeless propellant is also about 3X to 4X more powerful than black powder (of the same weight/volume) and produces significantly less smoke and fouling when burned. Black powder is also a "powder," while smokeless propellant is made up of granules.

A BRIEF HISTORY

Gunpowder, or black powder, changed the landscape of the world and the way wars have been fought for over 1,000 years. Chinese alchemists accidentally created the first known chemical explosive in the mid-9th century while trying to create an elixir of youth.[2] Originally, black powder was a composition of saltpeter (potassium nitrate KNO3, ~75 percent), sulphur (~10 percent), and charcoal (~15 percent), but the ratios and formula have changed over time. Black powder is classified as a low explosive because of the characteristics of its burn rate.

To create fire or combustion you need three things: fuel, oxygen, and a spark. With black powder, the sulphur and charcoal are used as fuel, while the saltpeter is used as a solid chemical oxidizer (consisting of one molecule of potassium, one molecule of nitrogen, and three molecules of oxygen). The spark came from direct flame, punks, rudimentary fuses, or pieces of flint. Black powder was used as a propellant and explosive for "firearms," rockets, cannons, mortars, grenades, and other implements of war for over a millennium and still finds some use with modern black powder breech and muzzleloaders as well as some black powder cartridges.

Along with being both impact and shock resistant, black powder is also hygroscopic, meaning it is efficient at absorbing water.[3] If black powder is not properly stored, the powder will absorb moisture from the air. This may cause the powder to fail to ignite or burn erratically. Outside of the white smoke that is produced when burning, black powder also burns very dirty (leaving the bore with contaminates and fouling) and is corrosive.

Through the years, attempts were made to improve and refine the formula for black powder, but despite the advances in design, the core mixture remains fairly original. Sources and processes for raw materials were standardized to ensure consistency between batches, and materials have been refined for purity, but the basic formula has remained unchanged. Even the techniques used to process raw materials and form kernels improved (rolling kernels in graphite to reduce hygroscopicity), but the base product remained the same.

The introduction of the self-contained cartridge and conical bullets necessitated a new fuel that would push these "modern" projectiles farther. Black powder is fairly inefficient, with 45 percent – 55 percent of its output being inert solids (smoke and fouling) that have nothing to do with the propulsion of the projectile.[4] It wasn't until the mid-to-late 19th century that we began to see the beginning of a suitable replacement for black powder. In the mid-19th century, two European chemists (one Italian and one Swiss) invented nitroglycerine and guncotton/nitrocellulose, respectively, both of which would lead to the next successful firearm "fuel."[5] Nitroglycerine is a high explosive created by nitrating glycerol, while guncotton is a highly flammable substance created by nitrating cellulose (cotton).

These new substances were found to burn cooler, cleaner, and produce more gas volume (and in turn, pressure) per original mass than black powder, but both guncotton and nitroglycerine were found to be too powerful and unstable and not suitable for small arms propellant. Near the end of the 19th century (~1884), a French chemist named Paul Veillie created what would become the first single base smokeless propellant.[6] By treating the guncotton with alcohol and ether, Veillie discovered he could stabilize the compound, which was gelatinized, rolled into sheets, and cut into flakes. Veillie called his new propellant Poudre B. Poudre B is made up of 68.2 percent insoluble nitrocellulose and 29.8 percent soluble nitrocellulose gelatinized with ether and 2 percent paraffin.

A few years later, Alfred Nobel discovered he could improve upon Veillie's formula by combining guncotton and nitroglycerine. Nobel called his formula "Ballistite," which became the first double base smokeless propellant. Ballistite, with its added nitroglycerine, was even more powerful than Poudre B. Ballistite is made up of 45 percent nitroglycerine, 45 percent nitrocellulose, and 10 percent camphor.

Shortly after, the British government obtained samples of both Poudre B and Ballistite for testing but concluded they were not suitable for their application. Two British chemists, Frederick Abel and James Dewar, discovered a method of dissolving a mixture of nitroglycerine, guncotton, and petroleum jelly in acetone to create a paste that could be pressed through a die and formed into strings. The new propellant was appropriately named "Cordite."

Figure 2: Poudre B.

Figure 3: Cordite.

The original formulation of Cordite (Cordite MK I: 58 percent nitroglycerine, 37 percent guncotton, 5 percent petroleum jelly) proved to be very corrosive on chambers and bores so it underwent a slight formula change to reduce its corrosiveness. Cordite MD (modified) was introduced (65 percent guncotton, 30 percent nitroglycerine and 5 percent petroleum jelly) and proved to be easier on barrels. During WWI and WWII, Cordite also saw several new formulations: Cordite RDB, SC, and N, the latter being the first triple base smokeless propellant. With Cordite N, guncotton and nitroglycerine were mixed with another explosive, nitroguanine. Unlike black powder, Cordite (and most modern smokeless propellants) will only burn rapidly when contained in a pressure vessel like a cartridge or chamber/bore. Outside of containment, Cordite will burn very slowly and uneventfully.[7]

Near the end of WWII (~1945), Cordite began to fall out of favor as a new generation of propellants began to gain popularity. During WWI, several new powders were developed in an effort to replace Cordite. The Dupont company introduced a new line of smokeless propellants they dubbed IMR (Improved Military Rifle) powders. These propellants are nitrocellulose based (single base) but include several additives to control burn rate (dinitrotoluene, DNT), stabilize (diphenylamine) and reduce muzzle flash (potassium sulphate). During the manufacturing process, the mixture is extruded, forming

Figure 4: IMR propellant.

Figure 5: Ball propellant.

small sticks. This is why IMR got the nickname "stick" powder. IMR has been manufactured in a variety of formulations and sizes.

In the early 1930s, a new process reshaped the manufacturing of smokeless propellant as well as the grain itself. Unlike the extrusion process that forms sticks that fall into a tray, the new process dripped the propellant mixture into water. As the droplets move through the water they are shaped by other droplets, which form them into balls or spheres.[8] This new propellant was appropriately named "ball" powder. This new propellant not only changed the way propellant was manufactured, but also made the process much safer because most of the process is under water.

Ball propellant is double base, consisting of both nitrocellulose and nitroglycerine. When formed, the droplets only consist of nitrocellulose. The nitroglycerine is added after the grains are formed and dried through surface impregnation. DNT or other similar substances may also be used to control burn rate. Ball propellant didn't gain popularity until the 1950s, but can now be found in a variety of formulas and sizes.

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Types of Propellant

Modern propellants haven't really changed much in the past 100 years. They are still mostly nitrocellulose and nitroglycerine based and are manufactured in much the same way as they were a century ago. The biggest change to modern propellants is the additives. These additives are designed to control the propellant's burn rate, provide longterm stabilization, reduce the amount of fouling and reduce the signature of the shot (in the form of flash and smoke).

Before discussing the various types of propellants, we need to briefly cover one of the characteristics of propellant: the burn rate. The burn rate is a product of the composition of the propellant, its additive and stabilizers, and the shape of the individual granules. Controlling burn rate is extremely important for the safety of the operator. Too rapid of a burn rate and the firearm becomes a grenade. Pairing the correct burn rate with a specific cartridge or firearm will ensure the combination is safe to use and provides the best possible performance.

EXPLOSIVES VS. PROPELLANTS

To understand propellant burn rate, you must first understand the difference between an explosive and a propellant. The major difference between the two is the speed at which the reaction propagates, meaning how fast each kernel burns and how quickly each adjacent kernel is ignited. A reaction wave that propagates faster than the average speed of sound (1,125 fps) or is supersonic is known as detonation. A reaction wave that propagates slower than the speed of sound or is subsonic is known as deflagration. Although all the base explosives utilized by various propellants (nitrocellulose and nitroglycerine) detonate at supersonic speeds (23,000+ fps and 25,000+ respectively), the manufacturing process and various chemical additives (retarders) slow the reaction dramatically.[1]

While modern propellant is designed to deflagrate under pressure, too much pressure may cause the velocity of reaction propagation to increase, possibly detonating. A detonation of a cartridge inside a firearm is possible and would be catastrophic and could potentially cause injury (or worse) to the operator. Bullet setback, an overcharged cartridge, the incorrect propellant type, or squibs can also lead to a situation where a pressure spike can destroy a firearm.

BURN RATE

All propellants are not created equal. Some propellants are meant to burn quickly, and some are designed to burn at a slower rate. The differences may only be measurable in milliseconds, but when you are dealing with a buildup of 50,000+ psi, the difference is very important. There is a huge variety of propellant types, with each manufacturer producing many different types for pistol, rifle, and shotgun cartridges. Modern propellants can be classified into two basic types and three basic shapes, all of which have a different burn rate. Manufacturers will classify propellant types even further by burn rate (fast and slow) and will typically publish a list of propellants from fastest to slowest. Both the type and shape of the propellant, along with a variety of additives, are designed to control burn rate.

The composition of the propellant is one major factor affecting burn rate. Explosive base reaction propagation will vary depending on the base used, as well as the amount of energy (pressure) and byproducts (smoke, carbon, fouling). Additives will also alter the reaction propagation, producing varied byproducts. The two propellant types are organized by the base(s) they utilize. The two types of propellants include:

Single Base – A single base propellant only utilizes one explosive compound in its formula. With single base propellants, the explosive base is typically nitrocellulose (guncotton). Single base propellants will also contain other additives used to control burn rate, provide stabilization, reduce fouling, and bind all the various chemicals. Because of the exclusive use of nitrocellulose, single base propellants tend to burn slower than double base propellants. Single base propellants will typically create a pressure curve that quickly peaks before plateauing and gradually falling off. Single base propellants tend to burn cleaner (less fouling) and cooler than double base propellants and are affected less by ambient temperatures.

Double Base – A double base propellant utilizes two explosive compounds in its formula. With double base propellants, the two base materials are nitrocellulose and, typically, nitroglycerine.[2] Other explosive bases may include nitroguanidine, bis-nitroxyethylnitramine (DINA), tetramethylolcyclopentanone tetranitrate, diethylene glycol dinitrate (DGN), acetyl cellulose, dinitroethylenglycol and dinitrotoluene. The addition of a secondary base increases a double base propellant's energy output as well as its burn rate. Double base propellants tend to burn much quicker than single base propellants. Double base propellants will typically produce a pressure curve that immediately peaks and then rapidly falls off. The second base also makes double base propellants burn hotter and produce more fouling. Like single base propellants, double base propellants also utilize additives to control burn rate, provide stabilization, reduce fouling, and bind all the various chemicals.

Additives – Propellant manufacturers utilize additives to control many aspects of the propellant's reaction. Some additives are used as preservatives or stabilizers to prolong the useful/safe life of propellants. Deterrents, moderants, and retarders are used to slow the burn rate of certain propellants. Plasticizers are used to protect the shape of the grain from breakage. Other additives act as detergents, removing fouling or copper deposits from the bore. Other additives are used to reduce muzzle flash and reduce wear on the throat and bore of the firearm.[3]

Nitrocellulose based propellants may break down over time due to an abundance of residual nitric acid leftover after manufacturing the guncotton. This deterioration could lead to an unstable material that could lead to spontaneous combustion. Stabilizers are used to slow down

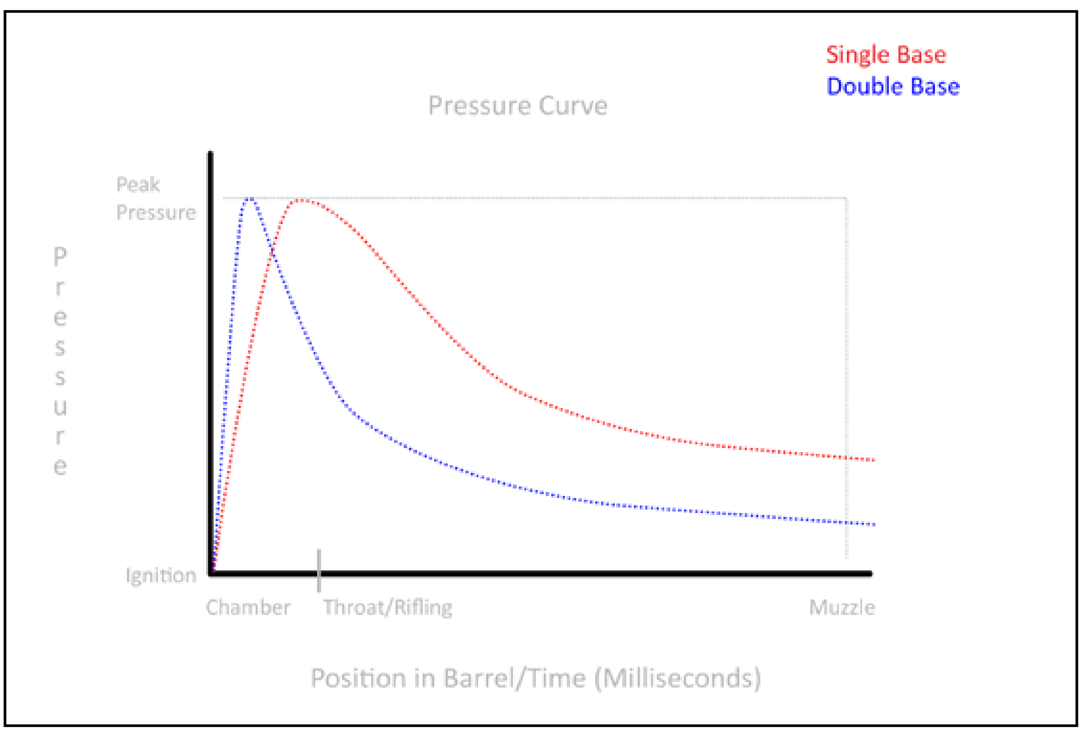


Figure 6: Single base vs. double base pressure curves.

the decomposition of the propellant. Single base propellants are more prone to degradation than double base propellants. Single base propellants utilize acetone or ethyl alcohol in their mixture, which is more volatile than nitroglycerine and therefore more likely to dissipate. When these compounds begin to deplete, the propellant will begin to deteriorate and may become unstable. Some compounds used as stabilizers include diphenylamine, petroleum jelly, calcium carbonate, magnesium oxide, sodium bicarbonate, and beta-naphthol methyl ether.

Pure nitrocellulose and nitrocellulose/nitroglycerine compounds alone burn too quickly to be safely used as propellants. Deterrents/moderants are utilized to slow the burn rate of both single and double base propellants. Modifying the burn rate of a propellant allows the manufacturer to tune the propellant for the best possible performance for a given caliber. Slowing the burn rate of a propellant allows it to create steady pressure for longer. Deterrents may be layered on the grain to prolong its burn rate even further. When the granule is ignited, the outer layer of deterrent is burned (slowly) first until the layer of nitrocellulose or nitroglycerine is reached. The kernel will then begin to burn more rapidly until reaching the next layer of deterrent. This process will continue until the whole granule has been consumed.

The consistency of the burn rate from granule to granule is dependent on the size of each kernel. Granules of the exact same shape and size will burn at the same rate. Granules that break or are crushed produce smaller pieces with greater surface area that burn faster than the complete granule. If too many of the propellant granules are crushed or break, it can cause a pressure spike that could be catastrophic. Plasticizers are used to reduce the brittleness of the individual grains of propellant. Plasticizers also reduce the need for solvents that may dissipate and cause the propellant to decompose.[4] Various plasticizers include di-normal propyl adipate (DNPA), diethyl phthalate, dibutyl phthalate, triacetin (glyceryl triacetate) nitroglycerine, dinitrotoluene, and ethyl centralite.[5]

Detergents are used to prevent and remove copper fouling and carbon buildup inside the bore. For every round fired, carbon and other solid waste byproducts are deposited in the bore as a result of the reaction of the propellant burning. The friction the projectile experiences as it is forced through the rifling, down the bore, can lead to a small amount of copper being deposited (galling) on the rifling. Adding certain compounds to the propellant can prevent this buildup from sticking to the bore, which will be "wiped" away by the next shot. Using materials like bismuth or various bismuth compounds will remove copper buildup in the bore. Copper dissolves in molten bismuth, which leaves a very brittle alloy that is easily wiped from the bore by the following shot. Other detergents include tin, tin dioxide, bismuth trioxide, bismuth subcarbonate, bismuth nitrate, and bismuth antimonide.[6]

Flash reducers are used to lessen the amount of flash that is seen from the muzzle of the firearm. The same way smoke produced from black powder marked a soldier's position during battle, muzzle flash can also give a soldier's position away. One drawback to using a flash reducer is the slight increase in smoke. Various flash reducers include potassium chloride, potassium nitrate, potassium sulfate, and potassium hydrogen tartarate.[7]

The last types of additives that may be used in modern propellants are wear reducers. These are typically solid lubricants designed to reduce friction as the bullet is pushed through the bore. Wear-reducing additives include wax, talc, titanium dioxide, ethyl acetate, rosin, and graphite.[8]

Outside of composition, the shape and density of the propellant plays a vital role in burn rate. The size and shape of the propellant directly control the rate at which pressure is released. When propellant is burned, the reaction (sublimation) will only occur along the exposed surface of the granule. If the surface area of the grain is increased (or decreased), the rate of the reaction (and pressure release) will change. The density of the granule will also determine the length of time that it burns. High density granules will burn longer than low density granules. There are three basic shapes of propellant, with many variations of each shape. The three basic propellant shapes include:

Ball/Spherical – Ball or spherical propellants, as their name implies, are formed into small orbs that may be perfectly round or may be slightly pressed or "flattened." Just like the original ball powder introduced around WWI, modern ball propellants are formed in water through a process of agitation. The gelatinized nitrocellulose is dripped into water, where the impact of other granules forms the globs into very dense spheres. All ball propellants begin life as single base propellants. It isn't until after the granules are dried that (if the propellant is designed to be double base) they are rolled in nitrocellulose and the surface is impregnated.

Figure 7: Various ball and flattened ball propellants.

The manufacturing process produces balls of varying sizes. The balls are sifted and sorted by size. The various sizes of granules will all have a different burn rate. Smaller spheres will burn faster, while larger spheres will burn for longer. The manufacturing process also removes much of the excess nitric acid from the nitrocellulose, lessening decomposition and extending storage life of ball propellants. The manufacturing process for ball propellant is also much quicker, often taking only a few days as opposed to several weeks for other propellant types.

Because of the size and high density of the individual granules, ball propellants tend to burn slowly. This slow burn allows pressure to build gradually, while peak pressure is maintained for a longer duration. Because of their shape, ball propellants will burn from the outside inward, reducing the amount of surface area of the granule as it is converted into gas. The pressure curve of ball propellants will typically peak rapidly before plateauing for a short duration and then gradually falling off. Flattened ball propellants will burn at a different rate than true spherical propellants. The flattened ball burns more like a flake, which increases the velocity of the burn rate.

Ball propellants will also typically burn cooler. A cooler burning propellant will transfer less heat to the throat and bore of the firearm, which will contribute to less wear. The shape and density of ball propellant also makes it ideal for metering specific amounts. It easily flows in powder dispensers, producing consistent charges between cartridges. Other propellant types may be crushed by the powder dispenser, yielding inconsistent results. One drawback to ball propellants is that they are typically temperature dependent. The performance of the propellant may vary depending on the ambient temperature.

Ball propellant is used primarily with rifle cartridges with lighter projectiles, especially U.S. military rifle cartridges (military WC 846 double base ball propellant for 5.56x45mm NATO M855 and 7.62x51mm NATO M80).

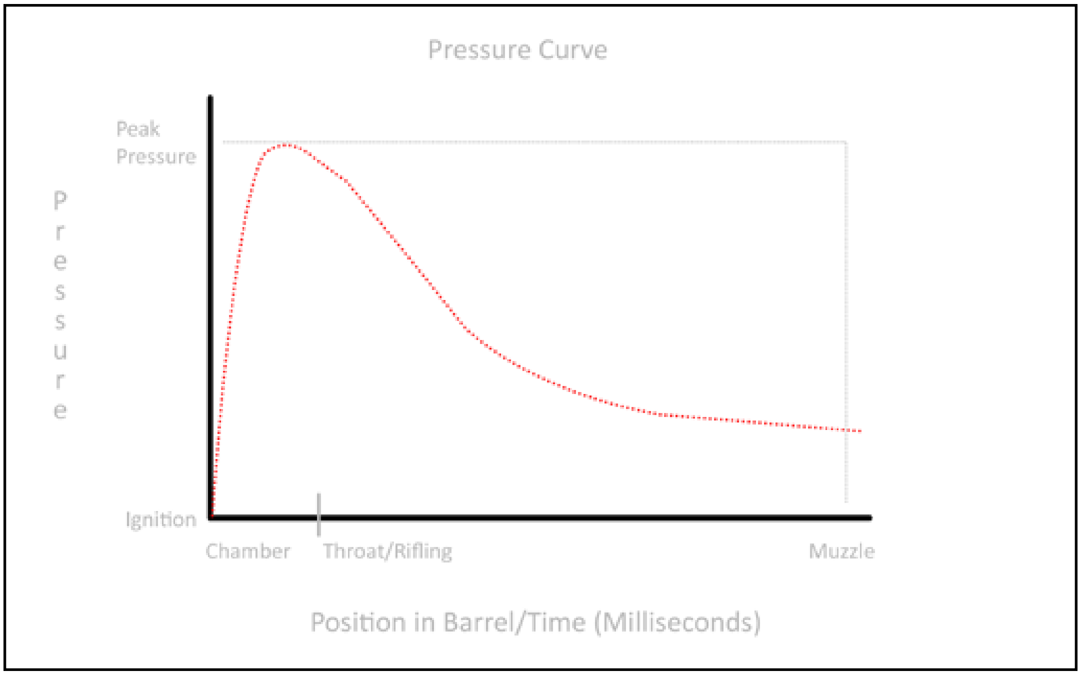


Figure 8: Ball propellant pressure curve.

Ball propellants are also used with some magnum (high velocity) pistol cartridges, such as the .357 Smith & Wesson Magnum and the .44 Remington Magnum. Some ball propellants may even see some use with shotshell cartridges, like the .410 bore.

Extruded – Extruded propellants are named after the process used to form the individual granules. Extruded propellants begin as a single or double base mixture that has the consistency of dough or clay. The mixture is pressed through an extrusion die that forms long tubes or cords that are then cut to size. The resulting granules are shaped like small sticks or tubes. This is why extruded propellant is often referred to as "stick" powder. With extruded propellants, the bases and most additives are mixed before being extruded. Other additives may be added after the granules are shaped and cut to size.

Extruded propellants can be manufactured in various shapes and sizes with varied lengths and surface areas. The basic shape of an extruded propellant granule is a short to medium cylinder, but small "tubes" are also very common. Tube-shaped granules feature a single (sometimes multiple) perforation through the center of the cylinder. These perforations are designed to allow the granule to burn from the outside in, as well as the inside out. As the granule burns from the outside in, the surface area of the granule decreases, but as the granule burns from the inside out, the surface area increases. This allows the surface area of the granule to remain fairly constant as the entire granule burns.

Figure 9: Extruded cylindrical propellant.

Figure 10a: Extruded tubular propellant.

Figure 10b: Extruded tubular propellant cut into smaller disks.

Like ball propellants, the size and shape of extruded propellants lend to a propellant that burns on the slow side. Outside of additives and deterrents, extruded propellant burn rate is controlled by the size and shape (cylinder or tube) of the individual granules. The burn rate of extruded propellant can be slowed by making the individual granules larger and/or longer and can be accelerated by making the granules smaller and/or shorter. Solid cylindrical granules will also typically burn slower than perforated, tubular granules. The pressure curve of extruded propellants will typically peak rapidly before plateauing for a longer duration and then will gradually fall off. Extruded propellants tend to burn slightly hotter than ball propellants and tend to leave more fouling in the bore.

The size and shape of extruded propellants present issues when metering them through powder dispensers. Longer granules can be crushed or cut off by the dispenser, yielding granules of varying sizes, which may alter the burn rate. This issue is resolved by making the granules shorter so they flow more easily through the dispenser.

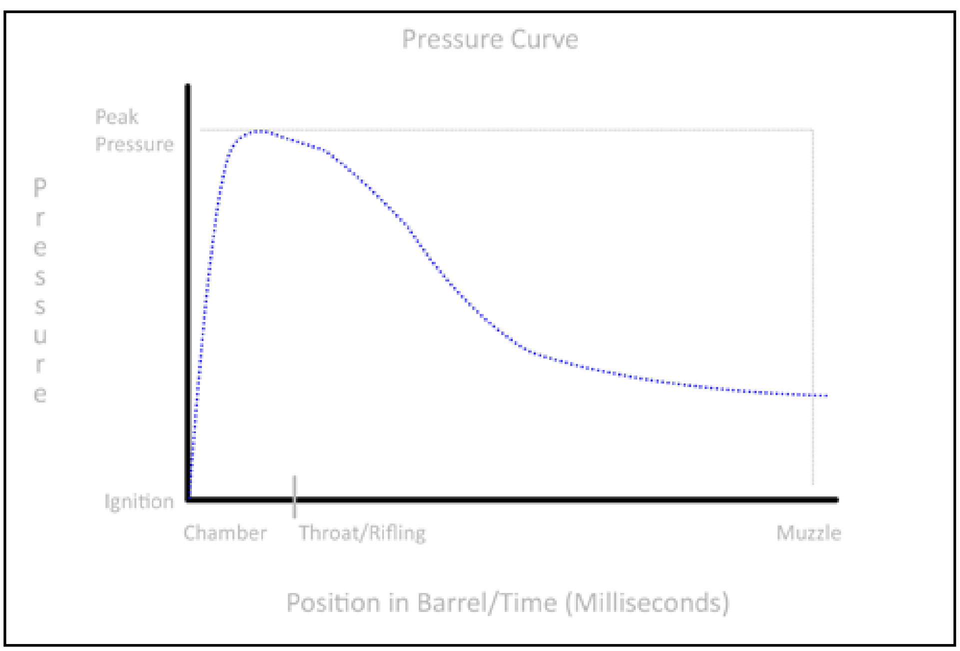


Figure 11: Extruded propellant pressure curve.

The manufacturing process may also create granules with varying densities and burn rates.

Extruded propellants are used primarily with large caliber rifle cartridges and heavy projectiles where case volume is a concern. Cartridges like the .300 Winchester Magnum and .50 BMG typically utilize extruded propellants because of their burn rates as well as their volume. Extruded propellants with shorter granules may also find use with some pistol calibers, such as the 9x19mm Parabellum .38 S&W Special, .44 S&W Special, and .45 ACP. Some faster burning extruded propellants may even be used with some shotshell cartridges.

Flake – Flake propellant is appropriately named so because the individual granules are shaped into small disks or "flakes." Like stick or tube propellants, flake propellants are also extruded; they are just cut into smaller (thinner) granules. Flake propellants can also be single or double base. Flake propellants can be manufactured in various sizes (diameters) and thicknesses to manipulate burn rate.

Flake propellants are designed to burn from the outside in, primarily from the large "flats" on each side. The large surface area on each side of the granules and the flakes' thin profile lend to a propellant that is very fast burning. Outside of size of the individual granule, additives are used to tailor the burn rate of flake propellants to suit their specific application. The pressure curve of flake propellants will (typically) immediately peak before rapidly falling off. This results in an immediate pressure release that will quickly dissipate.

Like other extruded propellants, flake propellants present issues when metering. Because of the shape of the flakes, the individual granules can stack up and cause inconsistent metering. This will lead to inconsistent performance when the cartridge is discharged. The density of the flakes may also vary, which will affect performance. Flake propellants burn hotter than ball propellants, which can lead to additional bore wear, but are not as temperature sensitive.

Flake propellants are common for low-pressure, low-volume applications like pistols and shotguns with lighter projectiles. Their size and shape make them perfect for low volume cases (with projectile and/or wad seated) where ball or extruded propellants would fill the case beyond capacity. Flake propellants are typically used with cartridges that use lighter projectiles moving at subsonic to just past supersonic velocities. Flake propellants are used with popular shotshell calibers, like the 12- and 20-gauge, and with pistol cartridges, like the .32 Auto and .45 Colt.

Now that we have a basic understanding of propellant granule shapes and their densities, we can discuss the characteristics of how the individual granules burn and how it affects performance. There is not a universal rule for burn rates based on granule shape and density. Each individual propellant type features a unique burn rate based on its formulation and the additives

Figure 12: Flake propellants.

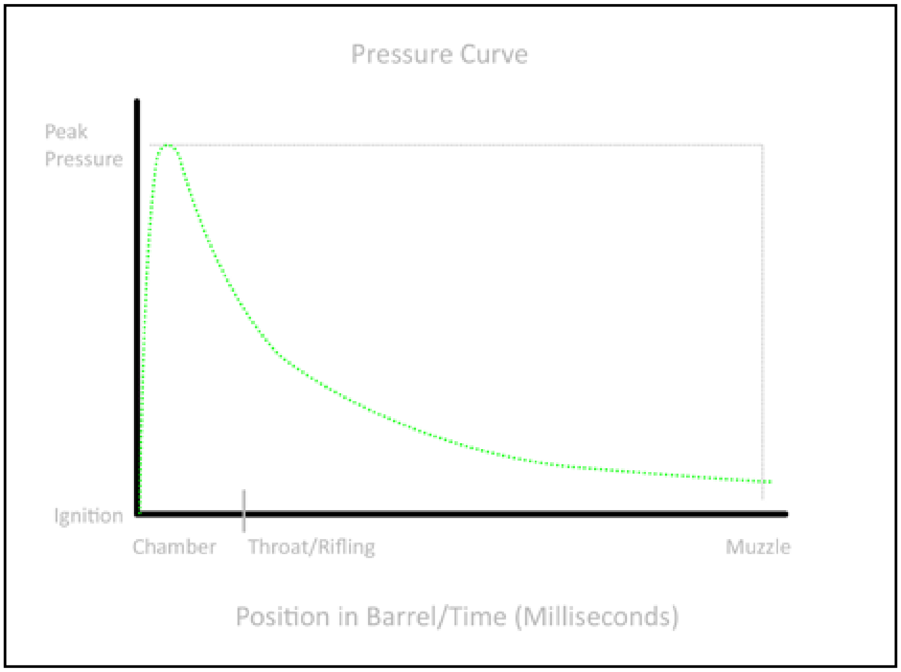


Figure 13: Flake propellant pressure curve.

used by the manufacturer. Granule shapes that burn fast or slow may have their burn rate altered by additives or deterrents. There are three basic types of burn rate:

Regressive – As the granule burns, its surface area decreases. As surface area of the grain decreases, so does the amount of gas released. A regressive burn rate is the most common type of granule decomposition. Ball, flake, and extruded (solid) cylindrical granules all burn regressively. Regressively burning propellants are typically fast burning but can be slowed by adding deterrents to the granule. The pressure curve of a regressive propellant will (typically) immediately peak before rapidly falling off. There will be an almost instant pressure release before rapidly dissipating.

Neutral – As the granule burns, its surface area will remain fairly consistent throughout the reaction. The pressure release from a neutral burning granule will remain fairly constant until the granule has been completely consumed. Extruded, single perforation granules will burn neutrally. As the outside of the granule burns (decreasing surface area), so will the inside of the granule (increasing surface area). Neutral burning propellants are typically slower burning but can be altered with additives and deterrents. The pressure curve of neutrally burning propellants will (typically) rapidly peak before plateauing and then rapidly fall off.

Progressive – As the granule burns, its surface area increases. As the surface area of the grain increases, so does the pressure released. Extruded granules with multiple perforations will burn progressively. Typically, progressive propellants are slow burning. A regressively burning granule can be made to burn progressively with the addition of surface deterrents. The deterrent will make the granule burn slowly initially, producing a minimal amount of pressure until the underlying layers are reached. Once the under layer is reached, the speed of the burn (and amount of pressure released) will increase. The pressure curve of a progressively burning propellant will (typically) rapidly rise before gradually peaking, plateauing for a short duration, and then rapidly fall off.

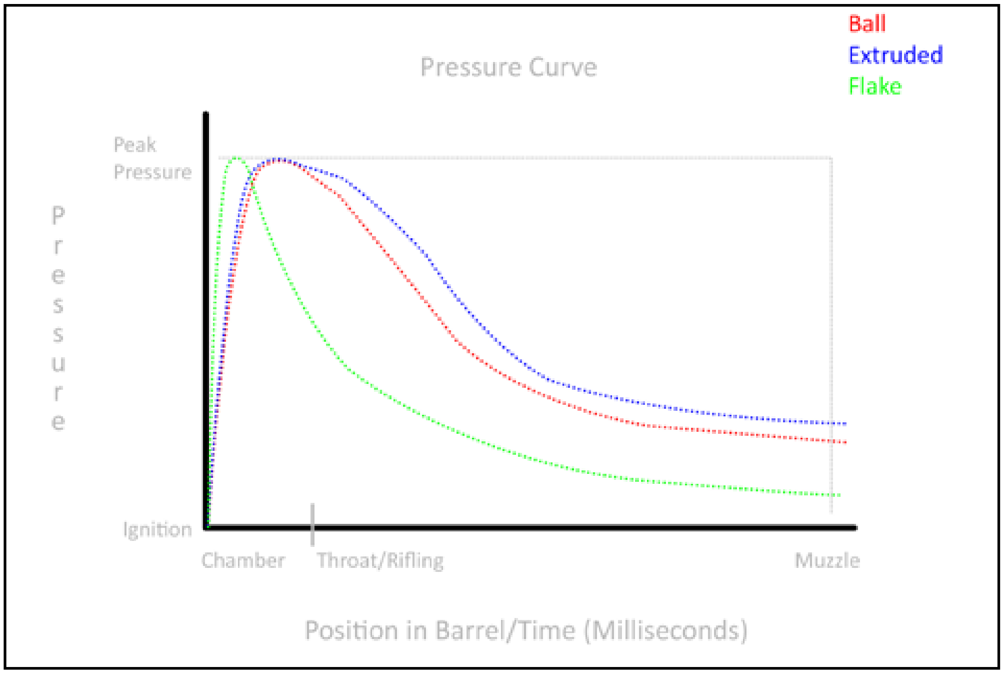


Figure 14: A comparison of propellant type pressure curves.

So why is burn rate important? A burn rate that is not properly matched to its application can lead to wasted energy or worse: destruction of the firearm and potential injury to the operator. When pairing a propellant to a cartridge and firearm, there are two very important considerations: barrel length and projectile weight.

Of the two factors, barrel length is the most important consideration. There is a direct correlation between the time of the reaction and the length of the barrel. A general rule of thumb is that longer barrels require slower propellants, while shorter barrels require faster propellants. With longer barrels the propellant must produce gas and pressure for a longer amount of time as the projectile travels through the barrel. With shorter barrels, the propellant must produce gas and pressure quickly before the projectile exits the muzzle. This is why rifles will typically utilize slower burning propellants, while pistols will use faster burning propellants. The exception to this rule is shotgun and some magnum pistol cartridges. Shotguns will typically utilize faster burning propellants, while some magnum pistol cartridges will utilize slower burning propellants.

If a fast burning propellant were to be used in a longer barrel, the reaction and pressure release would cease before the projectile left the muzzle. Depending on the length of the barrel, the friction of the rifling on the projectile may overcome the pressure behind it and cause the projectile to begin to decelerate before exiting the muzzle. With a worst case scenario, a fast burning propellant in a long barrel could lead to a pressure spike that would be catastrophic to the firearm and hazardous to the operator. In contrast, if a slow burning propellant were to be used in a shorter barrel, the reaction and pressure release may not be complete before the projectile exited the muzzle. This would result is a huge muzzle flash from the still burning propellant and a waste of pressure and energy.

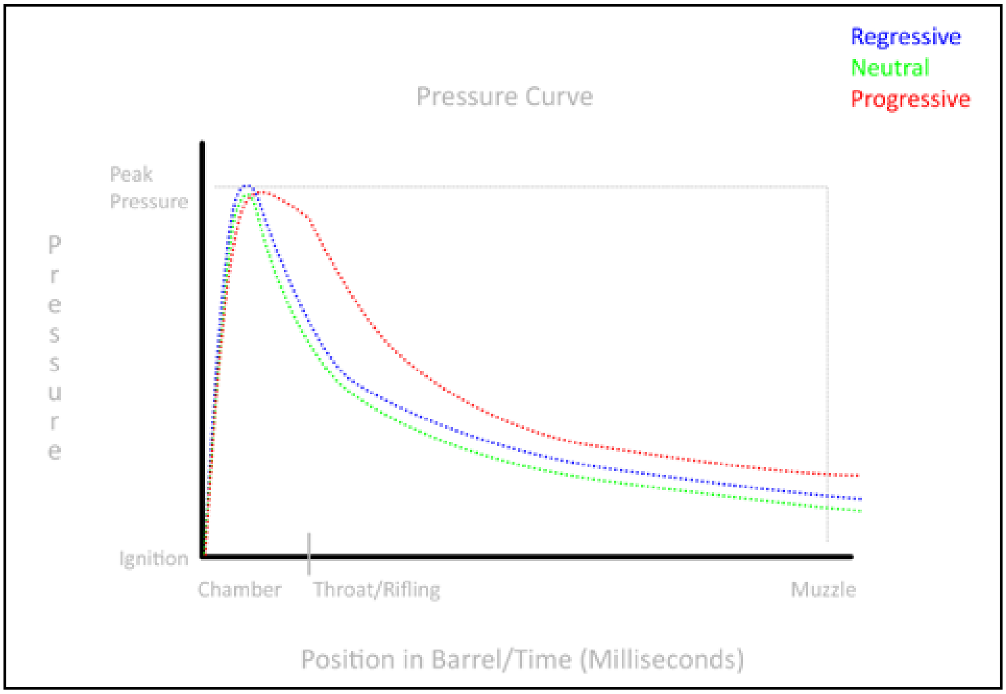


Figure 15: Burn rate pressure curves.

Shotguns utilize faster burning propellants because they do not face the same conditions as rifled pistol and rifle barrels. When a cartridge is fired through a rifled rifle or pistol barrel, the oversized projectile is squeezed through the bore. This requires an immense amount of pressure to accomplish. Because shotguns typically utilize smoothbore barrels, they do not require as much pressure to push the wad or projectile(s) out of the muzzle. The wad/projectile experiences far less friction than through a rifled barrel, so the rapid pressure release of a fast-burning propellant is all that is needed to drive them through the barrel at relatively low velocity (~1,200 – 1,300 fps).

Magnum pistol cartridges utilize a slower burning propellant to provide more pressure to drive the projectile at a higher velocity. The slower propellant and longer pressure buildup lead to velocities far greater than standard pistol rounds (1,500 – 1,600 fps). The biggest downside to using slower propellants for magnum pistol cartridges is the wasted energy. With most magnum cartridges, there is a huge muzzle flash when the projectile exits the muzzle, which is caused by propellant that is still burning.

Projectile weight also plays an important factor in propellant selection. Typically, a heavy-for-caliber projectile will require a slower burning propellant than a light-for-caliber projectile. The reasoning behind this is that a heavy projectile requires more energy to move than a lighter projectile. If too fast of a propellant is used with a heavy projectile, the chamber pressure may peak before the projectile has begun to move. Under the right circumstances (too fast of a propellant and too heavy of a projectile), this scenario can be catastrophic to the firearm and hazardous to the operator. In contrast, a slow propellant and a light projectile will lead to a projectile moving at a high velocity.

To add confusion to things, the propellant is not (typically) continually burning as the projectile travels the complete length of the barrel. Complete propellant burn usually occurs within the cartridge and the first couple of inches of the bore. Slower propellants may burn for a longer duration than faster propellants, but the reaction still only occurs within about 6 in. – 8 in. of the chamber with a small amount of the propellant.[9] The projectile will reach its maximum velocity shortly after leaving the case and will continue to be propelled by the continually expanding gas. As the projectile moves down the barrel, the volume inside the bore increases and provides more room for the combustion gas to expand, which in turn causes a decrease in pressure regardless if the propellant is slow or fast burning. Slower propellants will experience less gradual pressure loss than fast propellants but will still experience loss as the bore volume increases.

CHARGE WEIGHT

Charge weight is the measurement of the mass of a particular amount of propellant for a specific cartridge and projectile weight (see Figure 16). Charge weight will vary with caliber, propellant type, and projectile weight. As a rule of thumb, a heavier projectile utilizes a lighter charge than a light projectile. With all things being equal (caliber, case capacity, and propellant type), a lighter charge will propel a heavier projectile at a slower velocity, while a heavier charge will propel a lighter projectile at a greater velocity, with both loads producing almost the same chamber pressure. For example, if you were to throw two rocks, one heavy and one light, with the same force, the heavier one will travel a shorter distance at a slower velocity, while the lighter rock will travel a farther distance faster.

So why does this happen? Why doesn't a heavier projectile require more propellant, or why doesn't a lighter projectile require less propellant and why do both loads produce almost the same chamber pressure? The answer is case volume, which is a product of projectile weight. To confuse things more, it's not so much the weight of the projectile, but its length. Because projectiles face diameter constraints, as the weight of the projectile increases, so does its length. Also, because most cartridges face length constraints (overall length OAL), as the length, weight, and/or length of the projectile increases, it must be seated deeper into the case to meet OAL requirements. As the projectile is seated deeper into the case, the volume inside the case is reduced.

Figure 16: A propellant charge from a .380 ACP (~3.5 grains) versus a propellant charge from a .50 BMG (~240 grains).

As the volume inside the case is reduced, less propellant is needed to reach a peak chamber pressure. With lighter projectiles, there is more volume inside the case for the combustion gas to expand. As the volume inside the case is increased, more propellant is needed to reach the same peak pressure. Even small variances in the wall thickness of the case can cause variations in chamber pressure.

Charge weight is typically measured in grains. One grain is equal to 1/7000 of a pound or ~ 1/15 of a gram. As the size of the cartridge increases, so will the charge weight. Small cartridges, like the .380 ACP, may only utilize around 3.4 grains of propellants, while the .50 BMG requires around 241.5 grains of propellant. Table 1 is a list of various charge weights by cartridge and projectile weight.

