Y-12

Y/AMT-477

OAK RIDGE Y-12 PLANT

LOCKHEED MARTIN

Final CRADA Report
for
CRADA Number Y-1294-0254

APPLICATION OF POWDER METALLURGY TECHNIQUES FOR THE DEVELOPMENT OF NON-TOXIC AMMUNITION

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May 30, 1997

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Prepared by the
Oak Ridge Y-12 Plant
managed by
LOCKHEED MARTIN ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ABSTRACT

The purpose of the Cooperative Research and Development Agreement (CRADA) between Martin Marietta Energy Systems, Inc., and Delta Frangible Ammunition (DFA), was to identify and evaluate composite materials for the development of small arms ammunition. Currently available small arms ammunition utilizes lead as the major component of the projectile. The introduction of lead into the environment by these projectiles when they are expended is a rapidly increasing environmental problem. At certain levels, lead is a toxic metal to the environment and a continual health and safety concern for firearm users as well as those who must conduct lead recovery operations from the environment. DFA is a leading supplier of high-density mixtures, which will be used to replace lead-based ammunition in specific applications. Current non-lead ammunition has several limitations that prevent it from replacing lead-based ammunition in many applications (such as applications that require ballistics, weapon recoil, and weapon function identical to that of lead-based ammunition). The purpose of the CRADA was to perform the research and development to identify cost-effective materials to be used in small arms ammunition that eventually will be used in commercially viable, environmentally conscious, non-lead, frangible and/or non-frangible, ammunition.

CRADA OBJECTIVES

The objectives of this CRADA were to: (1) identify candidate materials and compositions, (2) ensure materials are properly characterized, (3) identify cost parameters of materials and forecast manufacturing cost, and (4) fabricate projectiles from the identified cost-effective materials. All objectives of this CRADA were not met as test results of sample projectiles were never received from the Partner.

DOE BENEFITS

Significant reductions in environmental pollution can be achieved through the development of ammunition projectiles, which are composed of materials that are not environmental or health hazards and are economically recyclable. The Department of Energy (DOE) expends > 10 million rounds of small arm ammunition each year in training its security force. This deposits over 300,000 pounds of lead and copper into DOE ranges. The DOE usage of ammunition is small compared to the civilian, law enforcement, and Department of Defense (DoD) usage which combined is estimated at tens of billions of rounds per year which translates into hundreds of tons of lead and copper per day. One estimate is that 400 tons of lead per day is used in the fabrication of bullets in the United States alone. Most of this material (lead and copper) is never recycled or reclaimed. DOE estimates that for each dollar spent on ammunition, one hundred dollars are spent for cleanup and reclamation.

DOE has begun the development of rifle and pistol bullets composed of materials which are not significant environmental or health hazards, and which are economically recyclable. The primary objective of the project is to develop a non-toxic projectile for use in training of security personnel. The bullets must meet all performance specifications of currently acceptable bullets, significantly reduce or eliminate exposure of the shooter to hazardous materials, and minimize the release of toxic materials into the environment. Controlled impact behavior and penetration are secondary considerations. The use of a fragile projectile that disintegrates upon impact reduces damage to training facilities, lowers the risk of ricochet and thus personal injury, and permits the use of a broader range of weapons in situations where over-penetration is a problem (e.g. inside a nuclear reactor or hazardous waste storage facility).

TECHNICAL DETAILS

APPLICATION OF POWDER METALLURGY TECHNIQUES TO THE DEVELOPMENT OF NON-TOXIC AMMUNITION

PURPOSE

The purpose of the Cooperative Research and Development Agreement (CRADA) between Martin Marietta Energy Systems, Inc., and Delta Frangible Ammunition (DFA), was to identify and evaluate composite materials for the development of small arms ammunition. Currently available small arms ammunition utilizes lead as the major component of the projectile. The introduction of lead into the environment by these projectiles when they are expended is a rapidly increasing environmental problem. At certain levels, lead is a toxic metal to the environment and a continual health and safety concern for firearm users as well as those who must conduct lead recovery operations from the environment. DFA is a leading supplier of high-density mixtures, which will be used to replace lead-based ammunition in specific applications. Current non-lead ammunition has several limitations, which prevent it from replacing lead-based ammunition in many applications (such as applications that require ballistics, weapon recoil, and weapon function identical to that of lead-based ammunition). The purpose of the CRADA was to perform the research and development to identify cost-effective materials to be used in small arms ammunition and that eventually will be used in commercially viable, environmentally conscious, non-lead, frangible and/or non-frangible, ammunition.

The objectives of this CRADA were to:

(1) Identify candidate materials and compositions;
(2) Ensure materials are properly characterized;
(3) Identify cost parameters of materials and forecast manufacturing cost; and
(4) Fabricate projectiles from the identified cost-effective materials.

BACKGROUND

The expenditure or firing of small arms ammunition for training, sporting, law enforcement, and military purposes is a major source of environmental pollution which poses a health hazard to the world population. Recent tests have confirmed that lead is a significant environmental and health problem emerging with increasing frequency at many of the public, private, and government-operated shooting ranges nationwide. Many of the sights are contaminated with hundreds of tons of lead, the result of years of target practice and skeet shooting. The lead is tainting grounds and water, and is being ingested by wildlife, and thus has become a serious threat to the health and safety of human and animal populations. Indoor ranges pose other serious concerns such as increased lead exposure to the shooter due to the enclosed space and the subsequent need for high capacity ventilation and air filtration systems. Handling of ammunition and contaminated weapons can also produce elevated lead levels in the blood by absorption through the skin.

Small arms ammunition is comprised of several components; the projectile (the portion of the ammunition which exits the barrel of the firearm), the cartridge case (the portion of the ammunition which acts as a container to hold the projectile, the propellant, and the primer as a single unit), the propellant or powder (the portion of the ammunition which reacts upon firing to produce high pressure gases to propel the projectile from the firearm's barrel), and the primer (the portion of the ammunition which initiates the burning of the propellant material). Each of these components contributes to environmental pollution when the ammunition is expended. The ammunition's projectile is the major source of this pollution, since the projectile is traditionally composed of lead and/or lead and copper. Both of these elements are environmental pollutants and health hazards when introduced into the environment in either reacted (evaporated by the heat of firing) or un-reacted (raw metal) forms. Reacted compounds (of lead or barium) from the ammunition's primer is a second source of pollution from small arms ammunition. The reaction (burning) of the propellant and abrasion of the cartridge case also contribute minor amounts of pollutants.

