SUCCESS IN DEVELOPING LEAD-FREE, EXPANDING-NOSE CENTERFIRE BULLETS

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ABSTRACT.—The historical practice of using lead in projectiles is declining due to its toxicity, and the search for replacements is well underway. At present the preferred replacement for shot pellets is steel and for bullets it is copper. Steel is much less dense (7.9 g/cm^3) than lead (11.3 g/cm^3), but moderate compensation is achieved with increased velocity. Copper, with a density of 8.96 g/cm^3, is considerably nearer lead, and the Barnes Bullet Company succeeded in 1985 in designing lead-free copper bullets that demonstrate good expansion without shedding copper particles. They have proper rotational moment of inertia, are made in traditional bullet weights, and despite the lower density, the over-all loaded cartridge lengths are within specification. These and other factors make them as capable as traditional lead-cored bullets. They are on the market as the X-Bullet series, in several varieties, chief of which are the Triple Shock and the MRX. The latter is shorthand for Maximum Range X-Bullet, which has an all-metal tungsten-composite core that is more dense than lead. It shoots further, with flatter trajectory, than any other lead-free bullet and surpasses many lead-containing bullets. Some of the science of achieving these lead-free, centerfire bullets is reviewed. Other companies are now making all-copper centerfire bullets, and availability is increasing. *Received 28 May 2008, accepted 20 August 2008.*

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THERE ARE NOW LEAD-FREE, expanding-nose centerfire bullets that are superior to their lead-cored predecessors. Development began twenty-five years ago, long before widespread cognizance of the toxicity of lead to wildlife. The motivation was not to become lead-free, but to improve the terminal ballistics of big-game bullets of the expanding-nose type. Large "solid" bullets of the kind used in Africa on very large game have long been available, usually made of brass, but without the expanding nose; they are not legal for most hunting uses in the USA.

Lead cores have been used for a very long time, for two main reasons. First, lead is inexpensive, abundant, dense, and malleable, making it easy to buy and to form, while its high density provides excellent exterior ballistics. Second, in soft point or hollow point bullets, it provides an expanding nose. However, the core and the jacket of such bullets often separate in the terminal ballistic phase, with the lead core dispersing in both large and small particles. The jacket usually stays in one piece, but has very little inertia and does not contribute to the wound channel. Such separation of jacket and core greatly reduces bullet penetration, promotes path deviation, and reduces lethality. There followed an unsuccessful quest for a metal as dense as lead with which to make the entire bullet, sometimes imprecisely called a search for a replacement for lead.

Table 1. Selected metals by density and cost.

By density, g/cm^3			**By cost, in 1988 US dollars per pound**			
Os	Osmium	22.57	Precious	Rh	Rhodium	5,556.00
Ir	Iridium	22.50		Os	Osmium	
Pt	Platinum	21.45		Pt	Platinum	4,809.00
Au	Gold	19.32		Lu	Lutetium	
W	Tungsten	19.30		Ir	Iridium	
Ta	Tantalum	16.60		Au	Gold	
Rh	Rhodium	12.44		Ag	Silver	
Tl	Thallium	11.85				
Th	Thorium	11.66	Refractory	Ta	Tantalum	
Pb	► Lead	11.36		W	Tungsten	12.00
Ag	Silver	10.49		(some precious metals)		
Mo	Molybdenum	10.22		Cb	Columbium	11.00
Lu	Lutetium	9.85		Mo	Molybdenum	
Bi	Bismuth	9.80				
Cu	► Copper	8.96	Other	Tl	Thallium	527.00
Ni	Nickel	8.90		Th	Thorium	305.00
Co	Cobalt	8.85		In	Indium	115.00
Cd	Cadmium	8.65		Zr	Zirconium	113.00
Cb	Columbium	8.57		Co	Cobalt	25.00
Fe	► Steel	7.87		Mn	Manganese	4.90
Mn	Manganese	7.43		Sn	Tin	3.90
In	Indium	7.31		Bi	Bismuth	3.60
Sn	Tin	7.30		Ni	Nickel	3.10
Cr	Chromium	7.19		Sb	Antimony	1.50
Zn	Zinc	7.13		Cu	► Copper	1.30
Sb	Antimony	6.62		Cd	Cadmium	1.00
Zr	Zirconium	6.49		Fe	► Steel	.60
				Zn	Zinc	.54
				Pb	► Lead	.44

The complexities in arriving at the present all-copper bullets were considerable. A few of them will now be reviewed, in appreciation of the success that was achieved and also to point out something of the remaining challenges.