LOAD DENSITY

Load density is measurement of the volume the propellant charge occupies inside the case. Load density is a product of case capacity and propellant bulk density.[10] Bulk density is a ratio of a grain of propellant's mass to its volume that it occupies, typically expressed in grams per cubic centimeter (g/cc). Most cartridge loads will feature a load density that is around 80 percent – 90 percent case capacity, meaning that after the propellant is loaded into the case and the projectile is seated to depth, there will be around 10 percent – 20 percent empty (air) space left in the cartridge. A load density of 100 percent or greater is known as a "compressed" load. This means that the seated projectile is actually compressing the propellant inside the case.

Various Cartridge Charge Weights*		
Cartridge	**Average Projectile Weight (in Grains)**	**Average Charge Weight (in Grains) ** **
.380 ACP	90	3.4
9x19mm NATO	115	5.2
.40 Smith & Wesson	140	6.9
.45 ACP	230	5.7
5.7x28 FN	40	6
.22 Hornet	40	11.3
.357 S&W Magnum	125	7.4
.44 Remington Magnum	240	10.7
.500 S&W Magnum	500	22.9
.223 Remington	55	23.1
.300 Blackout (Subsonic)	220	10.2
7.62x39	125	28.8
6.5mm Grendel	100	27.4
6.8 SPC	110	26.8
.30-30 Winchester	150	30.5
.243 Winchester	55	44.4
.45-70 Government	300	54.5
6.5 Creedmoor	130	34.5
6.5x55 Swede	120	42.2
.308 Winchester	150	44.7
.257 Weatherby Magnum	115	63
.30-06 Springfield	165	46.8
.300 Winchester Magnum	180	68
.358 Winchester	220	44.8
.338 Lapua Magnum	250	84.6
.416 Rigby	350	101.7
.450 Bushmaster	250	40
.50 Browning Machine Gun	750	241.5
12-Gauge 2¾“ 1 oz. Slug	437.5 (1 oz.)	32.3

**These figures are only averages based upon several propellant types. Do not try to use these figures as reloading data. Always refer to manufacturer's load data for specific cartridges and propellants.*

***Data gathered and averaged from www.hodgedonreloading.com.*

Table 1. Various cartridge charge weights.

NOTES

Figure 1: Various primer types.

Centerfire Primers

The primer is the ignition system of the cartridge. The spark and flame created when the primer is struck ignites the propellant and initiates combustion. There are three basic types of primers, with several different sizes, none of which are interchangeable. Depending on the style of primer, it may consist of two to four components.

Centerfire primers are used exclusively with centerfire pistol, rifle, and shotgun cartridges. Rimfire cartridges utilize a rim-incorporated primer. The centerfire primer resides in the primer pocket of the cartridge case. The primer is slightly oversized (.001 in. – .002 in.) and must be pressed into the primer pocket. The use of a separate priming assembly allows a cartridge to withstand immense pressure without compromising the case's integrity. Another benefit of using a removeable primer is that the centerfire cartridge can be reloaded. Because a rimfire cartridge utilizes a hollow rim that is filled with priming compound, they are generally not able to be reloaded.

PARTS OF A PRIMER

Although all centerfire primers function in the same basic manner, the three basic types differ significantly in their construction. These three basic types are battery cup, Berdan, and Boxer. The various components that are used in the different primer types include:

- **Cup** – The primer cup is the centralized component of the primer, and the only component the average shooter ever sees. It is the component in which all of the other components are imbedded. The cup is appropriately named because it is shaped like a tiny, shallow cup. The cup may either be composed of thin-walled brass, copper, or in some cases, steel, and may be nickel plated in some instances. It utilizes a fairly thin material thickness so that it can be reliably deformed by the firearm's firing pin or striker.

  This is one reason that rimfire cartridges cannot be utilized for more powerful cartridges. As pressure inside the case is increased, so must the case's wall thickness to contain the pressure. The firing pin or striker would not be able to reliably crush the rim of the cartridge and initiate combustion. The thin material of the primer cup allows for reliable deformation, while the cartridge case walls can be substantially thicker to contain higher pressure.

  Depending on the type of primer, the cup may contain other parts to help initiate ignition or may only contain the priming compound. The battery cup primer type utilizes a smaller cup inside of a larger, inverted cup to help strengthen the assembly. The cup-in-cup assembly provides structure for the components and is used in a primer pocket that could not otherwise support the reaction without it. The outer cup of this primer type features its own "flash hole" because the case does not. The outer cup also features a flange or lip around its mouth to prevent it from being seated too deeply into the primer pocket.

  Like brass cases, cups are also formed on presses with dies. The cups are then tumbled in abrasive media to polish and remove any burrs from the mouth of the cup and to ease insertion into the primer pocket. The cups may also be nickel plated to add a layer of material to enhance corrosive resistance.

- **Anvil** – The anvil is a small, triangular, pyramid shaped component used to help initiate ignition in the primer. The anvil

Figure 2: Various primer cups.

Figure 3: Various types of anvils.

sits inside the cup and provides a backing for the cup to work against. The anvil sits just shy of flush with the inside of the cup and provides a small space for the priming compound to sit between. When the cup is crushed, the resulting crater bottoms out against the point of the anvil and initiates ignition. The three "legs" of the anvil bottom out against the floor of the primer pocket. The area around each leg is where the spark and flame from the priming compound move to pass through the flash hole of the case.

Only two of the three primer types utilize an anvil. These are the Boxer and battery cup primer designs. Battery cup primers feature a flat anvil that sits perpendicularly in the inside cup. The anvil features two legs that sit against the outside cup and a point that faces the inside of the inside cup. The two legs of this anvil bottom out against the inside of the outer cup and the inside cup's crater contacts the tip of the anvil. The spark created blows through the flash hole of the outer cup.

The Berdan primer does not utilize a self-contained anvil at all. This type of primer features only the cup and priming compound. The anvil is located in the primer pocket of the case. When the cup is impacted by the firing pin, it bottoms out against the protrusion in the center of the primer pocket. Because of this, the flash holes are located along the side of the case's integral anvil.[1]

- **Priming Compound –** The priming compound is a very sensitive, very volatile explosive. The chemical compound used for priming is known as a primary explosive. A primary explosive is a compound that is very sensitive to heat, friction, impact, or electricity. The primary explosive used as a priming compound is sensitive to impact. Outside of the primary explosive that is used for detonation, the compound also utilizes oxidizers, sensitizers, and metals, such as aluminum and magnesium.

The composition of priming compound has evolved many times over the years. The first primers that we would recognize as a "modern" primer utilized mercury fulminate as the primary explosive compound. The first primer adopted by the U.S. military utilized a compound composed of mercury fulminate, potassium chlorate, glass dust, and gum arabic.[2]

Figure 4: Priming compound.

The issues with this compound were that the mercury reacted with the brass of the cartridge case, making it brittle and susceptible to failure upon discharge, and the potassium chlorate was very corrosive to the chamber and bore of the firearm. The decomposition of potassium chlorate creates potassium chloride, which is very *hygroscopic*, drawing moisture into the bore and chamber and causing corrosion and rust.

Because of the corrosive nature of mercury fulminate/potassium chlorate primers, a need arose for a non-corrosive priming compound. In 1928, a German company named RWS introduced the first non-corrosive primer.[3] The compound utilized a mixture of lead styphnate and barium nitrate. Although the new compound was non-corrosive, it did not meet the U.S. military standards for storage and reliability, so the U.S. continued to use corrosive primers throughout WWII.

It wasn't until around 1955 that the non-corrosive priming compound was adopted by the U.S. military.[4] Since then, almost all U.S.-made priming compounds (both military and non, as well as rimfire cartridges) have been non-corrosive. This non-corrosive priming compound consisted of lead styphnate (40 percent), barium nitrate (40 percent), and tetrazene (4 percent).[5, 6] The mixture also contains aluminum, antimony sulfide, and PETN (pentaeythritol tetranitrate) to account for the final 16 percent. Lead styphnate is the explosive, while barium nitrate is used as an oxidizer. Tetrazene is used as a sensitizer to ensure the lead styphnate ignites when crushed by the cup and anvil. The aluminum, antimony sulfide, and PETN are all used as fuel. The use of aluminum also ensures ignition of the propellant as the molten metal comes in contact with the individual granules.

Depending on the manufacturer, modern priming compounds may also contain magnesium and powdered glass. The magnesium serves the same purpose as aluminum, providing spark and molten metal to increase the reliability of combustion. Powdered glass is used to increase friction and improve the reliability of ignition in the primer. Most rimfire cartridges will also use powdered glass in the priming compound to increase the reliability of ignition.

Because of the growing concerns for lead exposure, the latest generation of primers is moving toward a priming compound that is lead-free. The solution to this issue is replacing lead styphnate with a lead-free alternative such as nitrocellulose.[7] These lead-free primers utilize a compound that consists of nitrocellulose (20 percent), bismuth oxide (60 percent), aluminum (10 percent), and a mixture of sensitizers, fuels, and binders (10 percent). Nitrocellulose is utilized as the explosive, while the bismuth oxide is used as an oxidizer. The aluminum is used to sensitize the nitrocellulose as well as help ignite the bismuth.

- **Foil/Paper –** The primer (sometimes) utilizes a small, thin piece of paper or foil to cover the priming compound. The paper/foil serves to prevent any loose priming compound from mixing with the propellant as well as prevents any propellant from mixing with the priming compound. The foil/paper also serves as a barrier from any moisture coming in contact with the priming compound.

Figure 5: Foil/paper.

HOW A PRIMER WORKS

The process of initiating combustion inside a cartridge may seem simple, but it is one of the most crucial steps in firing a cartridge. The reliability and performance of the primer translate to the reliability and performance of the cartridge. If the primer fails to ignite, the cartridge will not fire, no matter how many times the firing pin strikes the primer. If the performance of the primer is not consistent, accuracy and precision will suffer.

When a cartridge is fired, ignition is initiated by one of two means, either with a firing pin or striker. The firing pin is driven by the hammer, while the striker is self-propelled by its own spring. The momentum of the steel firing pin or striker will create an indentation in the soft brass (or copper) cup of the primer. As the cup deforms, the protrusion formed on the inside of the cup will butt against the anvil. The anvil, being bottomed out against the inside of the primer pocket (or against the inside of the outer cup or integral to the case) has no room to move.

As the crater in the cup moves into the anvil, it will begin to crush the priming compound. Being a shock-sensitive primary explosive, the small amount of compound (~20 milligrams for small primers and ~36 milligrams for large rifle primers[8]) detonates. Sensitizers and (sometimes) the use of glass powder, assist in the detonation of the priming compound. The reaction creates flame and spark in the form of molten metal (aluminum, magnesium, zirconium, titanium, nickel, zinc, and bismuth). The reaction also produces enough gas to begin to pressurize the case. The flame and spark are forced through the flash hole(s) and onto the propellant. The pressure created is substantial enough to push the primer cup from the primer pocket until it contacts the breech/bolt/slide face. The entire reaction lasts about 200 to 1,500 microseconds (1/5,000 – 3/2000 of a second).[9]

The cartridge's load density will determine how far the flame and spark will reach into the case. With very dense or compressed loads, the flame and spark will only reach the propellant closest to the flash hole(s). With less dense loads, the propellant can shift in the case, which allows the flame and spark to reach granules closer to the case mouth. The number of propellant granules ignited initially by the propellant can affect the propellant reaction's pressure curve.

Any variance in the amount of priming compound can also alter the pressure curve. Too little compound, and the flame and spark will not initially ignite as much propellant. Too much priming compound, and the reaction may create so much pressure that the propellant is compressed and experiences erratic ignition.[10] Once the propellant ignites and begins to build pressure, the case will begin to expand and stretch to fill the chamber. The head of the case will stretch and butt up against the breechblock/bolt/slide face, pressing the primer back into the primer pocket.

TYPES OF PRIMERS

To again briefly summarize the various primer types, we provide the following descriptions:

- **Boxer** – The Boxer primer is the standard primer type used in the United States. The Boxer primer consists of a cup, pyramid shaped anvil, priming compound, and a foil or paper cover. The Boxer primer resides in a primer pocket that utilizes a single, centrally located flash hole. The major benefit of the Boxer primer is that it can be easily removed and replaced so that the cartridge case can be reloaded. One drawback is that it is more complicated and costs more to produce than a Berdan primer. The Boxer primer comes in five basic sizes: small pistol and rifle, large pistol and rifle, and .50 BMG, as well as magnum and benchrest variations.
- **Berdan** – The Berdan primer is the standard primer type used in Europe, Asia, and most of the world. The Berdan primer consists of a cup, priming compound, and a foil or paper cover. The Berdan primer resides in a primer pocket that features its own integral anvil with two flash holes on either side of the anvil. The major benefits to the Berdan primer are its simplicity and cost. Berdan primed cases can be reloaded but are much more difficult to do so because of the dual flash hole arrangement. The Berdan primer comes in several sizes, but the most common are small pistol and rifle and large pistol and rifle.
- **Battery Cup** – The battery cup primer is the standard primer type used in all shotshells and with some muzzleloaders. The battery cup primer is also known as the

Figure 6: Various Boxer primers.

Figure 7: Berdan primers.

209 primer because its average body diameter is .209 in. The battery cup primer consists of a smaller cup inside of a larger cup that features a lip around its mouth and its own flash hole. Unlike other anvil types, which are cone or pyramid shaped, the battery cup primer utilizes an anvil that is flat and features two legs that butt against the inside of the outer cup. The priming compound and foil/paper cover reside in the inner cup. The purpose of this cup-in-cup design is that the shotshell does not utilize a flash hole with either a "floor" or a flash hole. Like the Boxer primer, the battery cup primer can also be easily removed for reloading. The battery cup primer is only available in one standardized size.

- **Magnum** – The magnum primer is a variation of the Boxer primer. Magnum primers utilize more priming compound and more metal powder in the compound. Magnum primers are used for applications where case capacity is beyond that of the average pistol or rifle. The increased amount of compound and metal in the compound ensures more consistent ignition with a greater propellant charge.
- **Benchrest** – The benchrest primer is another variation of the Boxer primer. Benchrest primers are manufactured more consistently than other primer types. This means that the amount of compound used is more uniform from primer to primer. Higher consistency in the manufacturing process leads to more uniform ignition from round to round, which will lead to more consistent accuracy and greater precision. Benchrest primers are (typically) only available in the small and large rifle sizes.

Figure 8: Battery cup primers.

PRIMER SIZES

Primers of varying sizes are used for cartridges of varying sizes. Larger cartridges will require larger primers to reliably ignite a larger propellant charge. Smaller cartridges require less priming compound to reliably ignite the propellant. Although some pistol and rifle primer sizes are the same size, they are not interchangeable. Rifle primers utilize more (and often more powerful) compound than pistol primers.

Primer Sizes		
Primer Type	**Diameter (Inch)**	**Depth (inch)**
Boxer		
Small Pistol	.175”	.118”
Large Pistol	.210”	.118”
Small Rifle	.175”	.118”
Large Rifle	.210”	.127”
.50 BMG	.315”	.215”
Berdan		
Small Pistol	.177”	.091”
Large Pistol	.197”	.091”
Small Rifle	.177”	.081”
Large Rifle	.217”	.111”
	.217”	.101”
	.250”	.111”
	.254”	.091”
	.254”	.134”
Battery Cup		
209	.209”	.299”

Table 1. Primer sizes.

NOTES

NOTES

Chapter 7 - A Complete Cartridge

Figure 1: Complete cartridges.

A Complete Cartridge

Up to this point we have discussed projectiles, cases, propellants, and primers, and now it is time to complete the cartridge. For most cartridge types, the assembly process is very similar. Some cartridges require fewer steps to complete, while others may require more. Regardless of whether the cartridge is loaded in an automated machine by a large-scale manufacturer or one-by-one by hand in a small-scale custom shop, the process is almost identical. The only difference is time and quality.

Every cartridge begins life as a fully formed and properly sized case. The cases are cleaned and the mouth of the case is (typically) flared, ready to accept a projectile. With both centerfire and rimfire cartridges, the first step is priming. With

Figure 2: A primed centerfire case.

Figure 3: Crimped primers.

rimfire cartridges, the priming process involves dropping a small "pellet" of (wet) priming compound into the case. Utilizing centrifugal force, the cases are spun until the priming compound is forced into the case rim. The cases are spun with such force that the priming compound is compacted into the rim. The priming compound is allowed to dry before moving on to the next step.

With centerfire cartridges, the priming step is much simpler. With the head of the case secured in a shell holder or shell plate, a primer of the appropriate type and size is inserted into the primer pocket of the case. Utilizing a press or hydraulic ram, the primer is pressed into the primer pocket of the case until it sits just below flush of the face of the case head. This process is the same for Boxer, Berdan, and battery cup primers.

CRIMPED PRIMERS

Cartridges intended for military use undergo a couple of additional steps beyond just seating the primer. With sustained fire through an automatic weapon, there is a greater chance that the pressure inside of the case can build up to a point where the primer is forced out from the primer pocket. The loose primer can wedge itself into the action and seize the firearm. Excessive heat in the chamber from automatic fire can cause chamber pressure to rise beyond standard operating pressure, "popping" the primer from its pocket.

To prevent the primers from popping, manufacturers crimp the primer in place. A small amount of material from the mouth of the primer pocket is displaced over the seated primer. When the

Figure 4: Sealed primers.

cartridge is hot enough to cause a pressure increase, the displaced material holds the primer in the pocket and prevents it from popping. Various manufacturers will crimp primers in different ways. The most common crimp styles include several small stakes or a complete ring around the mouth of the pocket.

Military cartridges also utilize sealer on the primer. The sealer serves to create a moisture proof barrier and retain the reliability of the primer. The sealer is typically a type of dyed lacquer. Ammunition intended for civilian use does not typically utilize a primer sealer because it will not undergo the harsh conditions a soldier may experience. The primer being oversized already creates a tight enough seal in the pocket to provide enough moisture protection for civilian use; the sealer is just a guarantee under extreme conditions.

CHARGING

Once the case has been primed (or filled with priming compound), it is ready to be filled with propellant. Most major manufacturers will fill cartridges with a charge based on the volume it occupies. The manufacturer will determine the correct propellant charge for a specific propellant and cartridge and determine its volume. A chamber on the charging machine is adjusted to match the volume the cartridge requires. As the case moves along the assembly line, propellant from a hopper is dropped down into the chamber through a trap door. As the case reaches the funnel of the charge machine, a second trap door under the chamber opens and drops a specific amount of propellant into the case. This method is precise enough to ensure cases are loaded with a fairly consistent amount of propellant from round to round. For greater precision, charges would have to be weighed out individually, increasing the time and cost of manufacturing. Some machines will utilize an extra stage where the case is checked to ensure the case was not under- or overcharged.

SEATING THE PROJECTILE

The final component(s) to be incorporated into the case is the projectile. This operation may seem straightforward, but there are several considerations to address. The weight and length of the projectile (or number of projectiles), how far the projectile is inserted into the case, and how

Figure 5: Charged cases. From left to right: .308 Winchester, .300 AAC Blackout (Supersonic), 9x19mm Parabellum, .22 Long Rifle.

Figure 6: Seated bullet.

Figure 7: Sealed bullets.

the projectile(s) is secured must all be considered. The seating process will vary with shotshells and rimfire/centerfire pistol and rifle cartridges.

With centerfire pistol and rifle and rimfire cartridges, a single projectile is pressed into the mouth of the case. This stage is where the process begins to differ for shotshells. Before dropping projectiles into a shotshell case, wads and cups are inserted to separate the propellant from the bird, buckshot, or slugs. Without a wad or cup, the propellant would mix with the bird or buckshot and would not properly ignite. The wad also serves to act as filler inside the case, occupying any empty space in the case and preventing the other components from shifting around. The wad(s) also helps the components reach a specific length so that once crimped, the cartridge will reach a specific length. Once the wad(s) or cup has been inserted, the shot or slug can be added.

With centerfire pistol and rifle and rimfire cartridges, the process is much more simple. Seating typically occurs in two stages. In the first step, a projectile is placed in the mouth of the case. As the cartridge moves down the assembly line, the next machine presses the projectile down into the case by its ogive to preserve the shape of its tip. Manufacturers adjust their seating dies to produce a cartridge with a specific overall length.

Every SAAMI standardized cartridge must fall within a specified maximum cartridge overall length (COAL). This requirement ensures that manufacturers produce a round that will fit in every firearm that is chambered for that specific caliber. This specification also ensures that every cartridge produced will fit inside of magazines designed for that specific caliber. Cartridges loaded beyond maximum COAL may hang up or jam in the magazine or may not fit at all. Once the projectile has been seated, the cartridge can move on to its final process.

Cartridges intended for military use undergo an extra step before the projectile is seated. Like the primer, the projectile is also sealed. Typically, tar or some type of lacquer sealer is applied to the bullet before it is seated into the case. Sealing the projectile and primer ensures the cartridge will be completely moisture proof and will extend the storage life of the ammunition.

Types of Crimps

Now that the bullet is seated, it needs to be secured to the case. If the bullet is not secured, there is a high probability that the projectile could be pushed into or pulled out of the case. If the bullet is inserted too deep, it can create a pressure spike when discharged because of the reduced internal volume. This can be catastrophic to the firearm and dangerous for the operator. If the bullet is pulled or falls from the case, the propellant can fall out into the action or the feeding device.

Outside of securing the projectile(s) in the case, the crimp also serves to increase neck tension. The increased neck tension helps with combustion by allowing the pressure inside the cartridge to build. Without the increase in neck tension, the projectile would begin to move from the case as pressure begins to rise, increasing case volume and decreasing peak pressure. The consistency of neck tension can affect both accuracy and precision. The measure of the force required to push the bullet from the case is known as bullet pull.

When the bullet is seated in the case, the flared material around the mouth remains. Crimping the mouth of the case moves material inward to secure the bullet. There are three basic crimp types. The type of crimp utilized is based on how the cartridge headspaces and on the type of projectile used. The three crimp types are as follows:

- **Taper** – The taper crimp simply flattens out the flare along the mouth of the case and creates a slight taper that decreases from the neck to the mouth. The taper crimp is utilized with cartridges that headspace against the case mouth or with projectiles that do not feature a cannelure or crimp groove. The reason the taper crimp is used with cartridges that headspace against the neck is that it leaves a substantial step on the mouth of the cartridge to bottom out against the inside of the chamber. Almost all cartridges intended for use with semi-automatic firearms use taper crimps.

Figure 8: Cartridges with a taper crimp.

- **Roll** – The roll crimp displaces material from the mouth of the case inward. The roll crimp is utilized with cartridges that do not headspace off of the case mouth and with projectiles that feature crimp grooves or cannelures. When a cartridge is crimped using a roll crimp, the mouth of the case is rolled inward into the groove in the projectile. The roll crimp is not utilized with cartridges that headspace against the case mouth because the displaced material shortens the length of the case, which does not allow it to properly headspace in the chamber. The roll crimp is also not used with projectiles

Figure 9: Cartridges with a roll crimp.

Figure 10: Shotshells with a roll crimp.

that do not feature a crimp groove or cannelure because the displaced material has nowhere to go and forces the mouth of the case outward. The roll crimp is used primarily with rimmed cartridges intended for use in revolvers.

There is a variation of the roll crimp that is used for shotshells. When a shotshell is loaded with a slug, the mouth of the case is rolled inward over the projectile, leaving the nose exposed. When fired, the slug pushes against the crimp and causes it to unfurl. The roll crimp can only be used with slugs or with buck/birdshot loads utilizing an overshot wad/card. The overshot card prevents the shot from falling out of the front of the cartridge.

- **Star** – The star crimp is a type of crimp that is only utilized with shotshells. With the star crimp, the end of the case is folded over the top of the shot cup, forming triangular segments. The purpose of the star crimp is to prevent shot from falling out of the case. The crimp will typically feature six or eight segments. When fired, the segments unfold and open up to form the top portion of the body. The star crimp is used exclusively with shotshells loaded with bird and buckshot. There are some examples of blank cartridges that utilize a star crimp on the neck and mouth of the cartridge.

Figure 11: Shotshells with a star crimp.

Figure 12: Blank cartridges with star crimps.

Top: Figure 13a: Complete cartridges. Bottom: Figure 13b: Cartridge cutaways.

From left to right: .50 BMG, .30 – 06 Springfield, .458 Winchester Magnum, .257 Weatherby Magnum, 7.92x57mm Mauser, 7.62x51mm NATO, .410 Bore 3 in., .444 Marlin, 12 Gauge 2¾ in., .300 AAC Blackout (subsonic), 5.56x45mm NATO, .458 SOCOM, 4.6x30mm HK, .22 WMR, .17 HMR, 10mm Auto, .45 ACP, .22 TCM, 9x19mm Parabellum, .357 SIG, .22 LR, .32 ACP.

Types of Cartridges

Now that we have an understanding of the individual components of a cartridge and how cartridges are assembled, we can discuss cartridge types and their intended uses. The four types are pistol, rifle, rimfire, and shotshell cartridges. Things become confusing because there are no standardized rules of classification, meaning some rifles are chambered for pistol, rimfire, or shotshell cartridges, while some pistols may be chambered for rifle, rimfire, or shotshell cartridges. Shotguns are almost always chambered for shotshell cartridges but may feature a second (or third) barrel chambered for a pistol, rifle, or rimfire cartridge.

We can begin to group cartridge types together by their size, but there will always be exceptions to the rule. The size of the cartridge will be our first clue as to whether it is classified as a pistol, rifle, rimfire, or shotshell cartridge. Shorter cartridges will be able to fit within the constraints of a pistol's magazine and grip or cylinder, while longer rifle and shotgun cartridges would be too long to be practical. Shorter pistol cartridges may be able to fit and function in a rifle, but the fast burning propellants would be detrimental in the longer barrel.

- **Pistol –** Pistol cartridges are typically much shorter than rifle cartridges and feature a straight-walled design. Cartridges that are designated as pistol cartridges typically must fit within the dimensional constraints of a magazine that fits within the grip frame of a semi-automatic pistol or the cylinder of a revolver. Pistol cartridges may be rimmed, semi-rimmed, rimless, rebated rim, straight-walled, tapered, or bottleneck in calibers ranging from .25 (.25 ACP) to .50 (.500 Smith & Wesson Magnum). There is also a small segment of pistol "shotshells," which are pistol caliber cartridges like the 9x19mm Parabellum and .357 Smith & Wesson Magnum that fire small diameter (#9 – #12) birdshot.

  Pistol cartridges are used primarily with semi-automatics, revolvers, and single-shot pistols, but the current trend of the pistol caliber carbine (PCC) has created a huge segment of pistol caliber rifles. Popular rifle actions, like the AR- and AK-style of firearms, can now be found in popular pistol cartridges

Figure 14: Pistol shotshells.

Figure 15: Various pistol cartridges. From left to right: .500 S&W Magnum, .44 Remington Magnum, .50 Action Express, 10mm Auto, .45 ACP, .40 S&W, .357 SIG, 9x19mm Parabellum, .25 ACP.

Pistol Cartridge Performance				
Cartridge	**COAL (Inches)**	**Bullet Weight (Grains)**	**Velocity (Feet-Per-Second)**	**Muzzle Energy (Foot-Pounds)**
.25 ACP	.91	45	815	66
.380 ACP	.984	90	1,025	210
9x19mm Parabellum	1.169	115	1,180	355
.357 SIG	1.140	125	1,400	543
.40 Smith & Wesson	1.135	135	1,400	587
.22 TCM	1.265	40	2,070	380
.45 ACP	1.275	230	835	356
10mm Auto	1.260	180	1,300	675
.38 Smith & Wesson Special	1.55	125	1,000	277
4.6x30mm HK	1.516	31	2,300	364
.45 Colt	1.6	250	900	449
.50 Action Express	1.610	300	1,500	1,498
5.7x28mm FN	1.594	31	2,350	380
.357 Smith & Wesson Magnum	1.59	125	1,450	583
.44 Remington Magnum	1.61	240	1,350	971
.454 Casull	1.77	300	1,650	1,813
.460 Smith & Wesson Magnum	2.300	300	2,060	2,826
.500 Smith & Wesson Magnum	2.300	500	1,425	2,254

Table 1. Pistol cartridge performance.

like the 9x19mm Parabellum, .40 Smith & Wesson, .45 ACP and 10mm Auto. Many also use already available magazines like the Glock and HK MP5. There is no real performance advantage of using a pistol caliber in a rifle; the real advantage comes from cost of operation and a reduction in recoil. Some pistol cartridges have also been used with lever-action rifles for over a century.

With the exception of some specialty revolvers, the largest caliber revolver (and all handgun) chambering is the .500 Smith & Wesson Magnum, a straight-walled, semi-rimmed cartridge. The largest chambering for a semi-automatic pistol is the .50 Action Express, a straight-walled, rebated rim cartridge. Other pistol cartridges include the .44 Remington Magnum (straight-walled, rimmed), .357 SIG (bottleneck, rimless), 9x19mm Parabellum (tapered, rimless) and .25 ACP (straight-walled, semi-rimmed).

Pistol cartridges can also be categorized by their performance. The average pistol cartridge has an effective range of about 100 m (110 yd.), with some calibers shorter, some longer. Many pistol calibers are lethal to a much greater distance (200 m+), but with short barrels, short sight radiuses, and limited stability, most pistols (and shooters) cannot accurately reach out to these distances. In fact, most pistol shooting occurs from 3 to 50 yd. Pistol cartridges are limited to these performance standards by two factors: case capacity and projectile selection.

Part of the limitations of pistol cartridges can be attributed to projectile selection. Pistol bullets are often short and wide and feature a blunt nose. Pistol bullets often have very low SD and BC and because they are typically moving

Figure 16: Various rifle cartridges. From left to right: .50 BMG, .458 Lott, .308 Marlin Express, .444 Marlin, 5.56x45mm NATO, .300 AAC Blackout (Subsonic), 7.62x39mm, .458 SOCOM, .17 Hornet.

at subsonic speeds, drop fairly quickly. Pistol bullet types include solids, FMJs, hollow points, soft points, polymer tipped, and wadcutter.

The restrictions on COAL limit the pistol cartridge to short cases with long bullets, longer cases with shorter bullets, and everything in-between. Outside of cartridges intended for revolver use (which can be fairly long), the only way to increase the power and performance of a pistol cartridge intended for a semi-automatic pistol is to increase its diameter. Semi-automatic cartridges are limited to about 1.6 in. to ensure that the grip is not impractically large. Most cartridges intended for use in semi-automatics are around 1.250 in. Revolvers can be designed to accept much longer cartridges because the length of the cylinder has no bearing on the size of the grip. Most revolver cartridges fall below 1.6 in., but there are some calibers as large as 2.3 in.

Because of their size restrictions, pistol cartridges are (typically) limited to lower velocities and energy levels below roughly 600 ft-lb. of energy. There are exceptions for both performance standards, with some cartridges reaching velocities as high as 2,300 fps and others producing as much as 2,800 ft-lb. of energy. As energy increases, so will recoil, making some of the larger caliber cartridges impractical for normal pistol usage (plinking, competition, and self-defense). Below is a chart comparing pistol cartridge performance.

- **Rifle** – Rifle cartridges may be a bit harder to classify, especially with some of the smaller calibers. The typical rifle cartridge features a bottleneck design and is larger than a pistol cartridge. Rifle cartridges are not limited in size like pistol cartridges and can be scaled to fit any size magazine or action. Rifle cartridges may be rimmed, semi-rimmed, rimless, rebated rim, straight-walled, tapered, bottleneck, or belted in calibers ranging from .17 (.17 Hornet) to .50 (.50 BMG).

While rifle cartridges are used primarily with semi-automatic and repeating (bolt- and lever-action) rifles, the current trend of the rifle caliber pistol has created a growing segment of pistols chambered for rifle cartridges. Popular rifle action types, like the AR and AK series of firearms, can now be found in pistol configurations (no stock and short 8 in. – 12 in. barrels) chambered in calibers such as the 5.56x45mm NATO, 7.62x39mm, and .300 AAC Blackout. These rifle caliber pistols are also able to accept high capacity magazines as well as drum magazines. The greatest advantage of the rifle caliber pistol is the ability to utilize a powerful rifle cartridge in an easy-to-maneuver, compact package. The major downside to the rifle caliber pistol is the short barrel. Many cartridges will not be able to produce the same performance from the shorter barrel as they would a full length (16 in.) barrel. Although there is a reduction in performance, many rifle cartridges are still able to produce power levels substantially higher than a pistol cartridge.

With the exception of some specialty, single-shot bolt-action rifles, the largest commercial rifle cartridge is the .50 BMG, a rimless bottleneck cartridge. The .50 is also the largest chambering for a semi-automatic rifle. Other rifle cartridges include the .17 Hornet (bottleneck, rimmed), .458 SOCOM (bottleneck, rebated rim), .444 Marlin (straight-walled, rimmed), .308 Marlin Express (bottleneck, semi-rimmed) and .458 Lott (straight-walled, belted).

It is more difficult to categorize rifle cartridges by their performance because of the huge disparity in performance between small and large rifle cartridges. A smaller rifle cartridge may have an effective range of about 300 m (330 yd.), while a large rifle cartridge may have an effective range beyond 1,000 m. Some cartridges are capable of incredible accuracy beyond 1,000 m. At the time of this writing, the world record long distance (sporting) shot is 5,280 yd. or 3 miles, held by the .408 Cheytac. Most rifle cartridges will be utilized between 100 and 800 yd. The only limitation to rifle cartridge performance is the size of the cartridge.

Rifle projectile selection is one of the main contributors to the performance of rifle cartridges. Before the advent of the spire point or spitzer bullet, rifle bullets were blunt like pistol bullets and had an effective range of about 200 m. Modern rifle bullets all have higher BCs than pistol bullets, some of which outperform the BC of the test model (1.0). Many rifle calibers utilize bullets with BCs between .3 and .8. The high BC of rifle bullets also makes it possible for them to reach velocities beyond 3,000 fps and maintain supersonic velocities for a greater distance. Rifle bullet types include solids, FMJs, hollow points, soft points, polymer tipped, match, and VLD.

Because rifle cartridges are not typically restricted by COAL constraints, they can reach performance levels far beyond pistol cartridges. The average rifle cartridge generates velocities beyond 2,500 fps and 2,500 ft-lb. of energy. Many cartridges reach far beyond the standard, with some cartridges producing as high as 3,900+ fps and others producing as much as 13,000 ft-lb. of energy. Below is a chart comparing rifle cartridge performance.

- **Rimfire –** Out of all of the cartridge types, rimfire cartridges may be the easiest to classify. Any cartridge that does not feature a centrally located, replaceable primer and is fired from the rim is a rimfire cartridge. Because of the pressure

Figure 17: Various rimfire cartridges. From left to right: .22 BB/CB, .22 Short, .17 PMC Aguila, .22 Long Rifle, .17 Hornady Mach II, .22 Long Rifle Stinger, 5mm Remington Magnum, .17 Hornady Magnum Rimfire, .22 Winchester Magnum Rimfire, .17 Winchester Super Magnum.

Rifle Cartridge Performance				
Cartridge	**COAL (Inches)**	**Bullet Weight (Grains)**	**Velocity (Feet-Per-Second)**	**Muzzle Energy (Foot-Pounds)**
.17 Hornet	1.715	25	3,170	557
.22 Hornet	.1700	40	2,825	708
.17 Remington Fireball	1.780	25	3,790	797
.458 SOCOM	2.260	325	1,860	2,496
.243 WSSM	2.36	70	3,700	2,127
.50 Beowulf	2.125	400	1,800	2,877
5.45x39mm	2.244	53	2,900	990
5.56x45mm NATO	2.260	62	3,100	1,322
.224 Valkyrie	2.260	90	2,640	1,392
.300 AAC Blackout	2.260	220	1,050	538
7.62x39mm	2.205	123	2,420	1,599
.450 Bushmaster	2.260	250	2,410	3,223
.22-250 Remington	2.35	50	3,940	1,723
.35 Remington	2.525	200	2,070	1,902
.30-30 Winchester	2.540	150	2,390	1,902
.444 Marlin	2.55	240	2,350	2,942
.45-70 Government	2.55	300	2,275	3,447
.308 Marlin Express	2.60	140	2,800	2,436
.243 Winchester	2.7098	65	3,740	2,018
.308 Winchester	2.800	150	2,820	2,648
6.5mm Remington Magnum	2.800	120	3,210	2,745
.303 British	3.075	174	2,500	2,414
8x57mm Mauser	3.228	196	2,600	2,941
.270 Winchester	3.340	140	2,910	2,631
.30-06 Springfield	3.340	180	2,700	2,913
.458 Winchester Magnum	3.340	350	2,550	5,052
.300 Winchester Magnum	3.340	180	3,140	3,940
.257 Weatherby Magnum	3.209	100	3,600	2,877
.300 Weatherby Magnum	3.562	180	3,250	4,220
.458 Lott	3.60	400	2,550	5,774
.338 Lapua Magnum	3.681	300	2,710	4,891
.408 CheyTac	4.547	419	3,000	8,371
.50 BMG	5.45	750	2,820	13,241

Table 2. Rifle cartridge performance.

Rimfire Cartridge Performance				
Cartridge	**COAL (Inches)**	**Bullet Weight (Grains)**	**Velocity (Feet-Per-Second)**	**Muzzle Energy (Foot-Pounds)**
.22 BB/CB Cap	.343	18	780	24
.22 Short	.695	29	1,045	70
.22 Long Rifle	1.000	32	1,430	145
.22 Long Rifle Stinger	1.000	30	1,640	179
.17 PMC Aguila	.945	20	1,850	151
.17 Hornady Mach II	1.000	17	2,100	166
5mm Remington Rimfire Magnum	1.300	38	2,100	374
.17 Hornady Magnum Rimfire	1.349	17	2,650	265
.22 Winchester Magnum Rimfire	1.350	30	2,300	352
.17 Winchester Super Magnum	1.590	20	3,000	399

Table 3. Rimfire cartridge performance.

limitations of the rimfire case, rimfire cartridges are relegated to small calibers designed to fit into small pistol and rifle actions. The modern rimfire cartridge can be found in straight-walled and bottleneck types, in .17 (.17 HMR) and .22 (.22 Long Rifle) calibers. There is also a small segment of rimfire "shotshells," which are rimfire caliber cartridges like the .22 LR that fire small diameter (#10 – #12) birdshot.

Rimfire cartridges have found use with almost all firearm types. All types of pistols, including revolvers, single shots, and semi-automatics, as well as all rifle types, including bolt, lever, pump, and semi-automatic, have models chambered for a rimfire cartridge. This is part of the success of the rimfire cartridge and why it is the most widely used cartridge type in the world. Many firearms chambered for full sized pistol and rifle cartridges have also found success with offering similar models chambered for rimfire cartridges. This allows training on a familiar platform without the cost and recoil of a larger cartridge.

At the moment, the largest and most powerful rimfire chambering for any rimfire firearm is the .17 Winchester Super Magnum, a bottleneck cartridge. At the moment, the largest chambering for a semi-automatic rimfire pistol is the .22 Winchester Magnum Rimfire, a straight-walled cartridge. The average rimfire cartridge has an effective range of about 75 – 100 m. Even the mighty .17 WSM is only effective to around 250 m

Figure 18: Various shotshell cartridges.

Shotshell Cartridge Performance				
Cartridge	**COAL Fired (Inches)**	**Projectile Weight (Grains)**	**Velocity (Feet-Per-Second)**	**Muzzle Energy (Foot-Pounds)**
.410 Bore Slug	3”	109 (¼ oz.)	1,800	784
28-Gauge #8 Birdshot	2¾”	328 (¾ oz.)	1,286	1,204
20-Gauge #3 Buckshot	2¾”	437 (20 Pellets 1 oz.)	1,200	1,397
16-Gauge #6 Birdshot	2¾”	464 ($^{11}/_{16}$ oz.)	1,330	1,822
12-Gauge #7.5 Birdshot	2¾”	492 (1⅛ oz.)	1,200	1,572
12-Gauge 00 Buckshot	2¾”	~464 (9 Pellets 1 1/16 oz.)	1,180	1,434
12-Gauge Slug	3”	437 (1 oz.)	1,700	2,803
10-Gauge Slug	3½”	765 (1¾ oz.)	1,280	2,782

Table 4. Shotshell cartridge performance.

(275 yd.). Most rimfire cartridges will be utilized between 25 and 75 yd.

Outside of the pressure restrictions of the case, projectile selection is probably the greatest limiting factor in rimfire cartridge performance. Although many rimfire projectiles are pushed near or beyond 2,000 fps, the light weight of the projectiles allows for more deceleration. The low SD and BC of rimfire projectiles leads to a bullet that cannot readily overcome air resistance and gravity. The light weight of the projectile is also the greatest limiting factor in rimfire cartridge energy. Even with velocities in excess of 2,000 fps, most rimfire cartridges produce between 150 and 250 ft-lb. of energy. Below is a chart comparing rimfire cartridge performance.

- **Shotshells –** Like rimfire cartridges, shotshells are simple to classify. Their distinguishable, hybrid case construction, rimmed case head, straight body, and star or roll crimped mouth are all identifying features of the shotshell. Shotshells are typically also the only cartridge type to fire more than one projectile and be fired through a smooth bore, although there are shotshells that feature a single projectile meant to be fired through a rifled bore. Shotshells are often straight-walled and rimmed in calibers ranging from .410 (.410 bore) to 10-gauge (.775 in.); however, smaller shotshells are often used for pest control and are meant for short ranges.

  Shotshells can be used in break, pump, lever, bolt, pistol/AOW, and semi-automatic actions. There are even a handful of revolvers that are chambered for the .410 bore cartridge. Other shotshell calibers include (in order of size) 28-gauge, 20-gauge, 16-gauge, 12-gauge, and 10-gauge.

  Because shotshells headspace against the rim of the case, they can almost be any length up to the maximum length of the chamber. For example, a 12-gauge shotgun with a 3½-in. chamber can safely chamber and fire shotshells from 1¾ to 3½ in., and even if the shells will not cycle in the action, they can be single loaded by hand and fired. This allows the shooter to use light and reduced recoil loads to train, compete, or plink with and then switch to full power or magnum loads for hunting or self-defense. This is part of the versatility that has granted the shotgun so much success.