Significant reductions in environmental pollution can be achieved through the development of ammunition projectiles, which are composed of materials that are not environmental or health hazards and are economically recyclable. The Department of Energy (DOE) expends > 10 million rounds of small arm ammunition each year. This deposits over

300,000 pounds of lead and copper into DOE ranges. The DOE usage of ammunition is small compared to the civilian, law enforcement, and Department of Defense (DoD) usage which combined is estimated at tens of billions of rounds per year which translates into hundreds of tons of lead and copper per day. One estimate is that 400 tons of lead per day is used in the fabrication of bullets in the United States alone. Most of this material (lead and copper) is never recycled or reclaimed due to cost. DOE estimates that for each dollar spent on ammunition, one hundred dollars are spent for cleanup and reclamation.

Small arms ammunition is typically expended in either indoor or outdoor ranges. For indoor ranges, high capacity air handling and filtration systems are necessary to protect occupants from exposure. The high-efficiency filtration systems are expensive, as are maintenance and waste disposal costs. For outdoor ranges, the cleanup cost of lead-based ammunition is prohibitive. For remediation, the soil of an outdoor range must be excavated to a depth of at least four feet over the entire length and width of the range. The lead-contaminated earth must be removed, and processed as a hazardous waste at a cost of ~\$65 per cubic foot (approximately \$100 million would be needed to remediate a single 600 yard by 100 yard range at the given rate).

Currently the EPA is proposing to ban all lead- and possibly zinc-containing fishing weights.[1] The ban includes all fishing weights under 1 inch in diameter such as jigs, split shots, sliding and bullet styles. Lead, lead alloys, zinc, and zinc alloys including brass are on the list of prohibited materials. Many alternatives such as plastic-metal composites, tin, bronze alloys (copper-tin), and other tin compounds are being investigated and marketed. Projectiles are a more serious concern due to the vast quantities that are consumed; however, the development of replacements for lead bullets and shot is a more significant undertaking due to the great mechanical and physical demands of the application.

These issues have prompted the development and evaluation of alternative ammunition that eliminates the undesirable health and environmental aspects of lead. The ammunition must be fully functional and provide characteristics similar to those of "standard issue" analogs to allow personnel to maintain the highest degree of proficiency in training, and to meet the many needs for sporting, law enforcement, and military applications. Recent efforts have focused on metal powders in polymer binders[2,3] (e.g. tungsten and copper in nylon), plastic or rubber projectiles, and alternate metals such as steel,[4,5] bismuth,[6,7] or brass.[8] Unfortunately, these replacements have yet to meet all established specifications and performance goals.

The concept of environmentally safe or non-toxic ammunition has been explored in the past, but not with the vigor as seen in the last few years. At the end of World War II, projectiles for 0.30 and 0.50 caliber weapons for training and to replace lead were fabricated from tungsten, iron, and bakelite.[9] These were used for training and in special applications, however, attempts to reproduce these materials in the early 1970's were relatively unsuccessful. In addition, the use of Bakelite, some grades of which are fabricated from phenolic-formaldehyde mixtures, has experienced a decline as new inexpensive polymer materials are developed. Frangible, non-toxic projectiles are also employed as training ammunition in place of large caliber, high velocity, kinetic energy penetrators.[10] The simulated projectiles must exhibit similar flight characteristics as the actual penetrators, however, ideally self-destruct in flight or on impact for safety reasons. Generally, a partially densified iron powder component encased in a low-strength, thermally degradable plastic container are used. These replacements fail on light impact or after heating in flight thus meeting range safety requirements.

More recently, replacement projectiles for training and certification of personnel have been fabricated from tungsten and copper or brass powders in a nylon matrix.[11,12] The projectiles are formed employing injection molding techniques and ammunition in different calibers is being marketed by a number of companies. The ammunition is functional and acceptable for many applications, however, the density of the bullet material is much less than that of the lead components (5.8 vs. 11.3 g/cm^3). The low weight of the projectile may cause problems in weapon functionality and accuracy, especially at extended ranges. In addition, only the powdered metal portion of the components can be recycled. The plastic binder is a consumable that must be removed, likely through incineration, before the metals can be reclaimed.

Another solution is the replacement of lead with other metals such as steel, brass, and bismuth. Steel shot is required for hunting waterfowl in many areas. Due to high hardness and low density (7.8 vs. 11.3 g/cm^3), steels are less than desirable choices for use as projectile materials. Steel shot has caused intense controversy for it is believed that due to its reduced ballistic properties, many birds are being wounded and maimed, dying gruesome deaths. Bismuth and its alloys have also experienced much popularity as replacements for lead. Bismuth-tin shot is currently available, but again the density of this metal is only 86% of that of lead (9.8 vs. 11.3 g/cm^3), and again this creates concerns with regards to ballistic performance. As with steel, bismuth and brass also possess higher hardness and modulus than lead. Another concern with regard to bismuth is the lack of toxicological data. In many categories bismuth has not been evaluated, and is thus not a fully accepted lead replacement.

DOE has begun the development of rifle and pistol bullets which are composed of materials which are not significant environmental or health hazards, and which are economically recyclable. The primary objective of the project is to develop a non-toxic projectile for use in training of security personnel. The bullets must meet all performance specifications of currently acceptable bullets, but significantly reduce or eliminate exposure of the shooter to hazardous materials, and minimize the release of toxic materials into the environment. Controlled impact behavior and penetration are secondary considerations. The use of a fragile projectile that disintegrates upon impact reduces damage to training facilities, lowers the risk of ricochet and thus personal injury, and permits the use of a broader range of weapons in situations where over-penetration is a problem (e.g. inside a nuclear reactor or hazardous waste storage facility).

MATERIALS

The choice of materials for developing a less toxic material for replacing lead is driven by many factors including the physical, mechanical, and thermal properties and toxicological concerns. Another major consideration is cost. A review of potential constituents was conducted and a list of candidate metals assembled (Table 1). The process requires a high density metal that is to be encapsulated in a softer, typically lighter metal. When consolidated, the resulting compact or composite is to perform in a manner similar to lead. Density was the primary property of interest in this study. Tungsten and tungsten carbide were selected as the high density component with aluminum, bismuth, tin, and zinc as binders. Through experience and a review of the environmental and toxicological information regarding the aforementioned materials, many of the candidate metals were disqualified. Emphasis in this effort was thus placed on the tungsten-tin composition, a mixture of materials that has performed well in processing studies and preliminary testing.

