Third Generation Long-Range Rifle Bullets

James A. Boatright[1]

Introduction

In 1898 the French Army adopted the first long-range infantry rifle bullet aerodynamically designed for supersonic flight, the "*Balle D*" bullet for their pioneering 8x50mmR Lebel smokeless powder service cartridge. This new "*Balle D"* bullet designed by Capt. Desaleux was a lighter-weight, spire-pointed, boat-tailed rifle bullet made of a monolithic brass alloy. It could fly much faster and farther than the earlier round-nosed, heavy-for-caliber, lead-cored bullets which it replaced. By 1911, every major army had adopted a copper-alloy jacketed, lead-cored version of this more aerodynamic, lighter weight, spire-pointed, boat-tailed infantry rifle bullet. These ***first generation tangent-ogive*** bullets, in either flat-based or boat-tailed forms, have long been the accepted norm for best accuracy in rifle shooting at all ranges. In fact, most target rifles still use a 1.5-degree throat angle originally optimized for firing these long-nosed tangent-ogive bullets.

In the 1980's, ballistician William C. Davis, Jr., and Dr. Louis Palmisano developed the ***secant-ogive***, boat-tailed ***Very-Low-Drag*** (VLD) rifle bullet design to serve as a more efficient long-range target shooting bullet. The design of this VLD bullet is an improved version of the US Army *G7 Reference Projectile*. The design for the G7 projectile itself was taken directly from data supplied to the US by Great Britain in 1940 as part of the Lend-Lease Agreements. The War Department in England had developed this projectile design in the late 1930's and termed it the ***British Standard Streamline Projectile*** for use in long-range artillery and naval gunnery. Many of the today's best long-range rifle bullets are these ***second generation*** jacketed, lead-cored secant-ogive VLD bullets, and riflemen are still struggling to shoot them accurately.

Note 1; James A. Boatright is a retired Aerospace Engineer who worked throughout his career as a NASA contract engineer in Houston TX and holds a BSc degree from Texas A&M University in Physics (1965). In retirement, he competed in benchrest rifle matches and built several hundred precision rifles in his gunsmithing machine shop. Over a 10-year period, he regularly contributed articles to *Precision Shooting Magazine* about improving rifle accuracy. After studying the mature field of technical ballistics for several years, he developed a new "Coning Theory of Bullet Motions" which adds incrementally to our understanding of how bullets fly. He can be reached by email at bcgi@centurytel.net.

About six years ago, Dan McKenzie of Tulsa OK requested that I develop a new rifle bullet design which could be manufactured from brass rod-stock using Computer Numerical Controlled (CNC) machining. The resulting ***Ultra-Low-Drag*** (ULD) bullet design described here represents a new ***third generation*** of long-range rifle bullets which offers both greatly improved rifle accuracy and a further reduction in aerodynamic drag for enhanced long-range shooting. Applications for US Utility Patent (Number 14/867,941) and Design Patent (Number 29/539,988) have been filed with the US Patent and Trademark Office as of September 30, 2015. The Utility Patent, US Patent No. 9,857,155 B2, has been issued (January 2, 2018). This Utility Patent expires on September 30, 2035. Design Patent number D780,876 S has been issued (March 7, 2017). The Design Patent expiration date is May 7, 2032.

Dan Warner of the well-respected Warner Tool Company in North Swanzey NH has agreed to manufacture test bullets in 338 caliber from UNS C14700 “free machining” sulfured copper. Chuck Pierce of Baxter County AR has been conducting all initial ULD bullet testing using my 338 Lapua Magnum target rifle, including an invaluable series of rather dramatic test-firings into his family’s swimming pool. David Tubb of Canadian TX has recently begun conducting long-range testing of these 338-caliber ULD bullets. Dan, Chuck, and David are largely responsible for making these next generation ULD bullets available to long-range shooters.

With ongoing development and long-range testing, the need for two different types of these ULD bullets is becoming clear. First, this ULD bullet design with drilled bases, turned from copper rod stock in a CNC turning center, can meet the needs of shooters transitioning to monolithic bullets, but still using rifle barrels having conventional “land and groove” rifling patterns of standard or fast twist-rates. Base drilling allows improved gyroscopic stability and allows some elastic expansion which promotes perfect gas sealing in the “corners” of the grooves. These base-drilled bullets are light-for-caliber and allow extremely high muzzle velocities. Their maximum supersonic ranges can exceed those of existing rifle bullets in each caliber. Second, a solid copper, un-drilled, ULD Mark II bullet design having a lengthened ogive for increased bullet weight and even lower aerodynamic drag is ideal for Extra-Long-Range (ELR) shooting using purpose-made rifle barrels. These special rifle barrels will be made extra long and utilize an improved rifling pattern which eliminates the gas obturation problem with non-expanding bullets. Their rifling twist rates will be between 20 and 22 calibers per turn, which will "hyper-stabilize" these longer ULD Mark II bullets for lowest possible aerodynamic drag and greatest stability to absolute maximum ranges. Ideally, these hyper-stable ULD bullets will punch through the turbulent transonic speed range and continue on in stable flight as reasonably good subsonic bullets.

ULD bullets are calculated to have an average of 15 percent lower coefficients of aerodynamic drag (**Cd**) at all supersonic airspeeds than those of the G7 Reference Projectile which itself is a reasonably good VLD-style bullet design. Of course, all else being equal, reduced air-drag means proportionally less crosswind deflection in any given shooting conditions and more retained velocity at longer ranges. However, that ultra-low-drag feature is just the beginning of the ULD bullet story. The improvements in bullet obturation in the rifle barrel, in bullet gyroscopic stability in flight, and in practical rifle accuracy at any shooting distance offered by the ULD bullet are where this new design excels most importantly.

Manufacturing

The basic ULD bullet shape will be made from rod-stock of a free-machining brass or copper alloy in an automated CNC turning center in any of the various calibers currently favored for long-range rifle shooting. Except for minor variations to accommodate caliber-specific bore and groove diameter standards, all ULD bullets will have the same outside profile—just scaled by caliber size—and each version of the ULD bullet design within the same caliber will have exactly the same outside shape.

By partially drilling out the boat-tailed base and rear driving band during CNC machining, a Monolithic Brass (MB) or Monolithic Copper (MC) version of the ULD bullet can be produced which is rather light-for-caliber and is designed to be fired with great accuracy at very high muzzle velocities from many current target rifles for each caliber, other than those target rifles utilizing extremely slow-twist barrels. Precision base-drilling of these ULD bullets significantly improves their gyroscopic stability **Sg** in any firing conditions and allows these copper bullets to expand elastically during firing to obturate perfectly in conventional rifle barrels made with any reasonable groove diameters. Initial production ULD bullets will be these base-drilled Monolithic Copper (MC) long-range bullets in all popular calibers, starting with 338 caliber for initial test firing.

Each CNC-turned ULD bullet of any size has a volume of **3.0030 cubic calibers** before base-drilling as calculated using my unsophisticated spreadsheet design aid which slices the bullet lengthwise on **0.1-caliber** centers for numerical integration. The 338MC ULD bullets for initial testing are base-drilled using a **0.1660-inch** diameter (#19) drill bit to an effective cylindrical depth of **0.3451-inches**. Using a "1-caliber" reference diameter of **0.3302-inch** for these nominally 338-caliber bullets results in the removal of a calculated **0.20747 cubic calibers** of copper material from the solid ULD bullet. The undrilled 338MC bullet weighs **241.7 grains**, and the base-drilled version weighs **225.0 grains**, or **6.91 percent** less. This weight reduction percentage should be typical for all other calibers of Monolithic Copper ULD bullets. Using a density of **2235.6 grains per cubic inch** for this copper material brings these weight and volume calculations into agreement. This corresponds to a specific gravity of **8.840 grams per cubic centimeter**, which is reasonable for this copper material.

By drilling deeper through the bullet body into the base of the ogive and pressure-seating a precision-made, essentially pure lead core into the machined ULD copper-alloy jacket, we can produce a somewhat heavier Lead-Cored (LC) ULD bullet which can be fired accurately to greater ranges in most current long-range target rifles having standard-twist barrels.

The specialized 65-grain 6 mm PPC and 154.3-grain 308 PALMA bullets are made by drilling the bullet bodies to lesser depths to bring each of these special-purpose ULD bullet types to its final light-for-caliber weight. A second version of each bullet might be constructed by drilling slightly deeper into the bullet shanks and partially filling the resulting holes by insertion of precision polymer (plastic) cores, resulting in the same two final bullet weights, but restricting the obturating elastic expansion during firing to the back half of the rear driving band. These two superior specialized ULD bullets will allow (and require) the selection of faster twist-rate rifle barrels (rifled at about 6 to 8 inches per turn) than the sub-minimum twist-rate barrels which are currently utilized in their respective sports.

By hollowing-out larger portions of the ogive, even heavier lead-cored ULD bullets, the Heavy Lead-Core (HLC) and Maximum Lead-Core (MLC) versions, can be made for firing at greatest ranges from faster twist-rate barrels than are used today in each caliber. However, without resorting to the use of exotic tungsten or depleted uranium core materials, these ULD bullets can never be made quite as heavy-for-caliber as could similar conventionally jacketed, lead-cored bullets of the same caliber and over-all length (OAL).

Ballistically, the aerodynamic improvements and higher muzzle velocities of these ULD bullets more than offset their weight limitations in each caliber. These ULD bullets deliver significantly more kinetic energy farther downrange than is possible with conventional jacketed lead-core rifle bullets. Each type of ULD bullet is designed to be fired with new levels of accuracy, less crosswind sensitivity, and to greater ranges than current bullets can achieve. The higher muzzle velocities of these lighter ULD bullets mean that they also have reduced barrel dwell-times and reduced times-of-flight to any given range. Reducing barrel dwell makes “holding through the shot” easier for the rifleman. Barrel wear-rate, particularly in the barrel throat, is also generally reduced by firing lighter-weight bullets, probably due largely to their use with faster burning-rate propellants and their reduced barrel dwell-times.