  Another factor that has made the shotgun and shotshell so successful is projectile selection. With proper projectile selection, the shotshell can be utilized to harvest everything from birds and small game to bears, elk, and moose. Projectile selection also gives the shotgun a fairly wide effective range. Birdshot is effective out to about 50 yd., while buckshot can reach a bit farther out to 75 yd. Slugs will vary depending on whether they are fired from a smooth or rifled barrel but will typically have an effective range of 100 – 150 yd.

  What gives the shotshell its success is also its greatest performance limiting factor. Birdshot, buckshot, and slugs all have very low SD and BCs. Although the mass of the collection of projectiles is high, each individual pellet is often quite light compared to other projectile types. In contrast, the individual weight of a slug may be great, but it is also very blunt. The mass of the projectile(s) is the greatest contributing factor to the energy produced by shotshells. The average shotshell pushes the projectile(s) to around 1,300 fps and produces about 1,600 ft-lb. of energy. Table 4 is a chart comparing shotshell cartridge performance.

Figure 19: Handloading.

There are other cartridges that fall within the four major cartridge types but may not be standardized or factory manufactured. These cartridges may be loaded to be more accurate than factory ammunition to fill an existing performance gap or to fulfill a specialized purpose. These cartridges include:

- **Handloaded –** Handloaded cartridges are cartridges that are loaded by a person as opposed to being loaded in bulk by a machine. Handloading is utilized when the utmost consistency, reliability, and quality is desired, or to "tune" cartridges to a specific application. Handloaded cartridges can also be loaded in bulk, but there is little benefit (price or time) over commercially available bulk ammunition.

  A reloader (person who handloads) has control over every aspect of the loaded cartridge. Every projectile and case can be weighed and sorted for consistency and every propellant charge can be measured to a fraction of a grain (~.1 grains). Charge weights can also be tuned to increase velocity, accuracy, and precision, or to reduce recoil or signature. When seating bullets, great care can be taken to ensure every projectile is seated to the same exact depth, or seated past SAAMI recommended COAL for enhanced accuracy and precision. Loads (projectiles and charge weights) can be tuned for the greatest performance or reliability in a specific firearm. Handloading can be a slow and tedious process, but with patience, it can yield the greatest possible performance.

Wildcat – Wildcat cartridges are "custom" cartridges that have not (yet) been standardized by SAAMI. Wildcat cartridges are either brand new designs or designs modified from existing cartridges. The purpose of a wildcat cartridge is to fill a performance void or to increase the performance for a specific firearm platform.

A wildcat cartridge may utilize a case from one caliber and a projectile from another. Cases can be shortened, straight-walled cases can be tapered or have shoulders added and case mouths

Figure 20: Wildcat cartridges. From left to right: 6mm XC- A .250 Savage necked down to 6mm, .375 Reaper- A .308 Winchester shortened and necked up to .375, .277 Wolverine- A 5.56x45mm NATO case necked up to .277, .224 Montgomery Wildcat- A .25 ACP case necked down to .224.

can be "necked up" (increased in diameter) or "necked down" (decreased in diameter). Shoulders can also be moved back or "blown out" (moved forward). With some wildcat cartridges, the only modification may be that the angle of the shoulder is changed to increase case capacity. The rim of a rimmed or semi-rimmed cartridge may also be turned down to form a rimless or rebated rim cartridge. To lengthen a case, a new design must be utilized.

With some wildcat cartridges, the only thing that is needed to convert a firearm from one caliber to the new cartridge is a new barrel. Other conversions may require a new barrel, bolt, and modified feeding device. Sometimes, the wildcat cartridge is designed for a completely new firearm. A cartridge will remain a wildcat until it is adopted by the industry and standardized by SAAMI.

- **Subsonic –** Subsonic cartridges are standard calibers that are loaded with heavier-than-standard projectiles at slower-than-standard velocities. Subsonic cartridges are designed to be fired through suppressors to further reduce the signature of the shot. Projectiles traveling at supersonic velocities (~1,125 fps and above) produce a pressure wave ahead of the projectile that can be heard as a loud "crack" sound. Even when fired through a suppressor, supersonic rounds will still produce this crack sound. Projectiles moving at subsonic velocities (below 1,125 fps) do not produce the supersonic crack, thus reducing the shot's signature.

  While most pistol cartridges are naturally subsonic, specific loads have been developed to ensure the round is not moving faster than ~1,050 fps while still providing adequate muzzle velocity and energy. For example, the 9x19mm Parabellum has a standard loading consisting of a 115-grain projectile moving at about 1,180 fps, producing 355 ft-lb. of energy. A subsonic 9x19mm Parabellum may consist of a 165-grain projectile moving at around 900 fps, producing around 300 ft-lb. of energy.

The vast majority of rifle cartridges are supersonic, 2X – 3X over (2,250 fps – 3,375 fps/Mach II and III). When a rifle cartridge is loaded to subsonic velocities, the load often consists of a heavier-than-standard projectile and pistol propellant. While a standard rifle cartridge, like the 5.56x45mm NATO, consists of a 62-grain projectile moving at about 3,100 fps (producing ~1,322 ft-lb. of energy), a subsonic load may consist of a 130-grain projectile moving at 1,050 fps (producing ~ 318 ft-lb. of energy). The propellant selection for subsonic rifle rounds is crucial to the reliability and function of the cartridge. A low-density propellant is often utilized to help fill the empty space that would otherwise be filled with 2X – 3X more propellant.

Recently, with the sudden popularity of suppressors, there have been many new cartridges developed specifically for suppressed applications. One of the most popular suppressor cartridges is the .300 AAC Blackout. The Blackout is a .30 caliber cartridge designed to work in AR-15 and similar sized actions. The Blackout is a modified 5.56x45mm NATO case, shortened and necked up to .308. The blackout is capable of firing everything from 110-grain projectiles at 2,350 fps, to 220 – 230 grain projectiles at 1,050 fps. In many instances, the subsonic load utilizes a projectile that is longer than the case and leaves just enough internal volume for a small charge.

Figure 21: Cartridges next to subsonic bullets and their supersonic counterparts. From left to right: .300 AAC Blackout 190 grain (960 FPS/subsonic), 190 grain bullet, 212 grain bullet, 111 grain bullet (2,350 FPS/supersonic), 9x39mm 278 grain (1,050 FPS/subsonic), 278 grain bullet, .223 Winchester 130 grain (1,000 FPS/subsonic), 130 grain bullet, 55 grain bullet (3,240 FPS/supersonic), 9x19mm Parabellum 185 grain (950 FPS/subsonic), 185 grain bullet, 165 grain bullet, 115 grain bullet (1,200 FPS/supersonic).

Figure 22: Plinking ammunition. From left to right: 12 Gauge 2¾ in. #7.5 Birdshot, 20 Gauge 2¾ in. #7.5 Birdshot, 7.62x39mm, .223 Remington, .45 ACP, 9x19mm Parabellum, .22 Long Rifle.

INTENDED USE

Understanding the different cartridge types and their components is crucial to understanding why certain cartridges are used for some tasks. Like any task, the correct tool is crucial to proper or successful completion. The plethora of calibers, cartridge types, and projectile selection ensures there is a cartridge that will suit the task at hand. Always refer to federal, state, and local laws for the use of firearms and various ammunition types. The various uses for different cartridges include:

- **Plinking –** Plinking is a form of casual target shooting. It is usually done at non-standard shooting ranges, like home ranges, private or government-approved land, at non-standard targets like cans, bottles, pieces of metal, or other natural targets. The term "plink" is an example of onomatopoeia in that it comes from the sound of a projectile hitting a tin can or other small piece of metal. Plinking is more relaxed than other shooting types and does not face the same rules as a designated shooting range. This is not to say that people plinking are not following the universal safety rules, they are just not bound by range rules such as ammunition restrictions, fire rate, and designated targets. Plinking is also much cheaper than shooting at a traditional range because there is no range fee and you do not (typically) have to purchase targets or specialty ammo.

  Plinking is also much cheaper than other types of shooting because it often utilizes the cheapest bulk ammunition available. The most popular plinking cartridge is the .22 Long Rifle. The .22 LR is cheap to shoot, plentiful, with low recoil and low noise, and is the perfect cartridge for teaching new shooters. A shooter can fire hundreds of rounds of .22 LR a day without fatigue, sore shoulders or wrists, or headache from percussion. Other plinking ammunition includes cheap, bulk ball, or steel-cased ammo in a variety of popular calibers,

Figure 23: Long-range shooting cartridges. From left to right: .408 CheyTac- 419 grain solid projectile .949 G1 BC, .338 Lapua Magnum- 300 grain OTM .736 G1 BC, 6.5mm PRC- 147 grain polymer tipped VLD .697 G1 BC, .308 Winchester- 168 grain OTM .480 G1 BC, 6mm Creedmoor- 108 grain VLD .536 G1 BC, 6.5mm Creedmoor- 120 grain polymer tipped .450 G1 BC, .223 Remington- 77 grain OTM .372 G1 BC, 6.5 Grendel- 123 grain polymer tipped .510 G1 BC, .224 Valkyrie- 75 grain TMJ Match .400 G1 BC.

like the 9x19mm Parabellum, .45 ACP, .223 Remington or 7.62x39mm. When plinking with shotguns, the most popular calibers are 12- and 20-gauge utilizing birdshot (#7 - #9) shotshells.

- **Competition –** Competition shooting is more structured and serious than plinking. Competition shooting is done at traditional ranges with standardized sets of rules and regulations on officially sanctioned targets. While plinking is a more relaxed form of shooting, competitors are often placed in situations meant to mimic stresses. Competition shooting is often timed, and, in some instances, the shooter will have to run through or navigate a course. Competition shooting is a broad term for many different shooting sports, all with their own rules, regulations, and requirements. The various competition types include:

› **Target –** Target shooting is the most basic form of competition. With target shooting, the shooter and the target are (typically) stationary. The targets are standardized and are set at a specific distance (or distances) for every round of competition. The rate of fire is often very slow and the round count is often fairly low. The goal of the target shooter is the greatest possible accuracy and precision. Target shooting sports typically hold competitions for pistol (revolver and semi-auto) and rifle (bolt and semi-auto) shooters. Target competitions include bullseye, silhouette, and benchrest shooting.

Because target shooting is focused on accuracy and precision, the cartridges used are designed for the greatest possible consistency. Recoil is not really a concern because there is no need for rapid follow-up shots, so the ammunition is often full power. Pistol shooters will often utilize wadcutter bullets to create the most precise holes in the target for the most accurate scoring. Match ammunition and projectiles are also very popular with target shooting. Often, target shooters will handload their own ammunition, ensuring the greatest possible consistency. Handloading their own ammunition ensures the greatest possible accuracy and precision because the loads are tuned to the specific firearm they are being fired from. Calibers are often the preference of the shooter but must usually fall between a minimum and maximum size.

- **Action Shooting –** Action shooting is a form of competition that is in drastic contrast to target shooting. With action shooting, the competitor must navigate through courses of varying targets, which may also be moving. The rate of fire is often very high, with less emphasis on precision and more focus on speed. Unlike target shooting, where winning is based on how many shots are in the "bullseye," action shooting relies on a combination of time and target "zones." As long as a shot falls within a zone (typically the "A" zone), there is no time penalty added to the score. Action shooting sports typically hold competitions for pistol (revolver and semi-auto), rifle (almost exclusively semi-auto and some lever-action), and shotgun (both pump and semi-auto). Action shooting competitions include USPSA, IDPA, IPSC, 2-Gun, 3-Gun, and Cowboy Action.

Figure 24: Clay shooting cartridges.

Because action shooting is focused more on speed than precision, the cartridges used are often the cheapest bulk ball rounds available. Recoil is more of a concern with action shooting competitions because it limits the ability for rapid follow-up shots. Many competitors will handload cartridges to reduce recoil and allow for faster shooting and sight tracking. Action shooting competitions often require a minimum caliber (usually 9x19mm Parabellum, .223 Winchester, and 12-gauge) and cartridges to meet a specific "power factor," which is a product of projectile weight and velocity. Shotgun action shooting will utilize a variety of birdshot, buckshot, and slugs for different target types.

- **Long-Range** – Long-range shooting competition is a mixture of target and action competition. Long-range competition is similar to target shooting in that the targets are 300 – 600+ yd. away and require a great degree of precision. Long-range competition is similar to action shooting in that shooters compete in dynamic stages while under time constraints. The round count may not be as high as action shooting, but the rate of fire may be high. Long-range shooting competition is also similar to action shooting in that hits count anywhere on the target scoring zone and do not need to fall within a bullseye. Long-range shooting sports only hold competitions for precision bolt-action rifles. Long-range shooting competitions include PRS, NRA High Power, and F-Class.

  Because long-range shooting is focused on precision shooting at great distances, the cartridges used are often built to match standards, which means VLC and polymer tipped projectiles with very high SD and BCs, consistent propellant charges from round-to-round, cases with

Figure 25: Small game cartridges. From left to right: .243 Winchester, .410 Bore 2½ in. in. #9 Birdshot, .223 Remington, .17 Hornet, .17 Winchester Super Magnum, .22 Winchester Magnum Rimfire.

Figure 26: Medium game cartridges. From left to right: .30-06 Springfield, .308 Winchester, .234 Winchester, 12 Gauge 3 in. 00 Buckshot, .30-30 Winchester, .250 Savage, 12 Gauge 2¾ in. Slug, .44 Remington Magnum, .357 S&W Magnum.

uniform dimensions and volume, and benchrest primers. Competitors that do not utilize factory match ammunition will often handload their rounds. Like other shooting sports, long-range competitions will typically have stipulations on caliber and cartridge performance. Some of the most popular calibers include many different cartridges in .223, .264 (6.5mm) and .308.

- **Trap, Skeet, and Sporting Clays –** Trap, skeet, and sporting clay competitions are shotgun shooting sports that consist of shooting clay "pigeons"from varying directions. Trap competition consists of clay pigeons that move away from the shooter from a single position. Skeet competition consists of two pigeons that cross in front of the shooter from positions on either side of the shooter. Sporting clay competition consists of multiple clays moving from varying positions. Scoring is accomplished by hitting the clay and breaking it in the air or on the ground. Trap, skeet, and sporting clay competitions are shot exclusively with shotguns (break, pump, and semi-auto).

  Because clay shooting is done exclusively with shotguns, only shotshell cartridges are used. The projectiles of choice are always birdshot in sizes from #9 – #7. The most popular caliber is 12-gauge, with 20-gauge a close second.

- **Hunting –** Hunting is the process of harvesting animals for food, sport, or necessity/safety. Because of the immense amount of game types, it would be difficult to categorize hunting into a single type. To add confusion to things, all hunting is not accomplished with a firearm. Some types of hunting are accomplished through trapping, while others are done with a bow or crossbow. Various forms of hunting utilize pistols, rifles, shotguns, and rimfire firearms.

Figure 27: Big game cartridges. From left to right: .300 Winchester Magnum, .270 Winchester, .30-06 Springfield, 6.5mm Remington Magnum, .444 Marlin, .45-70 Government, .460 S&W Magnum, .500 S&W Magnum.

It may be easiest to classify the types of hunting by the size of the game. Varmint animals typically include pests like rodents, prairie dogs, and squirrels, predators like badgers, bobcats, foxes, coyotes, raccoons, and snakes, and invasive species like crows, ravens, starlings, and (small) wild boars. Many of these species are hunted because they pose a danger to crops, farm animals, and humans. They are not typically hunted to harvest meat, although some species are. Small game animals include rabbits, pheasants, geese, and ducks. Many of these species are hunted to harvest meat. Either way, these small animals are hunted the same way. Cartridges used for small game hunting include a variety of rimfire cartridges and small caliber (.17 and .22) centerfire cartridges utilizing hollow point, soft point, or polymer tipped projectiles. Shotshells are also used, loaded with birdshot (#7 – #12) in 20-gauge, 28-gauge, and .410 bore. Rodents and other small mammals are typically dispatched with small diameter birdshot or rimfire cartridges. Rabbit or bird intended for meat is typically dispatched with birdshot in sizes ranging from #7 – #9 to minimize damage to the meat. Many predators are dispatched with larger rimfire calibers such as the .22 Winchester Magnum Rimfire or the

Figure 28: Dangerous game cartridges. From left to right: .338 Lapua Magnum, .458 Lott, .375 H&H Magnum, .458 Winchester Magnum.

.17 Winchester Super Magnum, or small centerfire cartridges, like the .17 Hornet, .223 Winchester or .243 Winchester, to minimize pelt damage.

Medium game animals include deer, goat, sheep, pronghorn, antelope, and larger wild boars. Almost all species of medium game are hunted for meat, while some are hunted as trophies. Cartridges used for medium game hunting include centerfire pistol, rifle, and shotshell. Energy levels recommended for medium game are 800 ft-lb. and above.[1] Cartridges used for medium game hunting are always full power, with hollow point, soft point, and polymer tipped projectiles. Calibers used for medium game hunting include .243 Winchester, .250 Savage, .30-30 Winchester, .308 Winchester, .30-06 Springfield, 7mm Remington Magnum, 8mm Remington Magnum, .357 S&W Magnum, .44 Remington Magnum, and 12-gauge (buckshot and hollow point slugs).

Big/large game animals include elk, moose, caribou, muskox, bison, cougar, and several varieties of bear. Most species of big game are hunted for meat, while many others are only taken as trophies. Cartridges used for large game hunting include centerfire rifle and shotshells, with a few pistol examples. Energy levels recommended for big game are 1,200 ft-lb. and above.[2] Cartridges used for big game hunting are always full power or magnum, with hollow point, soft point, or polymer tipped projectiles. Calibers used for big game hunting include 6.5mm Remington Magnum, .270 Winchester, .30-06 Springfield, .300 Winchester Magnum, .338 Federal, .358 Norma Magnum, .444 Marlin, .45-70 Government, .460 S&W Magnum, and .500 S&W Magnum. These cartridges are also well-suited for small, thin skinned, dangerous game such as leopards, jaguars, and Russian wild boars.

Figure 29: Self-defense cartridges. From left to right: .300 AAC Blackout- 168 grain expanding frangible, .223 Remington - 73 grain polymer tipped, 12 Gauge 2¼ in. reduced recoil 00 buckshot, 12 Gauge 1¾ in. reduced recoil slug, .45 ACP- 180 grain polymer tipped, 9x19mm Parabellum- 135 grain polymer tipped, .380 ACP- 90 grain hollow point, .380 ACP- 102 grain hollow point.

Larger, thin-skinned dangerous game, such as lions, tigers and grizzly bears, require more power. The minimum energy level recommended for these animals is 2,000 ft-lb. and above.[3] Cartridges for hunting large, thin-skinned dangerous game include the .30-06 Springfield and 7mm Remington Magnum.

Large, thick-skinned dangerous game include cape buffalo, hippo, rhino, and elephant. Most species of thick-skinned dangerous game are only hunted for trophies. Cartridges used for thick-skinned dangerous game are almost exclusively centerfire rifles. Energy levels recommended for dangerous game are 3,500 ft-lb. – 5,000+ ft-lb.[4] Cartridges used for dangerous game include large caliber bottleneck, straight wall, and belted cartridges utilizing solid or jacketed FMJ projectiles. The reason hollow points or other expanding projectiles are not used is that the projectile must make it through the thick hide and heavy shoulder bone before reaching the internal organs. Expanding projectiles would open too soon and not penetrate deep enough. Calibers used for dangerous game include .338 Lapua Magnum, 416 Rigby, .458 Winchester Magnum, .458 Lott, .470 Nitro Express, and .500 Nitro Express.

- **Self-Defense –** Every person in the world has the natural right to defend themselves against threat of death or injury, but only Americans (and citizens of a few other countries) have the right to defend themselves (and sometimes their property) with a firearm, which is specifically written into the constitution of the land. Self-defense with a firearm is one of the most serious undertakings a civilian can take on. Self-defense may not only be a matter of life and death for yourself and others; there are also serious legal ramifications involved. This information is not intended to advise you when to use deadly force; it is intended to inform you of the best choice of ammunition.

  Self-defense is a very general term that covers the various ways a person may defend themselves. The means by which you defend yourself will change from individual to individual. While some individuals can manage the recoil of large caliber cartridges, others may not be able to and require smaller calibers. When you think about your daily activities, you will typically move through a handful of environments: your home, your vehicle, your workplace, and out in public areas. When selecting the appropriate cartridge for self-defense, you must consider the different variables in each environment.

  The caliber and cartridge you choose for self-defense will depend on several factors. Personal ability, experience, and skill will all dictate your cartridge choice. Shooters with more skill, experience, and ability may choose a larger, more powerful cartridge, while inexperienced shooters may choose a smaller, less powerful cartridge.

  Considering surroundings, when you are inside your home, is it a rural, urban, or suburban environment? Do you live in a house in the middle of nowhere, or do you live in an apartment with your closest neighbor only feet away? In your vehicle, what obstacles or barriers would you need to shoot through? In your place of work, what is the arrangement of the office or the work site and the area around it? When in public, is it a densely populated area?

  So, what is the best cartridge choice? Some people will strongly support one cartridge over all others, either because it has more stopping power, less recoil, higher capacity, or has a great "spread." The best cartridge selection, however, is going to be based on your preference,

Figure 30: Military cartridges. From left to right: .50 BMG M2, 7.62x51mm NATO M80A1, 7.62x51mm NATO MK319 MOD 0, 5.56x45mm NATO M855A1, 5.56x45mm NATO MK318 MOD 0, .45 ACP, 9x19mm NATO, 7.92x57mm Muaser, 7.62x54mmR, 5.45x39mm, 7.62x39mm, 7.65mm Browning Short.

skill, ability, and personal scenario. While larger calibers are going to have greater stopping power, they are more likely to over-penetrate and be slower for follow-up shots. Smaller cartridges may be easier to manage recoil, quicker with follow-up shots, and provide greater capacity, but they may not have enough energy to incapacitate a threat immediately.

While in an urban or suburban environment, over-penetration is a serious issue. Whether you hit or miss your intended target, the projectile may continue to travel through internal and external walls, creating a risk for people on the other side of the walls. In public environments, powerful cartridges create a risk of missing your intended target on follow-up shots from heavy recoil, creating a risk for other people in your surroundings. While in your vehicle, smaller cartridges may fail to deliver enough energy to pass through glass or sheet metal and effectively penetrate the target.

Self-defense cartridges are available for pistols, rifles, and shotguns in a variety of calibers and types, with both centerfire and some rimfire. Most self-defense cartridges utilize expanding projectiles, such as hollow points and polymer tipped, to limit over-penetration. Propellant charges may be reduced for those that are recoil sensitive or increased to +P and +P+ loads for those who want more energy. A +P or +P+ load features an increased amount of propellant for more pressure and energy. While +P and +P+ ammunition utilizes more pressure, it is still within a SAAMI recommended safe load. While many pistol cartridges may see an increase of energy, many rifles and shotshell cartridges will see a decrease in energy to reduce recoil and over-penetration. Shotshells may utilize a smaller birdshot or buckshot load or use lighter slugs. Shotshells may also utilize a mixture of bird/buckshot and slugs to create a balance of penetration and energy. Often, another feature of self-defense ammunition is nickel coated cases. The coating creates a barrier or corrosion and tarnish resistance, while increasing the reliability of the cartridge when loading and extracting.

- **Military** – Cartridges designed for military use are used in a primarily offensive application. There is often little to no concern for recoil or over-penetration. In fact, many cartridges are designed to penetrate as many barriers as possible. Military cartridges are designed to be manufactured cheaply in bulk. Although accuracy and precision are a concern, most cartridges will be fired in volume through automatic weapons. There are cartridges that are designed for precision, but they are reserved for sniper and DMR applications. There is also a variety of specialty ammunition available for various tasks.

  Most military cartridges are designed with ball or FMJ projectiles, extruded propellants, thicker-than-standard cases, and sealed primers and projectiles. The propellant charges are also greater than cartridges designed for civilian use, pushing chamber pressure to the maximum safest level. Military cartridges also utilize specialty projectiles such as AP, OTM, tracer, incendiary, and explosive. The tips of the projectiles are often painted to help identify cartridge types. Black tips are typically AP, while the tracer is red/orange, the incendiary may be silver or blue and silver, and the explosive is usually green and white. U.S. military calibers include 9x19mm NATO, .45 ACP, 5.56x45mm NATO, 7.62x51mm NATO, .300 Winchester Magnum, .338 Lapua Magnum, .50 BMG and 12-gauge.

NOTES

NOTES

Firing Sequence and Internal/Interior Ballistics

Now that we have a good understanding of how a cartridge works, let's hypothetically place one in a firearm to get a complete picture on ballistics. We will begin with internal ballistics: that which is occurring inside the firearm while the cartridge is being discharged. To be able to understand internal ballistics, we first need to understand the firing sequence.

NOTE: Many of the calculations use figures that are rounded to various decimal places. If you are following along with your own calculations, just note there may be slight variances in the results.

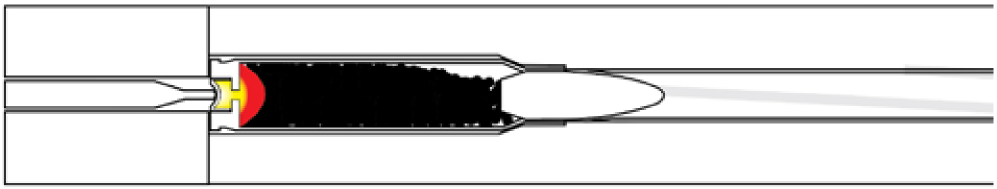


Figure 1a: The firing pin crushes the primer and initiates ignition.

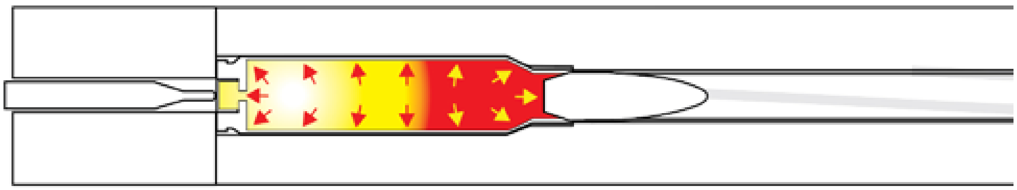


Figure 1b: As the propellant burns, the case exapnds and the bullet begins to move into the throat of the barrel.

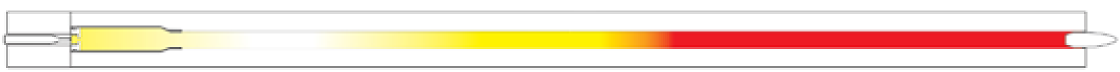


Figure 1c: As the pressure rises from the expanding gas the bullet is driven through the rifling and bore.

FIRING SEQUENCE

The firing sequence is a series of events that occur when there is a live cartridge locked in the firearm's chamber and the trigger is squeezed. Regardless of the action type, the firing sequence is always the same. The firing sequence is as follows:

1. The trigger is squeezed, releasing the hammer or the striker.
2. The hammer strikes the firing pin and the firing pin or striker strikes the cup of the primer. The priming compound in the primer is crushed between the primer cup and the anvil, creating ignition.
3. The flame, spark, and pressure produced travel through the flash hole(s), igniting the propellant in the case.
4. The burning propellant is converted into rapidly expanding gas that further pressurizes the case.
5. The cartridge case begins to expand and seal the chamber at the same time the pressure in the case builds to a great enough level to overcome the crimp. The projectile is driven from the case into the throat of the chamber.
6. The continually increasing pressure inside the chamber drives the projectile through the bore and out of the muzzle.
7. Once the projectile exits the muzzle, the pressure inside the bore and chamber will rapidly dissipate and the cartridge case will begin to contract.

The process sounds fairly simple, right? But let's take another look at the firing sequence with all of the factors addressed. You will quickly discover that the process is anything but simple.

Although the process is fairly similar between various cartridges and firearm types, we will discuss the remainder of the firing sequence as it applies to an AR-15, striker-fired pistol, pump-action shotgun, and a rimfire revolver.

The specs* for the firearms include:

AR-15:

- Caliber: .223 Remington
- Bullet weight: 55 grains
- Bullet diameter: .224 in.
- Bullet length: .745 in.
- Ballistic coefficient: .237
- Charge weight: 26 grains (Hodgdon BLC-2)
- Case length: 1.760 in.
- Cartridge OAL: 2.180 in.
- Bullet seating depth: .325 in.
- Velocity: 2,900 fps
- Energy: 1,027 ft-lb.
- Chamber pressure: 50,100 psi
- MAP: 55,000 psi
- Barrel length: 16
- Throat length (freebore): .085 in.
- Groove diameter: .224 in.
- Bore diameter: .219 in.
- Twist rate: 1 in 8 in.
- Firearm weight: 7 lb.

Figure 2a: AR-15.

Striker-Fired Pistol:

- Caliber: 9x19mm Parabellum
- Bullet weight: 115 grains
- Bullet diameter: .355 in.
- Bullet length: .549 in.
- Ballistic coefficient: .158
- Charge weight: 4.8 grains (Hodgdon Titegroup)
- Case length: .754 in.
- Cartridge OAL: 1.169 in.
- Bullet seating depth: .134 in.
- Velocity: 1,140 fps
- Energy: 332 ft-lb.
- Chamber pressure: 32,300 psi
- MAP: 35,000 psi
- Barrel length: 4 in.
- Throat length (freebore): .1718 in.
- Groove diameter: .355 in.
- Bore diameter: .346 in.
- Twist rate: 1 in 10 in.
- Firearm weight: 1.5 lbs.

Figure 2b: Striker-fired pistol.

**Figures are averages from www.hodgdonreloading.com reloading data and www. saami.com chamber and cartridge drawings.*

Pump-Action Shotgun in.

- Caliber: 12-gauge 3 in.chamber, 2¾ in. shell
- Projectile weight: 7/8 oz. birdshot (383 grains) #7.5
- Ballistic coefficient: .02
- Charge weight: 20.5 grains (Hodgdon Clays)
- Case length: 2.405 in.
- Cartridge OAL: 2.405 in. (folded crimp)
- Length unfolded: 2.760 in.
- Shot seating depth: .986 in.
- Velocity: 1,275 fps
- Energy: 1,382 ft-lb.
- Chamber pressure: 10,200 psi
- MAP: 11,500 psi
- Barrel length: 20 in. (smooth bore, no choke)
- Forcing cone length: .4272 in.
- Bore diameter: .725 in.
- Firearm weight: 7 lb.

Figure 2c: Pump-action shotgun.

Single Action Revolver:

Caliber: .22 Long Rifle

Bullet weight: 40 grains

Bullet diameter: .2255 in.

Bullet length: .5 in.

Ballistic coefficient: .138

Charge weight: 1.9 grains (Vihtavouri 3N37)

Case length: .613 in.

Cartridge OAL: 1 in.

Bullet seating depth: .113 in.

Velocity: 1,110 fps

Energy: 109 ft-lb.

Chamber pressure: 22,500 psi

MAP: 24,000 psi

Barrel length: 5 in.

Throat length (freebore): .826 in.

Groove diameter: .222 in.

Bore diameter: .217 in.

Twist rate: 1 in 16 in.

Cylinder length: 1.439 in.

Cylinder gap length: .006 in.

Firearm weight: 2 lb.

Figure 2d: Single-action revolver.

We will start with the cartridge locked in the chamber. Because of manufacturing variances between the firearm manufacturer and the ammunition manufacturer, it is unlikely that the cartridge is concentric with the chamber and bore (regardless of how precise each individual component is). Let's take four different cartridges as examples: the .223 Winchester, the 9x19mm Parabellum, the 12-gauge birdshot, and .22 Long Rifle. The SAAMI specifications for each cartridge are as follows:

.223 Remington:

Cartridge case length:* 1.4596 in. – 1.4666 in.

Cartridge case diameter: .368 in. – .378 in.

Chamber length: 1.4636 in. – 1.4736 in.

Chamber diameter: .3804 in. – .3824 in.

This means that a .223 Remington cartridge manufactured to the smallest dimensions can be up to .014 in. shorter and .0144 in. smaller in diameter than a chamber manufactured to the greatest dimensions. Because most shooting is done with the firearm level or nearly level to the earth's surface, we can safely assume the cartridge is resting on the "bottom" of the chamber. With a small cartridge and a large chamber, the centerline of the cartridge can be as much as .0072 in. below the centerline of the bore; however, the shoulder of the casing will help align the centerline of the projectile with the centerline of the bore.

**To point of headspace on shoulder.*

9x19mm Parabellum:

Cartridge case length: .744 in. – .754 in.

Cartridge case diameter: .384 in. – .394 in.

Chamber length: .754 in .– .776 in.

Chamber diameter: .395 in. – .399 in.

This means that a 9mm cartridge manufactured to the smallest dimensions can be up to .022 in. shorter and .015 in. smaller in diameter than a chamber manufactured to the greatest dimensions. With a small cartridge and a large chamber, the centerline of the cartridge can be as much as .0075 in. below the centerline of the bore.

12-Gauge 2¾ in.:

Cartridge case diameter: .777 in.– .797 in.

Chamber diameter: .798 in.– .803 in.

This means that a 12-gauge cartridge manufactured to the smallest dimension can be up to .026 in. smaller in diameter than a chamber manufactured to the greatest dimension. With a small cartridge and a large chamber, the centerline of the cartridge can be as much as .013 in. below the centerline of the bore. With shotshells, case length and chamber length are irrelevant because the cartridge headspaces off of the rim. It is quite common to use shorter cartridges than the shotgun is chambered for.

.22 Long Rifle:

Cartridge case length: .605 in. – .613 in.

Cartridge case diameter: .222 in.– .226 in.

Chamber length: .818 in.

Chamber diameter: .227 in. – .229 in.

This means that a .22 Long Rifle cartridge manufactured to the smallest dimensions can be up to .007 in. smaller in diameter than a chamber manufactured to the greatest dimension. With a small cartridge and a large chamber, the centerline of the cartridge can be as much as .0035 in. below the centerline of the bore. With rimfire cartridges, case length and chamber length are irrelevant because the cartridge headspaces off of the rim.

Luckily, most manufacturers (firearms and ammunition) will meet somewhere in the middle and most cases will be somewhere around .003 in. – .004 in. undersized, placing the cartridge around .0015 in. – .002 in. off the centerline of the bore. A difference of only a few thousandths of an inch is perfectly within spec and will not strain the cases (too much) when they expand to seal the chamber. If a small case had to expand to the greatest chamber dimensions, it could

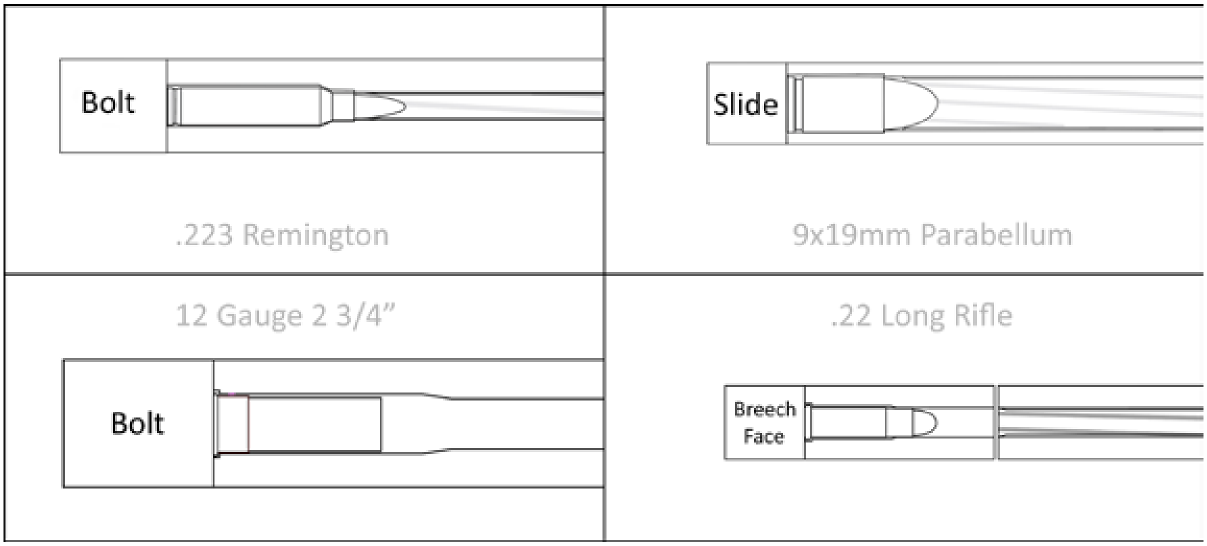


Figure 3: Cartridges sitting in a chamber.

lead to an array of issues from gas blowback to split cases.

Because the barrel length is measured from the bolt/slide face to the end of the muzzle, the projectile already has a head start in the barrel. The position of the projectile is dependent on the caliber and the seating depth. The projectile will be seated roughly as deep as the case mouth, but its position will vary based on the depth of its seating in the case. For example, a .223 Remington case is roughly 1.760 in., a 9mm is .754 in., a 12-gauge is 2.405 in., and a .22 is .613 in. With a .745 in. long bullet seated .325 in. in the case, the .223 bullet will travel roughly 14.565 in. (starting 1.435 in. deep from the breech face in the chamber of the barrel) before exiting the muzzle. With a .549 in. long bullet seated .134 in. in the case, the 9mm bullet will travel roughly 3.38 in. (starting .62 in. deep from the breech face, in the chamber of the barrel). The 12-gauge shot is seated roughly .986 in. in the case, meaning it must travel 18.581 in. (starting 1.419 in. deep from the breech face, in the chamber of the barrel) before exiting the muzzle. With a .5 in. long bullet seated .113 in. in the case, the .22 bullet will travel roughly 4.5 in. (starting .5 in. deep from the breech face, in the chamber of the cylinder).

With the shotshell, the projectile(s) (and wad/cup) will also move through part of the chamber when using a 2¾ in. shell in a 3 in. chamber. A crimped shell is roughly 2.405 in. long. With the crimp unfurled, the case is only 2.760 in. long. In a 3 in. chamber, the projectiles will move .24 in. through the chamber (after exiting the case) before reaching the forcing cone.

Currently the only forces the cartridge and firearm are experiencing are static friction. The projectile (or birdshot) experiences static friction from the case and crimp, while the case experiences static friction against the bottom of the chamber. When the trigger is squeezed, things begin to get interesting.

SQUEEZING THE TRIGGER

All of these forces can create disruptions in the point of aim (POA)/point of impact (POI) of the firearm. The duration of the ignition sequence can exacerbate these disruptions. The time from which the hammer/striker is released from the sear to the point where the firing pin/striker contacts the primer cup is known as lock

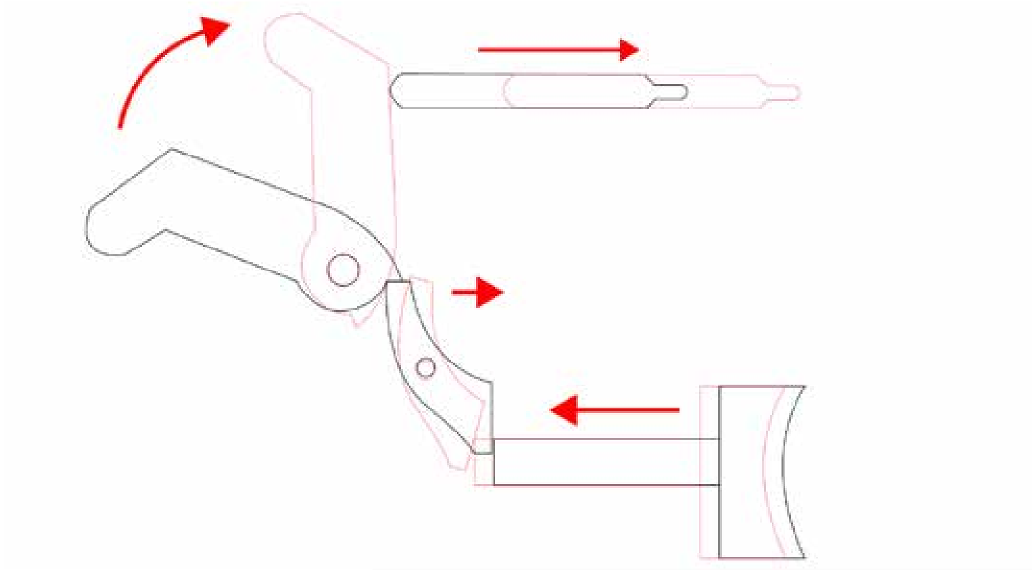


Figure 4: Hammer-fired sequence of events.

time. A longer lock time allows for a greater duration in which the firearm's POA can be disrupted, while a quicker lock time does not allow as much disruption. With all things being equal (parts mass, spring rates, travel), striker-fired firearms will inherently have quicker lock times because there are fewer moving parts. Lock times vary with firearm type and mechanism, but the average lock time is around 2 – 3 milliseconds (.002 – .003 seconds), while some of the fastest actions clock in at ~1.4 milliseconds (.0015 seconds). Slower lock times can be as long as 5 – 6 milliseconds (.006 seconds).[1]

Squeezing the trigger will yield the same results, regardless of action type, but by different means. Hammer-fired firearms (AR-15, pump-action shotgun, single-action revolver) utilize a two-part ignition system, while striker-fired firearms utilize a one-part system. When the operator squeezes the trigger on a hammer-fired action, they must overcome several forces before the hammer is released. First, the operator must overcome the trigger return spring. Depending on design, the spring may be a coiled, compressive spring, or a torsion spring rated anywhere from .5 – 2 lb. As the trigger rotates around its pin (sliding friction), the sear surface of the trigger or the sear itself will begin to move across the hammer's hooks (shearing, sliding friction). The hammer's hooks exert a substantial amount of force against the sear surface because the hammer utilizes either a heavy compressive or torsion spring rated between 4 and 16 lb. The sum of all forces typically equates to a trigger "pull" between 3.5 lb. and 6 lb. With revolvers, other action parts, such as the hand, bolt, and associated linkage and springs, are engaged when squeezing the trigger, so there is an increase in force required.