Table 1. Properties of Materials

Material	Symbol	Density (g/cm^3)	Strength (MPa)	Hardness (VHN)	Approx. Cost ($/lb)
Lead (99.94%)	Pb	11.35	13	0.049(3 HB)	0.43 - 1.00
Lead + 5 % Tin	Pb/Sn	11.00	23	8 HB*	
Lead + 4% Antimony	Pb/Sb	11.02	100	8.1 HB*	1.00 - 2.00
Copper	Cu	8.93	200	0.50	
Bismuth	Bi	9.81	NA	0.095	
Gold	Au	19.30	100	0.66	4,200
Silver	Ag	10.49	125	0.94	66.00
Platinum	Pt	21.45	140	0.86	> 5000
Aluminum	Al	2.70	45	0.25	0.75
Tungsten	W	19.25	3450	3.43	10.00 - 15.00
Tin	Sn	7.29	15	0.071	3.50 - 5.00
Iron	Fe	7.87	600	0.65	< 0.10
Molybdenum	Mo	10.22	500	0.38	
Tantalum	Ta	16.6	360	---	
Low Carbon Steel	Fe-FeC	7.5	350	90 HB*	< 0.10
Zinc	Zn	7.13	150	0.20	0.65 - 1.55

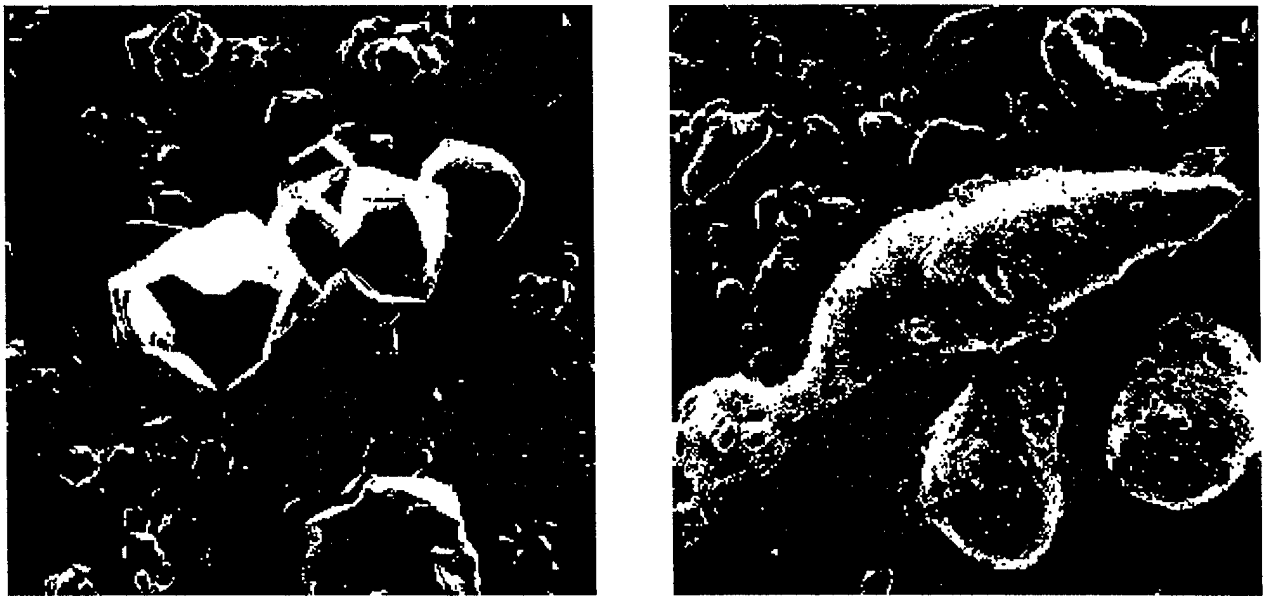
* As noted, the hardness of lead is 3 HB in similar units.

Tungsten

Various tungsten powders were evaluated prior to this effort, i.e. earlier in the development of the heavy, non-toxic bullets. It was found that the M-70 grade of tungsten powder, supplied by Osram Sylvania of Towanda, Pennsylvania was optimum for blending with the selected binder metal, and for the cold pressing of cores. The M-70 powder was specified to have an average particle size of ~ 20 - 40 microns, and was found to be a mixture of fine crystalline particles and agglomerates of varying size and shape [Figure 1(a)]. Typically, agglomerates could be detrimental to the production of dense composites without sintering, for the clumps usually contain porosity that cannot be accessed. However, the agglomerates in the M-70 grade are relatively dense. This allowed for efficient packing and consolidation with little porosity attributed to the pores within particle agglomerates. Information specific to the lot of powder used in this effort is included in the Appendix.

Tin

The tin powder was procured from Pyron Metal Powders (formerly Greenback Industries) of Greenback, Tennessee. The TC-125 grade of Sn powder was used in this study. The powder was found to have a broad range of particle sizes and shapes [Figure 1(b).]. The nature of the particles was evidently a result of the processing, and few if any agglomerates were observed. Information specific to the lot of powder used in this effort is included in the Appendix. Some sieving was conducted to remove the extra fine particles (< 500 mesh) from a small lot of powder. The powder was used to investigate bullets that produced less dust upon impact.



(a) (b)

Figure 1. Scanning electron micrograph of (a) M-70 tungsten and (b) TC-125 tin (500X).

Jackets

The copper jackets, both pistol and rifle were purchased from Berger Bullets of Glendale, Arizona. The jackets were fabricated by J4 of Anaheim, California, however; Berger is the sole distributor for J4 products in quantities < 250,000 pieces. The specifications for the jackets for each bullet type are summarized in Table 2.

Table 2. Specifications for jackets used in this study

Bullet Caliber	Weight (grains)	Bullet Style	Jacket Length (in)	Wall Thick. (in)	Jacket Weight (grains)
9 mm	124	FMJ	0.500	0.012	19.32 ± 0.13
9 mm	124	SP	0.437	0.015	15.99 ± 0.06
9 mm	115*	FMJ	0.580	0.012	21.98 ± 0.10
5.56 mm	57.5	OT FB	0.705	0.011	14.23 ± 0.12

FMJ - full metal jacket, SP - soft point, OT FB - open-tip, flat base
* 115 grain bullet in a 147 grain package

EQUIPMENT

Core press

An Enerpac tabletop hydraulic press was used to compact the cores. The press is a simple H-frame unit with a 1.5-inch hydraulic ram and 6 inches of travel. An electric hydraulic pump capable of 5,000 psi supplies pressure. The dies and punches were set on a spring-loaded table to allow the punches to float and thus compact the cores from both ends. The double action produces more uniform compaction

Core Forming Dies

The cores were pressed in simple cylindrical dies made from AISI D-2 steel hardened to R_c of 55 - 60. An example drawing is included in the Appendix. The diameter of the cores for pistol and rifle bullets were 0.309" and 0.190", respectively. A hemispherical cap was added to one end of the cores for the pistol bullets to prevent air from being trapped between the core and jacket, and to help in formation of the round nose of the bullets with a full metal jacket.

