<u>Development of Copper ULD Rifle Bullets</u>

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After two years of development and testing, our new copper ULD rifle bullets are working reasonably well, but some unexpected new problems have also come to light. We now realize that, in pursuit of the lowest possible air-drag for our rifle bullets, we have inadvertently increased the sensitivity of our fired test bullets to the long-known problem of yaw disturbances being acquired by the fired bullets while transiting the muzzle-blast zone and before they commence ballistic flight. This non-systematic initial ballistic yaw disturbance varies randomly both in roll-orientation and in magnitude from shot to shot. The random roll-orientation of the bullet's initial ballistic yaw angle causes enlarged group sizes at any range due to aerodynamic jump occurring during the first half coning cycle of ballistic flight. The random magnitude of the bullet's initial ballistic yaw angle causes significant variation in early velocity loss (and kinetic energy loss) suffered by the bullet while it is damping out its initial yaw attitude angle during its first few coning cycles.

<u>Progress</u>:

1. **<u>Self-Aligning Rifle Bullets</u>**. The dual-diameter design of these copper bullets makes them self-aligning in the throat of the rifle barrel before they are engraved by the rifling. They suffer no *in-bore yawing* as routinely occurs when firing conventional jacketed VLD bullets from standard chambers. These bullets do not need tight-necked chambers nor neck-turned brass in order to be fired in perfect alignment coaxial with the rifle bore. Neither do they need nor allow jam-seating against the origin of the rifling for front-end alignment. A 5-percent drag reduction and BC improvement is a direct benefit of selecting this dual-diameter bullet design. For example, our dual-diameter 338-caliber copper ULD bullet flies as if it were a conventional 0.330-inch diameter bullet, with a 5-percent smaller cross-sectional area **S** at the base of its nose.

2. **<u>Bullet Balance</u>**. Simply by lathe-turning these monolithic bullets from cold-rolled copper rod stock, the recurring problem of *bullet static*

imbalance, which is universal with all types of jacketed lead-cored bullets, has been eliminated. Center-of-Gravity (CG) offset from the bullet's axis of external form should be immeasurably small for each and every one of these machined copper bullets. Accuracy destroying trajectory deflections due to *lateral throw-off* do not occur in firing these lathe-turned copper bullets.

3. **Ultra-Low Aerodynamic Drag**. The design goal of producing *Ultra-Low-Drag* (ULD) rifle bullets has been well achieved. The aerodynamic Coefficients of Drag (CD's) measured for our Mark II copper 338-caliber bullets is just **72-percent** as large as those of the G7 Reference Projectile when averaged over all supersonic Mach speeds up to Mach 3.5; that is, the aerodynamic form-drag is **28-percent** less than that of the already "Very Low Drag" G7 Reference Projectile. This average ratio of aerodynamic drag functions is termed the G7 Form Factor (**i7**), and the lower it is, the better. The G7 Form Factor for most conventional long-range rifle bullets is in the range of 0.90 to 1.10, with VLD bullets ranging from 0.90 to 0.95. This Form Factor (**i7**) is used in calculating the bullet's Ballistic Coefficient (BC) in pounds per square inch (PSI) relative to the well determined drag function for the G7 Reference Projectile. A bullet's BC(G7) value is formulated as its Ballistic Sectional Density (bullet weight in pounds divided by the square of its caliber in inches) divided by its **i7** form factor. The Mark II bullet design uses a truncated secant-ogive head-shape having an RT/R ratio of 0.500 and full length of 3.2-calibers. The new Mark III design will use a similarly truncated LD-Haack nose shape of 3.5-calibers in full length and is expected to produce a G7 Form Factor of about **0.69**. Measured supersonic air-drag is largely determined by the fineness ratio (nose length divided by caliber) of these minimum-drag nose shapes. While manufacturability by lathe-turning mandates use of a small, blunt meplat of about 0.10 calibers in diameter, its slight drag penalty is offset by reduced skin-friction.