The left-hand column of Table 1 shows a list of some of the metals in order of density, with flags by steel (iron), copper and lead. Lead is 1.44 times as dense as steel and 1.27 times as dense as copper. For a pellet or bullet of a given volume, the lead article is considerably heavier. In flight, it is similar to the difference between driving a golf ball versus driving a ping-pong ball. Though the golf ball is only marginally larger than the ping-pong ball, it flies dramatically further. If the ping-pong ball were the size of the golf ball, the difference in distance would be greater, but being the same size means that they would have very nearly identical aerodynamic drag. However, the heavier golf ball has far more inertial energy, so it takes much less time for aerodynamic drag to bleed away the inertia of the ping-pong ball than that of the golf ball. Examining the left-hand column, which is price-based, shows that there is no candidate for replacing lead on a density-to-price basis. Gold and platinum would work exceptionally well technically for replacing lead, but are unlikely prospects due to cost and, alas, would also experience jacket-core separation in the terminal ballistic phase. Even if gold and platinum were as inexpensive as lead, this illustrates the fallacy of "replacing lead."

Shot pellets are available in several alternative metals, including steel and bismuth, so perhaps the same change should have been made with bullets. It is steel shot that has taken over the non-toxic marketplace, which happened because its cost is very much less than the cost of other non-toxic shot, and it works fairly well in that application. Like the ping-pong ball vs. golf ball comparison, but less dramatically, a steel pellet loses velocity more rapidly than a lead pellet, but an increase in the muzzle velocity of the load has provided partial mitigation. Steel for bullets appears advantageous from the point of view of aerodynamic drag, seeming to offer an advantage not available to shot pellets. Figure 1 shows the von Kármán Vortex Street that forms behind a sphere, which indicates high drag due to the shedding of vortices. A streamlined bullet does not create such vortices, so the loss of density in going from lead to steel would appear to impose a lesser penalty on a bullet than the same change exacts from a shot pellet. Weight compensation for a bullet is discussed below.

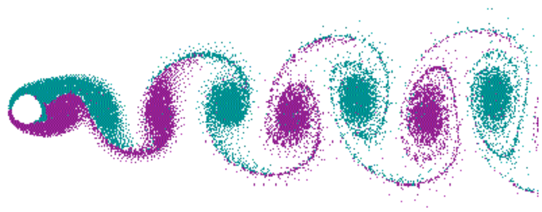


Figure 1. Von Kármán vortex street. (2007, October 3). *Wikimedia Commons,* Retrieved 17:41, February 4, 2009 from http://commons.wikimedia.org/w/index.php?title=Von_K%C3%A1rm%C3%A1n_vortex_street&oldid=7845680

These observations appear to indicate using steel for bullets. Further, during World War II, steel was used for both cores and jackets, and with the cost of steel being considerably less than the cost of copper, there is no lack of motivation to try to make it work. But it was used in war-time under the duress of material shortages, waiving its poorer performance in deference to the need for ammunition. The following discussions will show some of the reasons why steel is not adequate for the vast majority of current bullet applications, despite its continued use in some venues.

The aerodynamic drag on a bullet increases dramatically with increasing bullet diameter, but it increases very little with increasing bullet length. Therefore, a decrease in density of bullet material can be compensated with increased length of bullet, because bullet weight can be adjusted with increased length while avoiding significant increase in drag. So the new copper bullets are available in weights that match the traditional weights of lead-cored bullets by making them longer. But this led to other considerations in the development of the all-copper, expanding-nose bullets. One such item stems from the limitation on length of a loaded cartridge. A longer bullet cannot be allowed to cause a longer cartridge, so it must be seated deeper into the cartridge case. That is due to standards for the dimensions of the chamber into which the cartridge must fit, and the desirability of having the bullet be placed very close to the riflings. A bullet that protrudes too far can be pressed into the riflings and be gripped there so tightly that the bullet is pulled out of the case if the action is opened. Therefore unduly long bullets must be seated deeper than usual into the cartridge case, which can be fraught with hazards.