Swaging Dies and Presses

The dies and punches for fabrication of the pistol bullets were designed and manufactured by Corbin Manufacturing of White City, OR. A round-nose, or 3/4 elliptical ogive (3/4-E), design was selected for the pistol bullets. Core seat and point form dies and corresponding punches were used to swage the bullets. The die sets were selected to fit either a hand-operated or hydraulic press, both of which were available for the swaging of bullets.

The rifle bullets were fabricated using tungsten carbide lined dies designed and fabricated by Neimei Engineering of Vermont. A flat-based design with a very low drag ogive was selected. The precision dies and punches fit a modified hand press typically used in the hand loading of ammunition.

PROCEDURES

Fabrication of Cores

The cores for swaging into the bullets were fabricated using simple powder metallurgical techniques. Mixtures of powdered metals were dry blended, and consolidated under pressure at room temperature. These cores were then swaged into final form, whether into an unjacketed or jacketed product.

The composition of the cores was selected to mimic the density of lead. In this study, tin was used as the lighter, softer binder metal, with tungsten as the high-density phase. A rule of mixtures approach was utilized to determine a starting composition. The rule of mixtures relates the property of a combination of materials to the volume fraction of each phase in the composite or:

$$V_1X_1 + V_2X_2 + \ldots\ldots + V_nX_n = X_{composite}$$

where V is the volume fraction of the specified material and X is a property such density, modulus, etc. In this case, the volume fractions of tin and tungsten were calculated from:

$$V_{W\ W} + V_{Sn\ Sn} = {}_{composite}$$

where is density, and the chosen values for W and Sn were 19.25 and 7.35 g/cm^3, respectively. Table 3 shows the calculated relationship between composition and density for compacted mixtures of these two metals. This assumes no chemical interaction (e.g. alloying) which would not be expected for room temperature processing.

Table 3: The calculated "rule of mixtures" densities for tungsten-tin compositions

Desired Density (g/cm^3)	**Volume Fraction Tungsten**	**Volume Fraction Tin**	**Weight Fraction Tungsten**	**Weight Fraction Tin**
7.35	0.00	1.00	0.00	1.00
7.85	0.04	0.96	0.10	0.90
8.40	0.09	0.91	0.20	0.80
8.70*	0.11	0.89	0.25	0.75
9.00	0.14	0.86	0.30	0.70
9.80	0.21	0.79	0.40	0.60
10.60	0.27	0.73	0.50	0.50
11.35*	0.34	0.66	0.57	0.43
11.59*	0.36	0.64	0.59	0.41
11.70	0.37	0.63	0.60	0.40
12.90	0.47	0.53	0.70	0.30
14.50	0.60	0.40	0.80	0.20
16.50	0.77	0.23	0.90	0.10
19.25	1.00	0.00	1.00	0.00

* denotes mixtures used in this study

The rule of mixtures for density calculation assumes complete consolidation, i.e. no porosity. Full densification may not be possible depending upon many factors, such the form of the materials, efficiency of compaction, etc.. A study of the relationship between composition (fraction of each metal), materials properties, and density was conducted to determine the appropriate mixture of tin and tungsten, and compaction pressure needed to achieve the desired density of lead (11.35 g/cm^3). Core diameters similar to the caliber of bullets of interest, 0.356" and 0.224", were investigated.

It is well known that a range of powder particle sizes is necessary to obtain good "green" densities at minimal pressures. For the bullets, it is also desirable to encapsulate the hard, high density material in the softer binder metal, to ensure good bonding of the core, and in the case of an unjacketed bullet, to enrich the external surfaces with the softer metal to minimize contact of the hard tungsten with the steel barrel of a weapon. In addition to examining the correlations between composition and properties, the effects of particle size on density and strength were investigated. The tin and tungsten powders were sieved into various size fractions, and mixtures with different particle size relationships prepared and evaluated.

Powder Blending

One kilogram batches of powder were dry blended for 15 minutes with no lubricants or added binders in a 16 quart V-blender equipped with an intensifier bar. The powders appeared to be well blended as noted by appearance, however, some separation of constituents was observed for mixtures of coarse tungsten and coarse tin. The powders were stored in 500 ml plastic bottles.

Pressing

The powder for each core was individually weighed on a laboratory scale with 0.02 grain resolution. Cores were pressed at room temperature. A hemispherical cap was added to the end of the cores for the pistol bullets (0.309" diameter) to avoid trapping air between the core and jacket during seating operations. The inside diameter of the die was lubricated with stearic acid for each core. The lubricant was applied by wiping the inside diameter of the die with a cotton swab soaked with a saturated solution of stearic acid in acetone. The premeasured powder was poured into the die and compacted simultaneously from top and bottom using a hydraulic press. The double action of the pressing operation ensured more uniform densification. The cores to be used for jacketed bullets were then washed in acetone and handled only with gloves or tweezers during further processing to avoid contamination.

Compression Strength

The compressive strength of cylindrical specimens was measured using an mechanically-driven test frame and a cross-head displacement of 0.787"/min. Load and cross-head displacement were recorded, and strength was determined from the peak load as indicated on the curves.

SWAGING

Unjacketed Pistol Bullets

Unjacketed bullets were swaged in a single step using a hand press and the 3/4-E point form die. An unwashed core was placed in the die with the hemispherical cap toward the ogive part of the point form die. Spacers were used to properly position the die and ejection pins, and ensure formation of an acceptable bullet nose. A punch the same diameter of the bullet and die cavity was used to apply pressure. Bullet were formed to length and thus actual pressures were not measured when using the hand-operated press.

Soft Point Pistol Bullets

Soft point bullets were swaged in a one step process similar to the unjacketed bullets with three exceptions; a washed core was placed in a 3/4 length copper jacket (0.437" long), swaging lubricant (a mixture of lanolin and castor oil) was applied to the jacket, and the bullets were fabricated using a hydraulic press. The core was seated and the point formed in one operation using the 3/4-E point form die and a punch the same diameter as the inside diameter of the die. Bullets were formed at a pressure of ~600 psig, the pressure at which the bullet appeared to be fully seated, and the nose completely formed.