4. **Minimum-Drag Flight**. Our firing tests have shown that, as a necessary precondition for achieving their designed minimum aerodynamic drag in use, these new copper bullets must be fired with an initial gyroscopic stability **Sg** of at least about **2.5**. These copper

ULD bullets can then achieve “hyper-stable” (minimum coning angle) flight after just the first 20 yards or so of early, highest-drag ballistic flight through the ambient atmosphere (after having penetrated the muzzle-blast shockwave a few yards from the muzzle). At this high initial gyroscopic stability **Sg**, the bullet’s ballistic travel distance while damping out its initial yaw-drag is determined by its muzzle speed and the period (time duration) of its first gyroscopic coning cycle. The functional relationship between the bullet’s initial gyroscopic stability **Sg** and its rate of damping $\boldsymbol{\lambda_S}$ any initial (slow-mode) coning angle is not fully understood, but it is important because these bullets often suffer significant yaw disturbance while transiting the muzzle-blast zone. Because these new copper bullets are longer than conventional rifle bullets, they must be fired from rifle barrels made with a faster *rifling twist-rate* than would be used with shorter jacketed, lead-cored rifle bullets to achieve their desired higher initial **Sg** values. Lengthening the bullet’s nose to improve its fineness ratio for significantly reducing its zero-yaw Coefficient of Drag $\mathbf{CD_0}$ also just slightly decreases that bullet’s Coefficient of Yaw-Drag (**CDa**); so that the rapid damping of any initial coning angle-of-attack **a** remains critical for achieving minimum-drag flight to long ranges. A twist-rate of **20 calibers per turn** (6.6 inches per turn in 338-caliber) will produce an initial gyroscopic stability **Sg** of about **2.8** for these new Mark III copper bullets. A twist-rate of **24 calibers per turn** (7.75 inches per turn in 338-caliber) will produce an initial gyroscopic stability **Sg** of about **2.0** for these new copper bullets. David Tubb’s 338-caliber test barrel, having a twist-rate of 7.5 inches (22.7 calibers) per turn, will yield an initial **Sg** of about **2.17** in firing the new Mark III copper bullets.

5. **Barrel Obturation**. During development testing of our Mark II copper ULD bullets, we became aware that they were not *obturating the bore* of our test barrels nearly as well as do conventional jacketed, soft lead-cored match bullets. We recovered many copper ULD 338-caliber bullets fired from our 338 Lapua Magnum test rifle into a swimming pool and analyzed their barrel markings and soot deposition patterns. Solid test bullets made of half-hard copper with rear driving bands of **0.3382-inch** OD were not expanding enough

dynamically to seal the hot powder gasses in the bore effectively at a peak base pressure of 51,000 psi, when fired at 60,000 psi peak chamber pressures in our Krieger cut-rifled test barrel having **0.3380-inch** groove ID. Mechanical analysis showed the bore of this stress-free Krieger test barrel should be expanding internally by **1.65 thousandths of an inch** at this peak base pressure, which is the root cause of the gas sealing problem with these non-deforming copper bullets. Traditional soft lead-cored, jacketed match rifle bullets have always deformed plastically enough to fill any expanded bore and seal the powder gasses quite well. The 246-grain Mark IIc 338-caliber bullets were then designed with **0.3384-inch** OD rear driving bands and with **0.125-inch** drilled bases to port this base pressure internally for adequate gas sealing. David Tubb fired a 5-shot test group using these Mark IIc copper bullets over his 1,000-yard instrumented range and measured a **4 fps** extreme spread of the muzzle speeds—indicating very good gas sealing in his pre-stressed, button-rifled Schneider test barrel, which we estimate was expanding internally by only **1.1 thousandths** at similar peak base pressures. Gary Schneider's P5 rifling pattern is specifically designed to provide good sealing of the propellant gasses by the rifling-engraved bullet. We enlarged the base-drill diameter to **0.152-inch** for the Mark III bullet design largely to assure adequate gas sealing when they are fired from any other type of 338-caliber rifle barrel or rifling pattern having a standard **0.3380-inch** groove ID.