It is axiomatic that identical weights of materials of differing densities have proportionately differing volumes. That would require an all-copper bullet to have a greater volume than a bullet that contains considerable lead. Diameter is fixed for any given caliber, so the length of the copper bullet would necessarily be longer than its lead-bearing counterpart, in proportion to the densities. Fortunately, however, the new copper bullets were held to lengths approximately equal to traditional lengths of lead-cored bullets. That was accomplished by means such as making small changes to the ogive shape, and to boattail shape, and also by avoiding the air space that occurs in some lead-cored bullets. Though the length effect was overcome in the centerfire copper bullets, it remains a challenge in other bullets, particularly rimfire bullets and steel bullets.

The impetus to create the all-copper bullet was to eliminate jacket-core separation to develop a well-controlled expanding bullet nose. The object is for the nose of the bullet to expand during the terminal ballistic phase to a diameter significantly larger than the diameter of the as-manufactured bullet, in order to create the largest possible wound channel with a smaller diameter bullet. By treaty, the military bullets of World War II were non-expanding bullets, which aided the design of those steel bullets.

Much of the research on the all-copper bullet was directed at the design of the expanding nose, pictured in Figure 2. The nose splits into several petals upon striking the target, and they curl back but remain attached to the bullet body. They create the desired large wound channel but do not shed metal particles in the manner of lead-cored bullets. The terminology "retained bullet weight" means the weight of the bullet after it has come to a stop. The new copper bullets usually demonstrate retained bullet weights close to or equal to 100% of as-manufactured weight. If a particle does come off, it is probably too large to be ingested, unlike the very small lead particles frequently shed by lead-cored bullets. Even when a copper petal is shed, the bullet body retains a far greater percentage of initial bullet weight than a lead-cored bullet that loses its core. A fortunate attribute of the copper-petal nose design is its being a higher drag configuration than a mushroomed lead-cored bullet, so such bullets not only better endure a bone strike, but also are more likely to be brought to a stop within the target animal when traveling through tissue. Energy transfer to vital areas is increased compared to lead-cored bullets.

Another factor that was well handled in the all-copper expanding-nose bullet design was the matter of in-flight stability. For example, when a stick with a rock tied to one end is thrown into the air, it travels with the rock-end forward. The center of gravity of a single-metal bullet is aft of the mid-point of its axis, which is an unstable condition. The rock-on-a-stick illustrates that the bullet would try to fly with its base-end forward. But it is stabilized in point-forward orientation by its spin, which is imparted by the riflings. In the early days of man-made earth satellites, they were spin-stabilized, with the spin being imparted at the point of insertion into orbit. Figure 3 illustrates the satellite's spin axis remaining at a constant angle to the plane of the earth's ecliptic, because the inertial frame of reference is the solar system. It may be remembered that those satellites were rotated 360 degrees once every orbit of the earth, to "unwind the inertial guidance system," in order to avoid confusion due to its continual rotation with respect to the earth. Few modern satellites are spin-stabilized, and those that still are have on-board computers that program out that difficulty.

Likewise, a spinning bullet tries to keep its axis of rotation at a constant angle to the ecliptic, which of course means parallel to the axis of its launching tube. Figure 4 shows the launching tube, a rifle or pistol barrel in this case, and the trajectory of the bullet. The bullet falls to earth because it lacks sufficient velocity to go into orbit, though aerodynamic drag would soon slow it to less than orbital velocity—satellites are above the atmosphere. The top diagram, marked *Properly stabilized*, shows the bullet axis remaining parallel to the trajectory. The center diagram, marked *Over-stabilized*, shows the bullet axis remaining parallel to the barrel axis, like the earth satellite, and the third diagram shows that it is air pressure that keeps the bullet properly

Figure 2. An all-copper expanding-nose bullet. (Reproduced with permission from Barnes Bullets, Inc.)