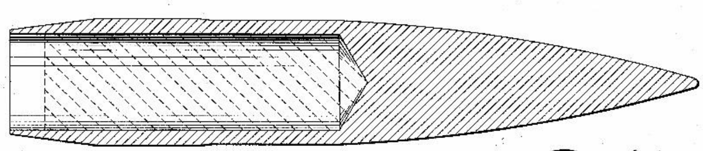
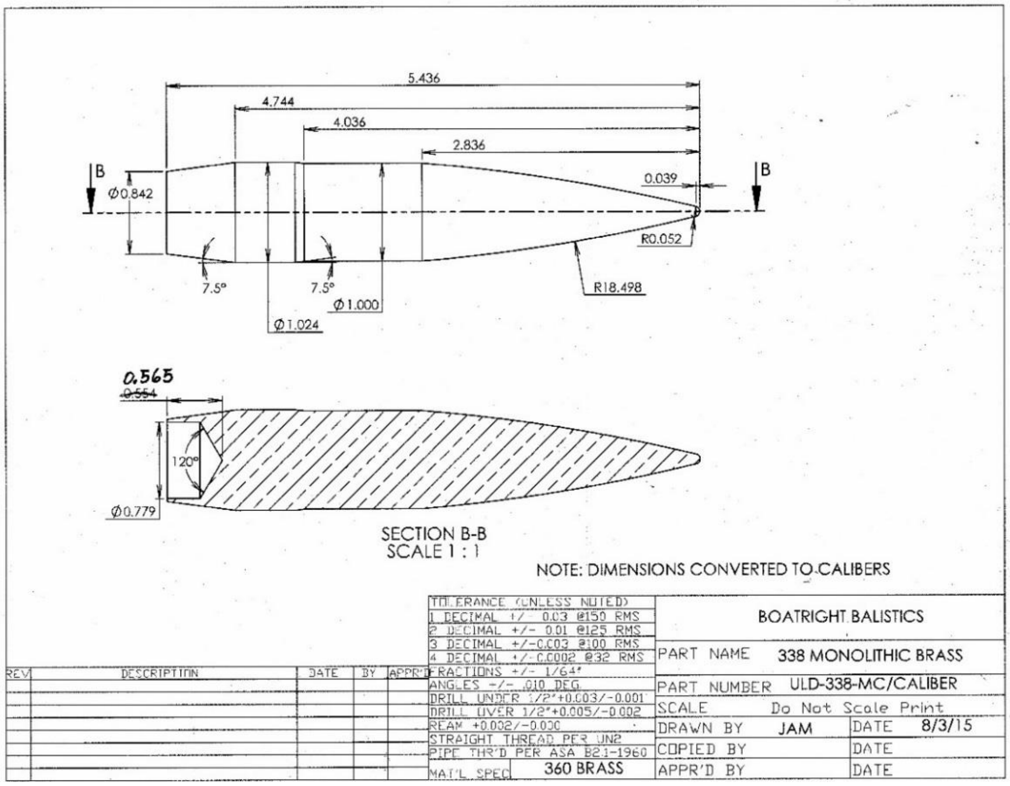
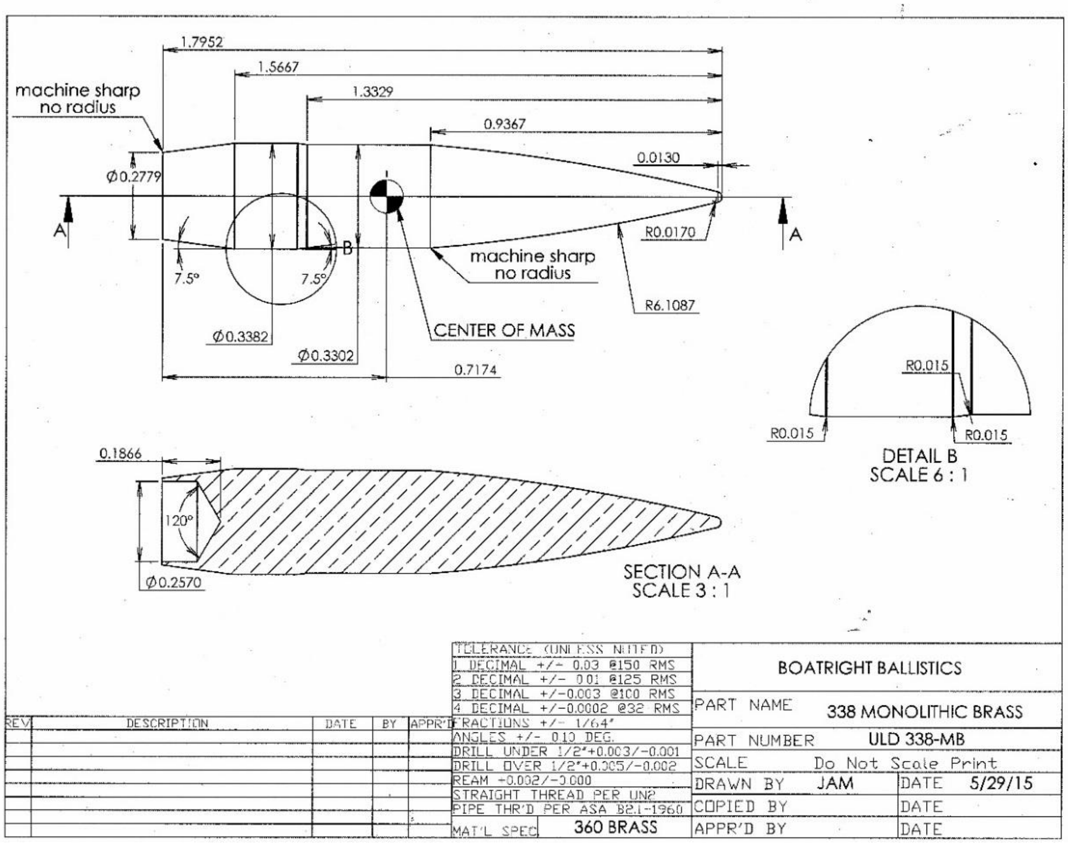


Fig. 6


5.436
4.744
4.036
2.836
B
Ø0.842
0.039
B
R0.052
7.5°
7.5°
Ø1.000
R18.498
Ø1.024
0.565
0.554
120°
Ø0.779
SECTION B-B
SCALE 1 : 1
NOTE: DIMENSIONS CONVERTED TO CALIBERS
TOLERANCE (UNLESS NOTED)
1 DECIMAL +/- 0.03 @150 RMS
2 DECIMAL +/- 0.01 @125 RMS
3 DECIMAL +/-0.003 @100 RMS
4 DECIMAL +/-0.0002 @32 RMS
FRACTIONS +/- 1/64"
ANGLES +/- .010 DEG.
DRILL UNDER 1/2"+0.003/-0.001
DRILL OVER 1/2"+0.005/-0.002
REAM +0.002/-0.000
STRAIGHT THREAD PER UN2
PIPE THR'D PER ASA B2.1-1960
MAT'L SPEC 360 BRASS
REV DESCRIPTION DATE BY APPR'D
BOATRIGHT BALISTICS
PART NAME 338 MONOLITHIC BRASS
PART NUMBER ULD-338-MC/CALIBER
SCALE Do Not Scale Print
DRAWN BY JAM DATE 8/3/15
COPIED BY DATE
APPR'D BY DATE


1.7952
1.5667
1.3329
0.9367
machine sharp no radius
Ø0.2779
0.0130
A
A
R0.0170
B
machine sharp no radius
7.5°
7.5°
R6.1087
CENTER OF MASS
Ø0.3382
Ø0.3302
0.7174
R0.015
R0.015
R0.015
DETAIL B
SCALE 6 : 1
0.1866
120°
Ø0.2570
SECTION A-A
SCALE 3 : 1
TOLERANCE (UNLESS NOTED)
1 DECIMAL +/- 0.03 @150 RMS
2 DECIMAL +/- 0.01 @125 RMS
3 DECIMAL +/-0.003 @100 RMS
4 DECIMAL +/-0.0002 @32 RMS
FRACTIONS +/- 1/64"
ANGLES +/- .010 DEG.
DRILL UNDER 1/2"+0.003/-0.001
DRILL OVER 1/2"+0.005/-0.002
REAM +0.002/-0.000
STRAIGHT THREAD PER UN2
PIPE THR'D PER ASA B2.1-1960
MAT'L SPEC 360 BRASS
REV DESCRIPTION DATE BY APPR'D
BOATRIGHT BALLISTICS
PART NAME 338 MONOLITHIC BRASS
PART NUMBER ULD 338-MB
SCALE Do Not Scale Print
DRAWN BY JAM DATE 5/29/15
COPIED BY DATE
APPR'D BY DATE

The Self-Aligning Bullet Design

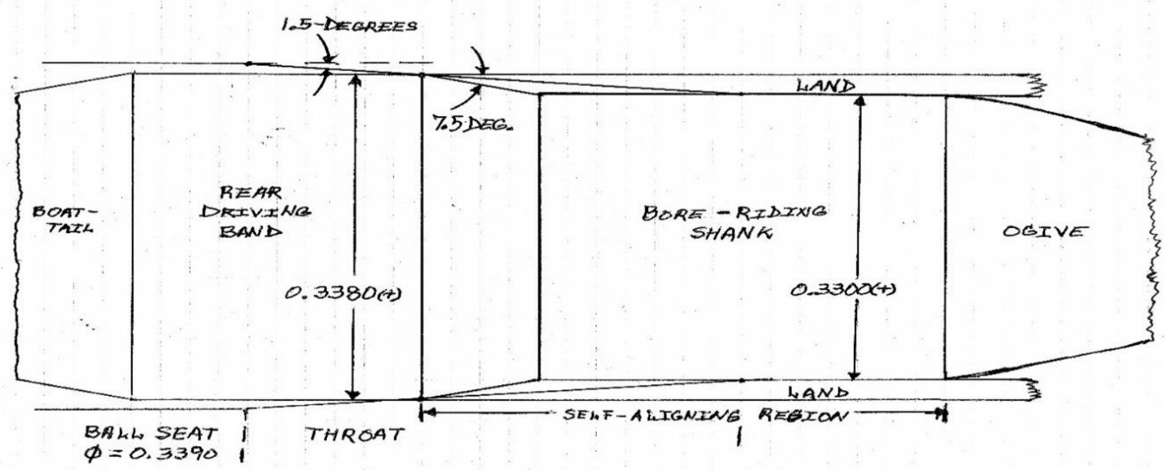
The ULD bullet is designed to be ***self-aligning*** as it enters the throat of the rifling in firing. This self-alignment capability is virtually independent of the design of the chamber and throat in the rifle firing it—anything from SAAMI- or CIP-specified standard chambers to specialized match chambers. The recurring VLD accuracy problem of ***in-bore bullet yaw*** is virtually eliminated by this self-aligning feature of the ULD bullet design. The ULD bullet mechanically centers itself in the bore and mechanically aligns its axis with the axis of the bore ***just prior*** to engraving the rifling pattern into its rear driving band.

The front-end of the bore-riding shank of the bullet mechanically centers the front of the bullet inside the rifling lands forward of any tapered throating-reamer cuts. The bore diameter of the bullet shank will be made oversize just enough (+0.0002 inch) to ensure positive bullet alignment, even if the resulting fit causes the rifling lands to mark the shank very lightly.

If all the rifling lands are of equal top-widths, any light engraving of the bore-riding shank must be concentric with the bore axis because the lateral engraving force and the engraving depth into the bullet shank are strictly proportional at each rifling land. These radially symmetric engraving forces constitute a powerful array of centering forces which repeatably positions the axis of the bullet precisely on the axis of the bore at the front-end of the bore-riding shank.

The 7.5-degree conical shoulder on the front end of the ULD bullet's rear driving-band strongly and reliably centers the back-end of the bullet on the barrel axis as it enters the shallower-cone-angled throat of any current target rifle. The interference ring of contact between the 7.5-degree inside and throat-angle outside cones is located at the full groove diameter rear of this transition ramp. This conical shoulder is located 1.3-calibers behind the front-most mechanical centering surface of the bore-riding shank. Thus, the axis of each ULD bullet is forcibly centered on the axis of the rifle barrel at two distinct places in the barrel separated by a lever-arm length of 1.3 calibers between them, or 0.4293 inches in 338-caliber.

If the throat angle is less than 7.5 degrees and greater than 0.5 degrees (as in almost all rifles), this two-point bullet guidance occurs simultaneously across the 1.3-caliber lever-arm length by ***bridging*** the throat-angle reamer cuts across the rear faces of the rifling lands as diagrammed below. This two-point mechanical alignment occurs ***prior*** to engraving the rifling lands into the rear driving band. For any shallower-angled or unusually deep barrel throats, the final self-aligning of the ULD bullet occurs very early in the process of engraving the rear driving-band as the bore-diameter base of the moving bullet's ogive smoothly enters the un-cut rifling lands.



If an accuracy gunsmith encounters a barrel blank in which the chamber end of the bore is not well aligned with the axis of the barrel's outside profile in front of that chamber, the barrel can be saved by rather tediously re-throating it in alignment with the last few inches of the bore ahead of the chamber. This misalignment occurs in barrel making when the deep-hole drill follows a slightly helical path during the initial drilling of that barrel blank. The misalignment problem is readily detectable through a bore-scope by looking for unequal-length chambering-reamer throating cuts across the rear faces of the rifling lands after chambering. Failure to correct this slight mis-alignment of the chambering-reamer throating cuts to the bore axis ahead of the reamer cuts, would produce a miniature version of the "VLD accuracy problem" (see below) when ULD bullets are fired.

However, the small lateral-jump and aerodynamic-jump impact errors of the fired bullets would each be ***systematic***, i.e., always the same size and in the same radial directions on the target face. Thus, the "wandering deep-hole drill" problem in barrel making should never directly affect rifle accuracy or group sizes. However, launching ULD bullets from such a barrel with a small, non-zero initial yaw angle would be slightly sub-optimal.

Both the tip of the ULD bullet's nose and its Center of Gravity (CG) will be right on the axis of the bore as the bullet traverses a well-made and well-fitted rifle barrel. By design, the "VLD accuracy problem" caused by ***in-bore yawing*** of the engraved bullet cannot occur with the self-aligning ULD rifle bullet.