<u>**Problems Remaining**</u>:

In test-firing the Mark IIc version of these copper ULD bullets in 338-caliber, two accuracy-related issues have emerged. Both issues appear to be caused an increased sensitivity of these new copper bullets to yaw destabilization while transiting the muzzle-blast zone.

1. <u>**Aerodynamic Jump**</u>. A serious accuracy problem appears to be due to significant randomly oriented trajectory deflections of randomly varying angular amplitudes caused by an aerodynamic jump occurring during the first half coning cycle (10 yards, or so) of ballistic flight, starting after the bullet exits the muzzle-blast shockwave. This problem has so far prevented firing 5-shot groups reliably smaller than **0.75 MOA** with these 338-caliber copper ULD bullets fired in my

wind-free indoor 105-yard test range from a 7-inch twist Schneider test barrel. This same test rifle with a 10-inch twist Krieger barrel chambered in 338 Lapua Magnum has reliably fired conventional 300-grain jacketed match bullets (Sierra MatchKings) into **0.35 MOA** groups in this indoor range.

a. Apparently, these bullets are being more disturbed in yaw and/or yaw-rate than would heavier conventional bullets while each is transiting the muzzle-blast zone, so that they are flying with significant yaw attitude at the beginning of ballistic flight. My take is that conventional bullets simply produce smaller angular trajectory deflections due to this same type of aerodynamic jump after entering the atmosphere with similarly caused, but smaller sized, yaw disturbances. As a first-order approximation, we might assume that the size of these yaw disturbances is *inversely proportional* to bullet weight. Using the 300-grain conventional bullet as a reference, the expected size of the initial yaw in firing a 246-grain copper bullet would then be increased by a factor of **300/246 = 1.22**.
b. In lengthening the secant ogives of these ULD bullets for significant drag reduction, we also simultaneously decreased slightly their Coefficients of Lift (**CL**) and, thence, their resulting cross-track aerodynamic lift forces which ultimately drive them away from their intended trajectories. [Bob McCoy's Interim Lift estimation program INTLIFT estimates **CL** directly from nose length alone for each Mach-speed above Mach 2.0.] Comparing the estimated **CL** of **3.04** for a jacketed match bullet having a typical 2.25-caliber nose length with a **CL** of **2.73** for the 3.2-caliber nose of our Mark II ULD bullet, INTLIFT estimates **CL** at only **89.6-percent** as much for the longer-nosed copper bullet at launch speeds of **Mach 2.8**. The presumed **22-percent** larger initial yaw disturbance, together with this 11-percent smaller **CL**, would result in a net **9.2-percent** greater cross-track aerodynamic lift impulse force $\mathbf{F_L}$ with the new copper bullet: **(300/246)*0.896 = 1.092**.
c. Another significant aeroballistic difference between shorter conventional bullets and these necessarily longer copper ULD bullets is in their mass distribution second

moment **Iy/Ix** ratios. These ratios of second moments of inertia for the bullet's crossed principal axes run from about **8:1** to **10:1** for conventional jacketed match bullets, but are about **17:1** for our longer monolithic copper bullets. Tri-Cyclic Theory shows *directly proportional* increases in the periods (i.e., longer time durations) of these slower-rate gyroscopic motions of the spin-axes of these longer, higher **Iy/Ix** inertial ratio, monolithic copper ULD bullets for any given bullet spin-rate. While we do spin these copper bullets up to twice as fast as conventional rifle bullets, the typical doubling of the **Iy/Ix** ratio actually results in them ***coning at much slower rates*** as determined by the increased gyroscopic stability (**Sg**) of these copper bullets. The time duration of the cross-track impulse force is *inversely proportional* to the bullet's coning rate. The time-duration of the cross-track impulse for a ULD bullet coning at **34.4 hertz**, relative to that of a conventional bullet coning at **60 hertz**, would increase by a factor **60/34.4 = 1.746**. Thus, the cross-track impulse (force multiplied by duration) which is laterally displacing the copper bullet would be larger by a factor of **1.092*1.746 = 1.907**. The initial (slow-mode) coning rate of a rifle bullet is nearly *directly proportional* to the rifling twist-rate **n** (in calibers per turn), all else bring equal. So, we can decrease the duration of the cross-track impulse by speeding up the initial coning rate of the bullet, which in turn is done by selecting a slower rifling twist-rate having more calibers per turn (larger **n** value). We have previously recommended that a rifling twist rate of **20 calibers per turn** be used to achieve lowest possible air drag when firing any type of monolithic bullet. Instead, we now recommend **24 calibers per turn** as a more generally optimal rifling twist-rate considering this newly discovered trade-off between minimum air drag and minimum group size.