As the sear surface of the trigger/sear clears the hammer's hooks, the potential energy stored in the hammer spring is released, driving the hammer around the hammer pin and into the firing pin. The momentum/energy from the hammer (hammer mass + hammer velocity) is transferred to the firing pin, which begins to move forward. The energy of the firing pin is focused on the point of the firing pin when contacting the primer. The firing pin must overcome its own inertia and sliding friction (inside the firing pin channel) to provide enough energy to properly crush the primer cup/rim. The firing pin may also have to overcome the (compressive spring) force of a firing pin return spring.

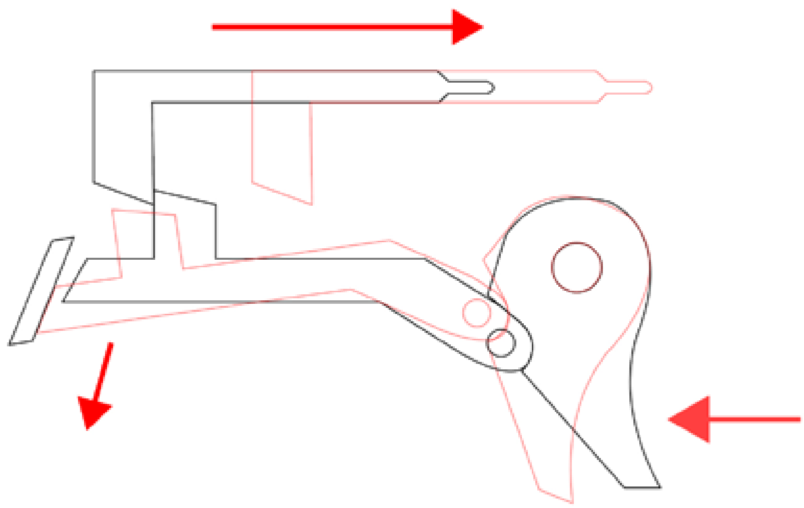


Figure 5: Striker-fired sequence of events.

When the operator squeezes the trigger on a striker-fired action, they must overcome several forces before the striker is released. First, the operator must overcome the trigger return spring. Depending on design, the spring may be a coiled, compressive spring, or an extension (tension) spring rated anywhere from .5 to 2 lb. As the trigger rotates around its pin, linkage connected to the trigger forces the sear face of the linkage or a separate sear to move across the sear surface of the striker. The striker's sear surface exerts a substantial amount of force against the sear's surface because the striker utilizes a heavy compression spring rated around 4 to 6 lb. The sum of all forces typically equates to a trigger "pull" between 3.5 and 6 lb.

As the sear's surface clears the sear surface on the striker, the potential energy stored in the striker spring is released, driving the striker forward into the primer cup/rim. The energy of the striker is focused on the point of the striker when contacting the primer/rim. The striker must overcome its own inertia and sliding friction to provide enough energy to properly crush the primer cup/rim.

IGNITION

The striker will deform the surface of the primer cup/rim, creating an indentation that will crush the priming compound between the cup and anvil/rim. Being shock sensitive, the small amount of priming compound detonates. The reaction creates flame and spark in the form of molten metal (aluminum, magnesium, zirconium, titanium, nickel, zinc or bismuth), with flame temperatures reaching 3000°+ F and the various metal powders reaching 2,000°+ F (1,220°, 1,200°, 3,371°, 3,040°, 2,647°, 787°, and 521 °Fahrenheit respectively[2]).

The flame and spark are forced through the flash hole(s) and onto the propellant (or directly onto the propellant with a rimfire cartridge). The reaction also produces enough gas to begin to pressurize the case. This will accelerate the propagation and reaction of the propellant's ignition. With centerfire cartridges, the pressure created is substantial enough to push the primer cup from the primer pocket until it contacts the breech/bolt/slide face. The pressure is also great enough to drive the projectile from the mouth of the case. The entire reaction lasts about 200 to 1,500 microseconds (.0002 – .0015 of a second).[3]

BUILDING PRESSURE

Once the flame and spark from the priming compound contacts the individual granules of propellant, they will begin to ignite (*exothermic reaction*). As the kernel burns or *deflagrates*, potential (chemical) energy stored in the kernel is converted into kinetic energy (expanding the case and moving the projectile), as well as into thermal energy (heat), light energy (flash), and sound. Smokeless propellant produces roughly 200 – 250 ft-lb. of energy per grain of propellant (energy density).[4]* This means that a .223 Remington cartridge with 26 grains of propellant would have roughly 5,850 ft-lb. of potential energy.** A 9mm cartridge (4.8 grains) would have 1,080 ft-lb. of potential energy, a 12-gauge cartridge (20.5 grains) would have 4,600 ft-lb. and a .22 LR cartridge (1.9 grains) would have 428 ft-lb. of energy. Only a fraction of the propellant's potential energy (20 percent – 30 percent) will actually contribute to the projectile's muzzle energy; much more of it will be lost to friction, heat, and other parasitic factors (70 percent +).

**Converted from megajoules per kilogram (MJ/kg) to foot-pounds per grain (ft-lb./gr).*

***Using an average energy density of 225 ft-lb. per grain of propellant.*

The individual kernel undergoes a phase transition known as *sublimation*, which occurs when a solid is converted directly into a gas and bypasses the liquid phase. As an individual kernel is ignited by the primer's flame and spark, it will begin to ignite surrounding kernels that are touching through an *endothermic* reaction. The propellant's load density, the efficiency of the primer, and several other factors, including propellant type, positioning, and case volume, will dictate how much of the initial powder charge is ignited by the primer.

.05 MILLISECONDS

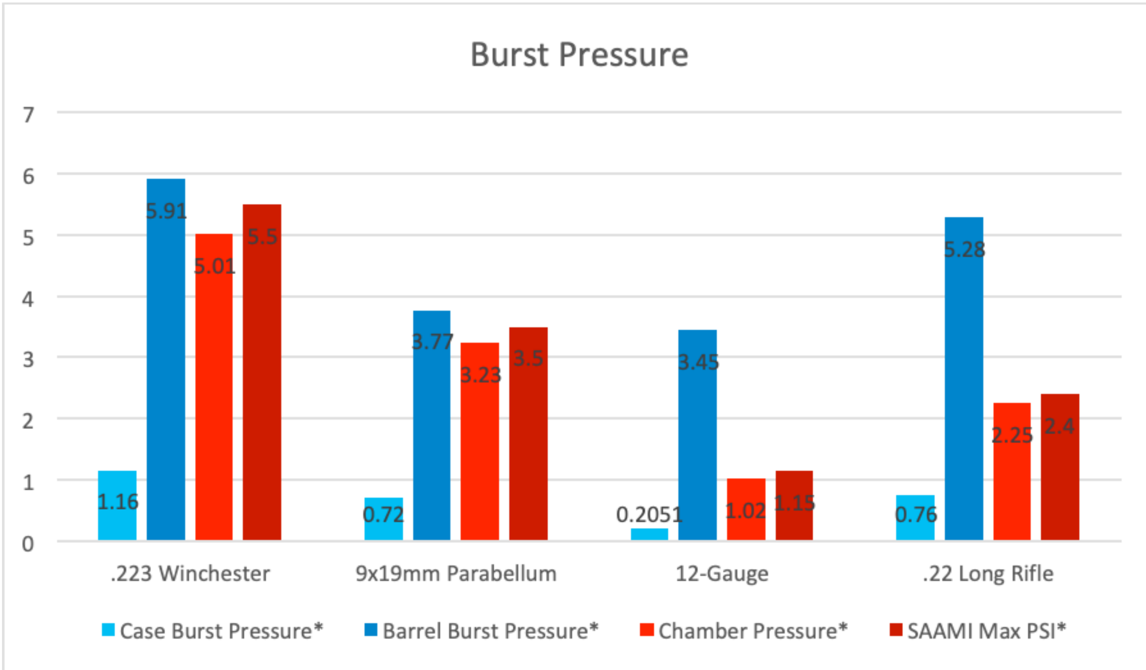
As each individual kernel ignites and releases its energy, the cartridge case continues to pressurize and begins to expand. The pressure from the rapidly expanding gas acts equally in all directions, pushing against the projectile (or cup/wad) and forcing the case to swell and stretch. Because the case is already bottomed out against the forwardmost point of contact with the chamber, the case will swell to seal the body of the case with the chamber walls and stretch to seal the case head against the bolt/breech/slide face. The case's rate of expansion will vary based on the case material and wall thickness, but polymer cases will expand faster than brass, aluminum, and steel respectively.

So far, roughly .00005 seconds have passed, and chamber pressure has reached nearly 7,400 psi for the .223 Remington. The .223 bullet has moved roughly .012 in. and is now positioned about 1.447 in. (from the breech face) in the chamber of the barrel. The bullet is currently moving at a velocity of 38 fps.

The 9mm cartridge has a chamber pressure of roughly 8,800 psi. The 9mm bullet has moved about .015 in. and is now positioned about .635 in. (from the breech face) in the chamber of the barrel. The bullet is moving at a velocity of around 51 fps.

The 12-gauge cartridge currently has a chamber pressure of about 340 psi. The birdshot has moved roughly .006 in. and is positioned about 1.425 in. (from the breech face) in the chamber of the barrel. The birdshot is currently moving at about 8 fps.

The .22 LR cartridge's chamber pressure has reached nearly 11,300 psi. The bullet has moved about .021 in. and is now roughly .521 in. (from the breech face) in the chamber of the cylinder. The bullet has reached a velocity of about 70 fps.[5]



BURST PRESSURE

Depending on case material and wall thickness, almost all of the cartridge cases are near or beyond their *burst pressure*. If it were not for the chamber, many of these cases would have burst before even pushing the projectile from the crimp. While case brass alloy will vary depending on manufacturer, we will use the alloy C26000 (cartridge brass) as an example.[6] Using Barlow's Formula (calculators available online, https://www.engineersedge.com/calculators/pipe_bust_calc.htm), we can get a good picture of how much pressure the case can handle. Barlow's Formula requires several figures to calculate burst pressure: the outside diameter of the case, wall thickness, and allowable stress (material tensile strength).

Depending on the temper, C26000 has an average tensile strength of 87,000 psi.[7] A .223 case is .373 in. in diameter with an average wall thickness of .025 in. A 9mm case is .485 in. in diameter with an average wall thickness of .020". A .22 case is .230 in. in diameter with an average wall thickness of .010 in. Using the calculator, we find that the .223 case has a burst pressure of roughly 11,600 psi, 7,200 psi for the 9mm and 7,600 psi for the .22.

Shotshells utilize a hybrid polymer (LDPE) body and a metal (typically mild steel) head. Low density polyethylene has an average tensile strength of 1,450 psi,[8] while mild steel has a yield strength of roughly 53,700 psi.[9] The head of a 12-gauge case is .805 in. in diameter with .014 in. walls. The polymer body is roughly .770 in. with .040 in. walls. Using the calculator, we find that the 12-gauge case has a burst pressure of roughly 2,051 psi (1,900 for the head and 151 for the body).

Luckily, the respective barrels are more than capable of handling the immense pressure the cartridges produce. Ordnance steel, or "4140, in. is an alloy type commonly used with gun barrels. The alloy 4140 has a tensile strength of roughly 95,000 psi. A .223 barrel roughly 1.005 in. in diameter with .3125 in. walls has a burst pressure around 59,100 psi. A 9mm barrel roughly .655 in. in diameter with .130 in. walls has a burst pressure around 37,700 psi. A 12-gauge barrel roughly 1.258 in. in diameter with .228 in. walls has a burst pressure of around 34,500 psi, while a .22 cylinder (individual chamber) with .142 in.

walls and .511 in. diameter (.142 in. walls X2 + .227 in. diameter chamber = .511") has a burst pressure of 52,800 psi.

**X 10,000*

BACK THRUST

The case is now fully sealed against the walls of the chamber and the breech/bolt/slide face. With semi-automatic pistol action types that lock, the locking surfaces of the barrel are forced against the locking surfaces of the slide/receiver. With blowback actions, the mass of the bolt/slide and the potential energy of the action/recoil spring prevents rearward movement of the bolt/slide. The force of the case head pushing against the bolt/breech/slide face is known as back thrust.

Because the expanding gas inside the case acts against all surfaces equally, we can calculate the amount of back thrust a particular cartridge exerts against the bolt/slide. All that is needed is a known pressure (psi) and the area of the inside of the case head (in inches). To calculate back thrust, you simply multiply the chamber pressure by the area of the inside of the case head.[10] For example, we know the .223, 9mm, 12-gauge, and .22 currently have chamber pressures of roughly 7,400 psi, 8,800 psi, 340 psi, and 11,300 psi respectively. The diameters of the inside of the case heads are .275 in., .320 in., .550 in. and .210 in. respectively. To calculate the area of the inside of the case head, multiply Pi (3.14) by the radius (squared) of the inside of the case head:

.275R = .1375, (.1375 x .1375) x 3.14 = .059 in.

.320R = .160, (.160 x .160) x 3.14 = .08 in.

.550R = .225, (.225 x .225) x 3.14 = .159 in.

.210R = .105, (.105 x .105) x 3.14 = .035 in.

Now multiply the area by the pressure:

.059 x 7,400 = 437 psi

.08 x 8,800 = 704 psi

.159 x 340 = 54 psi

.035 x 11,300 = 396 psi

This means that the .223, 9mm, 12-gauge, and .22 cartridges are exerting roughly 437 psi, 704 psi, 54 psi, and 396 psi respectively on the bolt/slide face (and locking lugs of locking breech actions). This is only a fraction of what the action can handle, so there is relatively little strain on the locking surfaces (or force against the action's inertia in the case of a blowback firearm).

Up to this point, most of the energy that has been released has been lost to the case's expansion and heat through *thermal convection*. Some of the energy has been converted to kinetic energy in the form of projectile movement, which has been minimal. Some of the energy is also being lost to friction in the form of sliding (kinetic) friction of the projectile and the case.

.1 MILLISECOND

As the pressure inside the case builds, it can no longer expand as it is now encased by the chamber and the bolt/breech/slide face. The case and chamber walls provide too great a resistance to the growing pressure inside the case, leaving the projectile/wad as the "path of least resistance. in. The increase in chamber pressure begins to push the projectile from the case more rapidly.

Chamber pressure has reached roughly 13,600 psi for the .223, which is an increase of about 84 percent over .00005 seconds. Distance has also increased by about .053 in., so that the bullet is sitting 1.5 in. in the chamber of the barrel. The bullet is still in the mouth of the case, but is moving farther into the throat. Velocity has jumped to roughly 99 fps, which is an increase of 161 percent.

The 9mm cartridge has reached a chamber pressure of 24,900 psi, which is an increase of 183 percent. Distance has also increased by about .062 in., so that the bullet is sitting .697 in. in the chamber of the barrel. The bullet is still in the mouth of the case but is moving farther into the throat. Velocity has jumped to roughly 198 fps, which is an increase of 288 percent.

Chamber pressure has reached roughly 640 psi for the 12-gauge, which is an increase of about 88 percent over .00005 seconds. Distance has also increased by about .023 in. , so that the shot is sitting 1.448 in. in the chamber of the barrel. The shot is still in the body of the case but is moving farther into the chamber as the crimp begins to unfurl. Velocity has jumped to roughly 20 fps, which is an increase of 150 percent. There are several factors that contribute to the "sluggish" start of the 12-gauge cartridge. The low tensile strength of the case materials allow the case to expand with less force, effectively increasing internal volume, which does not allow pressure to build. The inertia of the shot also limits how far and fast the expanding gas can push it.

The .22 cartridge has reached a chamber pressure of 21,700 psi, which is an increase of 92 percent over .00005 seconds. Distance has also increased by about .086 in., so that the bullet is sitting .607 in. in the chamber of the cylinder. The bullet is still in the mouth of the case but is moving farther into the throat of the chamber in the cylinder. Velocity has jumped to roughly 250 fps, which is an increase of 257 percent.

At roughly .12 milliseconds, the .22 cartridge will reach peak chamber pressure, 22,500 psi, which is 4 percent over .00002 seconds. The bullet has moved another .057 in., so that the bullet is sitting roughly .664 in. in the throat of the cylinder. Velocity is up to 330 fps, which is an increase of 32 percent. Back thrust has also peaked at roughly 788 psi.

At roughly .14 milliseconds, the 9mm cartridge will also reach peak chamber pressure, 32,300 psi, which is a 104 percent increase over .00004 seconds. The bullet has moved another .142 in., so that the bullet is sitting roughly .839 in. in the throat of the barrel. Velocity is up to 403 fps, which is an increase of 104 percent. Back thrust has also peaked at roughly 2,584 psi.

ENTERING THE RIFLING

At roughly .16 milliseconds, the 9mm bullet enters the leade of the rifling after moving another .0868 in., so that the bullet is sitting roughly .9258 in. in the throat of the barrel. Chamber pressure is declining, down to 31,220 psi (a decrease of 3 percent over .00002 milliseconds). Velocity is still increasing, up to 498 fps (an increase of 24 percent). The bullet is now positioned with its nose in the bore of the barrel, its base in the throat of the chamber and its body engaging the leade of the rifling. There is a spike in pressure behind the bullet as it is pushed into the bore and forced to conform to the bore's dimensions and shape.

The 9mm cartridge utilizes a bullet that is .355 in. in diameter, a .355 in. barrel groove diameter and a .346 in. bore diameter. This means the lands dig into the 9mm bullet about .0045 in. from opposing sides. This is known as bullet engraving. To clear things up, no part of the bullet

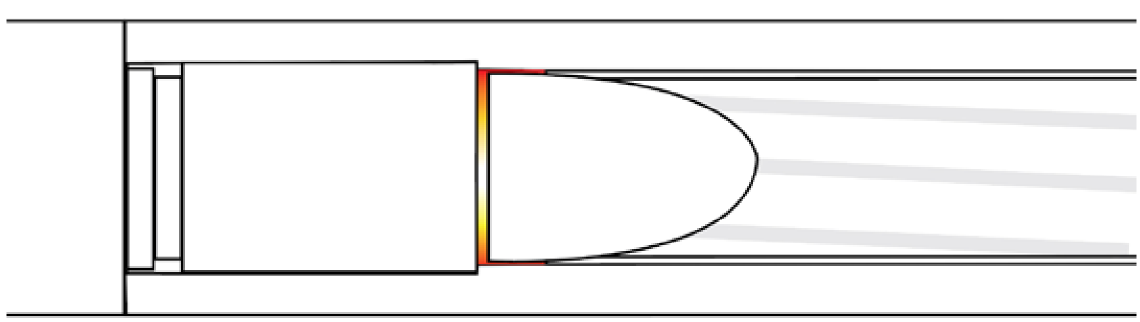


Figure 6: 9mm bullet entering the rifling.

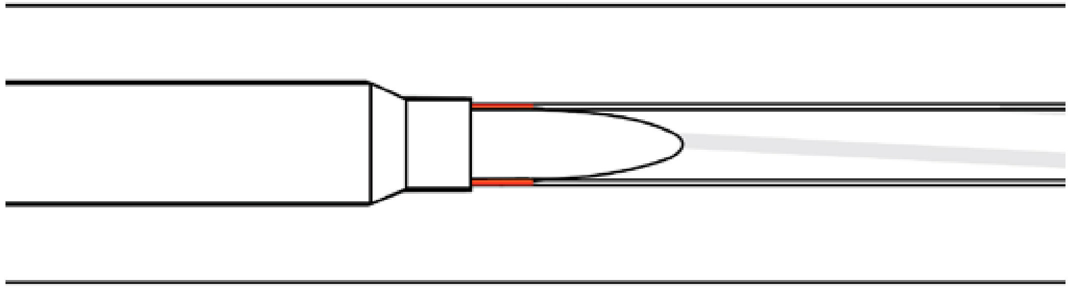


Figure 7: A .223 bullet entering the rifling.

is removed; the bullet's material simply "flows" under intense pressure to conform to the shape of the bore.

The pressure behind the bullet essentially "swages" or upsets the bullet so that it matches the shape of the bore. The force required to engrave the rifling into the bullet is roughly 12,000 – 14,000 psi.[11] The exact force required to mold the bullet will vary depending on the bullet's material, jacket material, dimensions of bullet, and the number and size of the lands.

As the projectile conforms to the bore it will also seal the area behind it. This is known as *obturation*. Good obturation will seal the bore tightly and allow the gas pressure behind the projectile to push against it more efficiently. Poor obturation will allow an excess of gasses to "blow-by" the projectile, which leads to less pressure driving it and in turn less velocity and energy. Gas blow-by can also lead to additional leading and copper fouling in the bore. Excessive blow-by can even lead to premature wear of the barrel's throat and leade.

Regardless of how well a projectile seals the barrel, there will still be a minimal amount of gas blow-by. Because the propellant gas is expanding at a faster rate than the projectile is travelling (roughly 1.25 – 1.75X faster), some of the gas is able to move ahead of the projectile. This blow-by usually occurs as the projectile is moving through the throat, before reaching, obturating, and sealing the bore.

At this time in the reaction, the heat and pressure have risen inside cases to a point that the individual kernels of propellant begin to ignite without contacting any other grains. This is known as the *auto ignition temperature*. Modern smokeless propellants have an auto ignition temperature in the range of 320 – 400° F.[12, 13] As the remaining kernels of propellant ignite and begin to release gas into the case, the chamber pressure grows rapidly.

.2 MILLISECONDS

Chamber pressure for the 9mm has dropped to 22,800 psi, a decrease of 27 percent in .00004 seconds. Travel and velocity have both increased to 1.246 in. (+ .3202") and 713 fps (+ 215 fps) respectively. Chamber pressure for the 12-gauge has increased to 1,880 psi (+ 194 percent in .0001 seconds). Travel and velocity have also increased to 1.5 in. (+ .052") and 45 fps (+ 25 fps) respectively. The .22 cartridge's chamber pressure is also declining, down to 14,900 psi (down 34 percent over .00008 seconds). Travel and velocity have both increased to 1.165 in. (+ .501 in.) and 650 fps (+ 320 fps).

At .2 milliseconds, chamber pressure has reached 34,900 psi for the .223, which is an increase of 157 percent over .0001 seconds. The bullet has moved .345 in. to 1.845 in., a 23 percent increase. Velocity is up to 390 fps, an increase of 294 percent. The .223 bullet has now entered the leade of the rifling. The bullet is positioned with its nose in the bore, its shoulder engaging the leade of the rifling, its body in the throat, and its base in the mouth/neck of the case. The .223 cartridge utilizes a .224 in. diameter bullet, a .224 in. groove diameter, and a .219 in. bore diameter. This means that the "lands" of the rifling dig into the bullet .0025 in. from opposing sides.

The rifling in the bore will force the projectiles to begin to spin. Each caliber will utilize a specific "twist" rate, used to stabilize the projectile in flight. Longer projectiles require a faster twist rate than short projectiles. Faster twist rates will force the projectile to make a full revolution in a shorter distance. For our examples, the .223 bullet utilizes a 1 in 8 in. twist, the 9mm utilizes a 1 in 10 in. twist, and the .22 utilizes a 1 in 16 in. twist. This means that for a given twist the rifling will make one full rotation in 8 in., 10 in. and 16 in. of travel respectively, regardless of barrel length. With the .223 and a 16 in. barrel, the rifling will make almost two full revolutions (45° of rotation for every inch of travel). Assuming proper projectile diameter, neither the 9mm or .22 bullets will make a full rotation before exiting their 4 in. and 5 in. barrels respectively. The 9mm bullet rotates 36° for every inch of travel, while the .22 rotates 22.5° for every inch of travel. The 9mm bullet will rotate roughly 144° before exiting the barrel, while the .22 will rotate only 112.5°. The 12-gauge birdshot will not rotate because it is being fired through a smoothbore barrel.

The bullet's rotation upon exiting the muzzle can be calculated in rotations per minute (rpm).[14] All that is needed to calculate rotation is muzzle velocity (mv) in feet per second, and twist rate (T) in inches. For example, a .223 projectile traveling at 2,900 fps out of a 1 in 8 in. twist barrel would have a rotation speed of:

$$MV \times 720^{*} \text{ (constant)}/T = \text{rpm}$$

$$2{,}900 \times 720/8 = 261{,}000 \text{ rpm}$$

This means if the projectile travels for one minute at a constant velocity, it will make about 261,000 full revolutions around its axis. A 9mm projectile traveling at 1,140 fps out of a 1 in 10 in. twist barrel would have a rotation speed of:

$$1{,}140 \times 720/10 = 82{,}080 \text{ rpm}$$

This means if the projectile travels for one minute at a constant velocity, it will make about 82,000 full revolutions around its axis. A .22 projectile traveling at 1,110 fps out of a 1 in 16 in. twist barrel would have a rotation speed of:

$$1{,}110 \times 720 / 16 = 49{,}950 \text{ rpm}$$

**1 foot per second = 720 inches per minute*

You can also determine whether or not the correct twist rate is being used for a given projectile. There are two basic formulas to verify the twist rate's effectiveness, the Greenhill Formula and the Miller Twist Rule. The Greenhill Formula requires the projectile's diameter (D), length (L) and varying constants (125, 150, 180) to provide the MINIMUM twist rate (T) needed to stabilize a projectile of a given size. The formula also utilizes various constants based upon the expected velocity range:[15]

- For velocities slower than 1,500 fps, use this formula: 125 x (D)^2 / L = twist rate (T)
- For velocities between 1,500 and 2,800, use this formula: 150 x (D)^2 / L = twist rate (T)
- For velocities faster than 2,800 fps, use this formula: 180 x (D)^2 / L = twist rate (T)

For example, a .224 in. diameter, .223 bullet, .745 in. long would need a twist rate of:

$$180 \times (.224 \times .224) / .745 = 12.12$$

This means that, at a minimum, a 1 in 12 in. twist rate is needed to stabilize a 55-grain, .223 bullet. A .355 in. diameter, 9mm bullet, .549 in. long would need a twist rate of:

$$125 \times (.355 \times .355) / .549 = 28.69$$

This means that, at a minimum, a 1 in 28 in. twist rate is needed to stabilize a 115-grain, 9mm bullet. A .2255 in. diameter, .22 bullet, .500 in. long would need a twist rate of:

$$125 \times (.2255 \times .2255) / .500 = 12.71$$

This means that, at a minimum, a 1 in 12 in. barrel is needed to stabilize a 40-grain, .22 bullet. Alternatively, if you already know the twist rate of your specific barrel and you want to know the longest bullet it will stabilize, you can modify the formula as follows:

125 x (D) squared / T = length (L)

150 x (D) squared / T = length (L)

180 x (D) squared / T = length (L)

The Miller Twist Rule is used to calculate twist rates more precisely than the Greenhill Formula with the inclusion of mass. The Miller Twist Rule will provide a twist rate that is satisfactory for a wider range of projectile weights. All that is needed to calculate twist rate is projectile mass (M) in grains, diameter (D) in inches, length (L) in calibers (length in inches divided by diameter) and the constants 30* and 2.** The answer will be expressed in calibers per turn (T) but can be converted to inches per turn (T) by multiplying by the diameter (D). To calculate for twist rate, the formula is:

(30 x M) / (2 x D^3 x L) (1 + L^2) = Square Root (SR) of T

For example, a .224 in. diameter (D) bullet, .745 in. (3.33 calibers) long (L) weighing 55 grains (M) will need a twist rate of:

30 x 55 / (2 x .224 x .224 x .224 x 3.33) (1 + 3.33 x 3.33) = SR of T

1,650 / .075 x 12.08 = SR of T

1,650 / .91 = SR of T 1,813.18

The square root of 1,813.18 is 42.58 or 42.58 calibers per turn. To solve for (T) just multiply by (D) or .224.

42.58 x .224 = 9.5 or a twist rate of 1 turn in 9.5 in. or 1:9.

A 115-grain, .355 in. diameter 9mm bullet, .549 in. long (1.55 calibers) requires a twist rate of:

30 x 115 / (2 x .355 x .355 x .355 x 1.55)
(1 + 1.55 x 1.55) = SR of T

3,450 /.14 x 3.4 = SR of T

3,450/.48 = 7,188

The square root of 7,188 is 84.8 or 84.8 calibers per turn.

84.8 x .355 = 30.1 or a twist rate of 1 turn in 30 in. or 1:30.

A 40-grain, .2255 in. diameter .22 bullet, .500 in. long requires a twist rate of:

30 x 40 / (2 x .2255 x .2255 x .2255 x 2.22) (1 + 2.22 x 2.22) = SR of T

1,200 / .05 x 5.9 = SR of T

1,200 / .295 = 4,067.8

The square root of 4,067.8 is 63.78 or 63.78 calibers per turn.

63.78 x .2255 = 14.38 or a twist rate of 1 turn in 14 in. or 1:14.

**The constant 30 is a product of an average velocity of 2,800 fps, a temperature of 59° F, and a pressure of 750mm mercury and 78 percent humidity.*

*** The constant 2 is a "safe" number based on a known number that will stabilize a projectile based on the Miller Stability Factor.*

The Miller Stability Factor (SF) is a scale that gauges how well a given twist rate will stabilize a specific bullet.[16] An SF of less than 1 will not properly stabilize a bullet. An SF between 1 and 1.4 will offer marginal stabilization. An SF of 1.5 or greater will be more than adequate to properly stabilize a bullet. To calculate SF, you need to know bullet mass (M) in grains, diameter (D) in inches, length in calibers (L) (length in inches divided by diameter), twist length (T) in calibers per twist (twist in inches divided by bullet diameter) and the constant 30.* To calculate SF use this formula:

30 x M/(T^2) (D^3 x L) (1 + L^2) = SF

For example: a .224 in. diameter (D) bullet, .745 in. (3.33 calibers) long (L), weighing 55 grains (M) shooting through a 1:8 (1 turn in 8 in. or 35.71 calibers (8 / .224)) (T) will have an SF of:

(30 x 55) / (35.71 x 35.71) (.224 x .224 x .224 x 3.33) (1 + 3.33 x 3.33) = SF

1650 / 1,275 x .04 x 12.08 = SF

1650 / 616 = 2.67

A stability factor of 2.67 means that a 1:8 twist rate is more than capable of stabilizing a bullet .905 in. long. A .355 in. diameter (D) bullet, .549 in. (1.55 calibers) long (L), weighing 115 grains (M) shooting through a 1:10 (1 turn in 10 in. or 28.17 calibers (10 / .355)) (T) will have an SF of:

(30 x 115) / (28.17 x 28.17) (.355 x .355 x .355 x 1.55) (1 + 1.55 x 1.55) = SF

3,450 / 794 x .069 x 3.40 = SF

3,450 / 186 = 18.54

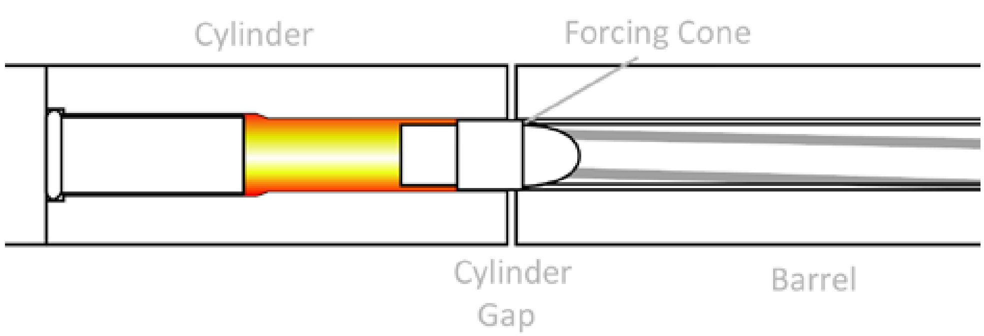


Figure 8: A .22 bullet entering the forcing cone of the barrel.

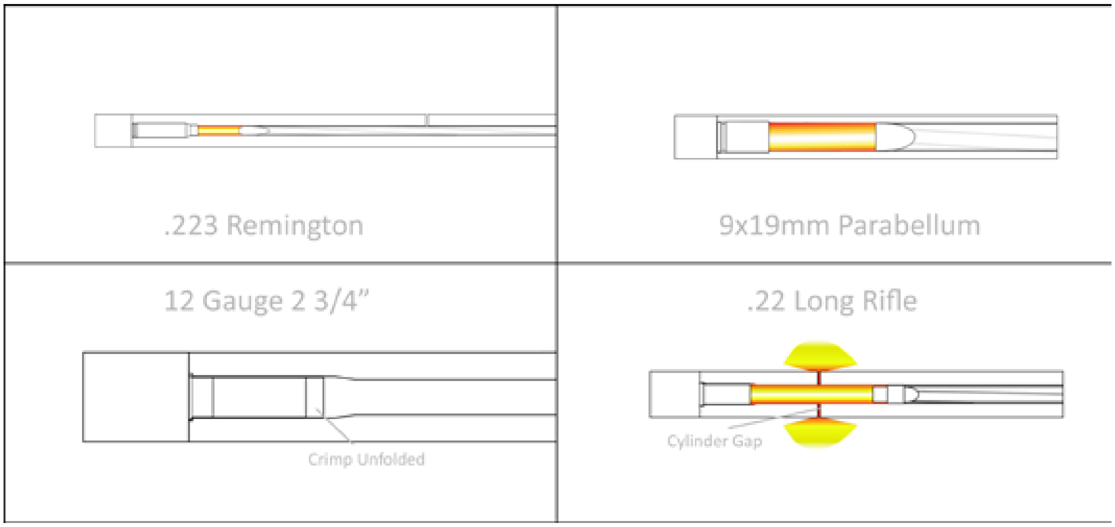


Figure 9: Projectile position at .3 milliseconds.

A stability factor of 18.54 means that a 1:10 twist rate is more than capable of stabilizing a bullet .549 in. long. A .2255 in. diameter (D) bullet, .500 in. (2.22 calibers) long (L), weighing 40 grains (M) shooting through a 1:16 (1 turn in 16 in. or 70.95 calibers (16/.2255)) (T) will have an SF of:

(30 x 40)/(70.95 x 70.95) (.2255 x .2255 x .2255 x 2.22) (1 + 2.22 x 2.22) = SF

1,200/5,034 x .025 x 5.93 = SF

1,200/746 = 1.61

A stability factor of 1.61 means that a 1:16 twist rate is more than capable of stabilizing a bullet .500 in. long.

**The constant 30 is a product of an average velocity of 2,800 fps, a temperature of 59° F, and a pressure of 750 mm mercury and 78 percent humidity.*

You may notice some inconsistencies with the results of the 9mm for both the Greenhill and Miller formulas. While the formulas show the 9mm should utilize a 1 in 28 in. and 1 in 30 in. twist respectively, the standard 9mm twist rate for the 9x19mm Parabellum cartridge is 1 in 10 in. (most other pistol cartridges utilize a 1 in 16 in. twist). To put things in perspective, the .357 S&W Magnum cartridge utilizes a .357 in. diameter bullet (.002 in. larger than the 9mm) and much heavier (longer) bullets ranging from 125 to 200 grains with a much slower twist rate (1 in 18 in.). While the slower twist rates will stabilize short, fat projectiles enough to stabilize at pistol ranges (~50 yd.), the 9mm cartridge was designed to be used in a pistol that utilized a detachable buttstock and could be used at extended distances; so a 1 in 10 in. twist was adopted as the standard. The faster twist rate is used to ensure the bullet stays stable at greater distances while the projectile's velocity drops off. The 1 in 10 in. twist has proven it will stabilize 9mm projectiles of various weights, so it remains the standard to this day.

Not only is twist rate important to the stabilization of the projectile, it also plays a big role with accuracy/precision and terminal ballistics. As the bullet moves through the rifling, it rotates around the bore's axis (invisible centerline from the chamber to the muzzle). Any imperfection in the construction of the bullet (non-concentric jacket or core, misalignment in the bullet's center of mass/form) is irrelevant at this point because the bullet is being guided by the barrel. Once the bullet exits the muzzle, these imperfections reveal themselves in the form of instability in flight.

Two different stability calculators can be found online here:

https://bergerbullets.com/twist-rate-calculator/

and here:

www.jbmballistics.com/cgi-bin/jbmstab-5.1.cgi

At .23 milliseconds, the .22 bullet has entered the forcing cone of the barrel. The bullet has traveled another .274 in. in .00003 seconds, a 24 percent increase. Chamber pressure is down to 11,900 psi. Velocity is still climbing to 735 fps (a 13 percent increase). The bullet is now positioned roughly 1.439 in. from the breech face, part way between the cylinder and the barrel. The forcing cone will guide and align the bullet with the bore and ease the bullet into the rifling. The .22 utilizes a .223 in. bullet, a .222 in. groove diameter, and a .217 in. bore diameter. The lands cut into the .22 bullet about .0025 in. from opposing sides.

At roughly .231 milliseconds, the .22 bullet has passed completely through the cylinder and is now moving into the barrel. As the bullet exits the cylinder, there is some pressure loss through the cylinder gap. The pressure loss is small and equates to roughly a 7 percent loss in potential velocity and energy.[17] Part of the reason for such a minimal pressure loss is that most pistol/revolver cartridges are near or at peak pressure before ever leaving the case or cylinder. The case and chamber will also serve to direct the pressure forward along the axis of the bore, like a thruster. The majority of the gas will continue to flow in the same direction, while only a small amount will be redirected through the cylinder gap. Regardless of the amount of pressure that escapes, the high velocity gas entering the ambient atmosphere creates an initial *shock wave* ahead of the muzzle blast.

.3 MILLISECONDS

At roughly .3 milliseconds, the .223 cartridge's chamber pressure has reached about 48,200 psi, a 38 percent increase in .0001 milliseconds. The bullet has moved an additional .7 in. and is now roughly 2.545 in. deep in the bore of the barrel, a 38 percent increase. Velocity is still rising and is now roughly 919 fps, a 136 percent increase.

The 9mm cartridge's chamber pressure is still on the decline at 9,450, a 59 percent decrease in .0001 milliseconds. The bullet has moved an additional 1.049 in. and is now roughly 2.295 in. deep in the bore of the barrel, an 84 percent increase. Velocity is still rising and is now roughly 984 fps, a 38 percent increase.

The 12-gauge cartridge's chamber pressure is still rising, up to 4,870 psi, an increase of 159 percent over .0001 seconds. The shot has

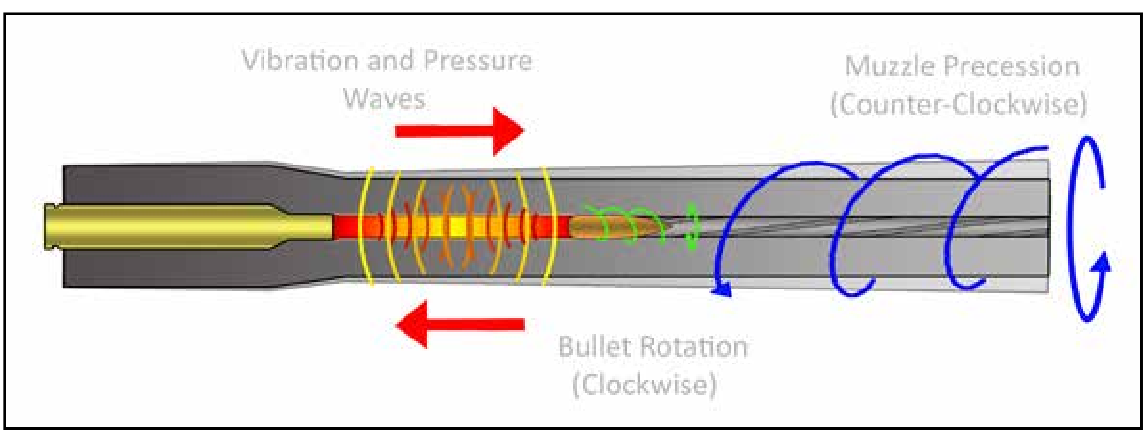


Figure 10: Barrel harmonics.

moved another .085 in. so that the shot is at roughly 1.585 in. in the chamber. The shot is still in the case, but the crimp has unfurled completely. Velocity is now at 106 fps, an increase of 203 percent.

The .22 cartridge's chamber pressure has dropped to 8,000 psi, a decrease of 33 percent over .00007 seconds. The bullet has moved an additional .654 in., sitting at roughly 2.093 in. in the bore of the barrel. Velocity is still rising, up to 870 fps, an 18 percent increase.

At roughly .33 milliseconds, the .223 cartridge reaches a peak chamber pressure of 50,100 psi, a 4 percent increase over .00003 seconds. The bullet has moved an additional .387 in., now roughly 2.932 in. in the bore of the barrel. Velocity has increased to 1,108 fps, a 21 percent increase. Back thrust has also peaked at 2,956 psi.

HARMONICS

With most of the projectiles moving through the bore of the barrel, let us take a minute to discuss what all of this pressure, heat, friction, and torque are doing to the barrel (and receiver) of the firearm. Vibrations in the barrel — the barrel's *harmonics* — is one factor that prevents "one hole" accuracy, even when the human factor is removed. Barrel composition, design, process of manufacturing, stress and heat treatments, load, and temperature can all affect the barrel's harmonics.

When the cartridge is discharged, there is an array of impulses that move through the barrel and receiver. One cause of these impulses comes from the pressure of the propellant when it ignites and expands. The velocity of the gas expansion can be upwards of 1.75+ times the muzzle velocity. This means the propellant gasses behind a 55-grain .223 bullet moving at 2,900 would expand at roughly 5,075 fps (roughly 4.5X the speed of sound in air). The rapid expansion of the propellant gasses and the pressure causes the barrel to stretch, swell, and vibrate. These vibrational waves will oscillate the length of a 16 in. barrel about 20X* before the bullet exits the muzzle. The waves are moving at roughly 20,000 fps [18] (the speed of sound through steel is roughly 20,000 fps) over the duration of about .003 seconds for the entire firing sequence. The area ahead of the bullet will also swell or stretch as the (slightly oversized) bullet is squeezed through the bore.[19,20]

The torque that is created from the projectile traveling through the rifling will also impact its harmonics. The action of rotating a projectile to the right (clockwise) has a counterclockwise torque applied to the barrel as the reaction. As the projectile travels through the rifling it causes the barrel to precess. The circular, writhing motion of the muzzle will cause the projectile to exit at a different point in its path if there is any variance in the reaction of the cartridge such as pressure, velocity, burn rate, projectile mass, timing, etc.