The VLD Accuracy Problem

With current VLD bullets of any type construction, riflemen have found that whenever the necessary cartridge case-neck and throat (ball seat) clearance dimensions and shallow throat angle of a rifle chamber mechanically allow these long-nosed, short-bodied, secant-ogive VLD bullets to enter the rifling at a canted angle to the bore axis, ***these bullets will always do exactly that in each firing.*** Once the shank of a VLD bullet has been engraved with the rifling pattern in this off-axis orientation, the bullet does not (and indeed cannot) correct its misalignment during the remainder of its trip through the barrel. This in-bore yawing problem causes the center of gravity (CG) of these VLD bullets to be shifted laterally away from the axis of the bore, usually in the randomly oriented radial direction of the nose-offset of the bullet.

The inside diameter of the SAAMI or CIP-spec chamber neck normally exceeds the outside diameter of the cartridge case-neck of a loaded round by 0.003 to 0.007-inch so that ammunition from many makers using bullets varying slightly in diameter can be loaded and safely fired. During firing, the outside diameter of each brass case neck ***must*** be able to expand enough inside the steel neck of the chamber to release the bullet safely. The chamber must also accommodate cartridge cases having slightly eccentric or crooked necks. "Tight neck" chambers having as little as 0.001-inch diametral neck clearance can be used safely with precision handloaded ammunition featuring uniformly turned, concentric case necks. Ball seat diametral clearances of 0.001 to 0.002-inch around the bullet shank are typical of standard factory rifle throats. Precision shooters often tighten this ball seat clearance to under 0.001-inch in their custom chambers. Even these two minimum, but necessary, clearances will still allow the rear bases of the bullet shanks to shift slightly off-axis before the rifling engraves them during firing.

Best “front-end” guidance of VLD bullets occurs when the rear faces of the rifling lands first contact the bullet at the bore-diameter point well forward of the base of its secant-ogive. This ideal forward-most first point of contact requires a throat angle of at least **5 degrees** for most VLD bullets. A shallower throat angle provides less front-end guidance by making first contact occur further rearward—usually all the way back to the groove-diameter bullet shank for a typical **1.5-degree** throat angle. So, the front of the shank of the VLD bullet is centered on the bore axis in firing, but the tip of the bullet’s nose and its afterbody are *offset in opposite directions* as the VLD bullet enters the rifling. The surface of the secant-ogive nose of the canted VLD bullet does not even contact the rifling until its leading side is being engraved at this canted angle. I have recovered buckets of fired 173-grain military .30-’06 bullets which were rifling-engraved all the way to the tip of the tangent-ogive nose on one side and all the way to the base of the boat-tail on the opposite side. Pity the poor recruits who were issued those WWII training rifles and ammunition—probably outworn M1917 Enfields and pre-war M1 Ball ammunition.

Any type of CG-offset from the axis of the rifle bore destroys long-range accuracy due to a one-time “lateral-jump” in some random lateral orientation when the bullet exits the muzzle. This trajectory-deflecting error is sometimes termed “lateral throw-off” in the literature of aeroballistics. The CG of the bullet literally “flies off on a tangent” just as soon as the in-bore spiraling motion of the CG is no longer constrained by the rifle barrel. The lateral motion of the CG of the bullet as it exits the muzzle and begins free flight shows up as a small cross-track “kick velocity” perpendicular to the intended trajectory and oriented randomly away from that trajectory. The on-target size of the trajectory deflection error caused by this lateral-jump problem is ***linearly proportional*** to: 1) the ***time-of-flight*** of the bullet to the target, 2) the ***spin-rate*** of the bullet at the muzzle, and 3) the ***offset distance*** of the bullet CG from the bore-axis of the rifle barrel. The radial direction of this lateral-jump miss-distance on the target is in any random orientation away from the bull’s eye. Groups of five or more shots on one target are enlarged in extreme spread by up to ***twice*** this radial miss distance on the target at any given range.

In-bore yawing also causes the just-launched VLD bullets to fly with a rather large initial coning (gyroscopic precession) angle, theoretically about 15 to 25 times the in-bore yaw angle for typical long, slender rifle bullets. Thus, VLD bullets fly with somewhat increased initial atmospheric drag and crosswind sensitivity until this large initial coning motion damps out after several coning cycles. Launching any spin-stabilized projectile with a large initial yaw angle also causes its trajectory to be permanently deflected by an “aerodynamic jump” angle as it encounters the atmosphere upon exiting the muzzle blast cloud and shock wave. This aerodynamic-jump deflection occurs as a one-time transient effect during the initiation of the bullet’s gyroscopic precession or “coning” motion. The angular magnitude of this deflection is determined by the bullet’s initial spin rate, its inertial properties, the density of the ambient atmosphere, and the size of the initial yaw and yaw rate. The roll-orientation of this trajectory deflection away from the intended path is always 90 degrees advanced from the initial yaw orientation in the sense of the bullet’s spin direction (usually right-handed, or clockwise, as seen from behind). Its effect on target is ***proportional to the distance*** to that target and is significant. If the initial yaw of the rifle bullet is due to firing through a typically horizontal laminar-flow cross-wind at near-ground level, its effect can be corrected by making a vertical-direction “elevation” aiming adjustment along with the needed horizontal “windage” aiming adjustment. If the initial yaw is due to an in-bore yaw which is randomly oriented as the bullet clears the muzzle, no predetermined aiming adjustment can correct it.

This combination of accuracy concerns constitutes the VLD accuracy problem. The incentive for long-range target shooters to select the ***slowest possible barrel twist-rates*** that will just marginally stabilize their VLD match bullets in ambient atmospheric conditions is largely an effort to minimize these lateral jump and aerodynamic jump accuracy problems caused by the in-bore yawing of their (perhaps also statically unbalanced) VLD bullets. Minimum twist-rate barrels are also selected for greatest accuracy with tangent-ogive, jacketed lead-core match bullets for similar reasons, but primarily to minimize the lateral jump caused by their typical static imbalance problem.

My published “Well Guided Bullet” integrated chambering-reamer design, and the dual-ogive VLD bullet design of Bryan Litz, Chief Ballistician at Berger Bullets, are two different efforts at remediating this “in-bore yaw” VLD accuracy problem. Each of these design approaches provides greatly improved front-end guidance in the barrel throat as these VLD bullets are fired, but only at the bore-diameter point near the base of the secant-ogive nose of each VLD bullet. In each of these design approaches, the guidance of the back-end of the VLD bullet can be improved only by minimizing the necessary case-neck and ball-seat clearances in the rifle barrel. The self-aligning feature of these ULD bullets provides a far more effective solution to this in-bore yaw problem by mechanically centering each ULD bullet in the barrel at two widely separated fore and aft locations along the bullet before it is engraved by the rifling lands. Permanently resolving this VLD bullet-guidance problem will go far toward allowing the use of faster twist-rate rifle barrels for improved bullet stability in long-range flight.

Bullet Balance

The same type of lateral-jump impact error can also be caused by firing a bullet which had been manufactured out of ***static*** or ***dynamic balance***. Due to the way in which gilding-metal bullet jackets are made, the thickness of these jacket walls cannot always be perfectly symmetrical about the longitudinal axis-of-external-form of the finished bullet. These impact-drawn copper-alloy bullet jackets tend to have a slightly thicker side opposite an equally thinner side which varies over their entire drawn length. A static imbalance then results for each jacketed bullet after a higher-density lead core has been seated into a slightly eccentric jacket. No matter how carefully they have been made, any production batch of conventionally jacketed, lead-cored match bullets will have a quantifiable statistical distribution of measurable CG offset distances. I expect batch mean CG offsets to be well less than 0.010 thousandths of an inch for turned copper-alloy 338-caliber bullets, for example, versus about 0.100 to 0.300 thousandths for batches of jacketed 30-caliber match bullets.

Having been CNC-turned from solid brass or copper rod-stock and having precision-made lead or plastic cores inserted and pressure-seated concentrically, these ULD bullets should possess virtually perfect static and dynamic balance. That is, the CG of the bullet should always be located somewhere along, and lying very nearly directly upon, its axis-of-form which would be the definition of static balance for a spin-stabilized rifle bullet. This order-of-magnitude improvement in bullet static balance as compared with the best of conventional jacketed bullets should also hold true for the versions of the ULD bullet manufactured with pressure-seated, precision-made lead or polymer cores.

Furthermore, there should be no internal skew-symmetric density gradients within the solid metal bullet body or pressure-seated bullet core materials which would introduce a dynamic imbalance. A free-flying spin-stabilized rifle bullet having this type of dynamic imbalance would be spinning about a principal axis of inertia skewed at a slight angle to its axis of external form, introducing a rapidly rotating aerodynamic lift force and increasing its aerodynamic drag. The situation of having a statically balanced but dynamically unbalanced bullet is so unlikely that you almost have to create it on purpose. A typical inclusion or void in a cast lead-alloy bullet, for example, simultaneously creates both types of bullet imbalance.

The only CNC machining operation in the manufacturing of the brass or copper portion of a finished ULD bullet in which a significant static or dynamic imbalance could be created would be in re-chucking the profile-turned bullets for base drilling and in subsequent internal machining. By rotating the bullet instead of the tooling during each internal machining step and by “spotting in” the base center in the lathe before drilling it, any possibility of introducing either static or dynamic imbalance in the resulting ULD bullets is mechanically eliminated. Great care must be exercised in centering the bores of the collets used for re-chucking and rotating each caliber of these ULD bullets for base-drilling and internal machining. If the final internal machining of the indexed bullet-holding collets themselves is done in the same machine which will be performing the base-drilling, virtually perfect alignment of the internal machining and static balance of the finished ULD bullets can be assured. Any coolant/lubricant or brass chips remaining inside the machined bullets must be completely removed from the bullet cavities before inserting the cores. The chronic bullet imbalance problems due to the unavoidable eccentric variations in jacket-wall thickness which have always plagued the manufacturing of jacketed, lead-cored, match-quality bullets should never affect any of these CNC-turned and precision-cored ULD bullets.

Concerning Barrel Twist Rates

Elimination of the chronic bullet problems of static imbalance and in-bore yaw frees riflemen to select match-grade barrel blanks having much faster twist-rates for greatly improved ***gyroscopic stability*** (**Sg**) of the fired bullets throughout their flights. For example, future INTERNATIONAL PALMA long-barreled 308 Winchester match rifles using 154.3-grain (10.0 gram) 30-caliber ULD bullets fired at 3,000 FPS will be equipped with 6 to 8-inch twist barrels instead of today's typical 12-inch twist barrels. For comparison, that 12-inch twist 308 rifle barrel corresponds to 40 linear calibers per turn, whereas long-range artillery tubes might have twist rates of only 20 to 25 calibers per turn (or 6.00 inches to 7.50 inches per turn in 308 caliber).

On the other hand, the hollowed-out bases of these ULD bullets shift the center of gravity (CG) of each bullet forward toward the center of pressure (CP) of that bullet in flight, when compared to the same bullet design without the base-drilling. This forward shifting of the CG reduces the mechanical "lever arm" length of the aerodynamic lift and drag forces acting at the instantaneous CP location forward of the CG. The aerodynamic overturning moment (vector) destabilizing the spinning bullet at any time throughout its ballistic flight is the instantaneous vector cross-product of the CP position vector (with respect to the CG location) and the total aerodynamic force vector acting through that CP. Here, the total aerodynamic force is the vector sum of its rectangular components, the instantaneous lift and drag forces acting on the rigid bullet through its CP. Because of this CG shift, these hollow-base ULD bullets can be fired with adequate initial gyroscopic stability (**Sg**) levels from most existing conventional twist-rate rifle barrels except for some of the most extremely "slow-twist" of specialized target rifle barrels.