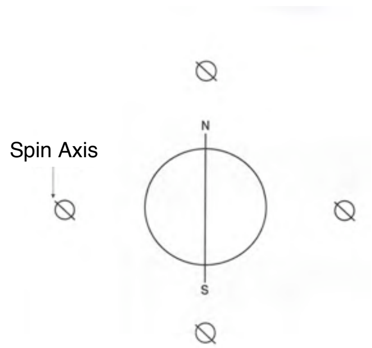


Figure 3. A spin-stabilized earth satellite illustrated.

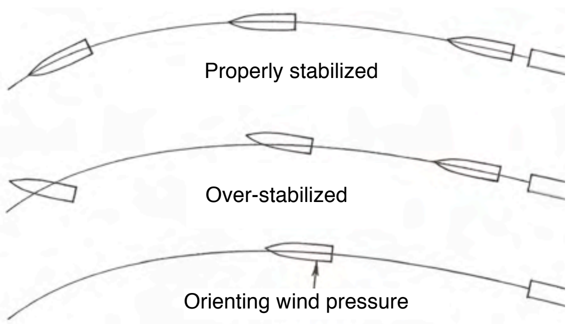
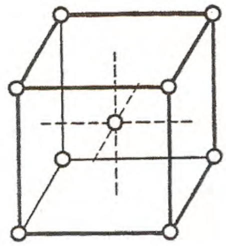


Figure 4. Bullet stability illustrated.

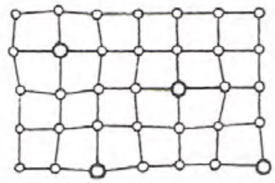
stabilized. It is the air pressure on the bottom of the bullet that overcomes the inertial attempt to over-stabilize it, and keeps it traveling point-first through the air in properly stabilized manner. In a vacuum a bullet would always be over-stabilized. The bottom diagram shows that the angle of attack is always positive but very small—smaller than shown. Another condition, not diagramed, is an under-stabilized bullet, which tumbles and travels erratically. Over-stabilization is caused by too great a spin rate, too great a rotational moment of inertia, or too short a bullet. These matters are properly balanced in the all-copper, expanding-nose bullets, which are not marginally stable but are fully stable. The stability complexities are compatible with present barrel designs, where the rifling twist rate in extant rifles is an unyielding constraint.

Recently there has become available a somewhat surprising variation of the lead-free, expanding-nose copper bullets. They are not all copper, but have a core that is of greater density than lead. It creates the MRX bullet, for "Maximum Range X-Bullet," wherein the core is a composite material that includes tungsten. This is the ping-pong ball concept in reverse, making a bullet core of greater density than the old lead cores. The bullet exhibits exceptionally flat trajectory and long range. It is of the genre of the new, all-copper bullets in having an all-copper nose that expands with copper petals as shown earlier in Figure 2. It costs a bit more, but is indeed an exceptional performer, while also being non-toxic. The core is in the base of the bullet, so that retained bullet weight in the terminal ballistic phase is as high as the all-copper bullets. The heavy core in the bullet base (the rock at the rear of the stick) makes bullet flight stability an interesting matter, but the design achieved a very stable bullet. It has a pointed plastic tip that also contributes to its excellent ballistic coefficient.

There are some myths to be dispensed with in the bullet material arena. The metallurgical basis is first reviewed. Metals are crystalline, meaning that their atoms are arranged in an ordered, repetitive spatial pattern such as cubic, hexagonal and others. They assume such locations upon freezing from the melt due to thermodynamic factors rather than to bonding with valence electrons. Changing the temperature of the metal can cause change to a different crystal structure without involving melting. Figure 5 illustrates the unit cell of a cubic structure, with Pearson symbol cI2. When differing metals are mixed in the making of an alloy, the atoms of the solute metal either replace solvent metal atoms in its lattice, which is substitutional alloying, as shown in the lower portion of Figure 5, or, the solute atoms crowd between the solvent metal atoms, which is interstitial alloying (not shown.) As with the pure metal, the atomic arrangement is thermodynamically driven, and there is no valence bonding of the type seen in chemical molecules. This results in the availability of the solute atoms to outside processes, including diffusional and solubility differences, without the need to break a valence bond. For example, if lead is used as an alloying element in copper, that lead is available to the environment, whatever it may be—a swamp, a stream, a digestive tract, muscle tissue—at rather low energy cost. The bioavailability rate is a different matter and is not treated here.