Even something as small as the hammer striking the firing pin will transfer sound waves. These waves will transfer from the action to the barrel and cartridge. The speed of sound through steel, copper, brass, and lead is 20,000 fps, 12,800 fps, 11,400 fps, and 3,800 fps respectively. All of the different types of metals will vibrate at different frequencies and amplitudes that bounce around and affect the barrel and action in various ways.[21]

**A vibrational wave travelling 20,000 fps will cover 32 in. (2X barrel length) in roughly .000133 seconds. Over .003 seconds the wave will oscillate along the barrel 22.5 times.*

.4 MILLISECONDS

At roughly .4 milliseconds, the .223 cartridge's chamber pressure is dropping, now at 46,800 psi, a 7 percent decrease over .00007 seconds. The bullet has moved an additional 1.082 in., now sitting at roughly 4.014 in. in the bore of the barrel. Velocity has risen to 1,515 psi, a 37 percent increase. Although the .223 bullet is moving at supersonic velocity inside the barrel, there is no shock wave (*sonic boom*) inside the barrel. The bullet pushes against the "air column" ahead of it and compresses it, increasing the speed of sound in the medium. Because

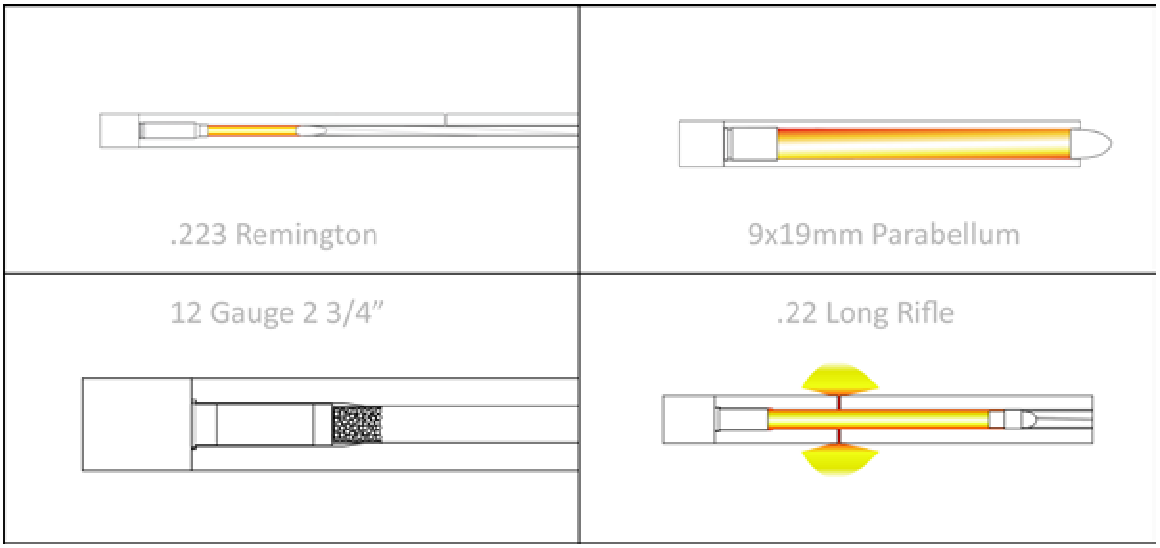


Figure 11: Projectile position at .4 milliseconds.

of the bullet's obturation, a seal is created that separates the propellant gas and the air column. The bullet's obturation ensures that it cannot accelerate faster than the air column, which prevents the creation of a shockwave.[22]

The 9mm cartridge's chamber pressure has dropped to 5,115 psi, a 46 percent decrease over .0001 seconds. The bullet has traveled an additional 1.233 in., sitting at roughly 3.528 in. in the bore of the barrel. Velocity is up to 1,112 fps, a 13 percent increase. At this point in time, both the barrel and slide will begin to recoil backwards a slight distance (~.080 in.). The chamber remains locked as the barrel and slide move and will remain locked until after the bullet has left the muzzle and the chamber pressure has dropped to a safe level.

The 12-gauge cartridge's chamber pressure has risen to 9,130 psi, an increase of 87 percent over .0001 seconds. The shot has moved another .109 in., now roughly 1.694 in. in the chamber of the barrel. Velocity has increased to 260 fps, a jump of 145 percent.

The .22 cartridge's chamber pressure is still dropping, now at 5,000 psi, a decrease of 38 percent over .0001 seconds. The bullet has traveled 1.084 in. farther, now roughly 3.177 in. in the bore of the barrel. Velocity has risen to 1,000 fps, an increase of 15 percent.

At roughly .43 milliseconds, the 9mm bullet will reach the muzzle of the pistol after 3.38 in. of travel (an additional .472 in.). Chamber pressure has dropped to 4,470 psi, a 13 percent decrease over .00003 seconds. Velocity has peaked at 1,140 fps, an increase of 3 percent.

At .47 milliseconds, the 12-gauge's chamber pressure will peak at 10,200 psi, an increase of 12 percent over .00007 seconds. The shot will have moved an additional .325 in., now roughly 2.019 in. in the chamber of the barrel (still inside the case). Velocity has increased to 420 fps, a 62 percent jump. Bolt thrust has also peaked at 1,622 psi.

At .49 milliseconds, the shot will finally clear the case after roughly 1.341 in. of travel. The shot is now sitting 2.760 in. deep in the chamber of the barrel and is now moving through the .24 in. of additional chamber. Chamber pressure has dropped to 10,000 psi, while velocity is up to 475 fps.

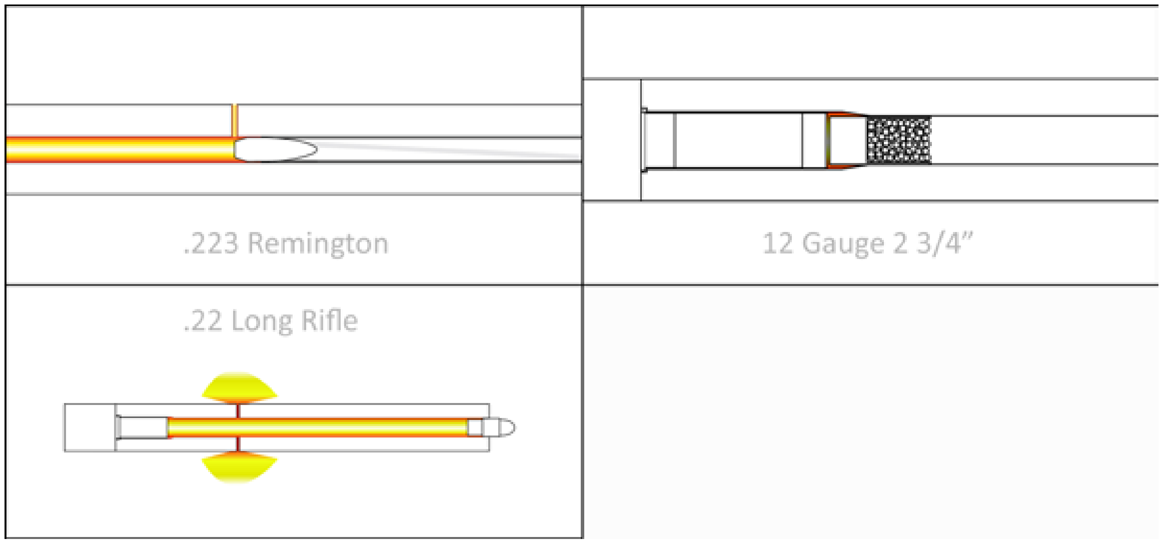


Figure 12: Projectile position at .5 milliseconds.

.5 MILLISECONDS

At .5 milliseconds, the .223's chamber pressure has dropped to 35,100 psi, a 25 percent decrease over .0001 seconds. The bullet has moved an additional 2.111 in., sitting roughly 6.125 in. in the bore of the barrel. Velocity is up to 2,009 fps, an increase of 33 percent.

The 12-gauge's chamber pressure has dropped to 9,880 psi, a 1 percent decrease over .00001 seconds. The shot has finally cleared the chamber (3 in.) after 1.581 in. of travel and is now moving through the forcing cone. The forcing cone acts like the leade of the rifling, guiding the cup into the bore of the shotgun. The diameter of the bore is around .725". Cups and wads are often the same size or slightly undersized (.005") but expand slightly when under load. As the cup/wad passes through the forcing cone, it is slightly compressed to provide a seal for the bore. Because the cup/wad is made of very soft material (plastic or paper), it creates very little resistance when entering the bore.

At .5 milliseconds, the .22 cartridge's chamber pressure has dropped to 3,500 psi, a decrease of 30 percent over .0001 milliseconds. The bullet has moved an additional 1.269 in., sitting at roughly 4.446 in. in the bore of the barrel. Velocity is up to 1,070 fps, a 7 percent increase.

At roughly .54 milliseconds, the .22 bullet will reach the muzzle of the pistol after roughly 4.5 in. of travel (an additional .554"). Chamber pressure has dropped to 3,100 psi, a decrease of 11 percent over .00004 seconds. Velocity has peaked at 1,110 fps, an increase of 4 percent.

At roughly .56 milliseconds, the .223 bullet will pass the gas port of the barrel after roughly 6.37 in. of travel. The gas port of an AR-15 with a 16 in. barrel and carbine length gas system is roughly 7.8 in. from the bolt face. The gas port of a carbine length gas system is around .0625 in. in diameter.[23] Chamber pressure is down to 28,100 psi, while velocity is up to 2,247 fps. The moment the bullet passes the gas port, some of

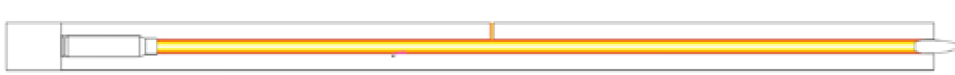


Figure 13: Projectile position at .8 milliseconds.

the propellant gasses will begin to bleed off into the gas port of the barrel, through the gas block and into the gas tube.

.6 MILLISECONDS

At .6 milliseconds, the .223 cartridge's chamber pressure has dropped to 26,200 psi, a decrease of 7 percent over .00004 seconds. The bullet has moved an additional .861 in. and is now sitting at 8.730 in. in the bore of the barrel. Velocity is up to 2,362 fps, a 5 percent increase.

The 12-gauge cartridge's chamber pressure is also dropping, down to 7,740 fps, a decrease of 22 percent over .0001 seconds. The shot has moved another .85 in., clearing the forcing cone and moving through the bore at roughly 3.85". Velocity is up to 700 fps, an increase of 40 percent.

The 9mm and .22 bullets are now clear of the muzzle and well on their way to the targets. The 9mm bullet is roughly 2.33 in. from the muzzle (1,140 fps at .00017 seconds). As the barrel is arrested by the locking block, it begins to move out of alignment with the slide and unlocks. The slide begins to move rearward to complete its cycle. The .22 bullet is roughly .80 in. from the muzzle (1,110 fps at .00006 seconds).

.8 MILLISECONDS

At roughly .8 milliseconds, the .223's chamber pressure has dropped to 15,400 psi, a loss of 41 percent over .0002 milliseconds. The bullet has moved an additional 6.183 in. and is now sitting at 14.913 in. in the bore of the barrel. Velocity has jumped to 2,750 fps, a 16 percent increase.

At .83 milliseconds, the .223's bullet has finally reached the muzzle after 14.565 in. of travel (an increase of 1.087 in. in .00003). Chamber pressure is down to 14,200, a drop of roughly 8 percent in .00003 seconds. Velocity has peaked at 2,900 fps, an increase of 5 percent.

.9 MILLISECONDS

At roughly .9 milliseconds, the 12-gauge cartridge's chamber pressure has dropped to 2,750 psi, a decrease of 64 percent over .0003 seconds.

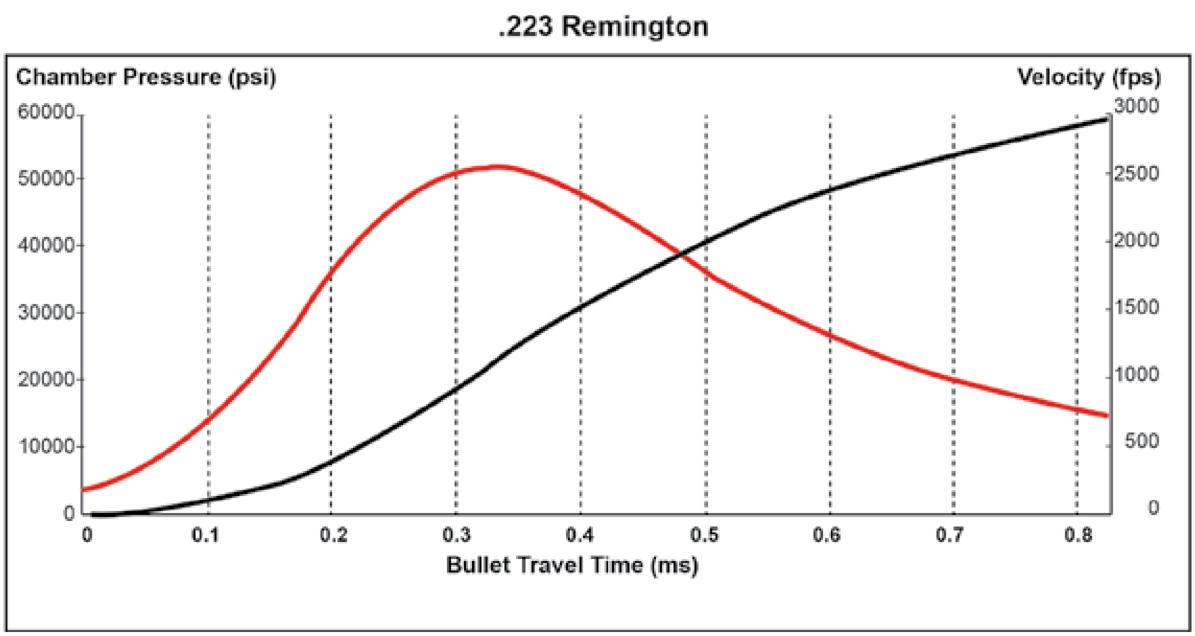


Figure 14a: The .223 time chart.

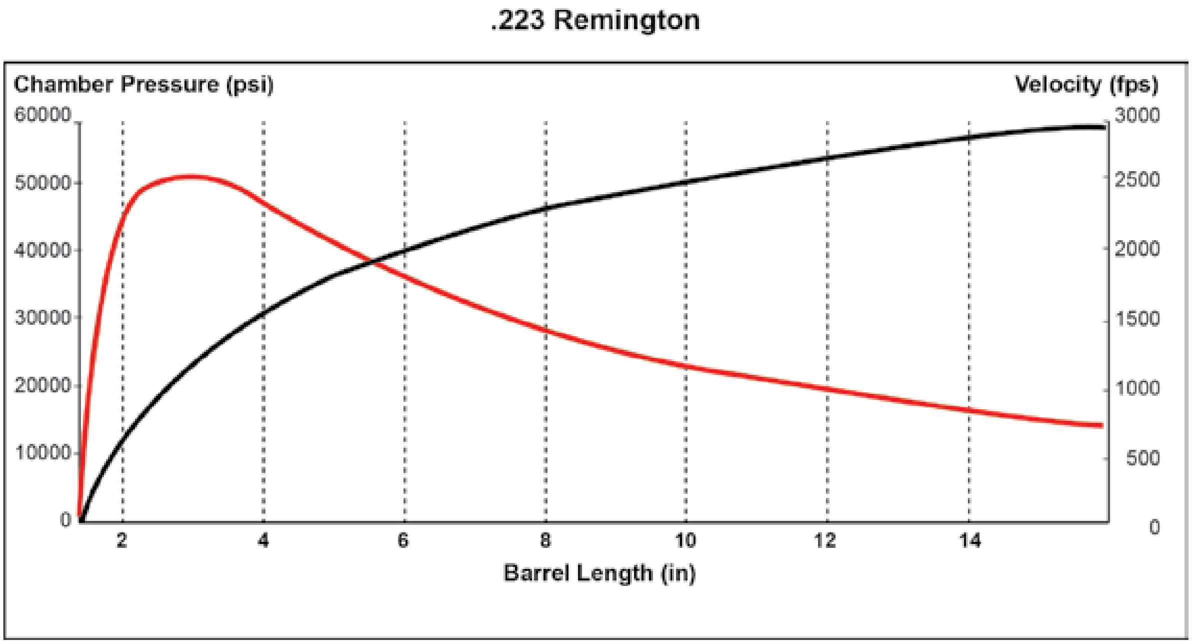


Figure 14b: The .223 travel chart.

Travel and velocity are both still increasing. The shot has moved another 3.67 in. and is now 7.52 in. deep in the bore of the barrel. Velocity has reached 1,020 fps, an increase of 46 percent.

The .223, 9mm, and .22 bullets are all well on their way to the targets. The .223 is roughly 2.436 in. from the muzzle. The chamber pressure has dropped to a safe level and the bolt carrier is beginning to move rearward, turning the bolt and unlocking the chamber. The 9mm bullet is roughly 6.43 in. from the muzzle. The slide is continuing rearward, still extracting the empty case from the chamber. The .22 bullet has moved roughly 4.80 in. from the muzzle.

1.5 MILLISECONDS

At .9 milliseconds, the 12-gauge's chamber pressure has dropped to 850 psi, a decrease of 69 percent over .0006 seconds. Travel and velocity are both still increasing. The shot has moved another 6.58 in. and is now 14.1 in. deep in the bore of the barrel. Velocity has reached 1,225 fps, an increase of 20 percent.

The .223, 9mm, and .22 bullets are still moving along their trajectories toward the target. The .223 is roughly 23.32 in. from the muzzle. The bolt carrier is still travelling rearward, and the bolt is still rotating to unlock the chamber. The 9mm bullet is roughly 14.64 in. from the muzzle. The slide is continuing rearward, still extracting the empty case from the chamber. The .22 bullet has moved roughly 13.85 in. from the muzzle.

1.8 MILLISECONDS

At roughly 1.84 milliseconds, the 12-gauge birdshot has finally reached the muzzle after 18.581 in. of travel (an increase of 5.9 in. over .00034 seconds). Chamber pressure has dropped to 660 psi, a decrease of 22 percent. Velocity has reached its peak at 1,275 fps, an increase of 4 percent.

The .223 is roughly 35.15 in. from the muzzle. The bolt carrier is still travelling rearward, and the bolt is still rotating to unlock the chamber. The 9mm bullet is roughly 19.29 in. from the muzzle. The slide is continuing rearward, still extracting the empty case from the chamber. The .22 bullet has moved roughly 17.32 in. from the muzzle.

The entire firing sequence lasts roughly .003 seconds from the moment the trigger is pulled, until the projectile reaches the muzzle. If we assume a lock time of .002 seconds and a primer ignition time of .00085 seconds, the .223's firing sequence (.00083 barrel time) lasted .00289 seconds, the 9mm (.00043 barrel time) lasted .00249 seconds, the 12-gauge's (.00184 barrel time) lasted .00390 seconds, and the .22's (.00054 barrel time) lasted .00260 seconds. To put things into perspective, a blink lasts roughly .1 seconds.[24] The 9mm firing sequence could theoretically occur roughly 40 times in the blink of an eye.

.223 Remington						
Time (Milliseconds)	Pressure (PSI)	Increase/ Decrease/ %	Distance from Breech (Inches)	Increase/ %	Velocity (FPS)	Increase/ %
			1.435 (Start)			
.05	7,400		1.447	.012/1%	38	
.1	13,600	6,200/84%	1.5	.053/4%	99	61/161%
.2	34,900	21,300/157%	1.845	.345/23%	390	291/294%
.3	48,200	13,300/38%	2.545	.7/38%	919	529/136%
.33	50,100	1,900/4%	2.932	.387/15%	1,108	189/21%
.4	46,800	-3,300/-7%	4.014	1.082/37%	1,515	407/37%
.5	35,100	-11,700/ -25%	6.125	2.111/53%	2,009	494/33%
.56	28,100	-7,000/-20%	7.869	1.744/28%	2,247	238/12%
.6	26,200	-1,900/-7%	8.730	.861/11%	2,362	115p/5%
.8	15,400	-10,800/ -41%	14.913	6.183/71%	2,750	388/16%
.83	14,200	-1,200/-8%	16	1.087/7%	2,900	150/5%

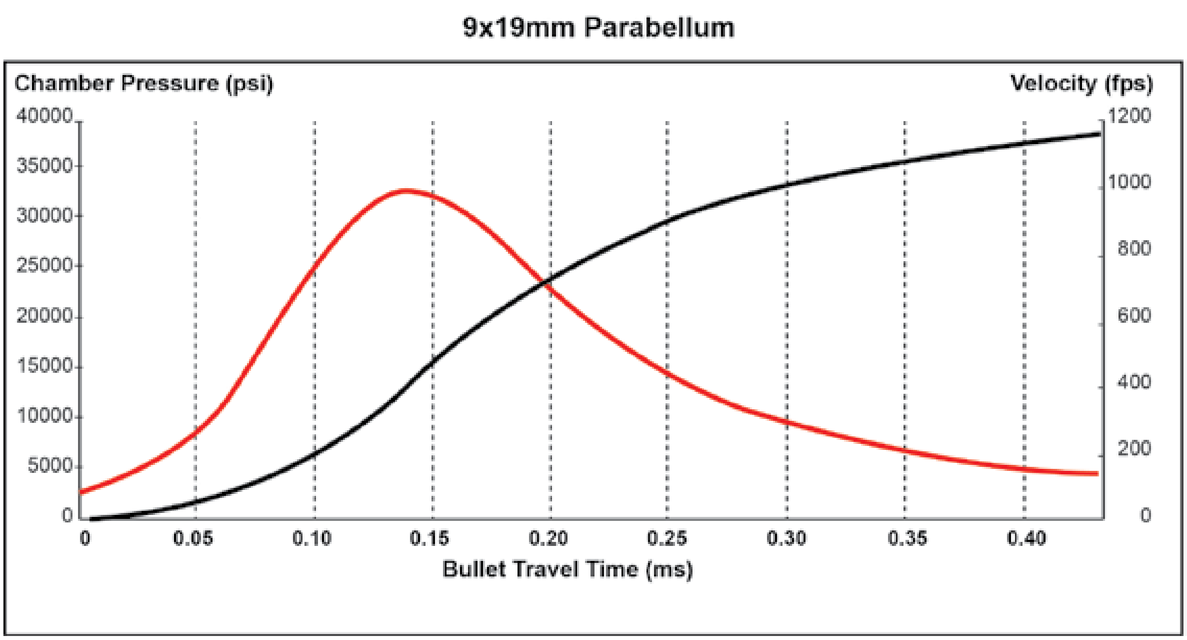


Figure 15a: The 9mm time chart.

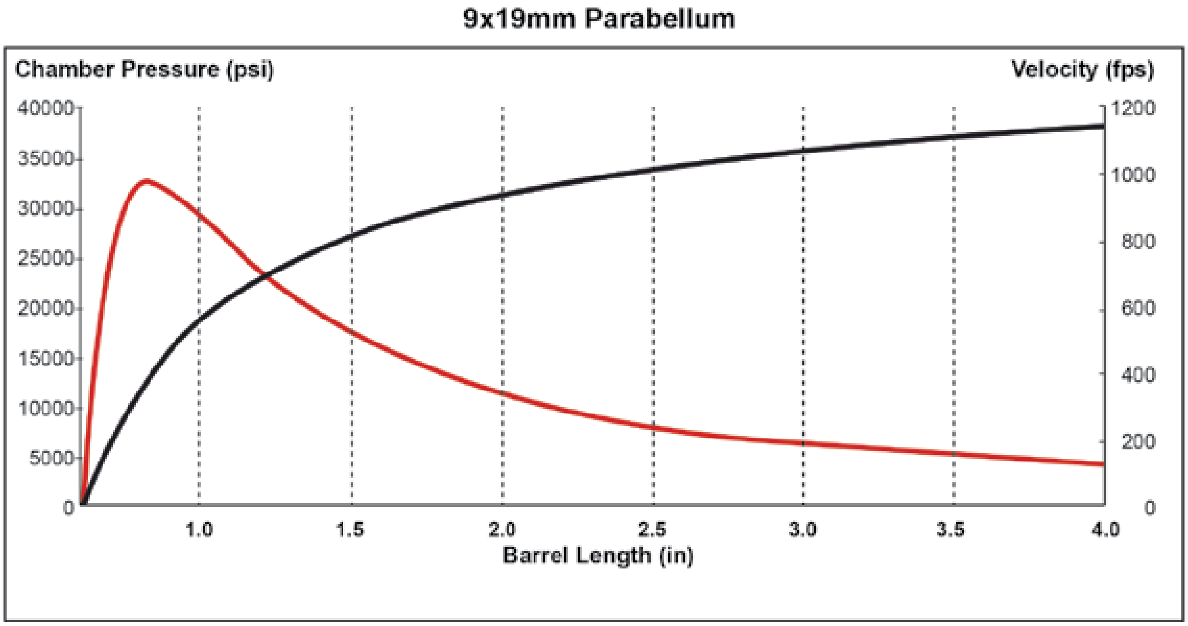


Figure 15b: The 9mm travel chart.

9x19mm Parabellum						
Time (Milliseconds)	Pressure (PSI)	Increase/ Decrease/ %	Distance from Breech (Inches)	Increase/ %	Velocity (FPS)	Increase/ %
			.620 (Start)			
.05	8,800		.635	.015/2%	51	
.1	24,900	16,100/183%	.697	.062/10%	198	147/288%
.14	32,300	7,400/30%	.839	.142/20%	403	205/104%
.16	31,220	-1,080/-3%	.9258	.0868/10%	498	95/24%
.2	22,800	-8,420/-27%	1.246	.3202/35%	713	215/43%
.3	9,450	-13,350/-59%	2.295	1.049/84%	984	271/38%
.4	5,115	-4,335/-46%	3.528	1.233/54%	1,112	128/13%
.43	4,470	645/-13%	4	.472/13%	1,140	28/3%

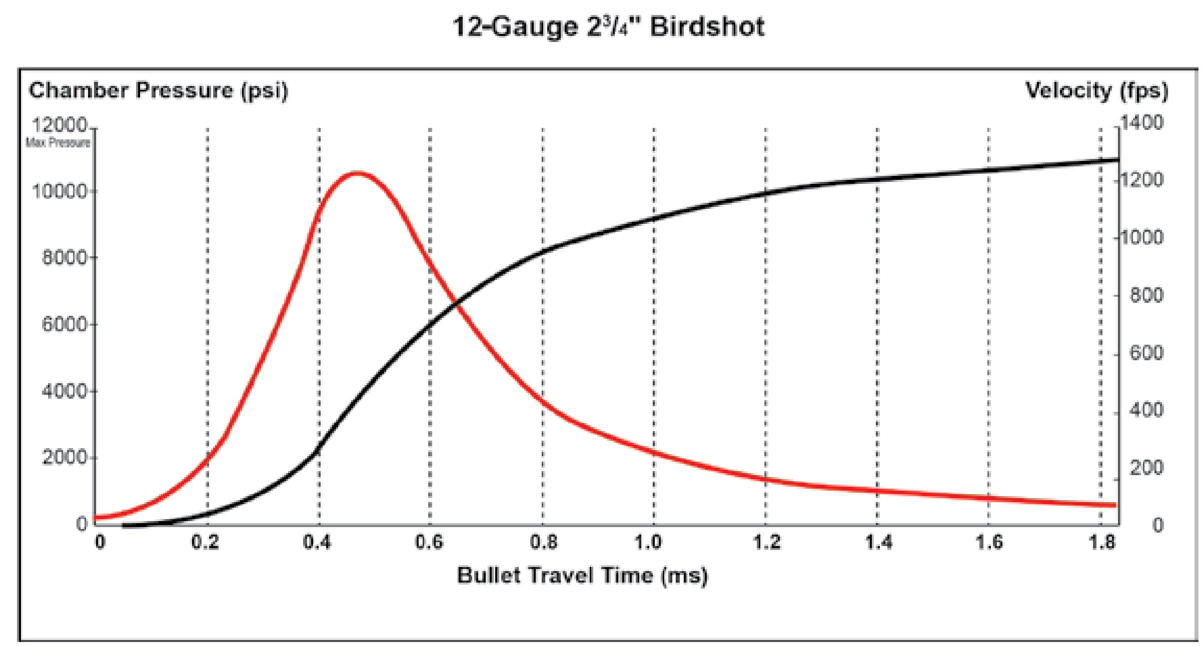


Figure 16a: The 12-gauge time chart.

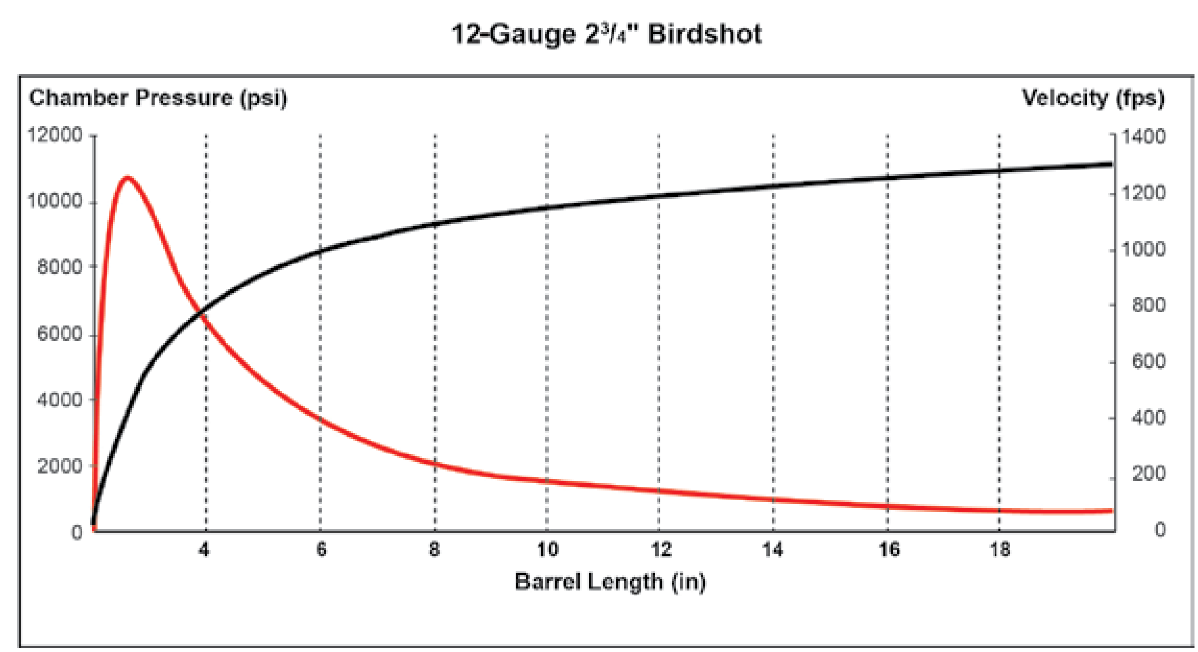


Figure 16b: The 12-gauge travel chart.

12-Gauge 2¾”						
Time (Milliseconds)	Pressure (PSI)	Increase/ Decrease/ %	Distance from Breech (Inches)	Increase/ %	Velocity (FPS)	Increase/ %
			1.419 (Start)			
.05	340		1.425	.006/.5%	8	
.1	640	300/88%	1.448	.023/1.5%	20	12/150%
.2	1,880	1,240/198%	1.5	.052/4%	45	25/125%
.3	4,870	2,990/159%	1.585	.085/6%	106	61/136%
.4	9,130	4,260/87%	1.694	.109/7%	260	154/145%
.47	10,200	1,070/12%	2.019	.325/19%	420	160/62%
.49	10,000	-200/-2%	2.76	.741/37%	475	55/13%
.5	9,880	-120/-1%	3	.24/9%	500	25/5%
.6	7,740	-2,140/-22%	3.85	.85/28%	700	200/40%
.9	2,750	-4,990/-64%	7.52	3.67/95%	1,020	320/46%
1.5	850	-1,900/-69%	14.1	6.59/88%	1,225	205/20%
1.84	660	-190/-22%	20	5.9/42%	1,275	50/4%

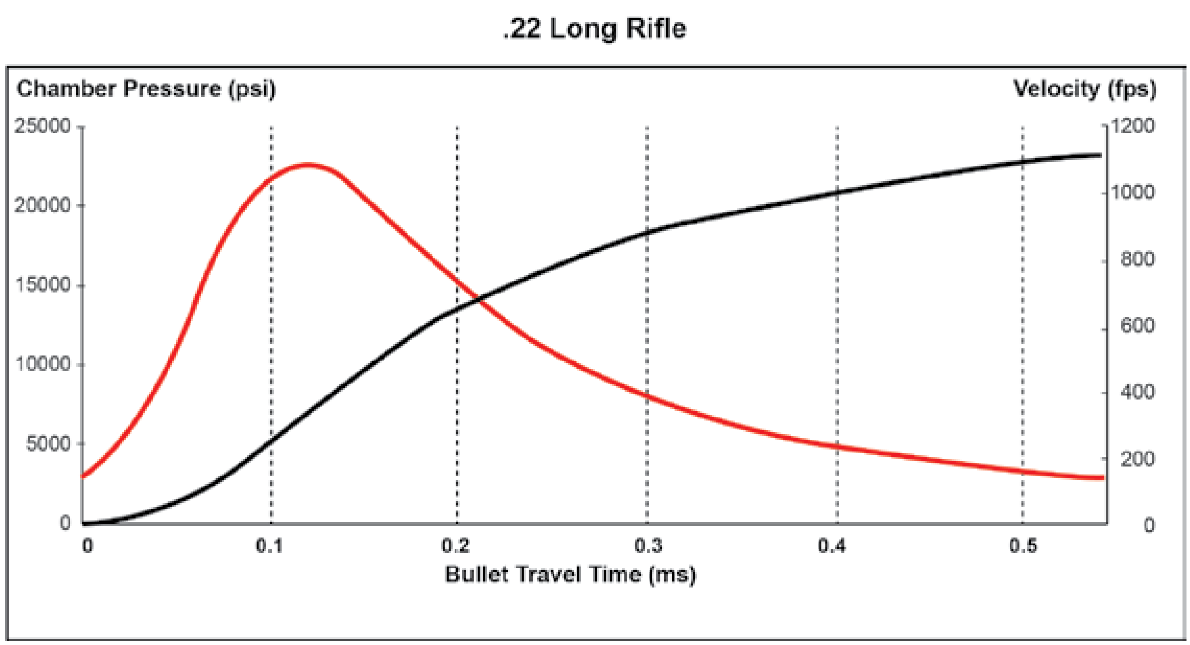


Figure 17a: The .22 time chart.

.22 Long Rifle

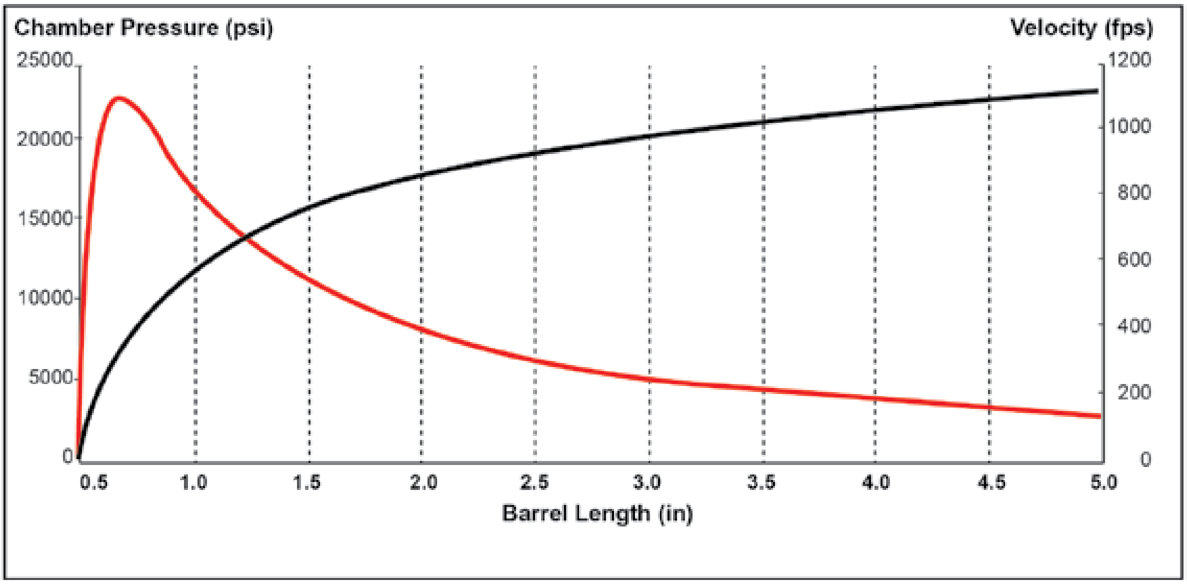


Figure 17b: The .22 travel chart.

.22 LR						
Time (Milliseconds)	Pressure (PSI)	Increase/ Decrease/ %	Distance from Breech (Inches)	Increase/ %	Velocity (FPS)	Increase/ %
			.5 (Start)			
.05	11,300		.521	.021/4%	70	
.1	21,700	10,400/92%	.607	.086/17%	250	180/257%
.12	22,500	800/4%	.664	.057/9%	330	80/32%
.2	14,900	-7,600/-34%	1.165	.501/75%	650	320/97%
.23	11,900	-3,000/-20%	1.439	.274/24%	735	85/13%
.3	8,000	-3,900/-33%	2.093	.654/45%	870	135/18%
.4	5,000	-3,000/-38%	3.177	1.084/52%	1,000	130/15%
.5	3,500	-1,500/-30%	4.446	1.269/40%	1,070	70/7%
.54	3,100	-400/-11%	5	.554/12%	1,110	40/4%

NOTES

NOTES

Chapter 9 - Recoil and Cycling, Transitional and Exterior Ballistics

Recoil and Cycling

From the moment the projectile begins to move forward in the chamber/bore, there is an equal force that is driving the firearm in the opposite direction (Newton's Third Law of Motion). This movement is inperceptible to the shooter until after the projectile has left the muzzle because the event occurs so rapidly, and the firearm and shooter provide enough inertia to resist the impulse while the projectile is moving through the barrel. This force that the shooter feels is known as recoil.

Recoil forces can be sorted into three basic types: free recoil, recoil impulse, and "felt" recoil. Free recoil is the actual amount of recoil the firearm experiences without any external factors involved (i.e. the shooter, gravity, friction, or any environmental factors). The recoil impulse is how the recoil is delivered, while felt recoil is how the shooter perceives it. There are many factors that can affect free, impulse, and felt recoil, including the mass and velocity of the projectile and firearm, the "jet" effect, the use of muzzle brakes, compensators and suppressors, the layout of the grip and stock and the use of soft buttpads or other devices used to dampen recoil forces.

The jet effect is caused by the high pressure, high velocity propellant gas exiting the muzzle. The .223's propellant gasses are exiting at roughly 5,075 fps, the 9mm's are exiting at roughly 1,995 fps, the 12-gauge's are exiting at roughly 2,056 fps, and the .22's are exiting at roughly 1,943 fps. The bore of the barrel acts like the thruster of a jet, directing the propellant gases forward, parallel to the bore's axis, which in turn drives the firearm in the opposite direction. Depending on the caliber and load, the jet affect will account for roughly 30 percent of the total recoil forces.[1] The use of light-for-caliber high velocity projectiles will increase the jet effect over heavier, slower-moving projectiles.

Recoil forces (*free recoil*) can be calculated with a few known factors. To calculate recoil, you will need to first calculate the velocity of the recoiling firearm in feet per second (fps). To calculate recoil velocity, you will need to know the weight of the projectile (W) in grains, the weight of the propellant (P) charge in grains, the muzzle velocity (MV) of the projectile in feet per second, the weight of the firearm (M) in pounds, and the constants 1.25 – 1.75* and 7,000.** The formula for recoil velocity is:

P x MV x (1.25 to 1.75) + W x MV/M x 7,000 = Recoil Velocity (RV) FPS

For example: a .223 cartridge with 26 grains of propellant, firing a 55-grain bullet at 2,900 fps out of a 7 lb. rifle would have a recoil velocity of:

26 x 2,900 x 1.75 + 55 x 2,900/7 x 7,000 = RV

131,950 + 159,50 /49,000 = RV

291,450/49,000 = 5.94 FPS

A 9mm cartridge with 4.8 grains of propellant, firing a 115-grain bullet at 1,440 fps out of a 1.5 lb. pistol would have a recoil velocity of:

4.8 x 1,140 x 1.5 + 115 x 1,140/1.5 x 7,000 = RV

8,208 + 131,100/10,500 = RV

139,30/10,500 = 13.27 FPS

A 12-gauge cartridge with 20.5 grains of propellant, firing 383 grains of shot + a 43-grain wad (426 total) at 1,275 fps out of a 7 lb. shotgun would have a recoil velocity of:

20.5 x 1,275 x 1.5 + 426 x 1,275/7 x 7,000 = RV

39,206 + 543,150/49,000 = RV

582,356/49,000 = 11.88 FPS

A .22 cartridge with 1.9 grains of propellant, firing a 40-grain bullet at 1,100 fps out of a 2 lb. pistol, would have a recoil velocity of:

1.9 x (1,110 x 1.5) + 40 x 1,110/2 x 7,000 = R

3,164 + 44,400/14,000 =RV

47,564/14,000 = 3.40 FPS

**The constant will vary by firearm type, propellant charge and type, projectile weight, and muzzle velocity. For long-barreled shotguns use 1.25, for normal length shotguns, pistols and revolvers use 1.5, for high powered rifles use 1.75.[2] The constant is derived from the acceleration of the expanding propellant gas.*

***There are 7,000 grains in 1 pound.*

Now that you have calculated recoil velocity, you can use those figures to calculate recoil energy (in ft-lb. force). To calculate recoil energy all you need to know is the mass (M) of the firearm in pounds, the recoil velocity (RV) of the firearm, and the constant 64.348.* The formula for recoil energy is:

M x RV^2/64.348 = Recoil Energy (RE)

For example: the AR-15 rifle would have a recoil energy of:

7 x (5.94 x 5.94)/64.348 = RV

7 x 35.28/64.348 = RV

246.96/64.348 = 3.84 ft-lb.