In removing this **6.7 percent** of the mass of the turned solid bullet by base-drilling the "solid of revolution" bullet shape, we are removing some of the most critical bullet mass near its principal spin-axis (**x-axis**) and near the bullet base some distance from its CG without affecting the form-drag of that bullet. This base-drilling improves the cross-principal-axis ratio (**Iy/Ix**) of the second moments of inertia of the distribution of the remaining bullet mass from a rather high **13.5:1** ratio for the solid bullet to approximately **12.1:1**, depending upon the base-drill diameter and drilling depth selected for these monolithic ULD bullets. Here, the **y-axis** represents any transverse principal axis through the CG of the spinning bullet. For any free-flying spin-stabilized projectile, the ***sum*** of its coning and nutation rates is always given by its actual instantaneous spin-rate divided by this constant ratio of the cross-axis second moments of inertia **Iy/Ix**. Most of the increase in the sum of these epicyclic rates due to base-drilling goes into increasing the fast-mode nutation rate, keeping it farther away from the slow-mode coning rate. If these two epicyclic rates should approach equality with each other, the bullet would become gyroscopically unstable (at **Sg ≤ 1.0**).

We have many similarity-based algorithms for estimating the gyroscopic stability **Sg** of a fired rifle bullet based upon its length, caliber, mass distribution, muzzle velocity, and rifling twist-rate of the rifle barrel, as well as the density of the prevailing atmosphere. The Greenhill Formula of 1879 is the earliest rifling twist-rate estimator still in common use. More recently, we have Robert L. McCoy's McGYRO program and Don Miller's VLD stability algorithms, which we are now using. However, none of these algorithms allow direct quantification of the improvements in **Sg** available by base-drilling these monolithic ULD bullets for better gyroscopic stability.

To quantify these gyroscopic stability improvements, I use an adjusted "effective length" **L(eff)** calculation for entry into McCoy's McGYRO or Miller's stability calculations for these base-drilled monolithic ULD bullets in place of their actual length **L**. I shorten the measured bullet length **L** for the base-drilled bullet by the ***square root of the ratio of the numerically integrated second moment ratios*** **(Iy/Ix)** about transverse (**y**) and spin (**x**) principal axes through the centers of gravity for the base-drilled bullet and for the solid bullet.

$$L(eff) = L*\{[Iy/Ix(drilled)]/[Iy/Ix(solid)]\}^{0.5}$$

For drilling a **0.500-caliber** hole to a depth of **1.10-calibers** in the bases of copper 338-caliber ULD bullets, the resulting effective bullet length **L(eff)** is the actual bullet length (**L**) shortened in this estimation by **0.285-caliber** (or about **26 percent** of the depth of the hole). The weight (or mass) of each bullet, **241.7 grains** before drilling and **225.0 grains** after base-drilling, divides out separately in each of the two **Iy/Ix** ratios. This effective length adjustment produces reasonable estimates of expected **Sg** improvements with both McCoy's and Miller's algorithms.

There might even be some sound physics behind this approach for estimating these improvements in **Sg** attributable to base-drilling since:

$$Iy/Ix = (m*ky^2)/(m*kx^2) = (ky/kx)^2$$

where

kx = Radius of Gyration about the spin-axis

ky = Radius of Gyration of the bullet about its transverse y-axis through its CG.

Then

$$L(eff) = L* \{[ky/kx](drilled)/[ky/kx](solid)\}$$

The ratio of the transverse and axial radii of gyrations (**ky/kx**) is a good metric for comparing the mass distributions of the drilled and undrilled bullets. This small-diameter, shallow base-drilling mostly reduces the transverse radius of gyration **ky** of the copper bullet, but it also slightly increases its axial radius of gyration **kx**, which further reduces the **Iy/Ix** ratio for the base-drilled bullet. Each ratio **ky/kx** shows the lengthwise mass distribution metric **ky** *normalized* by the axial distribution metric **kx** of that particular bullet. Reducing the relative lengthwise distribution of the mass of the uniform-density monolithic bullet makes it relatively easier to spin-stabilize.

Ballistician Robert L. McCoy of the US Army's former Ballistics Research Laboratory (BRL) at Aberdeen MD recognized an ***initial gyroscopic stability*** (**Sg**) of **1.5** as being the ***critical minimum initial stability*** required for stable artillery projectile flight to long ranges in whatever ambient atmospheric conditions pertain. McCoy said that initial gyroscopic stability **Sg** between **1.5** and **2.0** is required for long-range spin-stabilized projectiles. Independent rifle-firing test results recently published by Bryan Litz of Berger Bullets, confirm this critical minimum value (**Minimum Initial Sg = 1.5**) for long-range rifle bullets based on careful drag measurements instead of a critical minimum **Initial Sg = 1.2 to 1.4** as most riflemen had previously deemed adequate. Bullets fired with initial **Sg < 1.5** showed measurably more aerodynamic drag during the first 100 to 200 yards of flight than the same bullets fired simultaneously with initial **Sg ≥ 1.5**.

Coning Theory allows additional insight into this initial gyroscopic stability question. We use the ratio **R =** ω_1/ω_2 of the bullet's inertial gyroscopic fast-mode (nutation) rate ω_1 to its inertial slow-mode (coning) rate ω_2 as a more sensitive indicator of gyroscopic stability (**Sg**):

$$Sg = (R + 1)^2/(4*R)$$

The value of **R** also increases with **Sg** throughout the supersonic flight of the rifle bullet downrange.

The number of complete nutation cycles per coning cycle is always given by **R – 1**. These "relative" fast-mode cycles are relative to the ***moving*** slow-mode arm in the epicyclic motion of the spin-axis of the bullet. For example, when **R = 5.0**, a single fast-mode nutation cycle is completed during each quarter cycle (**90 degrees**) of coning motion, which seems to be a "sweet spot" in this epicyclic motion, **R = 5** being an odd integer numerical value within the desired stability range.

When **R = 3.0**, **Sg = 1.333** which represents *just marginal* bullet initial stability for long-range flight. Having an initial value of **R = 4.0** (**Sg = 1.563**) results in *minimum acceptable* long-range bullet stability. When the initial value of **R = 5.0**, truly *optimal* initial gyroscopic stability (**Sg = 1.800**) is obtained for jacketed, lead-core rifle bullets fired for accuracy at long ranges. An initial value of **R = 6.0** (**Sg = 2.042**) usually represents the *upper end* of the desired range for initial gyroscopic stability with these conventional jacketed, lead-cored match bullets.

However, CNC-turned monolithic copper-alloy bullets can withstand much higher initial spin-rates without self destructing in flight. David Tubb fired our 225-grain, base-drilled copper 338 ULD bullets at 3500 fps from his 35-inch long, 7.5-inch twist-rate, Schneider P5 barrel for an initial spin-rate of 5600 revolutions per second (rps). If this hardened copper material has an elastic limit of **40,000 psi**, these base-drilled bullets are calculated to fail due to "centrifugal force" at **9288 rps**. The initial gyroscopic stability **Sg** of these "hyper-stabilized" bullets was reliably estimated at **2.77** with an **R**-value of **8.96**.

Importantly, these bullets flew with **12.4 percent** less measured aerodynamic drag than estimated by Robert McCoy's McDRAG program for an average airspeed of Mach 2.5 over 1000 yards. McDRAG predicts drag coefficients for projectiles fired with initial **Sg = 1.5**. That drag includes significant yaw-drag for projectiles typically flying with **2** to **5 degree** coning angles which is a significant aerodynamic angle-of-attack. These bullets were flying with "minimum coning angles" of about **0.10 degrees**, so they had essentially ***no*** yaw-drag component.

For a rifle bullet in nearly horizontal supersonic flight through a typical terrestrial atmosphere, its velocity loss-rate (and the resulting decrease in the aerodynamic overturning moment acting to destabilize the bullet) always ***exceeds*** the rate-of-decay (slowing) of the bullet's spin-rate due to air friction. That being true, the gyroscopic stability **Sg** (or **R**) of a rifle bullet always ***increases significantly*** during the supersonic portion of its ballistic flight downrange. In fact, the in-flight **Sg** of the bullet increases with the *square* of the ratio of these two different decay rates. However, the spin-rate of the decelerated bullet as it enters the turbulent transonic airspeed region far down-range where both aerodynamic drag and overturning moment increase suddenly is still ***linearly proportional*** to the bullet's ***initial spin rate*** just out of the muzzle a couple of seconds earlier in actual clock-time. The relative decay-rates for the spin-rate and airspeed of different types of rifle bullets have yet to be well investigated in the ultra-long-range transonic and subsonic flight regimes. Thus far, competition shooters have always striven to keep their match bullets supersonic all the way to, and beyond, their known-distance targets, and these new ULD bullets greatly increase that maximum supersonic range achievable in each bullet caliber. We also need to note carefully any differences in spin-rate decay for these ULD bullets attributable to firing them from barrels made with different patterns of rifling.

Unfortunately, the ***dynamic stability*** (**Sd**) of the flying bullet is determined by that bullet's gyroscopic precession ("slow-mode") and nutation ("fast mode”) ***amplitude damping factors*** at each airspeed which are not reliably calculable from the design parameters of that bullet. These aeroballistic damping factors describe the rates of decrease of the bullet’s coning angle and nutation angle as it proceeds in flight downrange, undisturbed by any further wind changes. These dynamic parameters must be calculated from measurements gathered in actual firing tests. Both precession and nutation motions are most stable dynamically at **Sd = 1.0**, with the precession (or “coning”) motion becoming undamped as **Sd** approaches **0.0**, and the nutation motion becoming undamped at **Sd = 2.0**. **Sd** tends to approach **0.0** gradually at extreme ranges for most statically unstable rifle bullets. The gyroscopic stability **Sg** must exceed **1/(2*Sd)** for the coning angle to remain damped at these extreme ranges. The coning angle increases uncontrollably if it becomes seriously undamped. If these dynamic precession and nutation damping factors turn out to behave as with similar VLD bullets, these ULD bullets will be dynamically stable to very great ranges.

In any type of horizontal “flat firing” of target rifles to long ranges, the faster we can reasonably spin these ULD rifle bullets during firing, the better, and farther, these bullets will fly. [As a side note, a wise ammunition maker might place a “Dangerous within 6 miles” warning label on each box of rifle ammunition loaded with these ULD bullets.] For all practical purposes, there is really no such thing as an “over-stabilized” direct-fire rifle bullet. No practical rifle bullet can fly significantly “nose-high,” as many shooters suspect, during the descending limb of its long-range trajectory because of its being over-stabilized or for any other reason. [According to Coning Theory, any spin-stabilized projectile actually ***does*** fly slightly “nose-high” throughout its trajectory in flat-firing, but only by a vertical-direction ***Tracking Error*** pitch angle, usually of less than about **0.10 degree** relative to the approaching airstream.] The concept of projectile over-stabilization really applies only to the disastrous “failure to trail” problem encountered with indirect-fire spin-stabilized artillery projectiles fired at muzzle elevation angles exceeding about 70 to 80 degrees above the horizontal. In that kind of indirect firing, the air density gets quite thin at high-altitude flight apogee, and the very slow moving projectile has a rather large vertical pitch-angle through which to turn for proper nose-down descent. The vertical tracking error angle becomes uncontrollably large, and the shell occasionally falls sideways or even base-first somewhere far from its intended target.

The *maximum ranges* of these new ULD bullets fired at muzzle elevation angles of about 30 to 40 degrees above the horizontal might ultimately be found to be limited more by bullet instability due to spin-rate decay rather than by airspeed decay. Doppler radar measurements of the bullet's ultimate precession (or "coning") rate during maximum-range firing tests will shed light on this situation. The gyroscopic precession rate of the coning bullet shows up nicely in the Doppler radar data during its steep descent approaching maximum range.

Thinking that "ULD bullets ***require*** faster rifling twist-rates" is somewhat imprecise; rather, a rifle designed for firing ULD bullets can take ***full advantage*** of significantly faster barrel twist-rates.