Full Metal Jacket Pistol Bullets

Full metal jacketed bullets were fabricated using a three-step process. A washed core was first placed into a lubricated 0.500" long jacket, with the hemispherical cap placed toward the closed end of the jacket. The assembly was then placed into the 3/4-E point-form die with the closed end of the jacket toward the ogive forming portion of the die. The core was then seated and the nose of the bullet formed in one step using a punch with a diameter slightly less than that of the inside diameter of the jacket. The bullet was then placed in a truncated cone point form die with the base of the bullet facing the point forming portion of the die cavity (upside down). The bullets was pushed into the die using a punch with a hemispherical impression matching the shape of the point until the jacket near the base of the bullet was rolled slightly inward. The bullet was then transferred back to the 3/4-E point form die, and the base fully "crimped" using a punch the same diameter of the bullet. The two point forming steps were conducted employing the hydraulic press, again using bullet appearance as a guide to set the pressure. Pressure for seating and point forming was ~600 psig. The rolling of the jacket in the truncated cone die was done in a hand-operated press.

Open-Tip, Flat Base Rifle Bullets

The open-tip, flat-base 5.56 mm bullets were formed in two steps. A washed core was first placed into a lubricated 0.705" long jacket, with the hemispherical cap placed toward the closed end of the jacket. The assembly was then placed into the core seating die, and the core pressed into the jacket using a punch with a diameter slightly under that of the inside diameter of the jacket. The bullet was then placed in the point form die, and the nose formed.

Testing and Characterization (DDI/DFA)

The bullets were loaded and tested by Delta Defense, Inc. Procedures and results are summarized in the attached reports.

RESULTS

Core Pressing Studies

The results of the core pressing studies, conducted to examine the effects of composition, particle size and pressures on compaction efficiency and the properties of the composite simulant, are summarized in Table 4. A mixture of coarse tungsten with fine tin produced the highest densities at moderate pressure, 98.3% of lead at 50,000 psi. The green compressive strengths of these compacts were also the highest, >14,000 psi (Table 5).

Table 4. Properties of W-Sn Mixture Pressed at Room Temperature

Powder Mixture	Comments	Pressure (psi)	Diameter (in)	Density (g/cm^3)	% of Lead	Compressive Strength (ksi)
WSN-5743	Coarse W Coarse Sn	40,000	0.356	11.02 ± 0.01	97.1	
		50,000		11.04 ± 0.01	97.4	
		60,000		11.12 ± 0.01	98.0	
		75,000		11.11 ± 0.02	98.0	
WSN-5743	Fine W Fine Sn	40,000	0.356	9.69 ± 0.08	85.4	
		50,000		10.34 ± 0.02	91.2	
		60,000		10.49 ± 0.01	92.5	
		75,000		10.58 ± 0.01	93.3	
WSN-5743	Fine W Coarse Sn	40,000	0.356	9.99 ± 0.05	88.1	
		50,000		10.18 ± 0.03	89.8	
		60,000		10.29 ± 0.04	90.7	
		75,000		10.36 ± 0.05	91.3	
WSN-5743	Coarse W Fine Sn	40,000	0.356	11.08 ± 0.03	97.7	
		50,000		11.14 ± 0.01	98.3	
		60,000		11.14 ± 0.02	98.3	
		75,000		11.15 ± 0.02	98.4	
WSN-5941	M-70 TC-125	50,000	0.356	11.28 ± 0.02	99.5	10.39 ± 0.07
	M-70 +200 mesh Sn	50,000	0.356	11.21 ± 0.02	98.8	7.98 ± 0.32
	M-70 -200+400 mesh Sn	50,000	0.356	11.12 ± 0.03	98.1	
	M-70 -400 mesh Sn	50,000	0.356	11.32 ± 0.02	99.8	14.07 ± 0.15

WSN-2575 (M-70, TC-125)	for 115 in 147 package	50,000	0.356	8.44 ± 0.02	74.4	

The high strength combined with the difficulties in handling the powder mixture caused some concern. The composition was thus adjusted from 57 wt.% W - 43 wt.% Sn to 59 wt. % W - 41 wt. % Sn, to accommodate the 2% difference between the observed density of the cores and that of lead. Blended 59/41 mixtures of the "as-received" M-70 tungsten and TC-125 tin, flowed well, and readily pressed to a density of 99.5% of lead. Further study of powder size variations produced no appreciable difference in the density or properties of this core material.

A mixture consisting of 25 wt.% W and 75 wt.% Sn was also prepared and test pieces fabricated. This mixture has a density < 75% that of lead and was used in the fabrication of the cores for the 115 grain 9 mm FMJ bullets in a 147 grain package.

Bullets

Bullets were readily fabricated from the powder metallurgy cores. A total of 125 each of the following bullet configurations were supplied to Delta for testing and characterization. Examples of the pistol bullets are shown in Figure 3. Measured bullet dimensions and weights are summarized in Table 6.

- 124 grain 9 mm frangible, unjacketed
- 124 grain 9 mm soft-point, 3/4 jacket
- 124 grain 9 mm full-metal jacket
- 115 grain 9 mm full-metal jacket (115 grain weight in a 147 grain package)
- 57 grain 5.56 mm open-tip, flat-base

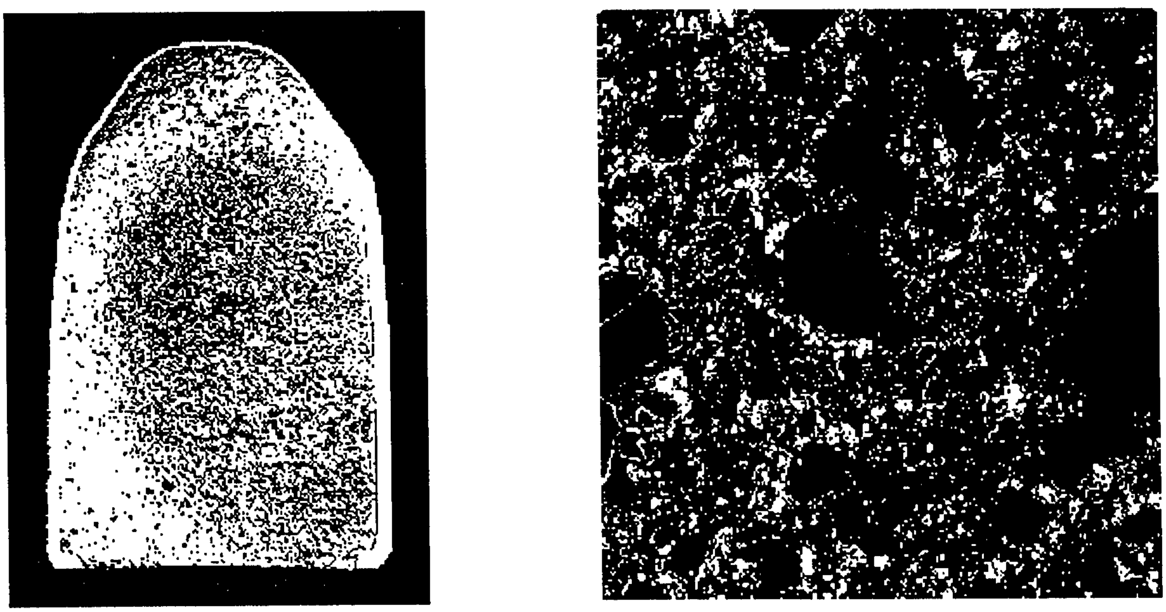
Figure 3. Examples of 9 mm bullets fabricated in this study, from left: 124 grain unjacketed, 124 grain FMJ, and 124 grain soft-point.