The striker-fired pistol would have a recoil energy of:

1.5 x (13.27 x 13.27)/64.348 = RV

1.5 x 176/64.348 = RV

264/64.348 = 4.1 ft-lb.

The shotgun would have a recoil energy of:

7 x (11.88 x 11.88)/64.348 = RV

7 x 141/64.348 = RV

987/64.348 = 15.33 ft-lb.

The revolver would have a recoil energy of:

2 x (3.40 x 3.40)/64.348 = RV

2 x 11.56/64.348 = RV

23.12/64.348 = .34 ft-lb.

**The constant is twice the acceleration of gravity: 32.174 x 2.*

Knowing the recoil velocity of the firearm will also allow you to calculate the recoil impulse.[3] The recoil impulse is the change in momentum of the firearm over a given time, or how the recoil "feels." A quicker recoil impulse will feel like a punch, while a slower impulse will feel like a strong push. Recoil impulse is expressed in pounds per second (lb-sec.) and requires the firearm's momentum to be known. Luckily momentum is a product of the firearm's mass (in lb.) and recoil velocity (in fps), both we know. Momentum is expressed in pound-feet-per-second (lb-fps).

AR-15: 5.94 x 7 = 41.58 lb-fps.

Striker-Fired Pistol: 13.27 x 1.5 = 19.90 lb-fps.

Shotgun: 11.88 x 7 = 83.16 lb-fps.

Revolver: 3.40 x 2 = 6.92 lb-fps.

Now you just need to divide the firearm's momentum by the constant 32.174 (gravitational acceleration). The AR-15 would have a recoil impulse of 1.29 lb-sec. The striker-fired pistol would have a recoil impulse of .62 lb-sec. The shotgun would have a recoil impulse of 2.58 lb-sec. and the revolver would have a recoil impulse of .22 lb-sec. These figures show the two handguns having very quick impulses, with relatively low force. The shotgun's recoil impulse is much longer, with a greater force. The AR-15's recoil impulse will be harder than the handgun's but sharper than the shotgun's.

CYCLING

With recoil-operated actions, the energy created during discharge will also be used to cycle the action. With the striker-fired pistol (recoil-operated), the recoil force acts directly upon the slide of the pistol and drives it rearward to cycle the action. In a gas operated system, high pressure gas is tapped from the bore and used to act against the action parts of the firearm, driving them rearward and cycling the action.

The striker-fired pistol's slide will move roughly 3.75 in. (1.875 in. backward and 1.875 in. forward) back into battery. It takes about .050 seconds from the moment one round is fired until the slide extracts the empty case, ejects it, compresses the recoil spring, strips a new round from the magazine and locks the new round in the chamber. For the AR-15, the bolt must travel roughly 7 in. (3.5 in. back and 3.5 in. forward into battery). It takes about .063 seconds to completely cycle the AR-15's action. This means that the 9mm bullet is roughly 57 ft. from the muzzle as the slide comes back into battery and the .223 bullet is roughly 183 ft. from the muzzle as the bolt comes back into battery.

Transitional Ballistics

Now that the projectiles have exited the barrel, we can begin to discuss their transitional ballistics. Transitional ballistics is the study of the projectile from the moment it exits the muzzle until the pressure around it has equalized to atmospheric conditions. There are several factors that affect transitional ballistics, including the projectile, firearm, and atmospheric conditions.

Continuing with the projectile's journey, let's assume, for example, that all four projectiles (.223, 9mm, 12-gauge, and .22) leave the muzzle at the same time. The .223 has an exit velocity of 2,900 fps and a remaining chamber pressure of about 14,000 psi. The 9mm has an exit velocity

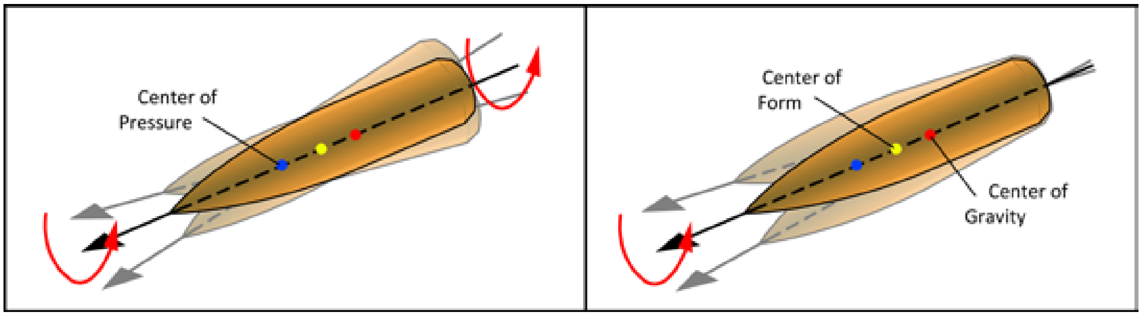


Figure 1: Left – Nutation or wobble. Right – Precession.

of 1,140 fps and a remaining chamber pressure of about 4,470 psi. The 12-gauge birdshot has an exit velocity of 1,275 fps and a remaining chamber pressure of 660 psi, and the .22 has an exit velocity of 1,110 fps and a remaining chamber pressure of 3,100 psi.

While three out of four of the projectiles (.223, 9mm, 12-gauge) exit the muzzle at supersonic velocity, the propellant gas from all four cartridges will exit the muzzle at supersonic velocities. If we assume the propellant gas is moving at a (moderate) value of 1.75X the projectile, then the .223's propellant gasses are exiting at 5,075 fps, the 9mm's are exiting at 1,995 fps, the 12-gauge's are exiting at 2,231 fps, and the .22's are exiting at 1,943 fps. So now we have relatively high pressure gas moving at greater velocity than the projectiles.

As the projectile exits the muzzle, it will push the air column out in front of it. This also includes any propellant gasses that may have escaped ahead of the projectile or any debris that may be in the bore. This creates an initial pressure front that disrupts the air in front of the muzzle. Once the projectile's base clears the muzzle and enters the turbulent air ahead of it, it will "uncork" the bore. The shockwave that is created when the propellant gas enters the surrounding atmosphere is what we recognize as muzzle "blast," or the loud noise and flash of the gunshot. The shockwave radiates 360° from the firearm's muzzle, creating a "bubble" of turbulent air. The flash or light from the shot comes from the super-heated, high pressure, fuel-rich gas in the bore, mixing with the oxygen in the atmosphere and igniting.

The exiting propellant gases (moving roughly 1.75X the speed of the projectiles) and the shockwave overtake the projectile and envelope it in a cloud of high pressure, high velocity, turbulent gas. Depending on the volume of gas exiting the barrel and the velocity of the projectile, the projectile may have to travel several feet to clear the propellant gas cloud and the shockwave created during the initial release of pressure.[4,5] Although the exiting propellant gases may not contribute to any additional velocity for the projectile, the gas and shockwave are still acting upon the projectile until it exits the transitional zone.

The bore of the barrel acts like the thruster of a jet, focusing the exiting propellant gas toward the base of the projectile. The concentricity of

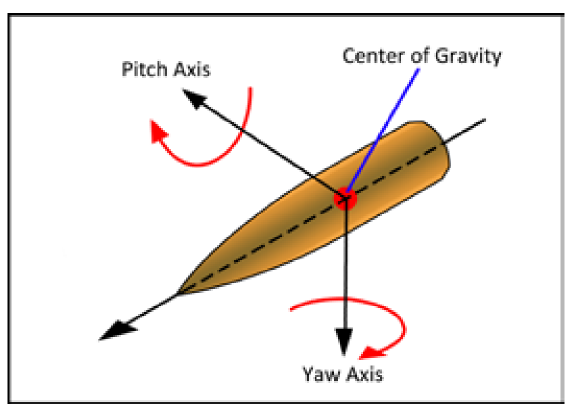


Figure 1b: Pitch and yaw.

Figure 2: Exiting the transitional zone.

the muzzle crown* and the shape and concentricity of the base of the projectile are crucial to the initial stabilization of the projectile's flight. If the muzzle of the firearm is non-concentric, angled, or is damaged, it will cause the propellant gas to exit the muzzle non-uniformly. The same is true of the base of the projectile: if it is non-concentric, the exiting propellant gas will work against the projectile in a non-uniform manner. If the exiting propellant gas is uneven or erratic, it can cause the projectile to *nutate, pitch, precess, and yaw*. The projectile may remain unstable until exiting the transitional zone, stabilizing once clear of the turbulent atmosphere. However, the projectile will be travelling on a trajectory that differs slightly from the bore's axis and its original (or intended) trajectory.

The projectile(s) will exit the transitional zone once it clears the shockwave created by the propellant gas. A supersonic projectile (.223, 9mm, 12-gauge) will clear the initial shockwave while "dragging" a secondary shockwave like the wake of a boat. The secondary shockwave also creates a loud noise similar to the bore's "uncorking," but is indistinguishable from the first shockwave because it occurs almost simultaneously. A subsonic projectile (.22) will clear the initial shockwave but will not create a secondary shockwave like the supersonic projectiles. It is also during the end of the transitional period that the cup/wad will begin to separate from the shot in the case of a shotshell. Once the cup/wad clears the muzzle and ceases to be propelled or pushed by the propellant gas, it will begin to decelerate faster than the shot charge, which has far greater momentum and aerodynamics. Assuming a transitional zone of roughly 3 ft., it would take the .223 projectile roughly .001 seconds to reach the external ballistic zone. It would take the 9mm projectile, 12-gauge birdshot, and .22 projectiles roughly .002 seconds to clear the transitional zone.

A cartridge's transitional ballistics will also have an effect on how any muzzle device will perform (i.e. flash hider, compensator, brake, or suppressor). Muzzle brakes and compensators both utilize the exiting propellant gas to help mitigate some of the firearm's recoil. The muzzle brake will divert some of the propellant gas sideways (horizontally) and back toward the shooter through the use of baffles. This will create a forward thrust that will drive the firearm forward, mitigating some recoil. The compensator will divert some of the propellant gas upward (vertically), using ports and driving the muzzle downward to help mitigate *muzzle flip*. Additionally, the baffles on the compensator will also allow the escaping gasses a surface to push forward on. This will reduce the rearward movement of the compensator and everything it is connected to, thus reducing felt-recoil. Muzzle brakes and compensators will perform better with high velocity, light-for-caliber projectiles because the volume and velocity of the propellant gas is typically greater than heavier, slower projectiles.

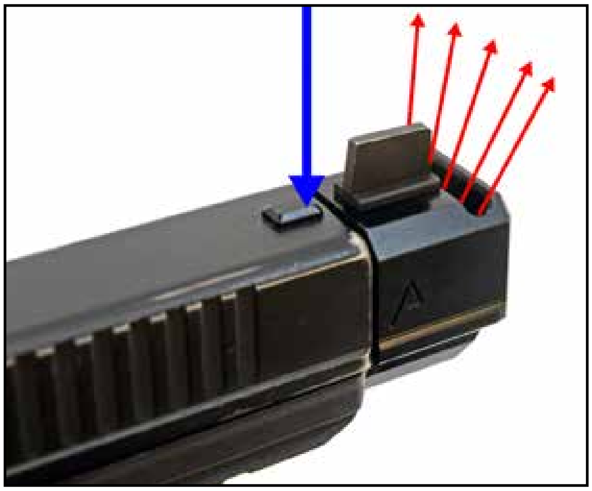


Figure 3a: How a compressor works.

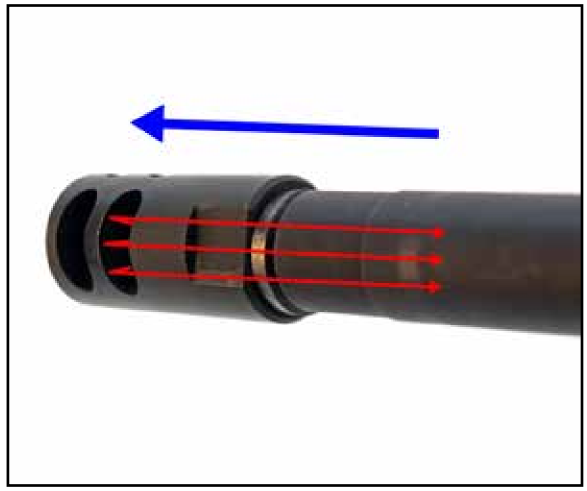


Figure 3b: How a muzzle brake works.

The opposite is true for flash hiders and suppressors. Flash hiders are designed to mix the exiting propellant gas with the atmosphere more efficiently than a bare muzzle, brake, or compensator. When the shockwave from the exiting propellant gas contacts the atmosphere, it creates enough heat and pressure to ignite the remaining fuel in the propellant gas and oxygen in the air.[6] The flash hider works by dividing the exiting propellant gas into multiple "streams" that cool the gas rapidly and limit the chance of ignition. A suppressor works by "trapping" the exiting propellant gas. The baffles or core inside the suppressor body create multiple "chambers" that allow the propellant gas to fill, slow, and cool. Suppressors and flash suppressors will be less effective with high velocity cartridges than with slower, heavy projectiles. Suppressors also cannot contain the shockwave created by the supersonic projectile.

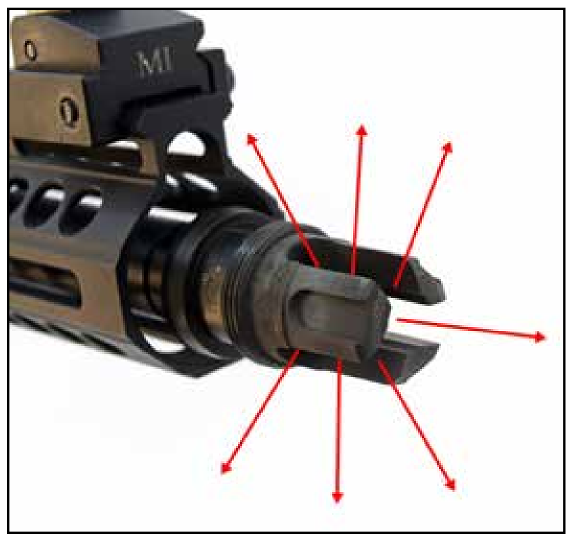


Figure 3c: How a flash hider works.

**The concentricity of the crown is more critical than its shape. The 11° crown is touted as the most accurate crown angle, but if it's not machined perfectly concentric to the bore, it will still perform poorly.*

Exterior Ballistics

The projectiles are now clear of the transitional zone and have entered "normal" atmospheric conditions. The study of the projectile from the moment it clears the transitional period until it has impacted the target is known as exterior/ external ballistics. There are several factors that can affect a projectile's exterior ballistics, both with the projectile and environment. Depending on how long the projectile is in flight, the rotation of the earth may also become a factor.

The design of the projectile will affect how capable it is of overcoming various environmental factors, while internal factors can lead to instability in the projectile during flight. Environmental factors include both gravity and air. Gravity works perpendicular to the projectile's path (which is mostly parallel to the earth's surface), affecting its elevation (vertical axis). Air, or more so the resistance it creates (*drag*), will work parallel to the projectile's travel and affect its velocity (horizontal axis, parallel to the projectile's path). Wind can act parallel, perpendicular, and diagonally to the projectile's path. All of these factors work negatively on the path of the projectile, altering its intended point of impact. This path is known as the projectile's *trajectory*.

THE PROJECTILE

The design of the projectile will play a very big role in how it performs in flight. The mass, shape, and dimensions of the projectile are all critical to the projectile's exterior ballistic performance. As previously discussed in the projectile section of the components of the cartridge, the performance of the projectile can be measured by its ballistic coefficient (BC). Projectiles with greater BCs are better-suited at overcoming any external force that would try to divert it from its intended trajectory. With our example cartridges, the .223 projectile has a BC of .237, the 9mm's is .158, the 12-gauge's is .02[7] and the .22's is .138, none of which are considered high BCs. The low BCs can be contributed to low mass, low SD (sectional density), and less aerodynamic forms.

Any variance in the projectile's form or dimensions caused by the manufacturing process or damage can lead to a projectile that is non-concentric. This is true of both the jackets and cores

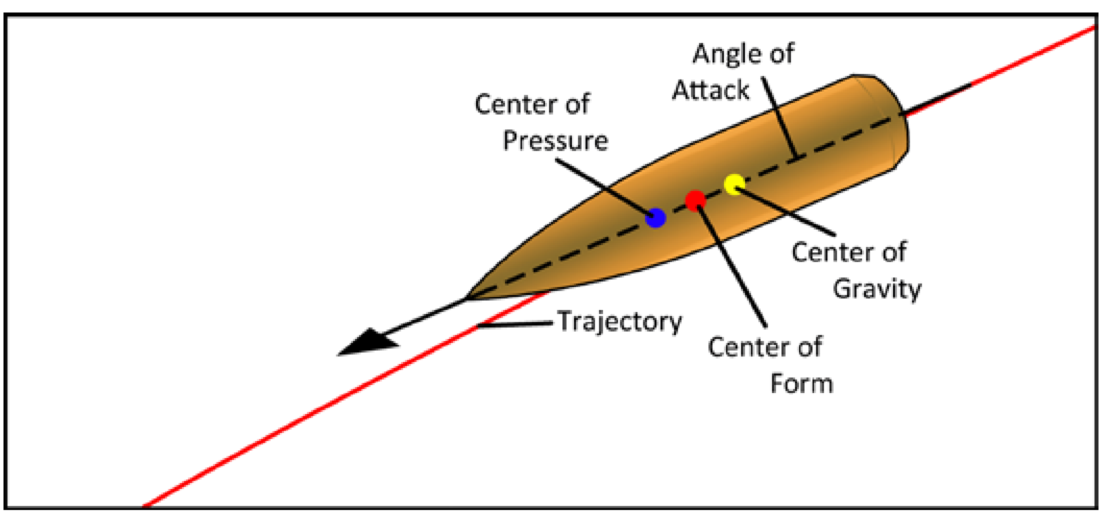


Figure 4: The projectile's center of form, gravity, and pressure.

of pistol and rifle bullets and all types of shot. Non-concentric jacket walls, a core that is non-concentric, or shot that is not perfectly round can lead to an imbalance of the projectile's center of gravity (mass) and the center of form. The projectile's center of gravity is the focal point that gravity acts upon or the projectile's balance point. The projectile's center of form is the center of the overall shape of the projectile. Of the two centers, the center of gravity is the only point of the projectile that aligns with its trajectory.[8] As the projectile is spun (or just propelled like with shot), any imbalance can lead to a wobble in flight. As the projectile moves through the bore of the firearm, any imperfections in the projectile are irrelevant as they follow the path of the bore's axis; but as soon as the projectile has cleared the support of the barrel, any imbalance is immediately magnified.

This is why the rifling of the barrel is so important. A properly stabilized projectile may momentarily become unstable then quickly stabilize once again. A projectile that has not been properly stabilized will experience instability from outside forces and will not be able to recover. This is why we often see a condition known as "keyholing." A projectile that is unstable will begin to wobble before tumbling end-over-end and hitting the target sideways. A properly stabilized projectile will overcome any outside force and restabilize thanks to its *rotational inertia* and *angular momentum* (a product of its mass and angular velocity rotating around its center of mass along its rotational axis).

Figure 5: Keyholing.

The projectile's angular momentum will resist any change in the orientation of its rotational axis and velocity until acted upon by outside forces. Like a spinning top, as long as it has enough angular momentum, it will remain upright with the position of its axis unchanged until acted upon by an outside force (friction, gravity). Even if you were to push against the top, as long as it still has enough momentum it will only wobble for a moment and return to its stable position. It is not until the momentum has dissipated that the top begins to wobble and eventually fall.

It is at this point in the projectile's trajectory (roughly 10 ft. – 15 ft. from the muzzle) that "muzzle energy" has been (traditionally*) measured. Muzzle energy, or the kinetic energy of the projectile, is a product of its mass and velocity. The projectile's muzzle energy can be easily calculated with only two known factors: mass (M) (in grains) and velocity (V) (in feet-per-second) and the constant 450,436.** Here is the equation for muzzle energy:†

M x V^2/450,436 = Muzzle Energy (ME in ft-lb.)

The muzzle energy for our example cartridges would be:

.223 Remington

55 x 2,900 x 2,900/450,436 = 1,027 ft-lb.

9x19mm Parabellum

115 x 1,140 x 1,140/450,436 = 332 ft-lb.

12-gauge

383 x 1,275 x 1,275/450,436 = 1,382 ft-lb.‡

.22 Long Rifle

40 x 1,110 x 1,110/450,436 = 109 ft-lb.

**Traditionally, the chronograph has been used to measure projectile velocity. Newer technology, such as the Doppler radar and the magnetic chronograph, are not sensitive to muzzle blast.*

***The constant comes from a product of gravitational acceleration (32.174 fps) x 2 x 7,000 (grains in a pound).*

†The formula can be used to calculate projectile energy at any distance as long as velocity is known.

‡The figure is a culmination of the energy of all the pellets. Seven-eighths ounce of #7.5 birdshot contains roughly 263 pellets (at 1.46 grains each), with each pellet producing around 5.2 ft.lb. of energy.

GRAVITY

Immediately upon exiting the barrel, the projectile will begin to be dragged down to the earth's surface by gravity. Up to this point the projectile was supported by the barrel, with gravity having little to no effect on the projectile's trajectory. Once the projectile clears the edge of the muzzle, gravity will begin pulling the projectile down, altering its path from the bore's axis. If the firearm were discharged in the vacuum of space, the projectile would continue along the same path, following the bore's axis forever.

Gravity acts on all things at a rate of 32.174 feet-per-second-per-second (fps/S) regardless if they are free-falling or propelled parallel or at an angle to the earth's surface. Gravity also only acts upon objects in an axis perpendicular to the earth's surface, meaning gravity only works in a vertical axis as a downward acceleration. To put this into perspective, an object that is dropped and allowed to free-fall for one second will travel roughly 16.08 ft.* If two bullets of identical mass were dropped and fired from the same height, they would contact the ground at the same time, regardless of the fired projectile's velocity. The propelled projectile would just be a greater distance from its starting position.

**The first second the object would be accelerating from 0 fps to 32.174 fps, with an average velocity of 16.08 fps. An object travelling 16.08 fps for one second would travel 16.08'. The next second the object would be accelerating from 32.174 fps to 64.348 fps with an average velocity of 48.261 fps. Travel would increase to 64.341 ft. (16.08 ft. + 48.261').*

Let's use our four flying projectiles as examples. The four firearms are held with the axis of the bore 5 ft. off the ground, with the axis parallel to the earth's surface (level). A fifth projectile is held 5 ft. off the ground, level with the other projectiles. If fired and dropped simultaneously,

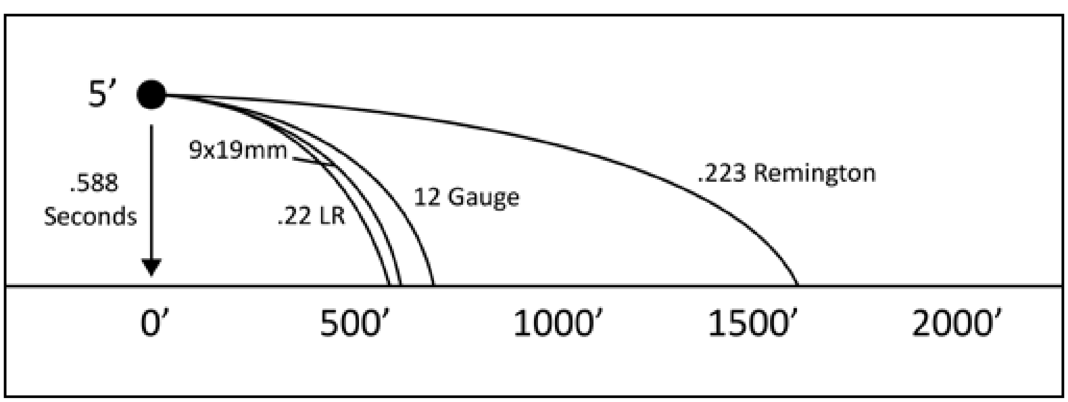


Figure 6: The effects of gravity.

all five projectiles would hit the ground at the exact same moment.

A projectile held 5 ft. off the ground will take roughly .558 seconds to hit the ground. The equation for the amount of time an object takes to free-fall is:[9]

$$T = \sqrt{(2H / G)}$$

Where:

T = Time in seconds

H = Height of the object in feet

G = Acceleration of gravity (32.174)

$$T = \sqrt{(2 \times 5)/32.174}$$

$$T = \sqrt{(10/32.174)}$$

$$T = \sqrt{.311}$$

$$T = .558 \text{ seconds}$$

With no other forces acting upon the projectiles but gravity, the .223 bullet will be roughly 1,618.2 ft. from its starting point after .558 seconds of travel at 2,900 fps. With a muzzle velocity of 1,140 fps, the 9mm bullet will be 636.12 ft. from its starting point, while the 12-gauge (1,275 fps) will be 711.45 ft. away and the .22 (1,110 fps) will be 619.38 ft. away.* To calculate the rough distance a projectile would travel before hitting the ground, all you need to do is multiply its time of travel (.558 seconds) by its initial velocity.

**Note that these figures are only for a projectile being acted upon by gravity. The addition of drag and other factors will alter these numbers.*

Now let's angle the barrel so that the bore's axis is at a positive angle to the earth's surface. When fired, the projectiles will follow a path shaped like a *parabolic arc*. Upon exiting the barrel, the projectile will begin to travel upward and away from the muzzle. Although the projectile is moving upward, it will never rise above the bore's axis. The upward angle of the barrel creates a vertical (upward) velocity component that immediately experiences a downward acceleration force from gravity. As the projectile moves along its trajectory, the upward velocity will slow to zero (at the top of its arc) as the force of gravity overcomes the projectile's upward velocity. Once the projectile has reached the peak of its trajectory, it will begin to accelerate downward. The angle the barrel is held at is known as the *line of departure.*[10]

TRAJECTORY AND SIGHTS

Most new shooters believe that the projectile rises when exiting the barrel. We know this is not true because gravity acts immediately on the projectile after exiting the barrel, pulling it down to the earth's surface. The misconception comes from the way sights and optics are designed. Sights and optics are designed to create a "line of sight" that is at a negative angle to the bore's axis. When the sights are aligned with the target, the barrel is being pointed at a slight positive angle.

As the projectile follows its line of departure, it will intersect with the line of sight of the sights. This is known as a "point of zero." The point of zero is the distance from the muzzle of the firearm at which the projectile intersects with the line of sight. Depending on the firearm type, caliber, and sight dimensions, there may be one or two points of zero.

Firearms with relatively short effective ranges, like pistols and shotguns, may typically only have one point of zero. The sight arrangement will only angle the barrel slightly. As the projectile exits the muzzle following its line of departure, the projectile will rise into the line of sight of the sights. The top of the arc of the projectile will intersect with the line of sight, creating a zero point and then begin to fall below the line of sight. Firearms like rifles, with much longer effective ranges, will typically have two points of zero. The sight arrangement will angle the barrel slightly steeper than a pistol or shotgun. As the projectile exits the muzzle following its line of departure, the projectile will rise into the line of sight of the sights forming the "near zero." Because of the steeper angle of the barrel, the projectile will continue to rise above the line of sight (but not above the bore's axis). As the

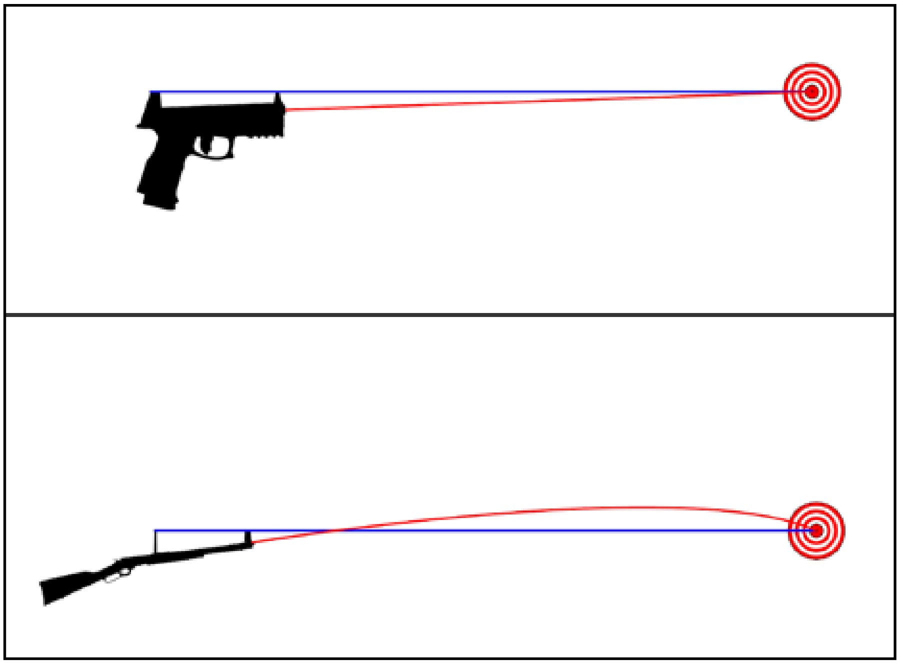


Figure 7: Single point of zero versus near/far zero.

projectile reaches the top of the arc of its trajectory, it will begin to fall and intersect the line of sight again. This is the "far zero." Most rifle sights and all optics can be adjusted to adjust the point of zero to suit the needs of the situation.

AIR

Of all of the forces acting upon the projectile's flight, air is the greatest variable. Although air is a mixture of gas and vapor, its flow is similar to a liquid. This is why *aerodynamics* is a subscience of *fluid dynamics*. Air currents are continuously changing, with any variance in temperature, humidity, and altitude changing how a projectile performs in flight. Changes in atmospheric conditions will result in fluctuations in air density. Wind can also act upon the projectile from any direction. A projectile traveling far enough may experience wind from several different directions.

As the projectile flies through the air it is basically penetrating a fluid with a very low density. The friction created by this low-density fluid is what we know as drag. If the fluid the projectile is moving through is continuously changing its density, the projectile will experience varying amounts of drag. If the air is less dense, the projectile will experience less drag and, in turn, fly farther than a projectile flying through air that is denser. Even the air directly around the projectile will vary in pressure as it creates various high pressure areas and shockwaves if it is supersonic. As well, projectiles that are travelling at subsonic velocities may experience supersonic flow as the air around them accelerates to move over its body.[11]

Pressure on the nose of the projectile, parallel to its rotational axis, is known as drag, while pressure acting upon any part of the projectile not in line (parallel) with its rotational axis is known as lift. These pressures create a new center on the projectile called the *center of pressure*. The center of pressure is the average location of a sum of various pressures against a projectile in flight. Pressure will vary around the projectile, with most being focused on the nose and under the tip. Of the three centers (form, gravity, and pressure), the only center that will vary is the center of pressure. As the projectile decelerates from drag, pitches, yaws, precesses, and nutates,

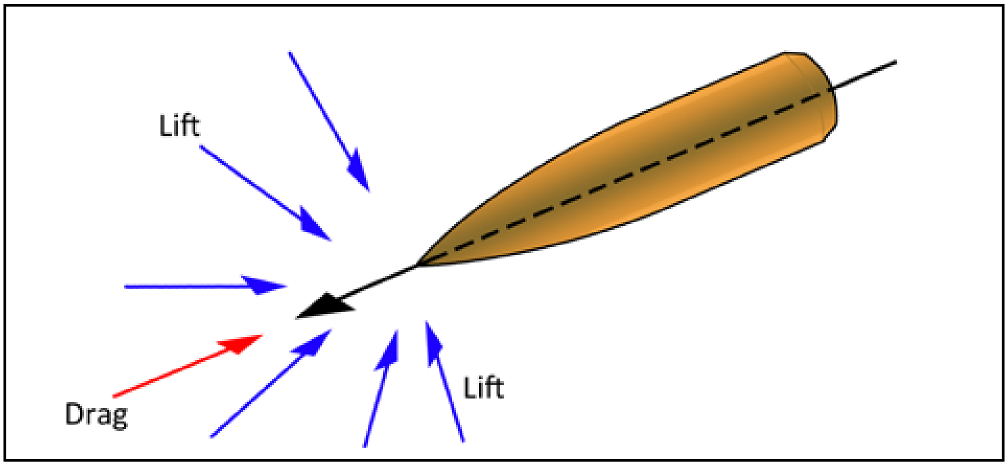


Figure 8: Drag and lift.

the center of pressure will continuously change. The projectile's flight is more stable when the center of pressure is close to or in line with the center of gravity. The farther the two points are, the more likely that the projectile will become unstable and begin to wobble.

The amount of drag and lift the projectile experiences is based on its velocity, the flow of air around it, and its orientation to its direction of travel. The projectile's rotational axis in relation to its trajectory is known as the *angle of attack*. If the angle of attack is not in line with the projectile's trajectory, the nose of the projectile will experience lift, causing the axis of the projectile to point at a positive angle (*pitch* up) to its trajectory. This is more prevalent with long, pointed bullets where the projectile's mass is the lowest and pressure is the highest. As the projectile flies through the air, variances in pressure and the angle of attack can make the nose of the bullet pitch up and down. Because most of the pressure on the projectile is on the tip and underneath, the tip tends to point upward in relation to its trajectory.

GYROSCOPIC DRIFT

A weird phenomenon occurs when applying force to a spinning object. Instead of the object moving in line with the direction of force, the spinning object will move perpendicular to the direction of force, in the direction of its rotation. With a projectile that is being pulled to the earth by gravity, the force causes a projectile with a clockwise (when looking from the back of the projectile) rotation to drift right. This is known as gyroscopic or "spin" drift.

The force of gravity (pulling down) on the projectile and its (clockwise) spin create a slight yaw (*yaw of repose*), which forces its rotational (longitudinal) axis to point slightly to the right. The oncoming air acts upon the left side of the projectile and forces it to the right. The projectile is also basically rolling or skidding across a "surface" of high pressure air. All of these contributing factors lead to an amount of drift that can be significant out to 500 yd. and beyond.[12]

The shape of the projectile, its rotational velocity, and flight time all contribute to the amount of drift it may experience. We can roughly calculate spin drift (D) (in inches). All that is needed is the projectile's time of flight (T) and *stability factor* (S). We know our time of flight is .558 seconds. We can use our Miller stability factors we calculated earlier (.223 - 2.67, 9mm - 18.54, .22 - 1.61) or we can use one of several calculators online: https://bisonballistics.com/calculators/stability or https://www.jbmballistics.com/cgi-bin/jbmstab-5.1.cgi. The online calculators

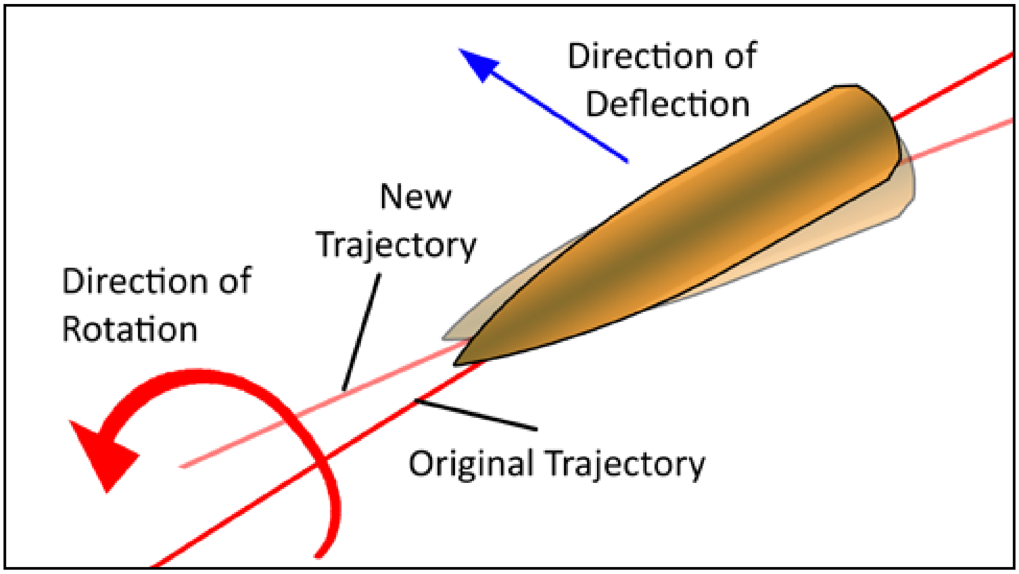


Figure 9: Spin drift.

do a better job of providing more accurate figures with the introduction of temperature and pressure. Our .223 bullet would have a stability factor of roughly 2.9, our 9mm would be 13.5,* and the .22 bullet would be 1.15. Here is the formula for calculating spin drift:[13]

D = 1.25** x (S + 1.2**) X T^1.83**

The spin drift of a .223 projectile is roughly:

D = 1.25 x (2.9 + 1.2) x .558^1.83

D = 1.25 x 4.1 x .343

D = 1.76 in.

This means that a .223 projectile will drift roughly 1.76 in. to the right (assuming a right-hand twist) after .558 seconds of travel. The spin drift of a 9mm projectile is roughly:

D = 1.25 x (13.5 + 1.2) x .558^1.83

D = 1.25 x 14.7 x .343

D = 6.30 in.

This means that a 9mm projectile will drift roughly 6.30 in. to the right after .558 seconds of travel. The spin drift of a .22 LR projectile is roughly:

D = 1.25 x (1.15 + 1.2) x .558^1.83

D = 1.25 x 2.35 x .343

D = 1.01 in.

This means that a .22 LR projectile will drift rough one inch after .558 seconds of travel.

**A stability factor greater than about 2.5 means that a projectile is over-stabilized. This means that the 9mm projectile, although stable, is spinning much faster than needed to properly stabilize.*

***Constants.*

CALCULATING DRAG

The deceleration of the projectile due to drag can be roughly calculated with a few known factors. The calculations are "rough" because drag forces will vary with velocity. Our calculations will only be based on the projectile's initial (muzzle) velocity. Now that we have established a baseline atmosphere for our projectiles to fly through, let us find out how much air density and the shape of the bullet will contribute to drag forces.

There is no standard temperature or atmospheric pressure anywhere on earth. Atmospheric conditions are constantly changing and cycling. For scientific purposes, many scientific governing bodies have established "standard" or "baseline" measurements for both temperature and pressure. The International Standard Atmosphere (ISA)[14] has set a standard for temperature at 59° F and an atmospheric pressure of ~14.7 psi* (14.6959) at sea level. Let us adopt 59° F, an atmospheric pressure of 13.43 psi (atmospheric pressure at 2,500'),[15] an air density of .06977 lb/cu.ft.[16], as well as a relative humidity of 50 percent and an average altitude of 2,500 ft. above sea level with no wind as our "standard" atmospheric conditions.

**Atmospheric pressure is a measurement of an air column 1 in. x 1 in. square that extends from sea level to the end of the atmosphere. This figure is a representation of the mass of this column of air and how much pressure is applied to the area.*

To calculate drag, we need to know the density (D) of the air (in lb/cu.ft.) and the projectile's velocity (V) (in fps), the cross-section surface area (A) (in ft.^2), mass (M) (in lb.) and coefficient of drag (C) (which differs from the projectile's BC). To calculate the projectile's surface area, you will need to use the following formula:

3.14* x R^2** = A/144†

The .223 bullet (.224 in.) has a surface area of .00027 ft.^2. The 9mm bullet (.355 in.) has a surface area of .00069 ft.^2. The total surface area for the 12-gauge shot charge is roughly .0023 ft.^2, measured from the inside of the cup (.650 in.). The .22 (.2255 in.) has a surface area of .00027 ft.^2.

**Pi.*

***Radius. Half the diameter in inches.*

†Constant. Converts inches ^2 to feet^2.

The only factor we still don't know is the *drag coefficient* of the projectile. The drag coefficient differs from the projectile's BC in that BC derives its figures from drag models of other projectiles, while drag coefficient derives its figures from various other shapes. While most projectile manufacturers only list bullet BC, we can assume our example bullet's drag coefficient based on proven examples.[17] For the 9mm and .22 bullets, we will adopt the drag coefficient of .295. For the shot, we will use .47. For the .223 bullet, we will use a drag coefficient of .15.[18]

Now that we have all of our figures, we can begin to calculate a rough trajectory with the inclusion of drag. We will utilize a "standard" density (Dn) of .06977 lb/cu.ft. and our example projectile's initial velocities (V), surface area (A), mass (M), and drag coefficients (C). We will also include our time of flight (.558 seconds) later in the equation. Initially we will calculate the drag force deceleration. To calculate the deceleration due to drag (DD) in feet-per-second-per-second (fps/S), use the following formula:

Dn x V^2 x C x A / 2 x M = DD

The deceleration due to drag of a .223 projectile is:

.06977 x 2,900 x 2,900 x .15 x .00027/2 x .0078 = DD

23.76/.0156 = 1,523.07 fps/S

Based on the .223 projectile's initial velocity, mass, surface area, and coefficient of drag, it will experience a force of deceleration at a rate of 1,520 fps. This means that if allowed to fly long enough, drag would slow the projectile's velocity to 0 in roughly 1.9 seconds. Again, these factors are rough because the amount of drag the projectile experiences varies with velocity. To roughly calculate how much the force of drag deceleration affects the projectile's trajectory over a given time (DT) (expressed in feet), simply multiply the deceleration from drag (DD) by time of flight squared (T^2), which is .311 (.558 x .558).

DD X T^2 = DT

1523.07 x .558 x .558 = 474.23 ft.