Riflemen will find it difficult to blow-up these sturdy brass or copper ULD bullets in flight by over-spinning them at high muzzle velocities from fast-twist barrels. Analysis of several possible failure points in the lead-cored ULD bullet structure, shows the full-diameter rear driving-band of the ULD bullets (types LC, HLC, and MLC) to be the spin-rate limiter. Textbook formulas are employed to calculate hoop-stress levels in the (non-engraved) copper-alloy material of the spin-stressed driving-band. A "super-density" value is calculated for each bullet caliber and type to combine all of the mass of the lead core material within the driving-band into the mass of the brass walls of the "thick-walled cylinder" of that driving-band. Rather conservatively, this analytical approach spins the mass of the lead-core material at the mean radius of its enclosing brass driving-band cylinder and discounts any strength contribution from the core material itself or from the adjacent smaller-diameter brass walls. A yield stress of just 18,000 psi, which is the lowest strength rating cited for "dead soft" UNS C36500 free-machining brass stock, is (very) conservatively assumed for this copper-alloy material. To illustrate the range of these strength ratings, a yield stress of 60,000 psi is also cited for "fully hardened brass" of this same type material. A value of 0.31 is universally cited for Poisson's Ratio for this 60Cu/37.5Zn/2.5Pb copper/zinc/lead "free machining" brass material. Cold-rolled (H00) copper material has a minimum yield strength of 20,000 psi. Half-hard (H02) cold-rolled copper has a minimum rating of

40,000 psi yield strength. Poisson's Ratio for copper (Cu) is 0.33. Poisson's Ratio is the lateral shrinkage ratio in test-bar samples of a given material undergoing tensional stressing to failure in laboratory testing.

A maximum allowable spin-rate (SR) in revolutions per second (RPS) is calculated for each bullet with no additional "safety factor" used for these very conservative calculations. Then, an estimated maximum reasonable muzzle velocity for each bullet is used to convert these maximum spin-rates into "quickest" allowable rifling twist-rates (in inches per turn) for convenient interpretation. These results are tabularized below for the Lead-Cored (LC-type) C360 brass ULD bullets by calibers:

Caliber	224LC	244LC	264LC	284LC	308LC	338LC	510LC
Wt. (gr.)	70	90	115	140	175	250	850
Max MV (FPS)	3500	3400	3200	3150	3150	3100	2600
Max SR RPS	7568	7070	6468	5959	4886	4479	3216
Fastest Twist (in./turn)	5.55	5.77	5.94	6.34	7.74	8.31	9.70

When the ULD bullets are instead fabricated from copper having a yield strength rating of 40,000 psi, these maximum spin-rates are over twice as high. The spin-rates used in all ballistic studies for the ULD bullets are well below these conservatively estimated maximum RPS values.

The difficult-to-detect problem of occasional "core stripping" at high spin-rates should be reduced in the design of the ULD bullets by using lead cores having relatively smaller outside-diameters in each caliber. If a core-stripping problem is reliably diagnosed in ULD bullets, a change to a harder (and stronger) lead-alloy core material and/or employing a core-bonding technique should resolve the issue.

Effects of ULD Bullet Use on Peak Chamber Pressures

Bullet engraving forces, and subsequent peak chamber pressures, should be little (if any) higher for these "rear driving-band" brass or copper ULD bullets compared to firing conventional, soft lead-cored jacketed bullets of the same weights. First, these ULD bullets need not (and cannot) be seated-out into contact with the rear-facing slopes of the rifling lands, so they get a good running start before impacting the rifling lands. Second, the volume of the combustion-chamber of any particular rifle cartridge is *maximized by this ULD bullet design*, thus reducing peak chamber pressures with the ULD bullet, by 1) the fully “seated-out” starting position of the ULD bullet in the case neck and by 2) the recessed, hollow-base design of these ULD bullets.

Even small changes in combustion chamber volume can produce dramatic changes in peak chamber pressure for any given cartridge and powder charge. I use and recommend QuickLOAD© software for studying these interior ballistics effects. We find good agreement of predicted and measured muzzle velocities for these monolithic brass ULD bullets by setting the “shot start” pressure to **3500 psi** versus **2900 psi** for conventional jacketed soft-lead-cored bullets and up to **6525** psi for other monolithic copper bullet designs and for hard-lead-cored Full Metal Jacket military bullets. [We do use a shot-start pressure of **6525 psi** for the copper ULD bullets, but do not see that as a load development problem.]

Because of their rather narrow 0.60-caliber driving-band top-widths, there is no real variability allowed in bullet seating depth. This design feature is actually beneficial because deep-seating bullets to produce more “bullet jump” is one of the easiest ways to drive chamber pressures too high inadvertently. Load tuning with ULD bullets must rely upon primer and propellant choices and upon charge-weight or charge-volume variations.

> **Important Note on Seating ULD Bullets:** Firing tests have shown that the ***front third*** (0.20-caliber in axial length) of the 0.60-calibers wide, full groove-diameter top-width of each ULD bullet’s rear driving band ***must be seated out of the cartridge case neck*** to avoid shearing some brass or copper material from that driving band if it encounters the roughened back-end of the ball seat at the origin of the barrel throat. The remaining 0.40-caliber width of full-diameter driving band material allows adequate gripping by the case neck in holding the ULD bullets for loading and firing. This “seating out” of each bullet is uniquely required for the ULD bullet because of its dual-

> diameter shank design. Any driving band shearing caused by failure to seat ULD bullets out to the required cartridge OAL will prevent proper bullet obturation and will devastate accuracy. The first several firings of any new barrel will erode this 45-degree shoulder at the origin of the throat into something resembling welding slag. This small portion of the internal barrel steel surface is directly impinged by burning powder granules and exposed to the hottest erosive propellant gasses for the longest period of time during each firing.

Because these new ULD bullets are designed to be self-aligning *wherever* they reach the rifling in the bore, rifle builders can experiment with barrel throats featuring longer "free-bores." For example, this could be done to renew the accuracy-life of "shot out" barrels having worn throats. Experiments with propellants having differing burning-rates and with rifle barrels having long, or even very long, free-bores might lead to achieving slightly higher muzzle velocities at acceptable peak chamber pressure levels, all while retaining match-level accuracy with these tough brass or copper ULD bullets.

> **A word of caution about barrel free-bores:** Due to the non-deforming nature of these brass or copper ULD bullets, the material of the rear driving-band can be melted by excessive "blow-by" of hot propellant gasses caused by free-bores which are both excessively over-diameter and unusually long. The rear driving bands of these hollow-base ULD bullets can elastically expand only by up to about **0.001 inch** at peak chamber pressure to seal these hot gasses. This melting problem would show up as unusual "copper fouling" of the barrel throat together with poor accuracy. The inside diameter of the free-bore, regardless of its length, should be closely sized to the driving-band diameter of the ULD bullet to be fired through it.

Bullet makers (and bullet designers) prefer to think of their carefully made match bullets being engraved during firing by narrow-land, three-groove, four-groove, 5R, P5, or six-groove rifling patterns in clean match-grade barrels which were recently hand-lapped by skilled barrel makers. However, shooters will experiment with many different rifling styles, including some which will displace a lot of the copper-alloy material of the ULD bullet's rear driving-band. Rough, worn, and fouled barrels will also be encountered, which could cause small chunks of alloy material to be sheared (more or less symmetrically) from the driving-bands. Lead-cored ULD bullets should survive these abuses better than most conventional bullets because of their strong, thick copper-alloy wall structure. These ULD bullets should also shoot well from polygonal rifling, providing standard “bore” and “groove” inside diameters are maintained for proper barrel obturation and bullet guidance.

Bullet Obturation Considerations

Lead-alloy and copper-jacketed lead-alloy bullets obturate very nicely by “upsetting” in the barrel as chamber pressure first exceeds about 15,000 psi to 25,000 psi. Soft lead-alloy bullet materials routinely deform “permanently” when driven at even these low pressure levels. Monolithic copper-alloy bullets have significantly higher yield strengths and do not typically upset, or permanently deform, inside the rifle barrel. These “non-expanding” monolithic copper-alloy types of bullets usually obturate via a sequence of narrow, over-diameter driving and sealing rings formed around their shanks similar to the softer driving and obturating rings around a hard steel artillery shell. We use a single, smooth “rear driving band” both to rotate the copper-alloy ULD bullet in the rifled barrel and to seal the hot gasses propelling that bullet through the barrel.

Recovered examples of test-fired 338-caliber solid brass and solid copper ULD bullets show *adequate* obturation due to tight tolerance control of the outside diameter (0.3382 inch, +/-0.0002 inch) of the rear driving bands of these precision CNC-made long-range bullets. However, there is evidence of slight gas leakage in the “corners” of the barrel grooves with conventional “land and groove” rifling patterns. No unusual copper fouling has been observed. This type of gas leakage has always typically occurred when firing tough, full-metal-jacketed military or controlled expansion hunting bullets having unusually hard lead-alloy (or carbide penetrator) cores. Even slight gas leakage past the obturating surface of a bullet can decrease the muzzle speed which it might otherwise have attained. It should be mentioned here that Gary Schneider’s unique P5 rifling pattern offers greatly improved gas obturation with any type of bullet, including our “non-expanding” solid copper ULD bullets.

Test firings of 338-caliber ULD bullets made of UNS C14700 copper (99.9Cu) show that a base-drill diameter of **0.165-inch** (**0.500 calibers**) allows the copper rear driving band to expand temporarily in outside diameter during firing at **60,000 psi** peak chamber pressure by enough to ***obturate completely*** in any reasonable-sized rifling grooves. Visual evidence of this temporary outside diameter (OD) expansion carries just as far forward on the fired bullet as the shoulder depth of the drilled base cavity. Using a Modulus of Elasticity (**E**) of **16,700,000 psi** for copper, Lamé's Equation for thick-walled pressure vessels indicates a maximum elastic OD increase of **0.000772 inches** for these copper ULD bullets at this **60,000 psi** peak internal pressure (**P**). That is, *if unconstrained by the surrounding barrel steel*, the drilled portion of the **0.3382-inch** OD rear driving bands of these copper ULD bullets would expand temporarily to **0.3390 inches** in OD at this typical peak chamber pressure (rounding the calculated OD expansion to **0.0008 inches**). This very desirable total obturation can be achieved by drilling to a shoulder depth extending at least half way under the 0.60-caliber top width of the rear driving band. The desired amount of maximum OD expansion (**$2*Ur_o$**) can be varied simply by adjusting the base-drill diameter (**$2*r_i$**) slightly.

The operative form of Lamé's Equation for thick-walled cylindrical pressure vessels is:

$$U(r) = (P*r/E)*[(1 - \mu) + (1 + \mu)*(r_o/r)^2]/[(r_o/r_i)^2 - 1]$$

where

U(r) = Radial expansion at radius r from axis of cylinder
P = Internal pressure in psi = 60,000 psi here
E = Young's Modulus of Elasticity (Cu) = 16,700,000 psi
r_o = Outside radius of cylinder = 0.1691 inches here
r_i = Inside radius of cylinder = 0.0825 inches here
μ = Poisson's Ratio = 0.33 for Cu.

Here, we are calculating the maximum temporary elastic radial expansion (**U**) of the rear driving band of our 338-caliber copper ULD bullet as a function of radius (**r**) from the cylinder axis for **$r_i \le r \le r_o$**. In particular, we want to find the radial expansion at the outside diameter (OD) for the special case of **$r = r_o$**. In this case Lamé's Equation reduces to:

$$U(r_o) = (2*P*r_o)/\{E*[(r_o/r_i)^2 - 1]\}$$

Substituting our numerical values for this copper 338-caliber ULD bullet, we have:

U(0.1691) = (2*60,000*0.1691)/(16,700,000*3.151)
U(0.1691) = 0.000386 inches

Thus, the ***outside diameter*** of the rear driving band temporarily increases by a calculated **0.000772 inches** when a hydrostatic pressure of **60,000 psi** is applied to the inside of the obturating surface of the hollow-base copper bullet. This temporary diameter increase significantly improves the obturation of the monolithic copper ULD bullet ***exactly when it is most needed***. Fired test bullets recovered from the waters of a swimming pool show perfect obturation of these base-drilled bullets forward to the shoulder depth of the internal drilling.