The body-centered-cubic cell cI2.



Lattice distortion in a substitional system.

Figure 5. A unit cell and lattice distortion.

The non-involvement of valence electrons is true even when an alloy phase diagram shows what appears to be a molecular structure. For example, the phase diagram of the copper-magnesium alloy system shows phases designated $CuMg_2$ and Cu_2Mg. Another illustration is the common iron-carbide structure Fe_3C present in steels and cast irons. The designator makes it appear to be a molecular structure, but it is not. It is a thermodynamically necessary atomic ratio under the circumstance.

The results are:

1. it would be futile to search for a molecule consisting of a lead atom and one or more other *metal* atoms that are combined in such a way that the lead atom is rendered inaccessible to a digestive system, because such molecules do not exist; and

2. it would be valueless to find a chemical molecule, bound with valence electrons, that included a lead atom tied up in an inaccessible manner, because the density of such a compound would be too low to be a projectile material, the lead atom notwithstanding. The conclusion is that presently known chemistry and metallurgy make pipe dreams of such concepts.

There is another pipe dream that is defeated by metallurgical realities. It consists of looking for a technique to alloy metals in such a way that the density of the alloy is greater than that of any constituent. Referring again to Figure 5**,** the two-dimensional representation of lattice distortion in alloying is a three dimensional phenomenon. When metals are combined in an alloy, the volume of the mixture is very close to the sum of the volumes of the separate metals. And of course the mass of the mixture is the sum of the masses of the constituents. The density of the alloy, then, is in linear proportion to the densities of the constituents, on a mass basis. For example, zinc cannot be added to copper with the result that the zinc atoms squeeze between the copper atoms in a manner that increases the density of the copper. Zinc is less dense than copper and the density of the alloy (which is brass) lies between the densities of copper and zinc. As the proportion of zinc decreases, the density of the brass approaches the density of copper, and vice-versa. Density magic of creating an alloy that is more dense than either constituent is impossible. The approach that was taken in the development of the new all-copper, expanding-nose bullets was the necessary approach.

Centerfire target bullets are not required to have an expanding nose, and are available both with and without lead cores. The word “centerfire” has persisted here because rimfire cartridges remain a dilemma. The State of California has included the .22 rimfire cartridge in its ban on lead in designated portions of the state, despite absence of a known alternative for common .22’s. A copper bullet has been developed for the .22 WMR (Winchester Magnum Rimfire) but with reduced exterior ballistic performance. It represents a miniscule portion of the .22’s, as the vast majority consists of the Short, Long, and Long Rifle versions, all of which have a shorter case than the WMR and do not offer the flexibilities outlined above for changing to non-lead bullets. It remains to be seen what can and will be done about lead .22 bullets, as the industry is presently non-committal[1]. Bismuth is too brittle to be used as a non-jacketed bullet, and when alloyed with tin to achieve adequate ductility, the density advantage is considerably reduced. Whether political action can catalyze a solution is questionable; perhaps research grants would be more productive.

Can lead be replaced? Not directly, because the density-cost-alloying-toxicity factors are insuperable as outlined above. Can lead be chemically tied up so strongly as to be unavailable? No. Is replacing lead desirable? Not in expanding-nose bullets, since a superior solution is in hand; for fish-line weights and other uses, yes. Doing without lead is not accomplished by direct replacement, it requires alternative product designs that come as close as possible to duplicating the function of the original product.

It has been the intent of this paper to crack open the door to some of the complexities of removing lead from ammunition. It is not exhaustive, but perhaps it somewhat acquaints the reader with the challenges involved, as well as with a real, though alternatively motivated, success.

[1] Editor's note: At the time of publication, February 2009, Winchester announced lead-free rimfire bullets chambered for both .22 Win. Mag. and .22 Long Rifle (LR) cartridges available beginning in 2009.