d. The typically 22-percent lighter-weight monolithic copper bullet is also typically launched at 12-percent faster muzzle speed V_0.

Thus the initial *linear momentum* (mass times velocity) of the lighter-weight, but faster, copper bullet is only **(246/300)*1.12 = 0.9184**, or **92-percent** of that of the heavier conventional bullet.

e. The tangent of the very small accuracy-robbing trajectory deflection angle is given by the ratio of the bullet's cross-track momentum to its initial linear (forward) momentum. But, from physics, the cross-track momentum (or actually its change from zero, initially) is equal to the cross-track impulse. In terms relative to the conventional bullet reference, the trajectory deflection angle for the new copper bullet would then be **1.907/0.9184 = 2.076** times larger. [In this analysis, the majority of this accuracy loss is attributable to the slower coning rate of the longer copper bullet, which is in turn due to firing them with higher initial gyroscopic stability **Sg ≈ 2.5** to **3.0**.] Group size (measured as its extreme spread) on a target at any range would increase by this same ratio of **2.076**. Thus, our **0.35 MOA** indoor 105-yard group size with conventional 300-grain match bullets would correspond to an indoor group size of **2.076*0.35 = 0.727 MOA** with our 246-grain Mark II copper ULD bullets, which is about what we are seeing in our indoor test range. David Tubb's **0.8 MOA** group at 1000 yards is then very impressive outdoor long-range rifle shooting indeed.

f. The larger base-drill diameter of **0.152-inch** selected for the Mark III 338-caliber bullet not only provides improved gas sealing, but also marginally improves (reduces) that bullet's **Iy/Ix** inertial ratio from 17.28 to 16.76 which speeds up its coning rate by **3.1 percent**. The penalty in bullet-weight for using this larger drill size increases from 10 grains to 15 grains, leaving the final Mark III 338-caliber bullet weight at **265 grains**. Repeating this comparative accuracy estimate for our new Mark III 338-caliber bullet indicates we should expect **0.600 MOA** 5-shot groups with that new prototype bullet fired from a barrel with a 6.6-inch twist (or **20 calibers per turn**). Perhaps a slightly slower recommended rifling twist-rate of about **24 calibers per turn** (or about 8-inches per turn for 338-caliber) would prove a better compromise in trading some marginal increase in air-drag for better real-world accuracy (**0.500 MOA**) with these new copper Mark III ULD bullets. David's P5 Schneider barrel is rifled at 7.5-inches per turn, which is **22.7 calibers per turn**.