Table 6. Specifications of bullets supplied to Delta for evaluation

Bullet Caliber	Weight (grains)	Bullet Style	Measured Weight (grains)	Measured Diameter (in)	Measured Length (in)
9 mm	124	ball	not measured	0.355	0.610
9 mm	124	Frangible[a]	124.1 ± 0.3	0.3550	0.544 ± 0.007
9 mm	124	FMJ	not measured	not measured	not measured
9 mm	124	SP	124.0 ± 0.2	0.3550	0.560 ± 0.010
9 mm	115[b]	FMJ	115.0 ± 0.3	0.3550	0.639 ± 0.004
5.56 mm	57	OT FB	56.9 ± 0.3	0.2245	0.745 ± 0.008

[a] Early lot of 39 bullets
[b] 147 grain length

A selection of the 124 grain FMJ 9 mm pistol bullets were sectioned, and metallographically polished to examine the distribution of materials, and efficiency of compaction. The composite core material appeared to be homogeneous with no evidence of separation, settling, or segregation of the two metal powders during handling and processing. Good contact between the core and jacket was noted. Small pores were observed in the material (Figures 4(b) and 5), as would be expected for a 98 % dense compact. The larger more pronounced pores, evident in the bullet cross-section in Figure 4(a), appeared to be the result of polishing. Closer examination of the pores showed these to be formed where tungsten particles or agglomerates were pulled out during the polishing process.



(a) (b)

Figure 4. (a) Cross section of 124 grain 9 mm FMJ with WSN-5941 core. (b) Micrograph shows distribution of tungsten (well-defined, larger particles) in the tin matrix (100X).

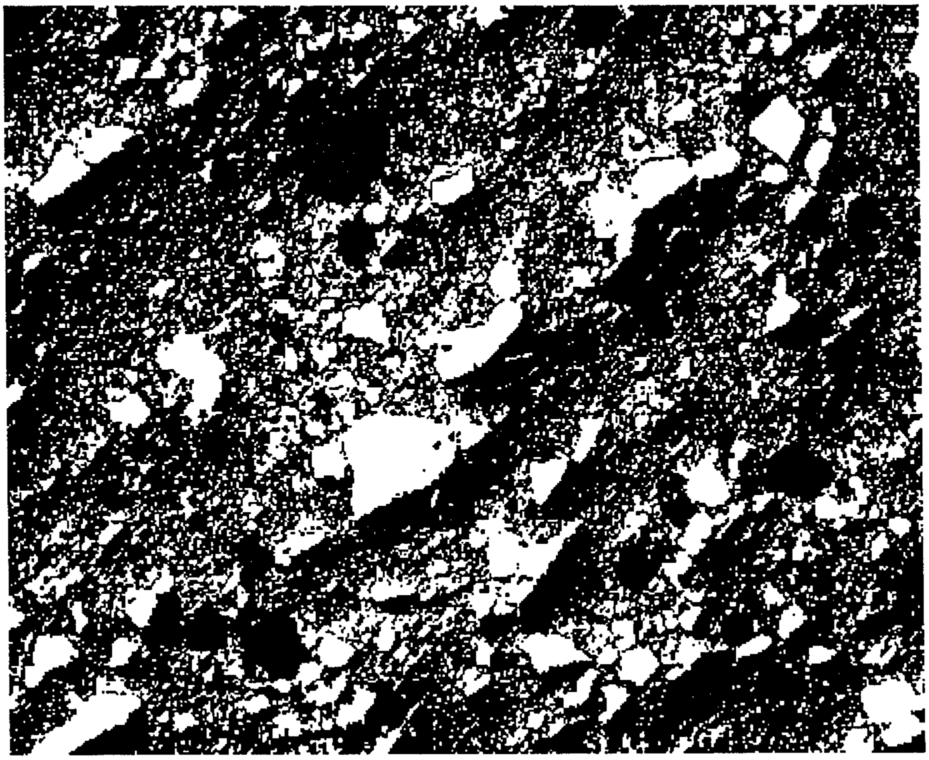


Figure 5. Enhanced micrograph showing details of microstructure of WSN-5941 core. Darkest areas appear to be pores formed where particles of tungsten were pulled from the matrix during polishing (200X).

A fracture surface from a test specimen was examined using electron microscopy. Good materials distribution and bonding between constituents was observed (Fig. 6).

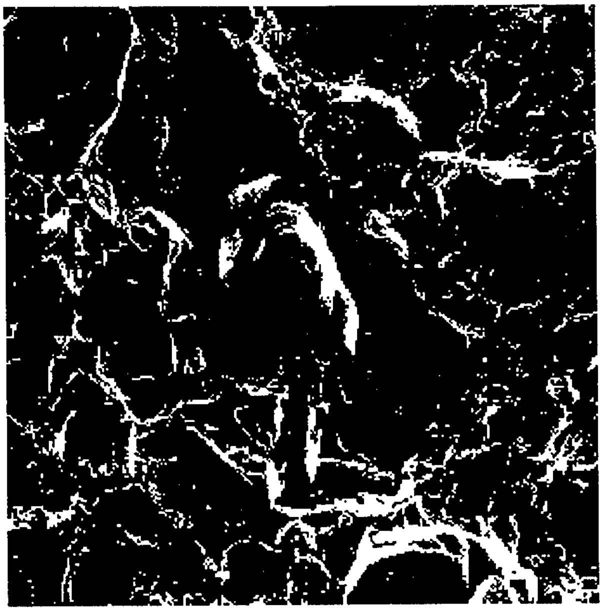


Figure 6. Scanning electron micrograph of bullet fracture surface (500X).