In actual firing, there is considerable dynamic, acoustic-wave pressure also acting at the entrance aperture of the base-drilled bullet. Chamber pressures typically measured with conformal Piezo-electric transducers are essentially “quick-acting” hydrostatic pressures—acting equally in all directions everywhere within the combustion chamber of the rifle cartridge. No amount of hydrostatic pressure could deform the hollowed out boat-tails of these copper-alloy ULD bullets because it also acts equally on the outside surfaces of that boat-tail. However, recovered test bullets ***do*** show fracturing and failure of these boat-tails whenever the base-drill diameter is too large. Calculations of the amount of differential overpressure, inside versus outside the boat-tail, required to fail some of these bullets (but not others) indicate that between 8,000 psi and 12,000 psi of differential dynamic pressure must be occurring. This dynamic overpressure also serves to increase the temporary expansion capability of the base-drilled ULD bullets and further improves their obturation during firing. Perhaps the explanation for this type mechanical failure might lie in a hydraulic ram effect created during the violently dynamic deflagration of the propellant charge.

Since the full-obturation advantages of this base-drilling design feature have only recently been discovered during careful testing of prototype ULD bullets, shallow base-drilling has been added as a preferred design feature for these monolithic copper-alloy ULD bullets of all types and calibers. By reducing the base-drill diameter to ***one half the bullet caliber***, the drilling depth can be increased slightly, so as to penetrate below most of the top-width of the rear driving bands without removing too much weight (about 6.7 percent) from the basic profile-turned, solid copper-alloy bullets. Removal of this particular 6.7 percent of the copper-alloy bullet material greatly improves the gyroscopic stability (**Sg**) of these monolithic bullets in flight while simultaneously allowing significant improvement in bullet obturation. This 6.7 percent bullet weight penalty is mostly offset in exterior ballistic performance by the approximately 5 percent increases in muzzle velocity achievable with these 6.7 percent lighter bullets from any given long-range target rifle and cartridge chambering.

Many other long-range, monolithic copper-alloy rifle bullet designs, especially those of near maximum-length construction, might also benefit by adopting this half-caliber base-drilling concept instead of requiring ever-faster-twist barrels to fire them successfully even with marginal initial gyroscopic stability **Sg**. The improved barrel obturation of these modified bullets in any given rifle barrel might also be a welcomed side benefit. My US Patents on these ULD bullet designs do not cover this single bullet design feature in isolation.

Ballistic Flight Considerations

Whereas many marginally stabilized conventional rifle bullets go unstable and basically “fall out of the sky” while transiting the turbulent transonic airspeed region, these ULD bullets should punch through the buffeting and higher aerodynamic forces experienced in that speed range around the “sound barrier” and then continue on without deviation in stable flight as reasonably good low-drag subsonic projectiles. This will be especially true when “much faster than the minimum required” rifling twist-rates are specified for the rifle barrel.

The long 3-caliber nose of the ULD bullet design, together with its small 0.10-caliber meplat diameter, theoretically narrows down the *critical transonic speed range* to between Mach 1.106 (1235 FPS) and Mach 0.904 (1009 FPS) for these superbly aerodynamic ULD bullets. That is, all of the air-flow fields around the bullet remain supersonic down to a free-stream Mach-speed of 1.106, and none remain supersonic below Mach 0.904. This is ***less than half the total speed range*** in the critical transonic region for most shorter conventional rifle bullet designs having larger meplat diameters, usually from about Mach 1.24 (1385 FPS) down to about Mach 0.81 (900 FPS).

Moreover, the sharp-cornered, non-radiused, machined termination of their 7.5-degree tapered boat-tails reduces any tendency toward "limit-cycle yawing" of these ULD bullets at transonic and subsonic airspeeds as compared to most conventional jacketed bullets typically having rounded (radiused) rear corners and convex bases. These conventional bullets experience much stronger alternating vortex shedding at their rounded rear corners which tends to de-stabilize them in transonic flight.

Even at a very high spin-rate, the axis of a perfectly launched ULD bullet will experience gyroscopic precession and nutation motions in flight as long as the flying bullet experiences external aerodynamic torques. The flying, statically unstable rifle bullet experiences an external torque whenever it encounters a cross-trajectory component of the relative motion of the local air-mass through which it is flying. The spin-stabilized bullet can only respond to each change in cross-winds by ***increasing*** its coning angle which is also its aerodynamic angle-of-attack. The gyroscopic precession ("slow-mode") damping factor of that bullet at that airspeed then determines how rapidly that increased coning angle damps out.

Any rifle bullet fired more or less horizontally experiences a small, but persistent, external torque due to the downward arcing of its flight path angle caused by the relentless acceleration of gravity. For right-hand spinning rifle bullets, a steady sequence of "arcing-over" torque impulses due to gravity (occurring twice per coning cycle) produces the well-known rightward "yaw of repose" attitude bias and rightward horizontal "spin-drift" phenomena as gyroscopic reactions to these torque impulses.

While the aerodynamic design of the ULD bullet is optimized primarily for lowest possible zero-yaw *supersonic* drag, the maximum accurate *subsonic* range of these ULD bullets is essentially limited by the maximum muzzle elevation angle at which they can be fired from conventionally sighted rifles.

Designing the ULD Bullet Shape

The practical minimization of zero-yaw aerodynamic drag for these ULD rifle bullets in supersonic flight has been achieved by applying to the design of rifle bullets many of the principles used by the US Army in designing missiles, rockets, and large-caliber cannon and artillery projectiles. The resulting ULD rifle bullet design turns out to be similar in external shape to the US Army's 155 mm M549A1 artillery projectile from 1977 weighing 96 pounds and measuring nearly 3 feet in length. With its built-in rocket assist, this long-range artillery shell can reach a maximum range of 30 kilometers when fired from the 20-foot barrel of the M198 Howitzer. As a sectional density comparison, our monolithic copper ULD bullet design would weigh 210 pounds if scaled up to this 6-inch caliber.

Each projectile design parameter has been separately optimized for minimum zero-yaw air-drag in studies using supersonic wind-tunnel testing done by the Army's Ballistics Research Laboratory (BRL) at Aberdeen Proving Grounds in Maryland. I adapted many of these optimal projectile design features to rifle bullets with a few design ideas of my own added.

I greatly widened the rear driving band to allow seating the bullets securely into self-contained rifle cartridge cases and to make them better able to withstand the rigors of rifle interior ballistics. The M549 artillery projectiles are separately loaded before the desired propellant charge is loaded into the breach.

I specified a hollowing-out of the boat-tail bases of the rifle bullets to shift the CG slightly forward, thereby reducing the lever-arm creating the aerodynamic overturning moment in flight, for better in-flight bullet stability, for higher launch speeds due to reduced throw weight, and to enlarge the effective volume of the firing cartridge's combustion chamber slightly. We subsequently discovered in test-firings that bullet obturation also could be significantly improved in conventional rifling by drilling a slightly smaller-diameter base cavity deeper under the rear driving band. As gas pressure on the base of the bullet rises during firing, it acts as an internal hydrostatic (and dynamic) pressure within that base cavity (within and ahead of the obturation aperture), which temporarily expands the OD of the rear driving band allowing complete obturation. There is also evidence of at least 8,000 psi of differential dynamic pressure occurring briefly as peak chamber pressure is being produced during firing and acting more within that drilled cavity than external to the boat-tail afterbody of the bullet. The drilled boat-tails failed outward early in firing if the drill diameter was too large.

I considered the possibility of unburned powder becoming packed into that bullet-base recess, but did not believe this could ever be a practical problem in rifle firing. The high-pressure gasses typically exiting the muzzle behind the bullet at over twice the forward velocity of that bullet should quite effectively dislodge any unburned powder remaining in this drilled cavity before the rifle bullet exits the muzzle blast cloud and commences its ballistic flight. Early testing using Vihtavuori Oy N560 rifle propellant showed no evidence of powder remaining in small-diameter deep-drilled bases, but subsequent test-firing using Alliant Reloader-26 powder shows poor accuracy with the base-drilled bullets. We are investigating this problem further, as we do not want a bullet which is inaccurate with any suitable propellant.

BRL tests showed that longer ogive lengths, between 1.5 and 3.5 calibers, result in lower air-drag at Mach 1.8 bullet speeds. I selected a 3-caliber length, secant-ogive, circular arc nose design for the ULD bullet for the same practical reasons as did the US Army for their M549 projectile. I wanted to maintain the over-all length (OAL) of the complete ULD rifle bullet at less than 5.5 calibers, so a 3-caliber nose length was the longest ogive which could reasonably be accommodated within that OAL budget.

A secant ogive having ***exactly twice*** the circular arc generating radius of a tangent ogive for that same nose length was found to be "almost the lowest-drag nose shape ever tested by the Army" at supersonic airspeeds. This circular-arc head-shape is often specified as having an **RT/R** value of **0.500**. The large **18.5-caliber** radius-of-curvature **R** of the secant-ogive generating curve for these ULD bullets is just twice the radius-of-curvature (**RT = 9.25 calibers**) of a tangent ogive having a full length of 3-calibers, as required to achieve that lowest-drag circular-arc head-shape.

Blunt (or flat) meplat diameters between 0.10 and 0.15 calibers were shown to reduce total air-drag on projectiles at most speeds, compared to a full-length sharply pointed nose shape. A spherical meplat shape produces even slightly less air-drag than does a blunt meplat. The selected **0.10-caliber** *inscribed spherical meplat* is a minimum total air-drag nose tip configuration. The small amount of extra nose-drag added by using a meplat of this **0.10-caliber** size and this spherical meplat shape is more than offset by the resulting decrease in skin-friction drag due to truncating the sharply pointed full-length nose by **0.16 calibers**. [Manufacturing considerations indicate that a blunt meplat of **0.0808-calibers** diameter should be used for ULD bullets smaller than about 30-caliber. The outer edge of this blunt meplat will be slightly radiused during manufacturing. This meplat change does not affect the McDRAG-calculated coefficients of drag for these smaller-caliber ULD bullets.]

Longer conical boat-tail lengths, between 0.0 and 1.5 calibers in length, also reduce supersonic air-drag versus a flat-base (zero-length boat-tail) design when an effective boat-tail cone-angle is used. An effective conical boat-tail keeps the boundary layer flow-field attached to its surface until that flow-field slides smoothly off its sharply terminated base. In contrast, a flat base (or an ineffective boat-tail) will alternately shed vortices into a nearly 1.0-caliber diameter low-pressure wake trailing far behind the supersonic bullet. The selected boat-tail length of **0.7 calibers** should be quite effective in aerodynamically directing the turbulent boundary layer flow-field toward a compression point **3.2 calibers** behind the base of the bullet. The low-pressure wake region partially entrapped within the flow-field behind the base of the boat-tail travels with the bullet and acts as if it were effectively a part of that bullet. Thus, the zero-yaw air-drag of the flying ULD bullet is similar to that of a double-ended bullet of nearly **8.7 calibers** in effective aerodynamic length. However, the ULD bullet design does not have to spin-stabilize any significant extra mass behind the base of its solid core in ballistic flight.

The optimum lowest-drag boat-tail cone-angle was shown in BRL tests to lie between 7.0 and 8.0 degrees per side at Mach 1.7 air-speed, but with boat-tail angles between 5 and 9 degrees being *partially effective* in drag reduction at most speeds. I selected an optimum **7.5-degree** boat-tail angle with my desired base-drilling in mind. Each ULD bullet has a base diameter of **0.8420 calibers**.

I can envision no valid aerodynamic reason based on boundary layer flow theory to consider using a “rebated” (or “stepped”) boat-tail design for bullets flying in either the supersonic or subsonic airspeed regimes. The boundary layer flow-field likely would *detach* at the “step,” which is the opposite of what one should want here, and would cause the reduced-diameter boat-tail to be largely ineffective in drag reduction compared to a flat-based bullet design. However, the new science of computational fluid dynamics might allow us to understand the use of a specialized version of such a step to induce an annular “controlled vortex” flow-field which could also allow significant recovery of base pressure, perhaps more so in subsonic flight.