2. **Variation in Aerodynamic Drag**. David measured very low averaged and minimum air-drag values, but the time-of-flight measurements for each individual bullet over 1000 yards varied unacceptably from one shot to the next. While the 5-shot group spanned only **8 inches** on the distant target, the measured times-of-flight to the target varied significantly (by **1.08-percent** of the mean) even though the extreme spread in launch speeds was only **4 fps** (**0.13-percent** of the mean).
   a. This variance in flight times might be partially attributable to variations in aerodynamic skin-friction drag caused by lengthwise variations in the tripping point of the boundary layer flow-field from its initial lower-drag laminar flow into its final higher-drag turbulent flow. The design intent for these Mark II ULD bullets was for the 4.5-degree surface break-angle, where the base of the secant ogive joins the cylindrical shank of the bullet, reliably to trip the boundary layer flow at that point for all shots. Had the length of the secant-ogive nose been shorter (as with conventional VLD bullets), this break angle would have been larger, and the boundary layer tripping at that point might have been more consistent. The newly redesigned Mark III ULD bullet uses an LD-Haack nose shape which is essentially tangent to the shank at this join, and completely eliminates that surface break angle which seems only sometimes to be tripping the boundary layer flow-field. The inevitable tripping of the boundary layer flow-field should instead occur much farther aft at the 7.5-degree surface break angle at the start of the full-diameter rear driving band for Mark III 338-caliber ULD bullets. A firing test of these redesigned Mark III bullets will indicate how well this design approach works.
   b. Much more likely, the observed wide **1.08-percent** variation in times-of-flight to 1,000 yards is caused by variations in the ***sizes*** of the initial yaw attitude angles discussed in Problem #1 above. The extra loss in kinetic energy of any projectile due to yaw-drag from muzzle to target is the definite integral of that yaw-drag (force) over the full travel distance **Δx**. If the initial

yaw angle **a** damps out to insignificance after one or two coning cycles, essentially all of the extra velocity loss **ΔV** due to yaw-drag occurs during the first couple of coning cycles, so that **Δx** can be limited to the first 40 to 60 yards of flight. This earliest flight segment is also where the dynamic pressure **q**, and hence the total air-drag, are at their greatest initial values. Thus,

$$(m/2)*(\Delta V)^2 \approx q*S*(a^2)*CDa*\Delta x/3$$

and **ΔV** is directly proportional to the particular size of the initial coning angle **a** for each shot fired. The division by **3** on the RHS is an approximation for the assumed exponential damping out of the coning angle **a**. Based on David Tubbs measured **ΔV = 44 fps** at the 1,000-yard target, an estimated initial **CDa** of **3.2**, and an average airspeed of **3100 fps** over the first **25 yards** of flight for the tested **246.3-grain** Mark IIc copper bullets, the difference between the largest and smallest initial yaw angles **a** within the 5-shot string would be only about **45.5 milliradians**, or **2.61 degrees**, which is certainly within the realm of feasibility in explaining the variations in measured air-drag.

Summary

We have learned how to make statically and dynamically balanced monolithic copper rifle bullets which fly at supersonic airspeeds with ultra-low aerodynamic drag (ULD), which can be launched without having suffered from in-bore yaw, and which can demonstrate very low dispersion in muzzle speeds due to proper gas sealing within the rifle barrel. We are still working on improving the shot-to-shot consistency of that portion of the total air-drag which is attributable to each shot's initial yaw attitude (yaw-drag).

We can improve the target accuracy of these copper bullets at all ranges by using rifle barrels made with rifling patterns which promote improved gas sealing and by selecting a rifling twist-rate of approximately ***24 calibers per turn***, instead of the previously recommended ***20 calibers per turn***.

We still need to minimize the yaw disturbance of these bullets in transiting the muzzle-blast zone which causes inaccuracy due to aerodynamic jump deflections of their subsequent trajectories and (at long ranges) due to variations in their airspeeds remaining after the first couple of coning cycles. We are already radiusing the bases of the boat-tails of these copper bullets at **0.74-calibers** (convex) in an attempt at minimizing their yaw disturbance during reversed aerodynamic flight. By adding only a couple of grains of copper to its originally flat bases, we have stabilized the Mark IIc bullet's aerodynamic stagnation point location in reversed flight. That change did improve accuracy somewhat.

One method of reducing yaw destabilization which might be worth exploring would be to eliminate most of the muzzle blast itself by porting the top and sides of rifle barrel itself well behind the muzzle. While some of the gas pressure is being bled off, the bullets are still being guided in the bore until muzzle exit. However, this approach would have the significant disadvantages of slightly reducing muzzle velocities and of making muzzle-attached brakes and suppressors completely ineffective.