Test firing for pressure and accuracy was conducted by Delta. A small number of bullets were used to select a propellant and develop an acceptable powder charge. Once established, 100 rounds of each bullet type were loaded and tested in groups of ten each. Pressure, velocity, and accuracy (group size) were recorded. A summary of the testing is given in Table 7. Details are included in the attached reports.

Table 7. Summary of Bullet Testing

Bullet Caliber	Weight (grains)	Bullet Style	Chamber Pressure (ksi)	Velocity (ft/sec)	Group @ 25 yards (in, w x h)
9 mm	124	ball	38.4	1205	4.1 x 2.4 [7.0 x 3.8]
9 mm	124	Frangible	28.2	1052	0.8 x 1.8
9 mm	124	FMJ	not measured	not measured	not measured
9 mm	124	SP	37.8	1192	1.9 x 2.2 [4.1 x 6.6]
9 mm	115	FMJ	35.5	1125	2.1 x 2.9 [5.3 x 3.5]
5.56 mm	57	OT FB	53.5	3028	4.0 x 3.9* [8.5 x 7.9]

Mean group given. Composite group size listed in parentheses.
* Rifle bullets tested at 100 yards

Frangibility

The impact behavior of two types of the pistol bullets, the 124 grain unjacketed and 115 grain FMJ, was evaluated. The bullets were fired against a 0.5 in thick steel plate at close range, and fragmentation observed. The unjacketed bullets generated small particles and powder, the majority of which deflected sideways, and one larger piece for each bullet that rebounded to about 18 in from the target. The larger piece was most likely produced from material compacted into the dent in the steel plate during impact.

The FMJ bullets were not deemed "frangible." Parts of the copper jacket from the 115 grain FMJ bullets were found 10 ft from the target in a direct line from the muzzle of the test weapon.

DISCUSSION

The evaluation of the non-lead bullets fabricated employing powder metallurgy revealed a number of issues with regard to accuracy and reproducibility. Although the accuracy of the pistol ammunition using the non-lead bullets surpassed that of standard military ball ammunition, performance was not optimized. Variations in pistol bullet length influenced pressure and velocity, and thus accuracy. Changes to swaging procedures were used to improve reproducibility in length. Similarly, the rifle bullets did not perform as expected. For the rifle bullets, it was found that the core may have fragmented during point forming. Again, the swaging process was modified to correct the problem and improve performance.

It is desirable to encapsulate or surround the high density, hard particulates (coarse powder) with the softer lighter metal. This facilitates good mechanical interlocking of the materials through deformation of the soft metal, and allows the softer metal As would be expected, this behavior is most evident in mixtures of coarse tungsten and fine tin. Good densities and high strengths were achieved at moderate consolidation pressures. Unfortunately, this combination of particle sizes was difficult to handle, the powders did not flow well, and quantities of fine dust were produced upon impact. It was found that blends of powdered metals with a range of particle sizes, but with the aforementioned trend, i.e. the high density material of larger particle size, produced composite cores with acceptable densities and moderate strengths. These cores were readily swaged into bullets employing equipment and pressures similar to those used for lead-containing bullets of the same construction.

Variations in the lengths of the bullets was the primary concern. The length of a bullet can have a significant effect on pressure for the length of a bullet effects the available case volume in a loaded cartridge.[13] A cartridge is typically loaded to a specified length, and powder charge, determined by bullet design and weight, is also held constant. Differences in bullet length produce variations in the volume occupied by the propellant in the cartridge case. Longer bullets will protrude further into the case decreasing the available volume. The burning of powder begins in this case, and thus the influence of volume is considerable. This is especially true for pistol ammunition, where case volume is small. The effect is not as pronounced in rifle ammunition for case volumes are generally much greater, and bullet diameters smaller.

Significant differences in pressure can result when pistol bullet length varies by even small amounts. This can be seen in the pressure differences for the 9 mm 124 grain soft-point bullets. Table 8 shows the results for four of the aforementioned bullets from the same test group with similar weights, but differing lengths. As bullet length increased, pressure and velocity increased.

Table 8. Effect of Bullet Length on Pressure and Velocity

Bullet Number	Weight (grains)	Bullet Length (in)	Pressure (ksi)	Velocity (ft/sec)
14	124.1	0.550	36.9	1167
17	124.1	0.555	34.7	1165
16	124.1	0.560	37.9	1195
15	124.2	0.570	40.3	1199

The unjacketed and soft-point pistol bullets were fabricated employing the hydraulic press, using a constant pressure. Bullet appearance was used to determine appropriate pressure and dwell time. Items such as the look of the bullet nose, and flashing of the metal around the punches were used in setting the working pressures. The variations in length are most likely due to the use of pressure, and not length, as a constant during bullet formation. Minor differences in the amount of swaging lubricant on the bullet, the density of the core, and in the applied pressure would influence bullet length.

It was speculated that the variation in length could be due to inhomogeneities in the powder blend. Some settling and separation could have occurred during handing, since small portions of blended powder were poured from a container into a weighing dish during the fabrication of the cores. Powder was then scooped from the dish and weighed. This could have resulted in segregation of the powders, and produced variations in composition, and thus density and weight.

It is difficult, however, to deduct a firm reason for the variations in length. Although the 115 grain 9 mm FMJ bullets were processed in a manner similar to the other pistol bullets, they exhibited a smaller deviation in length, and subsequently, produced more reproducible pressures and velocities, and thus better accuracy (fewer fliers and smaller group size).

An additional 1020 each of the 9 mm 124 grain FMJ and SP bullets were fabricated keeping length constant. Reproducibility was significantly improved (Table 9).

Table 9. Specifications for the Additional Bullets Supplied to Delta for Evaluation

Bullet Caliber	Weight (grains)	Bullet Style	Measured Weight (grains)	Measured Diameter (in)	Measured Length (in)
9 mm	124	FMJ	123.97 ± 0.13	0.355	0.558 ± 0.001
9 mm	124	SP	123.71 ± 0.15	0.355	0.554 ± 0.002
5.56 mm	63	OT FB	62.86 ± 0.09	0.224	0.821 ± 0.002

The 57 grain 5.56 mm OT FB rifle bullets were fabricated employing a hand press, and length was used as the primary processing parameter. Length, or position, was used to control the core seating and point forming operations. Bullet length varied by about 1%, but there was little correlation between length, pressure, and velocity. As previously stated, rifle cartridge cases have a much greater volume, and thus bullet length variations have less of an influence on pressure. Accuracy was, however, not up to the expected level for the bullets.