While the rear driving-band of these ULD bullets has a generous bottom-width of 0.80 calibers for spinning-up the bullets without slippage, its top-width is only 0.60 calibers to facilitate its engraving by the rifling lands. Notice how each of the 7.5-degree sloping conical faces at either end of the rear driving-band serves two design purposes:

1) The groove-diameter back end of the front-side ramp is the rear-most “self-aligning” contact surface with the beginning of the conical throat in the rifle barrel, while the more forward bore-diameter end of that front ramp increases the lug-contact area with the rifling lands to minimize shearing of the brass driving-band material as spin-up torque is rapidly applied to the bullet during firing.

2) The 7.5-degree rear slope of the driving-band adds 0.10-caliber to the effective length of the 7.5-degree boat-tail of the bullet, versus some more forward driving-band location, as well as elongating the engraved length of the rear driving-band.

By dual-purposing each of these 0.10-caliber long ramps, a total of 0.20 calibers of overall length is saved in the 2.6-caliber “non-ogive” portion of the OAL budget for these ULD bullets versus a more forward driving band location.

Contrary to popular opinion, the spiral engraving of the rear driving-band by the rifling lands does not measurably increase the zero-yaw coefficient of drag (**Cd**) of the bullet. However, bullet engraving does slightly increase the magnitude of the spin-damping factor of the fired bullet, but only by 30-percent as much as when the whole 2-caliber length of the bullet shank must be engraved. Nor do bullet spin-up energy, the work done in bullet engraving, or bore-friction energy losses extract significant kinetic energy from the fired rifle bullets. To the contrary, some resistance to bullet movement beyond translational inertial force is expected in interior ballistics and may be required to allow more complete combustion of slower-burning rifle powders to achieve highest muzzle velocities.

The idea of using external circumferential “relief grooving” within the length of the driving-band was briefly considered and rejected. While these grooves would be quite easy to machine, external relief grooves are not necessary for engraving these narrow driving-bands, and each relief groove would become a significant source of secondary shocking in supersonic and transonic flight, increasing the air-drag as measured in actual firing tests. However, a broad ***internal relief groove*** will be provided inside the rear driving-band by micro-boring a shallow (0.0025-inch radial depth) undercut inside the full, 0.60-caliber, top-length of the rear driving-band for all lead-cored and polymer-cored ULD bullet types. This design provides the distinct added advantage of mechanically ***locking-in*** the pressure-seated precision cores. A small 0.002-inch (radial depth) by 0.1-caliber ***lead-in taper*** will also be bored at the mouth of the base-drilled hole to facilitate core insertions. The Monolithic Brass or Copper ULD bullets will lengthen very slightly as their driving-bands are engraved.

Reynolds number limitations on aerodynamic scaling actually work in our favor for these shorter rifle-caliber projectiles. A longer, large-caliber military projectile experiences the higher skin-friction drag of turbulent boundary-layer flow over its entire wetted area. However, we can safely assume lower-drag laminar boundary-layer flow over the smooth ogives of our ULD rifle bullets, at least in bullet calibers up through about 50-caliber with 3-caliber ogives. This laminar flow-field over the ogive neatly, and *consistently*, trips into turbulent flow upon encountering the 4.75-degree “break angle” in the bullet’s surface where the base of the secant ogive joins the cylindrical shank of the ULD bullet. The break angle here in the surface of the bullet body is machined sharp and never “radiused” or rounded over. One of the problems associated with using tangent-ogive rifle bullets longer than a critical Reynolds Number length of about 1.3 to 1.5 inches in long-range rifle matches is their *uneven and inconsistent* L/T flow transitions resulting in shot-to-shot variations in skin-friction air-drag. In the ULD bullet design, this L/T flow transition happens just in time for the increased kinetic energy content of the turbulent boundary-layer flow-field over the afterbody of the ULD bullet to enhance base-pressure recovery behind the boat-tail as described above. This same type of boundary-layer L/T flow transition at the base of its secant-ogive and a similar boat-tail design feature are exactly what makes a VLD rifle bullet “very low drag.” It should be pointed out that consideration of this boundary layer L/T flow transition is unique to small-caliber rifle bullet design and is not really important in the designing of aircraft or large-caliber military projectiles.

Following artillery projectile design practice, I use the ***bore diameter*** of the barrel as the “1.0-caliber” ***reference diameter*** in the design of these ULD bullets. This differs from the usual design practice for rifle bullets of using the nominal ***groove diameter*** of standard rifle barrels for each “bullet caliber” as the “1.0-caliber” ***reference diameter***. The OD (groove diameter) of the rear driving-band is thus a caliber-specific **1.020** to **1.034** “calibers.” The caliber-dependent **2.0** to **3.4 percent** smaller base-diameter of the resulting “3-caliber” secant-ogive nose reduces aerodynamic nose-drag for these ULD bullets. For example, the 338-caliber ULD bullet flies more like a **0.3302-inch** diameter bullet in exterior ballistics compared to a **0.3380-inch** OD conventional rifle bullet. In linear aeroballistic theory, the primary aerodynamic nose-drag experienced by any rifle bullet at any airspeed is linearly proportional to the *cross-sectional area* **S** *at the base of its ogive*. Thus, the potential reduction in nose-drag for these smaller-diameter bullets of each nominal rifle caliber is a caliber-specific **4.0** to **6.9 percent**. This significant aerodynamic advantage shows up in my performance estimates for these ULD bullets as an enhanced “effective ballistic sectional density” used in calculating the ***Ballistic Coefficients*** (**BC**’s) for each of these ULD bullets. Otherwise, this aerodynamic advantage would not be fully reflected in the form-drag calculations. The small air-drag penalty for using a rear driving-band in the design of these ULD bullets is separately calculated and added-in when estimating the total zero-yaw coefficient-of-drag (**Cd**) for each bullet size and type at each supersonic Mach-speed.

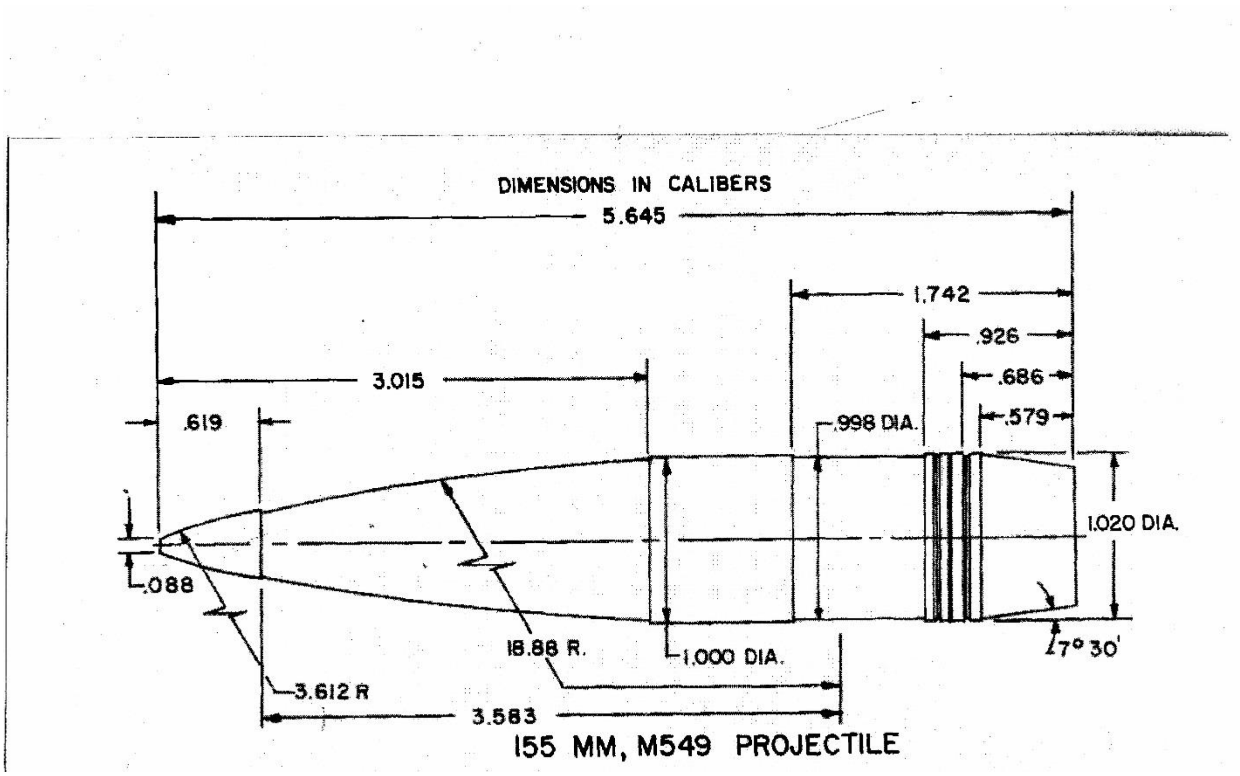
The very low **0.8475** average supersonic ***form-factor*** of these practical “338-caliber” ULD rifle bullets relative to the (VLD-shaped) G7 Reference Projectile indicates the eventual need for a lower-drag, ***ULD-shaped Reference Projectile and drag model*** to facilitate the accurate calculation of ULD point-mass trajectories. The new drag data needed can now be measured readily by firing several ULD-shaped projectiles in a Doppler radar-equipped firing range such as the Yuma Proving Ground. Meanwhile, we will have to endure a slight velocity-dependence in the ratios of the coefficients of drag (**Cd**’s) of our ULD bullets compared with the long used and well established **Cd**’s of the Army’s G7 Reference Projectile at different

Mach-speeds. For many years now, we have tolerated a corresponding problem of needing different G1-based BC's for different velocity-bands when referencing the air-drag of modern rifle bullets to the drag model of the ancient "lead slug" G1 Reference Projectile dating from the 1880's.

The **0.8475** form-factor estimation, (**i7**) relative to the G7 Reference Projectile, quoted here for the 338-caliber ULD bullet is the average of the supersonic **Cd**-ratios, **Cd(ULD)/Cd(G7)**, from **Mach 3.5** down to **Mach 1.5** for these ULD bullets. The estimated average **BC(G7)** for **225-grain** 338 ULD bullets over this speed range is **0.348**. The **i7** form-factor estimate at the important airspeed of **Mach 2.5** is slightly lower at **0.8378**. The estimated **BC(G7)** for **225-grain** 338 ULD bullets at **Mach 2.5** is **0.352**. These **Cd** estimates for each Mach-speed are obtained for these ULD bullets from the US Army's McDRAG FORTRAN computer program developed by Robert L. McCoy at BRL. This aerodynamic similarity-based software program accurately calculated the **Cd**'s for the Army's then new M549 artillery projectile within +/-0.5 percent for all supersonic Mach-speeds.

I also use McCoy's McGYRO FORTRAN program to estimate initial gyroscopic stabilities (**Sg**'s) for all versions of these ULD bullets. The **Sg** estimates produced by Don Miller's VLD stability formulas applied to ULD bullets are quite similar, but differ systematically for these ULD bullet shapes.

All of my ballistic data are calculated for a current ICAO standard atmosphere: dry (0-percent Relative Humidity), sea-level air at 59-degrees Fahrenheit and 760 mmHg absolute barometric pressure. This ICAO atmosphere is significantly denser (by 0.5 percent) than the 78-percent RH, 59-degree Fahrenheit, 750 mmHg Army Standard Metro (ASM) atmosphere originally used at Aberdeen Proving Grounds from the 1870's until modern times. The "speed of sound" (Mach 1.0) in this dryer, denser ICAO-standard atmosphere is 1116.45 FPS (340.294 m/s), versus 1120.27 FPS (341.458 m/s) for the old ASM atmosphere.



Shooting Equipment Changes

Just as custom rifle-barrel manufacturers can and will make faster twist-rate barrel blanks in the various rifle calibers when requested by their customers, precision reloading equipment makers will produce bullet-seating dies having deeper, shallower-angled seating stems and allowing a much longer bullet-seating cartridge overall length (COAL) for proper seating of these longer, sharper-pointed ULD bullets in the various cartridge cases used in long-range shooting. For example, the ***338 Lapua Magnum*** cartridge loaded with any one of these new 338-caliber ULD bullets will be **4.150 inches** in COAL as opposed to my current loading of 300-grain Sierra MatchKings seated-out to **3.850 inches** COAL. The maximum COAL for a CIP-standard 338 Lapua Magnum cartridge is **3.681 inches** for feeding from internal magazines.