This means that a .223 projectile traveling for .558 seconds will lose 474.23 ft. of trajectory due to drag. Subtract this figure from the gravity only trajectory (1,618.2') and you get a rough trajectory (in feet) based on gravity and drag.

1,618.2 – 474.23 = 1,143.97 ft.

So, a .223 bullet fired horizontally, 5 ft. off of the earth's surface, with an initial velocity of 2,900 fps and a mass of 55 grains, will fly roughly 1,144 ft. after .558 seconds of travel before hitting the ground. It will also deflect roughly 1¾ in. to the right of its intended trajectory. Now let us calculate the drag forces on a 9mm bullet.

The deceleration due to drag of a 9mm projectile is:

.06977 x 1,140 x 1,140 x .295 x .00069/2 x .016 = DD

18.45/.032 = 576.56 fps/S

Based on the 9mm projectile's initial velocity, mass, surface area, and coefficient of drag, it will experience a force of deceleration at a rate of 575 fps. Now, let us calculate how drag will affect the 9mm's trajectory.

576.56 x .558 x .558 = 179.52 ft.

636.12 – 179.52 = 456.6 ft.

So, a 9mm bullet fired horizontally, 5 ft. off of the earth's surface, with an initial velocity of 1,140 fps and a mass of 115 grains, will fly roughly 457 ft. after .558 seconds of travel before hitting the ground. It will also deflect roughly 6 in. to the right of its intended trajectory. Now, let us calculate the drag forces on the collective *shot charge* of the 12-gauge #7.5 shot. As stated previously, these are very rough calculations as the shot charge consists of hundreds of pellets that are all behaving differently as they encounter varying degrees of drag and lift. The trailing pellets may not experience as much drag as the leading pellets but will face more turbulent air as the leading pellets disrupt the flow of air.

.06977 x 1,275 x 1,275 x .47 x .0023/2 x .055 = DD

122.60/.11 = 1,114.55 fps/S

Based on the 12-gauge shot charge's initial velocity, mass, surface area, and coefficient of drag, it will experience a force of deceleration at a rate of 1,115 fps. Now, let us calculate how drag will affect the shot's trajectory.

$$1{,}114.55 \times .558 \times .558 = 347.03 \text{ ft.}$$

$$711.45 - 347.03 = 364.42 \text{ ft.}$$

So, a 12-gauge #7.5 shot charge fired horizontally, 5 ft. off of the earth's surface, with an initial velocity of 1,275 fps and a mass of 383 grains, will fly roughly 365 ft. after .558 seconds of travel before hitting the ground. Now let us calculate the drag forces on a .22 LR projectile.

$$.06977 \times 1{,}110 \times 1{,}110 \times .295 \times .00027/2 \times .0057 = DD$$

$$6.84/.0114 = 600 \text{ fps/S}$$

Based on the 12-gauge pellet's initial velocity, mass, surface area, and coefficient of drag, it will experience a force of deceleration at a rate of 600 fps. Now, let us calculate how drag will affect the shot's trajectory.

$$600 \times .558 \times .558 = 186.81'$$

$$711.45 - 186.81 = 524.64 \text{ ft.}$$

So, a .22 LR projectile fired horizontally, 5 ft. off of the earth's surface, with an initial velocity of 1,110 fps and a mass of 40 grains, will fly roughly 255 ft. after .558 seconds of travel before hitting the ground. It will also drift roughly 1 in. to the right of its intended trajectory.

Ballistic Tables

This was a lot of calculating just to give us a "basic" trajectory. What happens if we need to know where the projectile will be in relation to the sight's line-of-sight at various distances? Or what happens if we add variables like wind, or change our atmospheric conditions? Luckily, mathematicians and ballisticians have been working on calculating the trajectory of the projectile for over a century. Their research and calculations are what we now know as *ballistic tables*.

Based on all of the variables that we used to calculate a basic trajectory, plus several more, ballisticians created "spread sheets" to plot the trajectory of a given projectile based on a set zero of the sights. These tables are often broken up into rows and columns with the various distances for the rows and muzzle velocity, and energy and projectile "drop" in various measurements for columns. The columns will sometimes also feature figures for wind or even "*windage*" (horizontal adjustment) for spin drift and other environmental factors, as well as time of flight. This allows the shooter to see where the projectile is at various points of its trajectory and takes all of the "guess work" out of point of impact.

The downside to the ballistic table is that it will only get you close. The calculations are only for a specific cartridge, velocity, zero, and atmospheric condition. If your specific firearm/cartridge combination does not match the tables exactly, you will see variances with your results. Verifying your trajectories against the tables will allow you to create your own tables based on your results. Here is an example of a basic table for a .223 Remington cartridge with a 55-grain bullet, an initial velocity of 3,150 fps, a BC of .237, a 1 in 9 in. twist rate, a zero of 100 yd., and "standard" atmospheric conditions out to 600 yd.

We also need to consider the height of the sights above the axis of the barrel. This will dictate our trajectory based on our zero. This means that if the sights are 1.5 in. above the bore's axis, we will have to angle the barrel so that the projectile gains 1.5 in. in elevation so that it meets the sight's line of sight at 100 yd. You can see the path of the trajectory rise to meet the sights and fall back down. At 0, the projectile will be 1.5 in. (-1.5) below the line of sight.

As you can see from the chart, the .223 projectile starts off strong, but because of its low BC it quickly begins to shed speed and energy. This

Remington Ballistic Table

Distance (Yd.)	Velocity* (FPS)	Energy (FT-LB.)	Drop (Inches)	Windage (Inches to the Right)
0	3,150	1,212	-1.5	0
50	2,950	1,063	-.3	0
100	2,750	923	0	.1
150	2,550	794	-.9	.1
200	2,375	689	-3.1	.1
250	2,200	591	-6.9	.2
300	2,025	501	-12.5	.2
350	1,850	418	-20.2	.3
400	1,700	353	-30.4	.3
450	1,575	303	-43.6	.4
500	1,450	257	-60.3	.5
550	1,325	214	-81.2	.5
600	1,225	183	-107.1	.6

**Rounded to the nearest 25 fps.*

.223 Remington Ballistic Table				
Distance (Yd.)	Velocity* (FPS)	Energy (FT-LB.)	Drop (Inches)	Windage (Inches to the Right)
0	2,900	1,027	-1.5	0
50	2,700	890	-.2	0
100	2,525	778	0	.1
150	2,350	674	-1.2	.2
200	2,150	564	-4	.4
250	2,000	488	-8.7	.6
300	1,850	418	-15.5	.9
350	1,675	343	-25	1.3
400	1,550	293	-37.5	1.8
450	1,425	248	-53.6	2.5
500	1,300	206	-74.1	3.3
550	1,200	176	-99.7	4.2
600	1,120	153	-131.4	5.4

**Rounded to the nearest 25 fps.*

table does a fantastic job of providing a point of reference for a 55-grain projectile moving at 3,150 fps; but our example .223 projectile is only moving at 2,900 fps —250 fps slower than our first example. Let us look at the trajectory for our example .223 cartridge.

Although our example cartridge started with a 250 fps disadvantage, from 0 to 200 yd., the trajectory is fairly similar. The slower .223 projectile has only dropped about 1 in. more than the faster moving projectile. It isn't until after 250 yd. that we start to see significant differences. The faster moving projectile is also still supersonic out to 600 yd. while the slower moving projectile has become subsonic at 600 yd. You will also notice that when switching from a 1 in 9 in. twist to a 1 in 8 in. twist, we have significantly more spin drift because the projectile is spinning faster. If we were to use the first table for our example cartridge, we would miss our target by over 7 in. at 400 yd. and even more at greater distances. This is why it is important to find a ballistic table that closely matches your setup and test fire the setup to verify the table.

You may also have noticed that both of these trajectories only had one point of zero. The angle of the trajectory was so slight that the projectile never rose above the line of sight.

Let's look at one more table with the only change being the zero. Instead of a 100 yard zero, we will utilize a 300 yard zero. The 300 yard zero is very popular with the AR platform carbine chambered in .223 Remington because from point blank to 300 yd. the trajectory only varies about 8 in. for a projectile moving at 2,900 fps.

Utilizing a zero farther away causes the projectile to rise several inches above the rifle's line of sight. The steeper angle of the 300 yard zero creates a trajectory that sees only 6 in. of drop out to 350 yd. as opposed to 25 in. with the 100 yard zero. Even when considering the projectile rises roughly 6 in. above the line of sight, that is only 12 in. of vertical adjustment out to 350 yd. At distances past 25 yd., the shooter will need to hold their sights below the target; at 25 and 300 yd., the shooter will hold the sights directly on target; and at distances below 25 yd. and after 300 yd., the shooter will need to hold the

.223 Remington Ballistic Table (300 Yard Zero) *					
Distance (Yd.)	Velocity (FPS)	Energy (FT-LB.)	Drop (Inches)	Windage (Inches to the Right)	Time of Flight (Seconds)
0	2,900	1,027	-1.5	0	0
25	2,827	957	.5	0	.026
50	2,744	890	2.2	0	.053
100	2,584	778	4.7	.1	.109
150	2,429	674	6	.1	.169
200	2,279	564	5.7	.4	.233
250	2,135	488	3.8	.6	.301
300	1,996	418	0	.9	.374
350	1,862	343	-6	1.3	.451
400	1,735	293	-14.5	1.7	.535
450	1,614	248	-25.9	2.3	.625
500	1,501	206	-40.7	3	.721
550	1,396	176	-59.3	3.8	.825
600	1,302	153	-82.3	4.8	.936

**Conditions: 59° F, 27.344 in. hg pressure (inches of mercury), 50 percent humidity, 2,500 ft. altitude.*

sights above the target. You can see here how one small change in any one of the factors involved can create a drastic change in the results.

Without ballistic tables to provide a baseline or rough trajectory, it would be almost impossible for the average shooter to calculate their projectile's trajectory in the field, especially under pressure (while hunting) or with unknown factors. Luckily, the modern shooter is very spoiled. We have very powerful computer software that can plot the trajectory of a given projectile on an app on our cell phones. There are also several ballistic calculators online, available for free. Several very good, free calculators can be found here:

www.jbmballistics.com/cgi-bin/jbmtraj_drift-5.1.cgi

www.hornady.com/team-hornady/ballistic-calculators/#!/

http://gundata.org/ballistic-calculator/

www.shooterscalculator.com/ballistic-trajectory-chart.php

If you would like to follow along as we calculate the remaining trajectories, please keep in mind that the calculator will only provide an approximate trajectory based on several factors. Depending on the calculator used, there may be slight variances in the figures produced.

With a few known factors you can plot the trajectory of any projectile.* This calculator will even allow you to adjust environmental conditions to see how the projectile will perform in various environments. Let us use a calculator to plot the trajectory of our remaining example cartridges. First, we will need to establish a few base parameters. For now, we will leave the environmental factors alone. To keep the examples simple, we will only change the fields that we have figures for. Starting with the 9mm, let's calculate the trajectory for a 25 yard zero, in 5 yard increments and a maximum range of 100 yd.

**You may need to convert the air pressure figures from psi to inches of mercury (in. hg). A calculator can be found here: www.google.com/search?q=inches+of+mercury+to+psi&oq=inches+of+mercury+to+psi&aqs=chrome.69i57j6j0l4.7106j0j7&sourceid=chrome&ie=UTF-8*

9x19mm Parabellum Ballistic Table (25 Yard Zero)					
Distance (Yd.)	Velocity (FPS)	Energy (FT-LB.)	Drop (Inches)	Windage (Inches to the Right)	Time of Flight (Seconds)
0	1,140	332	-1.5	0	0
5	1,136	329	-1.1	0	.013
10	1,127	324	-.7	0	.026
15	1,118	319	-.4	.1	.040
20	1,109	313	-.2	.1	.053
25	1,101	309	0	.1	.067
50	1,062	287	-.3	.5	.136
75	1,029	270	-2.5	1.1	.208
100	999	254	-6.8	1.9	.282

Now let us calculate the trajectory of the 12-gauge cartridge with a 50 yard zero, in 10 yard increments and a maximum range of 100 yd. For caliber, utilize the figure .650 in. (the diameter of the inside of the cup). For bullet length, utilize the figure .986 (the depth of the shot in the cup). You will also want to uncheck the "spin drift" box to exclude these calculations as the shot is not spinning. These calculations are going to be very rough as we are using single figures for the mass of the whole shot charge and its dimensions. In reality, the shot charge will begin to disperse and lengthen the moment it leaves the barrel. Each individual pellet would experience varying levels of drag, lift, and deflection.

Finally, let us calculate the trajectory of a .22 LR cartridge with a 100 yard zero in 10 yard increments and a maximum distance of 150 yd.

Before we get into any changes in environmental factors, let us take a quick look at what the trajectory of the .223 Remington would look like if we used a projectile with a higher BC. A higher BC often means more mass and, in turn, length. Let us take a look at a .223 projectile weighing 77 grains, 1.065 in. long, with a BC of .420. To keep things as fair as possible, we will lower the muzzle velocity to 2,450 fps so that it has the same muzzle energy of the 55-grain projectile.

12-Gauge 2¾ in. #7.5 Birdshot				
Distance (Yd.)	Velocity (FPS)	Energy (FT-LB.)	Drop (Inches)	Time of Flight (Seconds)
0	1,275	1,382	-1.5	0
10	1,154	1,132	-.6	.024
20	1,029	900	.1	.052
30	946	760	.5	.082
40	882	661	.5	.115
50	829	584	0	.150
60	783	521	-1	.187
70	740	465	-2.5	.227
80	701	417	-4.7	.268
90	665	376	-7.6	.312
100	630	337	-11.3	.359

.22 Long Rifle Ballistic Table (100 Yard Zero)					
Distance (Yd.)	Velocity (FPS)	Energy (FT-LB.)	Drop (Inches)	Windage (Inches to the Right)	Time of Flight (Seconds)
0	1,110	109	-1.5	0	0
10	1,097	106	.1	0	.027
20	1,078	103	1.3	0	.055
30	1,061	100	2.3	0	.083
40	1,046	97	3	.1	.111
50	1,031	94	3.3	.1	.140
60	1,017	92	3.4	.1	.169
70	1,003	89	3	.2	.199
80	991	87	2.4	.2	.229
90	979	85	1.4	.3	.260
100	968	83	0	.3	.290
110	957	81	-1.7	.4	.322
120	946	79	-3.9	.5	.353
130	936	77	-6.4	.5	.385
140	926	76	-9.3	.6	.417
150	917	74	-12.6	.7	.450

.223 Remington Ballistic Table (55-Grain .237 BC/77-Grain .420 BC)					
Distance (Yd.)	Velocity (FPS)	Energy (FT-LB.)	Drop (Inches)	Windage (Inches to the Right)	Time of Flight (Seconds)
0	2,900/2,450	1,027/1,026	-1.5	0	0
25	2,827/2,412	957/995	.5/1	0	.026/.031
50	2,744/2,370	890/960	2.2/3	0	.053/.062
100	2,584/2,286	778/893	4.7/6	.1	.109/.127
150	2,429/2,204	674/830	6/7.3	.1/.2	.169/.193
200	2,279/2,123	564/770	5.7/6.9	.4/.3	.233/.263
250	2,135/2,044	488/714	3.8/4.5	.6/.5	.301/.335
300	1,996/1,967	418/661	0	.9/.7	.374/.410
350	1,862/1,892	343/612	-6/.6.7	1.3/.9	.451/.487
400	1,735/1,818	293/565	-14.5/-15.9	1.7/1.2	.535/.568
450	1,614/1,747	248/522	-25.9/-27.6	2.3/1.5	.625/.652
500	1,501/1,677	206/480	-40.7/-42.3	3/1.9	.721/.740
550	1,396/1,610	176/443	-59.3/-60	3.8/2.4	.825/.831
600	1,302/1,546	153/409	-82.3/-81.1	4.8/2.9	.936/.926

You can see that even though the 77-grain projectile started off with 550 fps less in velocity, its higher BC was able to overcome the effects of drag and drift better than the 55-grain projectile. In fact, the 77-grain projectile was so efficient at defeating drag that it retained more of its velocity and even surpassed the 55-grain projectile's velocity at 350 yd. The 77-grain projectile was even able to reach 600 yd. before the 55-grain. The higher BC and mass of the 77-grain projectile also resisted deflection from spin drift better than the 55-grain, with roughly 1.9 in. less deflection (to the right) at 600 yd. Although the 77-grain projectile was launched from a slightly steeper angle, both projectiles have a fairly similar trajectory, with the 77-grain rising 1.3 in. higher and dropping 1.2 in. lower than the 55-grain projectile.

Temperature, Humidity, Altitude, Wind, and Other Factors

Now that we have established a baseline trajectory for each of our example cartridges, let us see how they react when we begin to alter their environment. Temperature, humidity, and altitude will all affect the density of the air. Wind is unpredictable in magnitude and direction of force and can cause drag, lift, and drift of the projectile. For the following examples, we will only examine how environmental changes affect the .223 projectile's trajectory, as it has the greatest range. This will allow us to see the effects over a greater range and period of time.

TEMPERATURE

Let us start with temperature and see how it affects our projectile. For example purposes we will examine the effects under extreme circumstances, i.e. 0° F and 120° F. First, let us see how temperature affects air density. We can use this density calculator, www.omnicalculator.com/physics/air-density, and altitude calculator, www.omnicalculator.com/physics/air-pressure-at-altitude, to see the change in density from 0° F to 120° F.* At our "standard" temperature (59° F) and altitude (2,500 ft.), the density of the air is .06977 lbs/ft^2 (27.344 in. hg pressure). When we lower the temperature to 0° F (13.275 psi/27.03 in. hg pressure), the density increases to .07793, an increase of roughly 12 percent. When we raise the temperature to 120° F (13.558 psi/27.665 in. hg pressure), the density decreases to .06238 lbs/ft^2, a decrease of roughly 11 percent. Let's see how the change affects the trajectory of our example projectiles.

**Use the altitude calculator to find out the air pressure at various temperatures, and then use the density calculator to find out the air density. The air pressure at sea level is 14.7 psi.*

You can see from the table that an increase in air density means that there is more drag on the projectile. This means that the barrel will need to be held at a slightly steeper angle to achieve the same 300 yard zero. There is also much more vertical deflection out to 600 yd. for the

.223 Remington Ballistic Table (0 F)				
Distance (Yd.)	Velocity (FPS) at 59 F	Velocity (FPS) at 0 F	Drop (Inches) at 59 F	Drop (Inches) at 0 F
0	2,900	2,900	-1.5	-1.5
25	2,827	2,820	.5	.5
50	2,744	2,729	2.2	2.3
100	2,584	2,555	4.7	4.9
150	2,429	2,387	6	6.2
200	2,279	2,226	5.7	6.0
250	2,135	2,071	3.8	4
300	1,996	1,922	0	0
350	1,862	1,780	-6	-6.4
400	1,735	1,644	-14.5	-15.5
450	1,614	1,517	-25.9	-27.8
500	1,501	1,398	-40.7	-44
550	1,396	1,290	-59.3	64.5
600	1,302	1,194	-82.3	-90.3

colder temperature at 96.5 in. versus 88.3 in. for the warmer temperature. Now let's see what happened when we increase the temperature to 120˚ F.

You can see from the table that a decrease in air density means that there is less drag on the projectile. This means that the barrel will need to be held at a slightly more acute angle to achieve the same 300 yard zero. There is also much less vertical deflection out to 600 yd. for the warmer temperature at 80.9 in. versus 88.3 in. for the colder temperature. That is over 15 in. of additional drop at 0˚ F than at 120˚ F. Now let's see what happens when we adjust the environment's humidity.

HUMIDITY

Now we will examine humidity's effects on the projectile. The microscopic water droplets in the air will alter the air's density and the amount of drag the projectile experiences. Although water as a liquid is denser than air, water vapor does not make air denser. In fact, the opposite is true. Water vapor displaces air molecules, creating a "fluid" that is less dense because there is less matter occupying a given space.[19] We will return to our "standard" atmospheric conditions with one exception. We will turn the humidity down to 0 percent and up to 100 percent. You also use the density calculator to see how humidity affects the air density. At 50 percent humidity, the density of air is roughly .06977 lb/cu.ft. At 0 percent humidity, the density of air is roughly .06989 lb/cu.ft. At 100& humidity, the density of air is roughly .0694 lb/cu.ft.

You can see from the table that a decrease in humidity created slightly more drag on the projectile. The deflection from humidity is only marginal, with only .3 in. of additional drop out to 600 yd. Now, let's see what happens when we increase humidity to 100 percent.

Again, you can see from the table that an increase in humidity created slightly less drag on the projectile. The deflection from humidity is still only marginal, with only .3 in. less drop out to 600 yd. Of all of the factors that affect air density, humidity has the smallest impact. Deflection from humidity is only relevant for long-range shooting (1000+ yd.).

ALTITUDE

Now, let us look at how altitude impacts the projectile's trajectory. At our standard altitude of 2,500 ft. above sea level, air pressure is roughly

.223 Remington Ballistic Table (120 F)				
Distance (Yd.)	Velocity (FPS) at 59˚ F	Velocity (FPS) at 120˚ F	Drop (Inches) at 59˚ F	Drop (Inches) at 120˚ F
0	2,900	2,900	-1.5	-1.5
25	2,827	2,834	.5	.4
50	2,744	2,759	2.2	2.1
100	2,584	2,613	4.7	4.5
150	2,429	2,471	6	5.7
200	2,279	2,334	5.7	5.5
250	2,135	2,201	3.8	3.6
300	1,996	2,072	0	0
350	1,862	1,948	-6	-5.7
400	1,735	1,830	-14.5	-13.6
450	1,614	1,717	-25.9	-24.2
500	1,501	1,610	-40.7	-37.7
550	1,396	1,510	-59.3	-54.5
600	1,302	1,418	-82.3	-75.2

.223 Remington Ballistic Table (0 percent Humidity)				
Distance (Yd.)	Velocity (FPS) at 50 percent	Velocity (FPS) at 0 percent	Drop (Inches) at 50 percent	Drop (Inches) at 0 percent
0	2,900	2,900	-1.5	-1.5
25	2,827	2,826	.5	.5
50	2,744	2,744	2.2	2.2
100	2,584	2,582	4.7	4.7
150	2,429	2,427	6	6
200	2,279	2,277	5.7	5.7
250	2,135	2,132	3.8	3.8
300	1,996	1,992	0	0
350	1,862	1,859	-6	-6
400	1,735	1,731	-14.5	-14.6
450	1,614	1,610	-25.9	-26
500	1,501	1,497	-40.7	-40.8
550	1,396	1,392	-59.3	-59.5
600	1,302	1,298	-82.3	-82.6

.223 Remington Ballistic Table (100 percent Humidity)				
Distance (Yd.)	Velocity (FPS) at 50 percent	Velocity (FPS) at 100 percent	Drop (Inches) at 50 percent	Drop (Inches) at 100 percent
0	2,900	2,900	-1.5	-1.5
25	2,827	2,827	.5	.5
50	2,744	2,745	2.2	2.2
100	2,584	2,585	4.7	4.7
150	2,429	2,430	6	6
200	2,279	2,281	5.7	5.7
250	2,135	2,137	3.8	3.8
300	1,996	1,999	0	0
350	1,862	1,866	-6	-6
400	1,735	1,738	-14.5	-14.5
450	1,614	1,618	-25.9	-25.9
500	1,501	1,505	-40.7	-40.5
550	1,396	1,401	-59.3	-59.1
600	1,302	1,306	-82.3	-82

.223 Remington Ballistic Table (Sea Level)				
Distance (Yd.)	Velocity (FPS) at 2,500 FT.	Velocity (FPS) at 0 FT.	Drop (Inches) at 2,500 FT.	Drop (Inches) at 0 FT.
0	2,900	2,900	-1.5	-1.5
25	2,827	2,812	.5	.6
50	2,744	2,714	2.2	2.4
100	2,584	2,523	4.7	5.2
150	2,429	2,340	6	6.5
200	2,279	2,165	5.7	6.3
250	2,135	1,998	3.8	4.3
300	1,996	1,838	0	0
350	1,862	1,687	-6	-6.8
400	1,735	1,547	-14.5	-16.7
450	1,614	1,418	-25.9	-30.2
500	1,501	1,303	-40.7	-48.1
550	1,396	1,204	-59.3	-71.1
600	1,302	1,123	-82.3	-100

13.43 psi (27.344 in. hg) and has a density of .06977 lb/cu.ft. At sea level, air pressure increases to 14.7 psi (29.93 in. hg) and a density of .07637 lb/cu.ft., an increase of roughly 10 percent. At 5,000 ft. above sea level, air pressure is roughly 12.27 psi (24.98 in. hg) and a density of .06373 lb/cu.ft., a decrease of roughly 9 percent.

You can see from the table that the projectile will experience more drag at sea level than at our standard altitude of 2,500'. At sea level, the projectile will lose roughly 180 fps and experience over 17 in. more drop at 600 yd. Now let's see what happens when we climb to 5,000 ft. above sea level.

At 5,000 ft. above sea level, the projectile experiences much less drag as the air is thinner. The projectile gains roughly 200 fps more velocity and experiences 12 in. less drop at 600 yd. From sea level to 5,000', those numbers jump to an increase of nearly 380 fps velocity and a decrease of nearly 30 in. of drop at 600 yd. Of all of the factors that affect air density, altitude is the greatest contributor. At 10,000 ft. above sea level, air pressure drops to 10.24 psi (20.85 in. hg) and density drops to .05317 lb/cu.ft. At 10,000 ft. the projectile will gain roughly 750 fps velocity and experience 44.2 in. less drop. Now let's take a look at how wind will affect the projectile's trajectory.

WIND

Of all the factors acting on the projectile, wind may be the most unpredictable. Wind can affect both the horizontal and vertical components of the projectile's trajectory. Under our "standard" conditions, we did not account for wind, but there was still some horizontal deflection due to spin drift (4.8 in. to the right for a right-hand twist rate). Our first table shows what happens when the wind is perpendicular to the projectile's trajectory. We will examine both left-hand (from the shooter's right to left) and right-hand (from the shooter's left to right) winds working 90° from the projectile's trajectory. This is known as a "full value" wind because it is working exactly 90° from the projectile's trajectory. Winds working at any other angle than 90° are calculated in percentages of a full value.

.223 Remington Ballistic Table (5,000 FT.)				
Distance (Yd.)	Velocity (FPS) at 2,500 FT.	Velocity (FPS) at 5,000 FT.	Drop (Inches) at 2,500 FT.	Drop (Inches) at 5,000 FT.
0	2,900	2,900	-1.5	-1.5
25	2,827	2,839	.5	.4
50	2,744	2,770	2.2	2
100	2,584	2,635	4.7	4.4
150	2,429	2,504	6	5.5
200	2,279	2,377	5.7	5.3
250	2,135	2,254	3.8	3.5
300	1,996	2,134	0	0
350	1,862	2,018	-6	-5.4
400	1,735	1,906	-14.5	-13
450	1,614	1,792	-25.9	-22.9
500	1,501	1,694	-40.7	-35.5
550	1,396	1,595	-59.3	-51.2
600	1,302	1,502	-82.3	-70.3

.223 Remington Ballistic Table (20 MPH Perpendicular Wind)				
Distance (Yd.)	Velocity (FPS)	Drop (Inches)	Left Hand Wind (Inches to the left)	Right Hand Wind (Inches to the Right)
0	2,900	-1.5	0	0
25	2,827	.5	.1	.1
50	2,744	2.2	.5	.6
100	2,584	4.7	2.1	2.3
150	2,429	6	5	5.4
200	2,279	5.7	9.1	9.9
250	2,135	3.8	14.7	15.9
300	1,996	0	21.8	23.6
350	1,862	-6	30.7	33.2
400	1,735	-14.5	41.5	44.9
450	1,614	-25.9	54.3	58.9
500	1,501	-40.7	69.4	75.4
550	1,397	-59.3	86.9	94.6
600	1,302	-82.3	106.9	116.6

For example, a wind blowing at 45° would have a three-quarter value, meaning the wind will only cause three quarters of the drift as it would if it were blowing 90° perpendicular to the path of the projectile. This means that a 20 mph wind blowing at 45° would only deflect the projectile 87.45" at 600 yd. (for a right-hand wind). A wind blowing at 30° would have a half value and wind blowing at 15° would have a quarter value. With these calculations, a headwind and tailwind would be considered no value and be factored as 0 (even though we can see there is a slight deflection). There are several methods for calculating wind drift based on direction, but unless you have some type of equipment to measure the wind's direction in relation to the projectile's trajectory, a safe bet is to calculate all wind that is not perpendicular to the projectile's trajectory as a half value because it is easiest to calculate quickly.

From the table we can see that a 20 mph wind (although extreme) causes severe drift for the projectile in either direction. You can also see the difference between a right-hand and left-hand wind and how the spin drift offsets some of the left-hand wind drift. The right-hand wind also magnifies the right-hand spin drift. This occurs because most spitzer-shaped (long and pointy) projectiles act like weather vanes in the wind. The nose of the projectile will try to align with the direction of wind. For a left-hand wind, the nose of the projectile will turn slightly to the right, while the tail turns to the left. For a right-hand wind, the nose of the projectile will turn slightly to the left, while the tail turns to the right. As the nose of the projectile turns into the wind, the projectile is being pushed "downwind" in the direction of flow. Now let's see what happens when the wind is acting parallel to the projectile's trajectory.

You can see from the tables how headwind and tailwind can affect the projectile's velocity, which affects drop. A headwind slows the projectile's velocity while a tailwind decreases the projectile's deceleration from drag. Although the effects from the head and tailwinds are only minute, at greater distances (1,000+ yd.) they can mean the difference between a hit and a miss.

Although each factor that contributes to a projectile's drift and drop may seem marginal or insignificant, all factors involved have a cumulative effect. For example, a hunter from the coast (east, west, or gulf) who was planning a hunt in the Rocky Mountains and zeroed his rifle before the trip, would have to account for changes in temperature (typically colder), altitude (possibly 10,000+ ft.) and humidity (typically dryer). This is even before wind is taken into account. The cumulative effect of all of these factors could lead to a miss that can be measured in feet, not inches. We have not even taken into account other factors that can cause drift at distances beyond 1,000 yd.

.223 Remington Ballistic Table (20 MPH Tailwind)				
Distance (Yd.)	Velocity No Wind (FPS)	Drop No Wind (Inches)	Velocity Tailwind (FPS)	Drop Tailwind (Inches)
0	2,900	-1.5	2,900	-1.5
25	2,827	.5	2,828	.5
50	2,744	2.2	2,747	2.2
100	2,584	4.7	2,589	4.7
150	2,429	6	2,437	5.9
200	2,279	5.7	2,290	5.6
250	2,135	3.8	2,148	3.7
300	1,996	0	2,011	-.1
350	1,862	-6	1,880	-6
400	1,735	-14.5	1,755	-14.4
450	1,614	-25.9	1,637	-25.6
500	1,501	-40.7	1,527	-40
550	1,397	-59.3	1,424	-58.1
600	1,302	-82.3	1,332	-80.5

.223 Remington Ballistic Table (20 MPH Headwind)				
Distance (Yd.)	Velocity No Wind (FPS)	Drop No Wind (Inches)	Velocity Headwind (FPS)	Drop Headwind (Inches)
0	2,900	-1.5	2,900	-1.5
25	2,827	.5	2,825	.5
50	2,744	2.2	2,741	2.2
100	2,584	4.7	2,578	4.8
150	2,429	6	2,421	6
200	2,279	5.7	2,268	5.8
250	2,135	3.8	2,121	3.9
300	1,996	0	1,980	0
350	1,862	-6	1,844	-6
400	1,735	-14.5	1,714	-14.7
450	1,614	-25.9	1,590	-26.3
500	1,501	-40.7	1,475	-41.4
550	1,397	-59.3	1,368	-60.5
600	1,302	-82.3	1,271	-84.3

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Coriolis, Magnus, and Eotvos Effects, and Vertical Angles

MAGNUS EFFECT

Outside of air and gravity, there are other environmental effects that can alter the projectile's trajectory. The *Magnus effect* is a phenomenon that occurs with spinning objects moving through fluids with flows perpendicular to their rotational axis, meaning crosswinds. Unlike wind drift, the combination of the projectile's spin and the direction of the crosswind will create a vertical displacement. The effect is completely dependent on the direction of the projectile's spin (right-hand or left-hand), the direction of wind, and the acceleration or deceleration of air flow around the projectile. The Magnus effect creates a deflection that is perpendicular to both the projectile's trajectory and the direction of wind.[20] For example, a projectile with a right-hand spin (clockwise from the shooter's perspective) that is acted upon by a right-hand wind (blowing from the left to the right) will experience a positive lift component in the form of its nose pointing up. This will cause a high pressure area under the nose of the projectile, causing it to "skid" across the high pressure area, resulting in slightly less drop. The projectile will be positioned with its nose pointed (pitched) slightly up (from the Magnus effect) and (yaw) to the left (pointing into the wind), while being pushed to the right. The same projectile being acted upon by a left-hand wind (blowing from the right to the left) will experience a negative lift component in the form of its nose pointing down. This will cause a high pressure area on top of the nose of the projectile, resulting in more drop. The projectile will be positioned with its nose pointed (pitched) slightly down and to the right while being pushed to the left. Compared to other factors influencing the projectile, the Magnus effect is marginal, causing only a couple of inches of deflection out to 1,000 yd.

CORIOLIS AND EOTVOS EFFECTS

Depending on the time of flight of the projectile, the rotation of the earth can cause the target to move far enough that you miss your intended target. There are two effects that are caused by the rotation of the earth, the Coriolis effect and the Eotvos effect. The Coriolis effect impacts the projectile on a horizontal plane when shooting north or south. The Eotvos effect impacts the projectile on a vertical plane when shooting east or west.

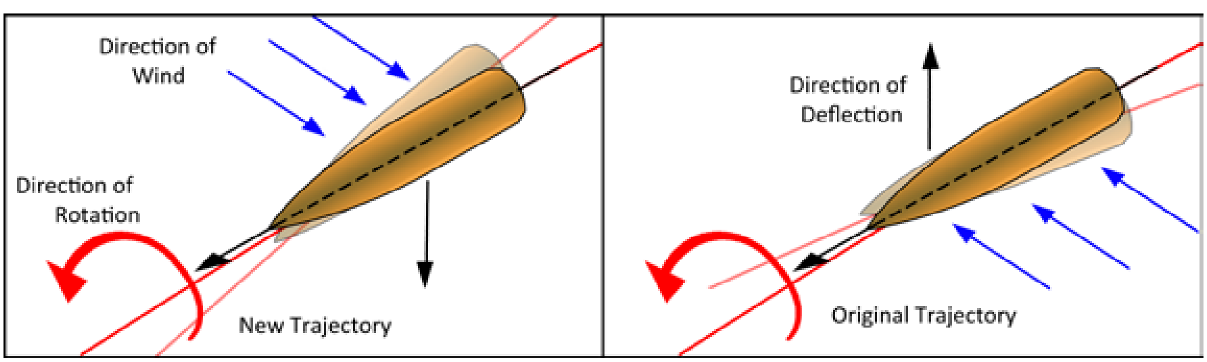

Figure 10: Magnus effect.

The Coriolis effect occurs when a projectile is fired in a right angle (north or south) to the earth's rotation. The deflection caused by the rotation will vary depending on whether you are shooting from the northern hemisphere or southern hemisphere. In the northern hemisphere, the deflection will ALWAYS be to the right, regardless if you are shooting from north to south or south to north. The opposite is true of the southern hemisphere. The deflection in the southern hemisphere will always be to the left.[21]

The Coriolis effect is a result of not only the earth's rotation but the shape of the earth as well. Because the earth is basically a giant ball spinning to the east (counterclockwise when viewed from the north pole), the surface of the center of the earth (equator) is moving faster than either of the poles because it must cover more distance in the same time period. The speed of the earth's rotation at the equator is roughly 1,037 mph or 1,521 fps. Any point above or below the equator is rotating slower because there is less distance to move before completing a revolution. At latitude 45° (north or south), the surface of the earth is moving at roughly 1,075 fps. At latitude 80° (north or south), the surface of the earth is moving at roughly 265 fps. At the poles, the speed of rotation is 0.

When shooting in the northern hemisphere, the deflection will always be to the right because when shooting north to south (from the north pole to the equator), the target is rotating faster to the east than you are, which makes you miss to the right. When shooting south to north (from the equator to the north pole), you are moving faster to the east than the target, resulting in a miss to the right. The opposite is true of the southern hemisphere.

The Eotvos effect causes deflection in two ways, both along the vertical plane of the projectile's trajectory. The first, because the earth is a giant spinning ball, when shooting east or west, the target is rising and falling (in relation to the projectile) because of the curvature of the earth. The Eotvos effect is strongest at the equator and weakest at the poles.

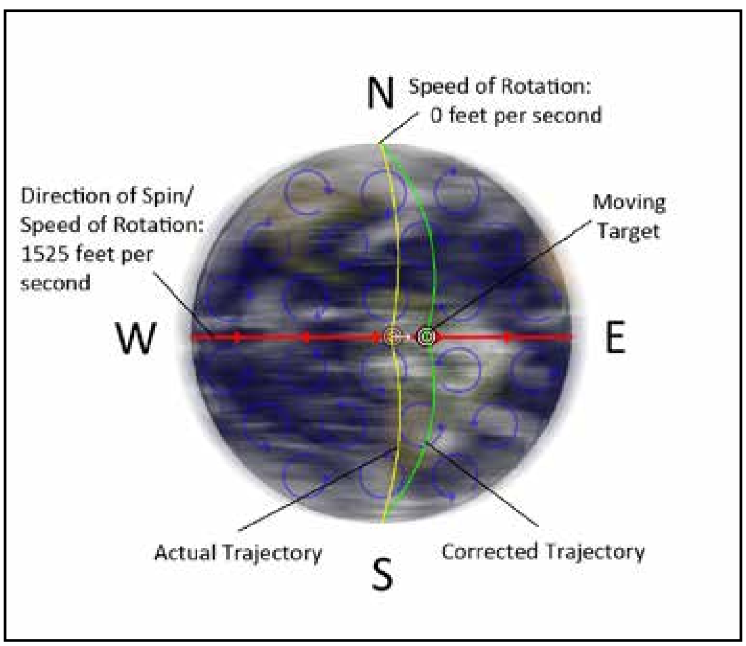

Figure 11: Coriolis effect.

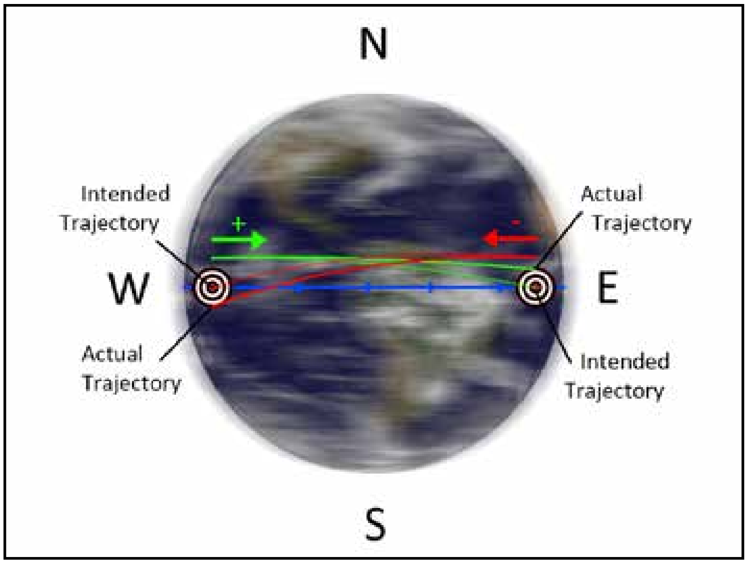

Figure 12: Eotvos effect.

The curvature of the earth is roughly 8 in. per mile. When a projectile is fired to the west, the target will move toward the projectile and rise in relation to its trajectory. If the earth is moving at roughly 1,521 fps, the target will rise roughly 2 in. (due to curvature) after one second of projectile flight time. This results in a low impact. When a projectile is fired to the east, the target will move away from the projectile and fall in relation to its trajectory. A projectile fired to the east with one second of flight time will hit roughly 2 in. high.

The second manner in which the Eotvos effect causes deflection is in the form of the earth's *centrifugal force*. There is a perceived change in gravitational force for projectiles that are fired with the earth's spin than ones that are fired against it.[22] Projectiles fired with the earth's rotation will impact higher than ones fired against the earth rotation because of the increase in angular momentum and centrifugal force. Projectiles fired against the earth's rotation are working against the centrifugal force and will experience more drop. Like the Magnus effect, the Eotvos effect will only account for around 2 in. – 3 in. of deflection at 1,000 yd.

VERTICAL ANGLES

When shooting at vertical angles, or uphill or downhill, it may seem like there is some hidden force that is deflecting the projectile's trajectory. There is no additional force acting on the projectile when shooting at vertical angles; there is only an incorrect estimation of distance. The reason for this is that gravity only works (relatively) perpendicular (square) to the earth's surface. When shooting uphill or downhill, it may appear like the target is a certain distance away, but gravity will only be working against it for a fraction of that distance.

For example, if we assume that we know our line of sight distance (300 yd.) from the target and our elevation (200 yd.), we can calculate the distance gravity is actually acting on the projectile. Using a variation of the Pythagorean Theorem (A^2 + B^2 = C^2), where we already know A (elevation) and C (line of sight), we can calculate for B (distance gravity is acting):

200^2 + B^2 = 300^2

40,000 + B^2 = 90,000

B^2 = 50,000

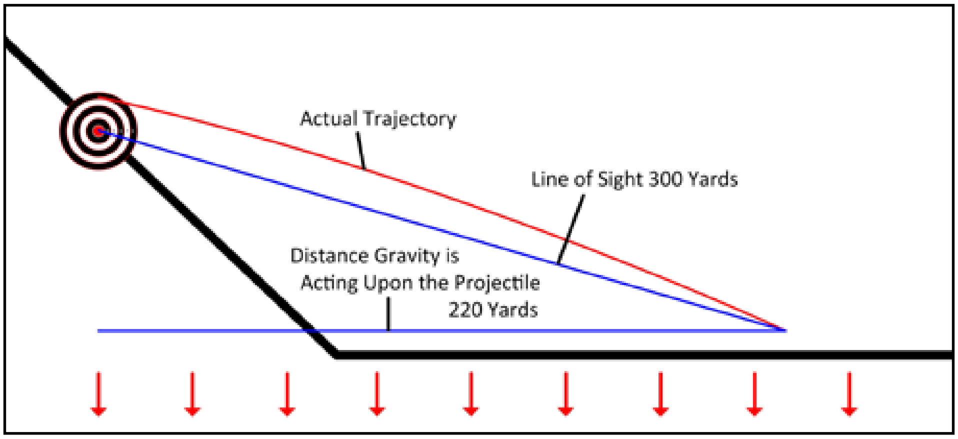

Figure 3: Vertical angles.