These new ULD bullets are designed to operate best when fired from match-grade barrels made with relatively narrow-land rifling patterns and produced in the following standard bore and groove ID’s:

Caliber	224	6 MM	6.5 MM	7 MM	308	338	50
Bore	0.2180	0.2360	0.2560	0.2770	0.3000	0.3300	0.5000
Groove	0.2240	0.2440	0.2640	0.2840	0.3080	0.3380	0.5100

Use of the tighter alternative standard 0.2760-inch bore diameter in 7 mm will simply result in 0.0005-inch deeper rifling engraving marks on the shanks of the fired ULD bullets.

The bore-riding shanks of these ULD bullets are made 0.0002 inches larger than these cited bore ID specifications in each caliber for best self-aligning during firing. The rear driving-bands are also made 0.0002 inches larger than these groove-diameter specifications in each caliber for best bullet obturation when firing these non-deforming brass or copper bullets. The manufacturing tolerance specification for the outside diameters (OD's) of these ULD bullets is not to exceed +/-0.0002 inches. Barrels made with tighter bores than these specifications will require close attention to throat lengths to prevent difficulty in loading the seated ULD bullets. Barrels made with deeper grooves than these specifications might not allow these non-deforming brass ULD bullets to seal the hot powder gasses properly.

Completely force-free chambering can be assured if the following barrel-throat dimensions (in inches) are observed:

Caliber	224	6 MM	6.5 MM	7 MM	308	338	50
Ball Seat ID	0.2244	0.2444	0.2644	0.2844	0.3084	0.3384	0.5104
Throat Length	0.2846	0.3138	0.3378	0.3592	0.3906	0.4266	0.6382

The ball seat internal diameter (ID) is also called the "free-bore" ID. These throat-length dimensions are measured from the neck-diameter start of the usual 45-degree conical transition to the ball seat ID out to the forward-most reamer-cut portion of the rifling lands. These minimum throat-length dimensions can be reduced by the 10 to 20 thousandths "safety margin" in cartridge case-neck lengths maintained by observing standard "trim-to" case lengths in careful re-loading. Because gas blow-by can be a problem with non-expanding brass bullets, these ball seat ID's should not be enlarged in custom chamber throat designs.

If an existing barrel chamber is to have its throat lengthened for completely force-free insertion of loaded ULD rounds, I recommend use of a separate live-piloted throating reamer followed by burnishing of the throat-angle cut with a hand-turned, custom-made, live-piloted, tool-steel polishing hob and a fine (1200-grit) abrasive paste. I recommend a **5-degree** throat angle for all rifles which fire secant-ogive VLD or ULD bullets for accuracy. By polishing the long, shallow-angled conical reamer cuts across the rear faces of the rifling lands, little or no “barrel break-in” shooting will be required.

Many shooters prefer a slight “bullet feel” when chambering a loaded round and will tolerate some “bullet drag” if a loaded round must be un-chambered—just as long as the seated position of the bullet in the case neck is not disturbed. If a short throat seems too tight when chambering a ULD bullet, it can easily be opened-up to the exact ID desired by *pressure fire-lapping* using abrasive-impregnated lead-alloy bullets (either jacketed or not) fired at reduced cast-bullet velocities. David Tubb’s Superior Shooting Systems and NECO© market kits for performing this process in a controlled manner. Actually, these ULD bullets should load freely and fire accurately with any standard SAAMI or CIP-specified chamber.

Because these brass ULD bullets do not permanently expand (i.e., permanently deform) as do conventional jacketed lead-core bullets while getting into motion during firing, the “nasty gap” in front of the neck of the chambered cartridge does not present any problem for these ULD bullets, provided they are seated out properly, as cautioned earlier, so that a portion of the full-diameter rear driving-band enters the ball seat as the round is being loaded.

Shooters have long been accumulating knowledge about barrel fouling characteristics and barrel cleaning requirements when firing monolithic rifle bullets made of various copper alloys. Occasional cleaning with a mildly abrasive agent such as J-B Bore Bright, either “Red” or “Original,” will keep the bore shiny. Competition riflemen will handle those issues competently in firing these new copper-alloy ULD bullets.

Longer factory and custom rifle actions (with longer internal magazine lengths for repeaters) will be selected when building future target and tactical rifles to fire these longer ULD bullets. Cartridges are single-loaded into single-shot bolt-action rifles for most long-range target shooting, so the length of the rifle action really comes into play only when a live round must be ejected. If the ejection port is too short, a convenient bolt-stop release will allow safe and easy removal of the bolt and live round together. The increased accuracy, better wind penetration, and greater velocity and kinetic energy delivered down-range by these new ULD bullets will easily justify each of these required equipment changes.

Comparison with Current Bullets

To compare the ballistic performance of these new long-range ULD bullets with that of currently available bullets, consider the new 338 Maximum Lead-Core ULD bullet (338MLC) weighing 270 grains, compared with the Berger 300-grain Hybrid-Ogive jacketed lead-cored match bullet, one of the better 338-caliber long-range bullets on the current market. Each bullet has an OAL of about 1.80 inches and stabilizes well enough (Initial Sg = 1.6+) when fired from a 338 Lapua Magnum rifle with a 10-inch twist barrel. Our 30-grain-lighter ULD bullet would be fired 150 FPS faster than would the Berger bullet from the same rifle at the same peak chamber pressure. Because their two G7-referenced BC's are virtually identical at 0.417 (calculated for the ULD bullet) and 0.416 (measured for the Berger), they follow similar airspeed versus time trajectories *en route* to a 1,000-yard target in a long-range match, but our ULD bullet arrives there in 1.241 seconds, while the Berger bullet takes 1.315 seconds to get there. The new ULD bullet impacts the 1,000-yard target with 122 FPS of retained speed advantage (and with 53 foot-pounds more retained kinetic energy) and suffers 30 inches less bullet-drop from the axis of the bore compared to the Berger bullet at that distance. If each bullet is fired through the same standard 10 MPH constant crosswind, our faster ULD bullet moves 42.5 inches downwind across the 1,000-yard target while the Berger moves 46.2 inches downwind. The faster bullet suffers less crosswind deflection even if the two **BC**'s are the same.

Because our ULD bullet design is self-aligning in the barrel, it solves the "VLD accuracy problem" even better than does the hybrid-ogive (secant/tangent-ogive) Berger design which improves the VLD-style bullet guidance problem only at the front-end of the tangent portion of its dual ogive. The entire rear portion of the Berger Hybrid bullet is remains free to shift around within the case neck and ball-seat depending upon the mechanical clearances which must be allowed in each location. Also, because the higher-speed ULD bullet suffers 3.7 inches less standard 10 MPH crosswind drift, and because the CNC-turned ULD bullet has better static balance to start with, the same rifleman, shooting the same rifle, should ***score significantly higher*** in any type of 1,000-yard competition with these new ULD bullets than with the Berger Hybrids under similar shooting conditions. For those interested in even longer-range shooting, our 270-grain ULD bullet stays above its critical transonic airspeed of 1235 FPS out to a maximum supersonic range of 1,855 yards or 1696 meters, while the 300-grain Berger fired from the same rifle slows to this same transonic airspeed 136 yards earlier at 1,719 yards or 1572 meters (all in a rather dense, standard sea-level ICAO atmosphere). One statute mile is 1760 yards or 1609.344 meters.

Advancing the Art of Long-Range Shooting

Fully adopting ULD bullet technology into the art of long-range rifle shooting will profoundly and permanently alter our perceptions of the rifle, bullet, and ammunition accuracy problems remaining to be tackled. The resulting greater effective ranges, higher scores, smaller group sizes, and higher probabilities of first-shot hits at greater ranges will establish new performance standards in all types of long-range shooting.

The ability to “dope” down-range wind effects accurately before each shot likely will remain the primary accuracy-limiting factor for all outdoor shooting, even as the technology to measure down-range winds remotely is being developed.

Statistically independent rifle accuracy-limiting errors combine as the **Root-Sum-Squares (RSS)** of the individual errors. Statistically independent errors are those which do not stem from any common source which would produce statistical correlation among the measured errors. In improving long-range rifle accuracy in a systematic way, we try to reduce the largest sources of target impact errors first so that we can detect and measure any improvement in subsequent shooting results.

With the complete removal of the impact dispersion caused by bullet static imbalance and the CG offset and large initial aeroballistic yaw due to in-bore yaw, the *next largest* source of bullet impact errors at long ranges likely will become the vertical-direction variation in “gravity drop” of the bullets caused by variations in muzzle velocity from one shot to the next.

While this launch-speed uniformity problem had once been pretty well solved during the latter days of black powder rifle competitions at 1,000 yards in the 1880’s, it has crept back into long-range riflery again with the widespread use of slow burning-rate smokeless propellants and heavy-for-caliber bullets. Re-creations of 1880’s technology long-range black powder rifle shooting can show muzzle velocity uniformities approaching the limits of measuring resolution using modern, commercially available chronographs (1.0 FPS).

Today, we continually strive for “single digit” (<10 FPS) extreme velocity spreads within each group of shots. Using canister-grade hand-loading propellants, I prefer to try the fastest-burning powders which will fill about 95-percent of the available combustion chamber volume without producing excessive chamber pressures. The comparatively lighter weight of the various types of ULD bullets having BC’s at least equivalent to heavier conventional bullets in each caliber is advantageous in this quest for better uniformity in muzzle velocities. Faster burning-rate rifle powders burn more completely, consistently, and cleanly due to their relative absence of chemical retardants. Lighter-weight bullets are also often easier to shoot well in each caliber due to their reduced felt recoil (rearward rifle impulse) and shot-induced rifle movement, and due to their significantly shorter barrel dwell-times and flight-times to the target.

Even at the higher muzzle velocities available with lighter-weight ULD bullets and modern powders, a shot that is, say, 10 FPS faster or slower than the group mean will impact between 1.5 to 2.5 inches above or below the group mean on a target at 1,000 yards due to this gravity-drop problem. By carefully tuning the load to adjust the timing of the bullet’s exit from the muzzle relative to the shot-induced vertical-plane transverse vibrations of the rifle barrel, the shooter can produce a “compensating muzzle-pointing error” which helps reduce this gravity-drop error significantly. A sub-1.0-

inch extreme spread for a 5-shot group fired in registered competition at 1,000 yards remains the elusive goal of many current long-range riflemen.

Future Development

Future development of this initial ULD bullet design might allow both the 3-caliber secant-ogive length and 0.6-caliber top-width of the rear driving band of ULD bullets to be lengthened for significantly lower air-drag and slightly deeper bullet seating into the cartridge case necks, respectively. We should plan to lengthen the secant-ogive bullet noses to 3.20 calibers and perhaps widen the top-width of the rear driving bands to 0.8 calibers (at some expense of bore-riding length) as a Mark II ULD design evolution. The radius-of-curvature of the ogive-generating curve would then become 21.0 calibers, and the reduction in air-drag promises to be about another 5.75 percent. We might discover that we can relax the current 5.5-caliber bullet OAL design limit nearer to 5.70 calibers using barrels having the fastest available twist-rates in each caliber.

Actually, we are already prototyping a Mark II 338-caliber ULD bullet for use in Extreme Long Range (ELR) rifle shooting. We are simply increasing the length of the secant ogive nose from 3.0 calibers to 3.2 calibers and eliminating any type of base-drilling with no other significant changes. These copper bullets will weigh 252 grains and have a BC(G1) of somewhere from 0.900 up to 1.000 at an airspeed of Mach 2.5. They are to be hyper-stabilized from special-made, extra-length, 7.0-inch twist-rate, 338-caliber Schneider P5 rifle barrels. Keep in mind that rifle barrel twist-rates are quite slow by artillery tube standards. That 7.0-inch twist-rate is 21.2 calibers per turn. Alternative bullet-making materials, friction-modifying coatings, and specialized terminal-ballistics performance requirements can also be considered, developed, and evaluated in the future.