The square root of 50,000 is 223.6, or roughly 224 yd. This means that if you were aiming for a 300 yard trajectory, you would miss high because gravity is only acting on the projectile for roughly 220 yd. The defection is always high, regardless if you are shooting uphill or downhill. The effect is more prevalent at steeper angles.[23]

SUPERSONIC PROJECTILES

Supersonic projectiles face their own set of issues when exterior ballistic factors are concerned. The biggest factor the supersonic projectile faces is the shockwave it is continuously creating and moving through. The shockwave is a result of the air ahead of the projectile being rapidly compressed. When the projectile is moving at supersonic velocities, the air cannot move around the projectile fast enough. The air is compressed forming a high pressure *shockwave*.[24] At supersonic speeds, this "wave" is the primary drag force acting on the projectile.

The shockwave is actually a series of continuous shockwaves that radiate from the nose of the projectile. As the projectile continues to fly at supersonic speed, the waves begin to stack up near the front of the projectile and spread farther apart behind the projectile. This is known as the *Doppler effect*. An example of the Doppler effect is when a car is blaring its horn as it drives past you. When the car is approaching, the sound of the horn seems to be a higher pitch as the sound waves stack in front of the car. As the car passes, the sound of the horn seems to be a lower pitch because the sound waves are spread farther apart.

The continuous shockwaves the projectile produces form a cone-shaped wave that trails the projectile. The trailing wave resembles the wake of a speedboat. The angle of this "wake" is known as the *Mach angle*. The more acute the angle, the faster the projectile is moving. Slower projectiles will produce a more obtuse angle. You can use the Mach angle to roughly calculate the speed of the projectile, but you would still need very sophisticated cameras to capture an image of the projectile and the shockwave.[25]

TRANSONIC PROBLEM

The transonic problem occurs with supersonic projectiles that drag has slowed to subsonic velocities. The transonic region ranges from about 788 fps – 1,340 fps (*Mach .70 – Mach 1.2*). As drag slows the projectile to subsonic velocities, the force of the drag decreases. This forces the center of pressure to shift further forward, away from the center of gravity. This causes an imbalance in the projectile and forces it to wobble.[26] Additionally, as the projectile begins to move slower, it will spend more time in the turbulent air created by the shockwave. This creates more instability in the flow of air around it. If the projectile is not properly stabilized, it will continue to wobble and drift off of its intended trajectory. A properly stabilized projectile will wobble for a moment and then recover.

SHOT/CUP SEPARATION AND SHOT STRING

Up to this point, all of our figures for the #7.5 birdshot have been calculated with the assumption that the shot charge is travelling as a single entity. The shot charge and wad/cup will remain together until shortly after passing the transitional ballistic region. The "petals" of the cup act like spoilers on an airplane wing and begin to open to increase drag. The cup begins to decelerate rapidly as the shot charge continues on and begins to disperse.

Pellet dispersion occurs because every single pellet of shot is not completely round or uniform. Any variance in the shape of the pellets can lead to a slight change in BC. The more aerodynamic pellets will remain in the head of the string, while the deformed pellets begin to form a tail as they trail behind. Depending on the time of flight, the string may extend several feet (6 – 8) as the more aerodynamic pellets gain ground more rapidly.[27] The trailing pellets are not left completely behind as they "*draft*" the leading pellets. The trailing pellets do not experience as much drag as the leading pellets but do experience more turbulent air as the leading pellets disrupt the flow ahead of them.

NOTES

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Terminal Ballistics

By now, the projectile is nearing the target and the completion of its journey. The study of the projectile when impacting a target is known as terminal ballistics. There are several factors that affect the projectile's terminal ballistic performance, including the design and makeup of the projectile and the target material.

PENETRATION VS PERFORATION

There are two performance standards that must be considered when discussing the terminal performance of a projectile: the ability to penetrate and to perforate. When a projectile penetrates a material, it is only entering to a certain depth. If the projectile were to perforate

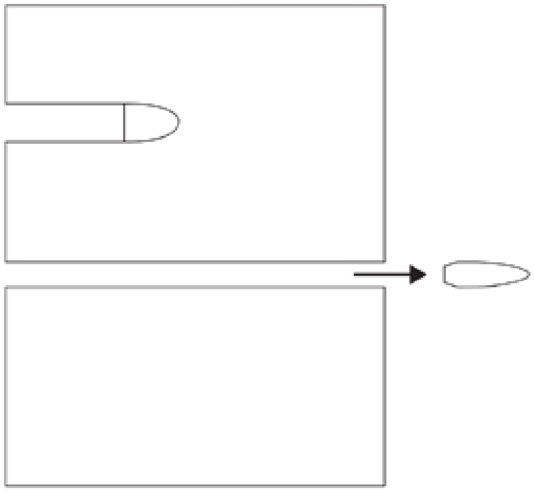

Figure 1: Penetration vs. perforation.

the target, it would travel completely through it and continue to travel until hitting something else. Depending on your intended target, each quality can be beneficial. If the projectile were to only penetrate its target, most of the energy the projectile carried with it will be transferred to the target, creating shock waves. If the projectile were to perforate a material, it would lose some energy to the target, but would also retain some of its energy as it continued to travel onward.

To perforate a target, the projectile will need to cut through or displace the target material with little to no distortion to the projectile (although heavily deformed projectiles and fragments can perforate with enough remaining energy). As long as the projectile is harder than the material it is travelling through and the thickness of the target is not so great that it slows the projectile to a stop, it will perforate the target. Basic jacketed ball projectiles are well suited for perforation. To penetrate a target, the projectile will need to "brake" or stop inside the target by some means. This is accomplished through material composition and projectile design. The basic manner in which a projectile prevents perforation is by increasing its frontal surface area. This increases drag against the target material and slows it to a stop.

Depending on your intended purpose, both of these qualities can be very desirable or undesirable. Let us take a second to re-examine the various reasons firearms are used. For shooting sports like plinking and the various types of competition and trap, skeet, and sporting clays, terminal ballistics is not a concern when selecting a projectile/cartridge. With shooting sports, the biggest concern is the projectile's external ballistics as it flies to the target. As long as the projectile impacts where it was supposed to, there is no concern for what happens to the projectile on impact. In most cases the projectile will just perforate the soft paper and cardboard targets with little loss of energy or deformation. When shooting clay pigeons, the shot will simply destroy the brittle clay disks with little loss of energy and distortion. When shooting steel targets (competition or plinking), the projectile's terminal ballistics are rarely ever considered as long as it makes the desired "ding" when impacting.

When hunting or for self-defense or military or law enforcement use, terminal ballistics is typically the main concern when selecting a projectile/cartridge. When hunting, the goal is to harvest game as humanely as possible. This means that you will want the projectile to dispatch the animal as quickly as possible without causing any unneeded suffering. This is mostly dependent on shot placement but is also heavily reliant on the projectile's terminal ballistics. For hunting applications, we want to deliver all of the projectile's energy to the target to increase the chances of an instantaneous and humane kill. This is why deep penetration is preferred by hunters. If the projectile were to perforate the target, it would carry any remaining energy with it, limiting the amount of damage incurred by the animal and possibly only injuring it.

When shooting for self-defense, the intent is to incapacitate the attacker and prevent injury or death to yourself or others. This is mostly dependent on shot placement but is also heavily reliant on the projectile's terminal ballistics. For self-defense applications, we want to deliver all of the projectile's energy to the target to increase the chances of instantaneous incapacitation. This is why penetration is preferred for self-defense. If the projectile were to perforate the attacker, it would carry any remaining energy with it, limiting the amount of damage delivered and possibly hitting an unintended target.

The major differences between projectiles used for hunting and self-defense are the distance of the target, the materials of the target, and the firearm used to fire them. Self-defense projectiles are used at relatively short ranges (~25 yd.) compared to most hunting projectiles that are used from 100 to 600+ yd. This means that a hunting projectile needs to be aerodynamic and be able to penetrate effectively. A self-defense projectile only needs to focus on penetration. A self-defense projectile may also have to perforate various layers of different materials (clothing and various barriers) before penetrating into flesh (and bone). Typically, a hunting projectile will only need to penetrate hide, flesh, and bone. Lastly, most hunting is done with rifles and shotguns (although some handguns are used), while people who carry firearms for self-defense utilize handguns (although rifles and shotguns are used for home defense). The qualities of the self-defense projectile are mirrored by the law enforcement (LE) projectile.

The performance of the military projectile is dictated by the rules of war set forth by international law. The Hague Convention of 1899 dictates that no expanding (or fragmenting) projectiles can be used in international warfare. This means that almost all projectiles used by the military are of the "ball" or FMJ variety. Because of the design of the projectile, perforation is more likely than penetration. Also, because of the nature of modern warfare, the target may be behind barriers or wearing armor, which makes perforation the desired result. This means that a military projectile may need to perforate through masonry and other hard barriers, glass, and steel plates, and still retain enough energy to penetrate and perforate flesh and bone. This is why most military projectiles utilize carbon steel, hardened steel, or tungsten carbide penetrators to increase the ability of the projectile to perforate.

TEMPORARY CAVITY AND PERMANENT CAVITY

When we evaluate the capabilities of projectiles used for hunting, self-defense, LE, and military use, we have to consider how they perform against flesh. Projectiles incapacitate and kill by damaging and destroying the central nervous system and causing massive blood loss, depriving the brain of oxygen. This is accomplished by cutting or damaging and displacing flesh, muscle, arteries, organs, and bone (skull/spinal cord), leaving a cavity that traces the projectile's path. This is known as the permanent wound cavity. The larger the cavity, the greater the chance of damaging one of these vital areas.

When a projectile impacts flesh, the flesh does not simply give like the projectile is just poking a hole. Flesh is extremely elastic and acts like a liquid when impacted by a projectile.[1] When impacting soft tissue, the flesh begins to stretch and a wave is formed like ripples in water.[2] When the flesh is stretched beyond its yield point, it will rip and tear, displacing outward, away from the projectile. The projectile will continue to stretch and tear flesh, muscle, and

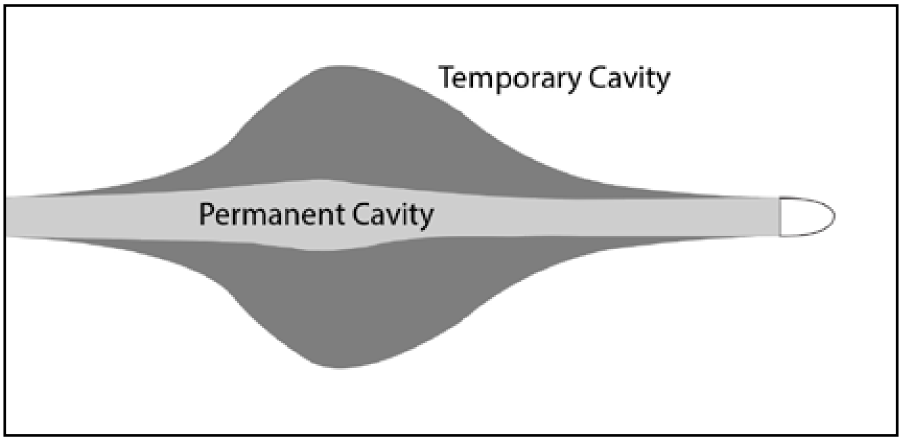

Figure 2: Temporary and permanent wound cavities.

organs, displacing soft tissue outward and away from the projectile. Being extremely elastic, the flesh rebounds back into its static position. The cavity created when the soft tissue is displaced outward is known as the *temporary wound cavity*. Like the permanent wound cavity, the larger the temporary wound cavity, the greater the chance of damaging one of these vital areas.

The size of the permanent wound cavity is dependent on the diameter of the projectile, including its diameter after expansion. The size of the temporary wound cavity is dependent on the projectile's kinetic energy (mass and velocity). The temporary cavity may be several inches in diameter as well as several inches deep, but the soft tissue will contract to roughly the size of the hole the projectile cut or slightly larger. While there is some tissue damage from the temporary cavity, the elastic nature of soft tissue prevents severe damage when it is stretched out by the projectile's impact. High velocity projectiles create larger temporary wound cavities, increasing the chance of the soft tissue stretching beyond its yield and causing more tissue damage. Although some tissue is damaged during the expansion of the temporary cavity, the majority of the damage exerted on soft tissue comes from the permanent cavity.

FRAGMENTATION AND TUMBLING

There are other ways that a projectile can damage soft tissue: fragmentation and tumbling. Fragmentation occurs when a projectile is distorted beyond its yield and breaks or tears apart. These fragments, varying in shape and mass, will create additional wound channels as they travel in various directions.[3] These fragments can be beneficial in that they increase the chances of destroying vital organs and tissue but can also increase the risk of excessively damaging and ruining meat while hunting. Fragmentation occurs more frequently with soft projectiles, expanding projectiles, and projectiles impacting at high velocities. Similar to a fragmenting projectile, shot (bird and buck) will also create multiple wound channels and increase the chances of damaging vital organs.

Tumbling occurs when a projectile's velocity and spin rate are slowed to the point of instability. The deceleration combined with a shift in the center of pressure causes the projectile to pitch and yaw in the soft tissue. The projectile acts like a top on a table, with its base *precessing* around the tip. If the yaw or pitch is severe enough, the projectile will begin to flip end-over-end inside

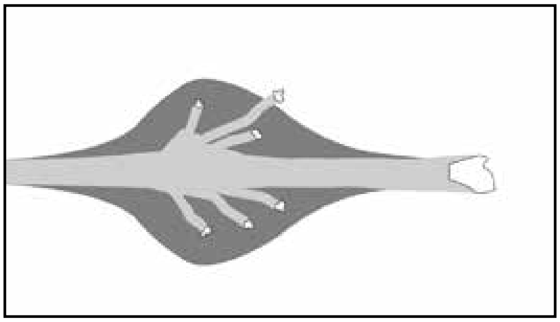

Figure 3a: Wound channels of fragmenting projectiles.

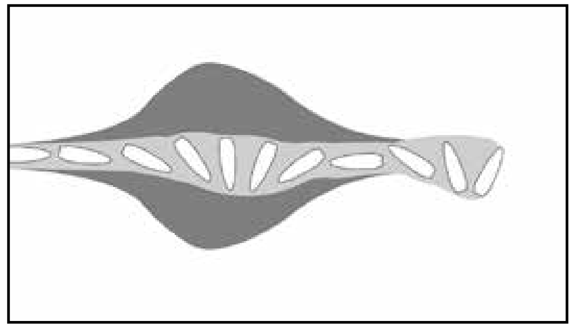

Figure 3b: Wound channels of tumbling projectiles.

the soft tissue. This creates a wound channel with a narrow entry that opens up to several roughly projectile-long (caliber-wide) cavities. Although not the intended result, tumbling can prevent perforation and limit the penetration of FMJ-style projectiles. Tumbling is more prevalent with long, pointed bullets whose base is much heavier than the nose and the center of pressure and gravity are farther apart. With some jacketed projectiles, tumbling can also lead to fragmentation. As the projectile flips end-over-end, the friction the soft tissue exerts against the jacket as it deforms is greater than the bond of the jacket and the core. This causes separation of the jacket and core and possible fragmentation of both.

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Terminal Ballistic Factors

There are several factors that dictate the terminal ballistic performance of the projectile, including its material(s), design, sectional density (SD), and energy (mass and velocity). All of these factors will contribute to how energy is transferred to the target. The target material will also change how the projectile performs.

MATERIAL AND DESIGN

The materials used in the construction of the projectile and its design play a big role in its terminal performance. Various material types will perform differently when impacting targets of varying materials. The material used (along with design and shot placement) will dictate whether the projectile will perforate or penetrate. Softer materials like lead and copper will deform when impacting most target materials, while harder materials will retain their shape. The design of the projectile will also determine whether it will penetrate or perforate, regardless of material.

Let's start with lead. As we discussed in the projectiles section, lead is a soft, dense metal that is very malleable. These properties make lead an ideal choice for a projectile that penetrates rather than perforates. When soft lead projectiles impact flesh, they deform dramatically, increasing their surface area and, in turn, drag. This is regardless of bullet design; both ball and hollow point projectiles will deform (although the hollow point will experience more deformation). Increasing the hardness of the lead (with the addition of antimony and tin) does not decrease the amount of deformation the projectile experiences by much but does make the lead more brittle and increases the chances of fragmentation. When lead impacts hard target materials like concrete (or other masonry) or steel, the amount of deformation will be extreme and in most cases the projectile will fragment.

Copper is used in various ways to try to control the deformation of the projectile. Because copper is harder than lead, it will experience less deformation when contacting flesh or hard targets but will also deform to an extent because it is still on the softer side when considering other metals. Copper jacketed or FMJ projectiles are more likely to perforate flesh than a solid lead ball projectile because the copper jacket will help the projectile retain its shape as it passes though muscle and organs. The copper jacket can also be used to control the rate of expansion and depth of penetration for expanding projectiles (hollow point, soft point, and tipped). By varying the thickness of the jacket from base (thicker) to tip (thinner), the front part of the projectile can expand, while the rear remains intact. Bonding the jacket and the core, either chemically or mechanically, will prevent jacket separation, even when impacting hard surfaces or bone. The jacket can also be used to separate the core into multiple sections so that the frontal section can expand while leaving the tail section whole.

Solid copper or brass "monometal" projectiles can be designed to penetrate, perforate, expand, fragment, and tumble. Solid, ball-style projectiles will perforate soft tissue easily and shatter bone with little to no distortion or deflection. Ball-style projectiles will also have a tendency to tumble because they are typically longer than jacketed lead core projectiles. The increased length is to increase mass because of the decrease in density compared to lead core projectiles. This increases the distance from the center of gravity and the center of pressure when the projectile impacts soft tissue. Even when impacting hard surfaces, solid copper or brass projectiles will experience much less distortion than lead or jacketed lead projectiles.

Solid copper or brass hollow points and tipped and fragmenting monometal projectiles rely on design rather than material to initiate expansion. Most expanding monometal projectiles utilize scoring or slitting around the nose and cavity to aid in expansion. When the cavity fills with soft tissue (hydraulic fluid) and the mouth of the projectile begins to expand outward, the nose of the projectile will begin to shear apart at the score lines/slits, forming individual petals. With polymer-tipped, solid copper hollow points, the tip drives back into the cavity like a wedge, causing the same expansion and shearing. As the petals begin to expand outward, they will begin to experience dramatically more drag, which forces them to expand outward and roll backward. With hollow point and tipped solid projectiles, the base of the petals is thicker than the area near the mouth. This allows the petals to roll backward without shearing and fracturing. With monometal projectiles designed to fracture, the area near the base of the petals is scored or slit so that the petals shear off and create an additional wound channel. This design utilizes multiple petals to create multiple wound channels, while the base continues forward like a ball projectile or FMJ.

Steel tipped, steel jacketed, and steel and tungsten core projectiles are almost always designed for perforation, with little concern for penetration. These projectile types often utilize copper or lead in their construction. When impacting soft tissue, the steel component of the projectile will experience little to no distortion, even when impacting bone. When impacting hard surfaces, like masonry or steel plates, the steel component will experience little to no distortion (depending on the steel's hardness), even though the lead and copper components may have distorted or fragmented from the steel component.

SECTIONAL DENSITY AND ENERGY

Two other factors that have great effect on a projectile's terminal ballistic performance are sectional density (SD) and energy (mass and velocity). We previously discussed SD in the projectiles section: section density is a ratio of a projectile's mass to its diameter. The higher the SD number, the greater the projectile's mass is in relation to its diameter. A greater mass-to-diameter ratio is beneficial for one purpose: deep penetration and (eventually) perforation, regardless of medium.

Figure 4: Various projectiles with lead, copper, and steel construction.

When talking about SD in relation to terminal ballistics, the medium being penetrated will vary. A projectile with a high SD features a smaller cross-section compared to its mass, focusing drag onto a smaller area on the front of the projectile while carrying more mass. A projectile with a high SD will perforate through soft tissue, bone, and hard targets (projectile material dependent) better than a projectile with a low SD (and all other factors being equal). Although a high SD is extremely beneficial when external ballistics is considered, it may be detrimental in some aspects of terminal ballistics. First, if perforation is not the desired result, a high SD projectile will need to be designed to expand. As the efficiency of penetration increases, the ability to slow and stop it must also increase (when desired). Second, the design of most high SD projectiles places the centers of gravity and pressure farther apart, increasing the chances of tumbling.

The projectile's energy can also significantly affect how it performs. The projectile's energy comes from a combination of its mass and velocity. This means the same amount of energy can be delivered in two ways: by a heavy, slow-moving projectile or by a lightweight projectile moving at high velocity (even though the lighter projectile will have less momentum*). Before we move any further, let us discuss the term "energy."

**Although both products of mass and velocity, kinetic energy (KE) (muzzle/projectile energy) and momentum are not the same. Momentum is a vector — it has both magnitude and direction. KE is a scalar quantity. KE only has magnitude with no spatial reference.*[4]

Energy describes the ability of an object to perform "work." The work the projectile performs is penetration, perforation, expansion, fragmentation, and transferring energy. When discussing projectiles, we often express their energy (KE) as foot-pounds (ft-lb.) of energy, or the ability to move a one pound object a distance of one foot. As previously discussed, we can calculate the projectile's KE with mass (M) (in grains) and velocity (V) (in fps). The formula is:

KE = M x V^2

You can see from the formula that higher amounts of KE are more dependent on velocity than mass. Because KE is proportional to the velocity squared, an increase in velocity has an exponential effect on KE.[5] While doubling a projectile's mass will double its KE, doubling the projectile's velocity will quadruple its KE. Let's take a look at two projectiles with the same KE, but by different means. The first projectile utilizes mass to achieve its KE: 200 grains moving at 1,000 fps. The second projectile utilizes velocity: 2,000 fps and 50 grains. Both projectiles produce roughly 444 ft-lb. of energy. You can see that even though the larger projectile is 4X heavier than the light one, the 50-grain projectile produces the same KE by moving twice as fast.

The way the energy is delivered to the target will differ with light and heavy projectiles delivering the same KE. Just as a light projectile will suffer the effects of drag greater than a heavy projectile in air, the same is true in other mediums. When impacting soft tissue, a light, fast-moving projectile will shed velocity rapidly, transferring a massive amount of energy to the target in a short duration (distance and time).* This rapid transfer of energy results in a massive temporary wound cavity, but a relatively small (diameter) and shallow wound cavity. With light, fast-moving projectiles, almost all of their KE is delivered to the target because the projectile will almost never perforate. Light, high velocity projectiles are also more likely to yaw, fragment, and tumble. The increased velocity increases the rate of deformation of soft projectiles.

A heavy, slow moving projectile will retain more of its energy due to its momentum. Although the projectile is shedding velocity through drag, its mass is maintaining its momentum, which resists drag to a greater degree than a light projectile. This allows the heavier projectile to penetrate deeper into the target and possibly even perforate it. The heavier projectile may not create as large a temporary wound cavity but will produce a larger and deeper permanent wound cavity. If the heavier projectile were to only penetrate the target, all of its energy would be transferred; but with the higher risk of perforation, some of this energy may be lost.

**Dependent on projectile and target material.*

Another way to look at a projectile's ability to do "work" is by looking at its momentum. You can look at the projectile's momentum as an impulse, or an amount of force over a given time. In America, momentum is expressed in slug-feet-per-second. One slug is equal to 32.174 lb. (equal to one force of gravity). We want to convert those units of measurement to inch-pound-force-per-second (in-lbf/sec.). To calculate a projectile's momentum you only need its mass (M) (in grains) and velocity (V) (in fps). We also need to convert mass from grains to lb. and then to slugs by dividing mass by 7,000 (grains in a pound) and 32.174 (pounds in a slug). The basic formula for momentum (P) is P = MV, but to convert to our desired units we will use the following formula:

$$((M/7{,}000)/32.174) \times V = P \times 144^*$$

Using our heavy projectile,
200 grains/1,000 fps:

$$((200/7{,}000)/32.174) \times 1{,}000 = P \times 144$$

$$(.0286/32.174) \times 1{,}000 = P \times 144$$

$$.00089 \times 1{,}000 = .89 \times 144$$

$$P = 128.16 \text{ in-lbf/sec.}$$

**Constant converts square feet to square inches.*

This means that for every second the projectile acts upon the target, it will exert 128 lb. of force over an area one inch square. Let us look at the momentum of the lightweight projectile, 50 grains/ 2,000 fps.

$$((50/7{,}000)/32.174) \times 2{,}000 = P \times 144$$

$$(.0071/32.174) \times 2{,}000 = P \times 144$$

$$.00022 \times 2{,}000 = .44 \times 144$$

$$P = 63.36 \text{ in-lbf/sec.}$$

The lighter projectile only exerts 63 pounds of force on the same 1 in. square. You can see with momentum, mass and velocity are treated equally. This occurs because of the *conservation of momentum*. In a closed system, like a cartridge inside a firearm, the entire system has a given momentum. When an event occurs, like the cartridge discharging, the momentum of the projectile moving forward and the momentum of the firearm recoiling backward will be equal to the original "potential' energy of the firearm and cartridge. The projectile, being much lighter than the firearm, requires a much greater velocity to achieve the same momentum as the heavier firearm recoiling at a moderate velocity.[6]

Although we can try to quantify the performance of a projectile based on its calculated KE and momentum, there are too many factors involved to say that one is better suited for incapacitation than the other. In fact, we already know that incapacitation or death occurs from destruction of vital organs (brain, spine, heart, etc.) and blood loss. No amount of KE or momentum can make up for poor shot placement. A small, low energy projectile placed directly in a vital organ will be more effective at incapacitating than a large, high energy projectile placed in just muscle or even bone.

Real World Terminal Ballistics

Up to this point, all of our discussion of terminal ballistics has been under ideal situations where the projectile performs as designed. In reality, real world terminal ballistics can be unpredictable, especially when self-defense, military, and LE applications are concerned. Let's look at a more realistic picture of a projectile's journey through flesh and bone. The anatomy of most animals and man is remarkably similar, with most of the vital organs in the chest cavity and abdomen, the brain in the top portion of the skull, and the spinal cord running along the back. The only difference is the size and proportions of the various bones and organs. To destroy vital organs or the brain, the projectile has to perforate hides, bones, and muscles of varying thicknesses and densities before reaching the brain or heart, lungs or liver.

In most cases, if the projectile impacts bone, square to its surface, the projectile will experience some distortion as it fractures the bone and continues through the soft tissue. Harder projectiles will experience less deformation as they destroy the bone. Depending on the thickness and density of the bone and material and energy of the projectile, it may fragment as it passes through. If the impact is at an angle to the surface of the bone, the projectile may *ricochet*, or deflect, changing its intended path. If the projectile were to strike the edge of the bone, it would chip the bone or simply deflect. Deflection or deformation from striking the bone can cause the projectile to yaw and tumble. Passing through muscle and other soft tissue can cause yawing and tumbling from the change in center of pressure as the projectile moves through various densities of matter.

The chaotic nature of a self-defense encounter or war makes terminal ballistics even more unpredictable. Layered or heavy (winter) clothing can prevent some hollow point designs from properly expanding, making them perform similarly to an FMJ. We also have to consider the projectile impacting belt buckles, jewelry, phones, or even bibles carried in pockets. There are many stories of layers of heavy clothing stopping low velocity, large caliber projectiles. There are also countless stories of people surviving a

Figure 5: Projectile stopped by cell phone.

gunshot because the projectile was stopped by a lighter or a coin or some other object they were carrying.

Now let's introduce a modern urban environment. What factors are introduced to the equation if the self-defense incident occurs inside a home, or even in a vehicle? Inside the home there are walls (sheetrock, studs, insulation, piping), furniture, appliances, and other obstructions. In a vehicle there are glass, sheet metal, and various plastic and composite components, not to mention the various thick metal components of the engine, drivetrain, and wheels. Impacting any of these "barriers" can cause disruption in the projectile's form and intended path. The results are projectiles that deform, deflect, fracture, ricochet, and tumble before ever reaching vital organs. If the projectile used is not armor piercing, it may fail to perforate any of the thicker metal components.

Hard barriers (cement, brick, and other masonry) and armor present unique challenges for a projectile's terminal ballistic performance. Soft projectiles (lead and jacketed) stand little chance against these hard targets. Although a soft projectile may destroy a brick or cinder block upon impact, the projectile will lose so much energy that it may fail to penetrate soft tissue on the other side. The projectile will also be heavily deformed or fragmented, meaning only small pieces of the original projectile will reach soft tissue. This is why most "ball" projectiles used by militaries around the world utilize a steel or tungsten spike in their construction. When impacting hard targets or armor, the jackets and soft lead core of these projectiles may fragment or be stripped from the hardened core when impacting hard targets, but the harder spike will continue through with little to no deformation. These hardened spikes will typically perforate soft tissue with little to no deflection.

Let's take a look at our previous four example cartridges (.223, 9mm, 12-gauge, and .22 LR) and the end of the projectile's journey. For these examples we will be looking at the projectile's effects through soft tissue alone, without any other factors. In our previous examples, the projectile type was unimportant, but for these examples we will examine what four different wound cavities would look like. For example purposes, our .223 projectile will be an FMJ (lead core, copper jacket), our 9mm projectile will be a jacketed hollow point, the #7.5 birdshot will be solid lead, and the .22 projectile will be a solid lead hollow point.

We will assume the target for the .223 projectile is 200 yd. away. From the ballistic table in the previous section (.223, 300 yard zero, standard conditions) we know that the .223 projectile is moving at roughly 2,279 fps at 200 yd.

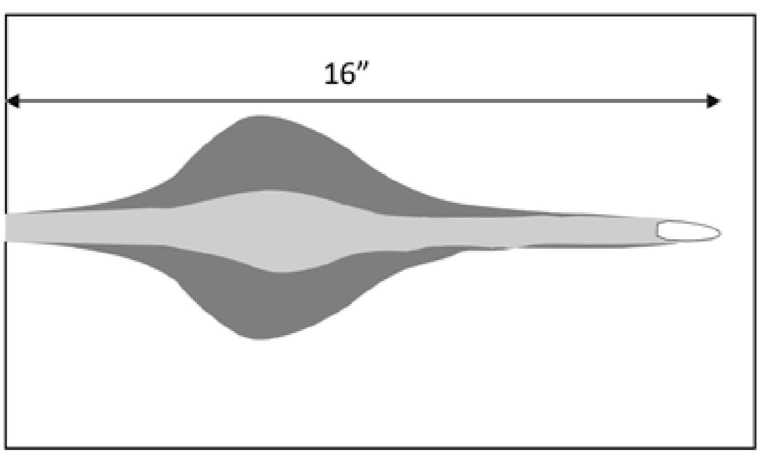

Figure 6: .223 Remington wound cavity.

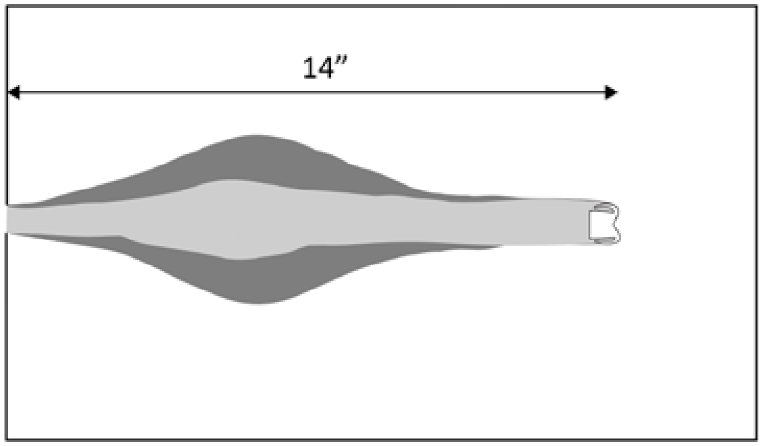

Figure 7: 9x19mm Parabellum wound cavity.

At this distance the .223 round has roughly 564 ft-lb. of energy remaining. The small diameter of the projectile will allow it to easily penetrate the soft tissue. Because of the velocity of the projectile, when impacting the soft tissue it will create a massive temporary wound cavity as the projectile displaces soft tissue near the entry point. Because of the mass of the projectile, the temporary cavity will begin to taper down as the projectile loses velocity from drag. Although there may be slight deformation of the projectile upon impact, its shape will remain fairly unchanged. In most cases the small diameter, high velocity FMJ will perforate 16+ in. of soft tissue, unless it tumbles. As the soft tissue contracts, it will leave a wound channel that is roughly caliber diameter upon entry that opens up in diameter where the temporary cavity was at its largest, before tapering back down to just over caliber diameter upon exit. Because of the length of the projectile (.745 in.), there is a good chance it will tumble or, at a minimum, yaw and divert from its original path. Depending on the jacket thickness, the jacket may fragment when impacting at higher velocities.

Let us assume the target for the 9mm projectile is 25 yd. away. From the table in the previous section, we know that the 9mm projectile is moving at roughly 1,100 fps at 25 yd. At this distance the 9mm round has roughly 309 ft-lb. of energy. As the projectile penetrates the flesh, the cavity of the projectile will fill with soft tissue, which initiates expansion. Because of the velocity of the projectile, the temporary wound cavity is slightly smaller than the .223 round. The projectile will expand to a maximum diameter when the petals fully unfurl and are perpendicular to the body of the projectile. As the projectile continues through the soft tissue, the petal will roll back toward the body of the projectile, reducing its maximum diameter to slightly larger than its unexpanded diameter. In most cases, the projectile's moderate diameter, low velocity, and expansion will limit it to less than 14 in. of penetration. The entry to the permanent wound channel will be slightly larger than caliber diameter but will increase in diameter as the projectile expands to maximum diameter. The wound channel will then taper off as the petals of the projectile roll backward but will still be larger than the entry wound. There will also be significant tissue damage from the petals slicing through the soft tissue because the projectile is still spinning as it penetrates. Depending on the thickness of the jacket, the projectile may remain intact or fragment as the petals break apart from the main body.

Now, let us assume the target for the 12-gauge #7.5 birdshot is 25 yd. away. From the table in the previous section, we assume that the

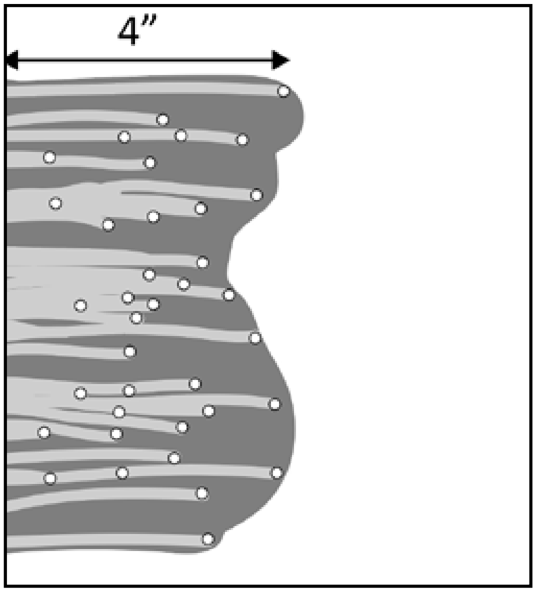

Figure 8: 12-gauge #7.5 birdshot wound cavity.

birdshot is moving at roughly 1,000 fps. At this distance, the shot string has increased to a diameter of roughly 40+ inches. If we assume that half of the roughly 263 pellets impact the soft tissue target, that is roughly 131 pellets .095 in. in diameter. Each pellet would have a remaining energy of 3.3 ft-lb. of energy (432 ft-lb. total). As each individual pellet enters the flesh, the soft lead will immediately deform. The low mass and energy of the shot pellets will leave small, shallow, permanent wound channels, but the energy transfer from the accumulated pellets can leave a fairly large, temporary wound channel. Because of the low velocity of the pellets and the soft lead construction, the pellets will only penetrate 2 in. – 4 in. Most pellets will never make it through the first layers of flesh and muscle, let alone make it to any vital organ.

Finally, let us assume the target for the .22 LR is 50 yd. away. From the table in the previous section, we know that the .22 projectile is moving at roughly 1,030 fps. At this distance, the .22 LR round has roughly 94 ft-lb. of energy. As the projectile penetrates the flesh, the cavity of the projectile will fill with soft tissue, which initiates expansion. Because of the low velocity and small diameter of the projectile, the temporary wound cavity is slightly smaller than the 9mm round. The projectile will expand to a maximum diameter when the hollow cavity unfurls outward. As the projectile continues through the soft tissue, the mouth of the projectile will roll backward onto itself, reducing its maximum diameter to slightly larger than its unexpanded diameter. In most cases, the projectile's small diameter, low velocity, soft material, and expansion will limit it to less than 10 in. of penetration. The entry to the permanent wound channel will be slightly larger than caliber diameter but will increase in diameter as the projectile expands to maximum

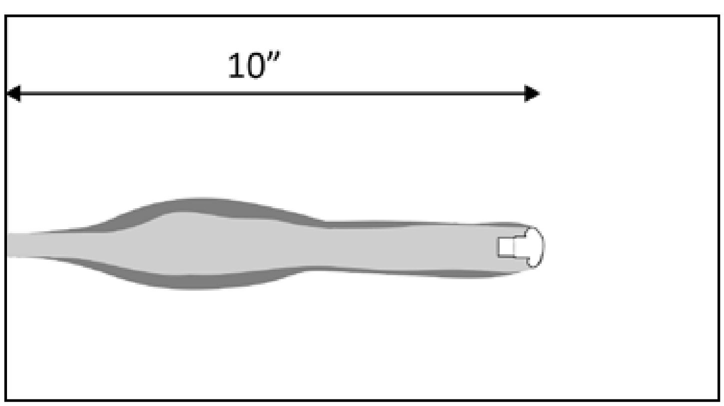

Figure 9: .22 LR wound cavity.

diameter. The wound channel will then taper off as the mouth of the projectile rolls backward but will still be larger than the entry wound. Because of the use of soft lead, there may also be a chance of the projectile fracturing near the hollow cavity.

TERMINAL BALLISTIC TESTING

So, how do we test our projectile's terminal ballistic performance in the real world. Luckily, we can simulate soft tissue using *ballistic gelatin blocks*. These blocks closely represent soft tissue in density and behavior. The procedure for testing a projectile's terminal ballistics has even been standardized by the Federal Bureau of Investigation (FBI). The test utilizes gel blocks 6 in. wide by 6 in. tall and 16 in. deep, containing 10 percent gelatin by weight.[7] The test is completed at various distances (10 ft. and 20 yd.) into bare gel and gel blocks behind various barriers (heavy clothing, sheet metal, wallboard, plywood, and glass).

Similar tests can be done by the average shooter with the many ballistic gel recipes available online. There are also many stores selling ready-to-go gel blocks online. Many of these blocks are made from synthetic gel and can be melted and reformed several times. Please note that the "clear" synthetic blocks are not the exact same density as the natural gel blocks and will produce slightly different results. Make sure to follow all shooting safety rules when performing your own tests.

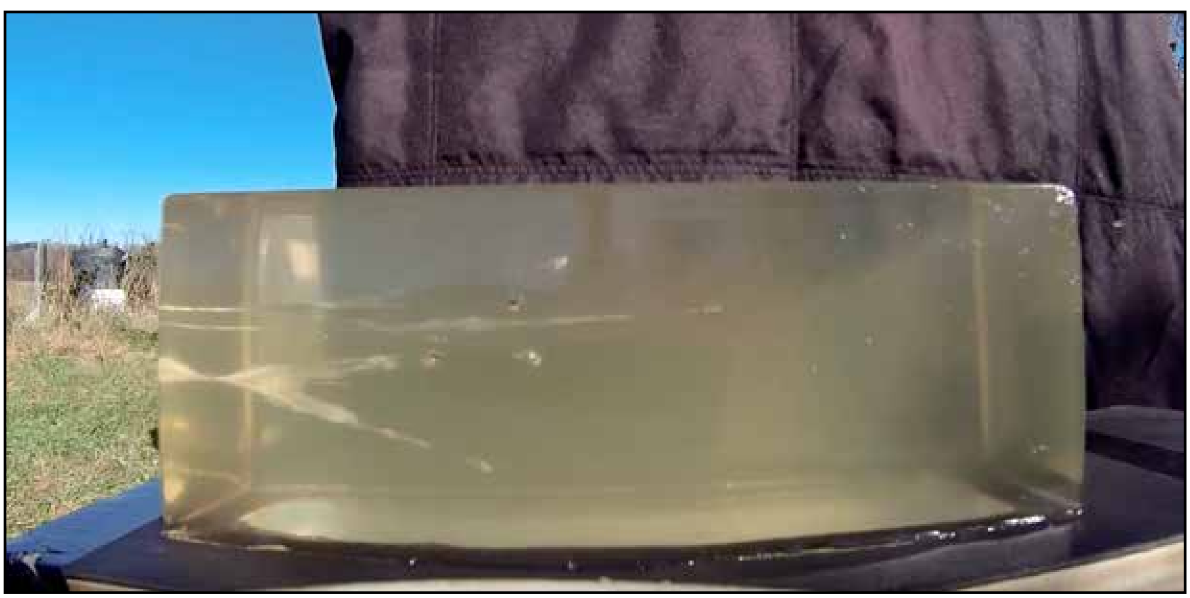

Figure 10: Gel block testing.

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