Weight or velocity variations produce a vertical dispersion or stringing. Horizontal stringing is generally attributed to cross-wind effects. A "good group" is typically round or circular. The composite group for 100 of the 57 grain 5.56 mm bullets was circular, but very large (8.5" x 7.9"), suggesting that velocity and wind effects were negligible. It is believed that the dispersion was a result of the flaking or crumbling of the core during the point form step. Forming a long tapered point on a small diameter bullet can be difficult, especially when using a core made from powdered metals. To investigate this issue, a number of the bullets were tapped point-first on a hard surface. Small metal particles were removed from the open tip with larger particles observed to be lodged in the cavity. It is obvious that the presence of loose, dense particles in the nose of a small diameter, high velocity bullet would have a detrimental effect on accuracy. A heavy particle lying off-center in a rapidly spinning projectile would diminish stability and accuracy, especially in the nose of a bullet.

An additional 1020 of a 63 grain 5.56 mm OT FB bullet were fabricated, with the addition of a small disk of pure tin in the tip of the bullet. The pure tin cap was seated with the composite core, and then the bullet point formed. No evidence of powder was observed upon rigorous tapping on a hard surface. The tin tip "sealed" the top of the core and prevented the powder metal material from fragmenting during swaging of the nose of the bullet.

A final and important issue is cost. One of the goals of the project was to produce "cost effective" replacements for lead bullets. At this time lead and lead alloys cost between $0.50 and $2.00 per pound. Tungsten is between $10.00 and $15.00 per pound. Tin and zinc are $3.00 to $5.00, and $0.60 to $1.00 per pound, respectively. The estimated cost of the tungsten-tin replacement is $8.50 per pound. This results in a three fold increase in the cost of the materials for a jacketed bullet as shown in the following examples.

For a 63 grain 5.56 mm bullets with a 46 grain core:

	Lead	W-Sn
Core	$0.005	$0.055
Jacket	$0.020	$0.020
Materials	$0.025	$0.075

For a 124 grain 9 mm bullets with a 100 grain core:

	Lead	W-Sn
Core	$0.01	$0.12
Jacket	$0.04	$0.04
Materials	$0.05	$0.16

This analysis does not include manufacturing costs. Once a core is fabricated, the process by which the bullet is assembled is the same as that for lead-containing products. Lead cores are produced by extruding the metal into wire, cutting to length, and typically swaging to final shape and weight. The heavy non-toxic cores are fabricated from powdered metals which are blended and pressed to the desired shape and weight. Production costs for the powdered metal cores should be similar to those for the swaged lead cores. Therefore, a three fold increase in the cost of bullet raw materials does not necessarily result in a similar increase in the total cost of the bullet or for loaded ammunition. If a box of 50 loaded 9 mm rounds is $10.00, each round is $0.20. If the cost of the lead bullet is $0.05, and the non-lead is $0.16, the projected cost of the non-lead round is $0.31 which results in a 55% increase in price or $15.50 per box of 50. The cost comparison does not consider the full life cycle cost for the lead-containing ammunition. Additional expenses involved such as clean-up, ventilation, disposal, taxes, etc. are ignored. Once factored in, the real cost of using lead ammunition would likely be much greater.

The cost and availability of tungsten are of concern. Other than that used in the alloying of steel, tungsten is generally available as fine powder of very high purity. The market is driven by the applications, such as light bulb filaments and hard materials. Although a significant portion of the hard materials such as cutting tools are recycled, the cost of tungsten has risen. The recycling of the tungsten requires the same complex chemical process as used for ore. In fact, cutting tools are recycled to reclaim the valuable cobalt binder, not the tungsten. For the given applications, the cost of tungsten is not decreased through recycling.

The high purity, small particle size tungsten is not optimal for the fabrication of bullets. In contrast to the many other uses of tungsten powder, the non-lead core materials require coarse tungsten. In addition, the purity does not have to be extremely high, as long as the contaminants are not toxic or hazardous. Recycling of the tungsten from the powder metallurgy bullets will not require the same complex processing as for the other applications (e.g. complete dissolution, chemical separation, etc.). If handled properly, the tungsten could be recovered from the non-lead bullets by heating the scrap from the range in an inert or reducing environment. The binder metals melt a low temperatures, and do not wet the tungsten. The liquid binder metals could be melted and removed leaving tungsten powder that could be re-used almost "as is." Once in the cycle, the cost of the non-lead bullets will decrease.

CONCLUSIONS

A powder metal composite simulant for lead was used to fabricate bullets, which were subsequently tested, and results compared to those for the lead-containing analogs. Powdered metals were blended and cores pressed at room temperature without further treatment. Swaging procedures identical to those used for lead bullets were employed to fabricate pistol and rifle bullets. Unjacketed, soft-point, full-metal jacket, and open-tip designs were readily produced.

The performance of the bullets with the tungsten-tin non-toxic simulant for lead exceeded that of military ball pistol ammunition with a similar bullet weight. Pressures and velocities were found to be nearly identical to those for lead bullets of similar weight and construction. From the results, it appears that the non-lead bullets can be substituted one-for-one with the lead analogs.

Preliminary testing of the pistol bullets found that variation in bullet length were affecting pressure and velocity, and thus accuracy. Procedures were modified to use length and not pressure as a constant in the forming of the pistol bullets. Rifle bullet accuracy was also not as expected. Small fragments of core materials were found in the open cavity at the tip of the bullets. The addition of a small pure metal cap corrected this problem. It is believed that the powdered metal technology can be used to replace the lead in small caliber bullets of most any design or caliber.

Although the cost of the core material is presently greater than that of lead and lead alloys, this does not translate into significant increases in the "total cost" of ammunition. Ignoring manufacturing costs, a three to five fold increase in the cost of the bullet is projected. It is evident that this does not result in a similar increase in the cost of ammunition, for the bullet is only one component of the loaded cartridge. Accounting for all costs, including environmental, safety, and health issues, and establishing procedures for capture and recycle, it is believed that life cycle costs for lead-containing ammunition are significantly greater than predicted for the powder metallurgy non-toxic replacements.

REFERENCES

1. "EPA Proposes to Ban Lead and Zinc Sinkers," Morgan Simmons, *Knoxville News-Sentinel*, Sunday, March 13, 1994, p. C10.

2. "Polymer/Tungsten Shot,'" L. P. Brezny, *Handloaders Shotgun*, Special Edition 1992, pp. 30-34.

3. "Super Shot," B. Brister, *Field and Stream*, November 1990, pp. 76-80.

4. "The Steel Shot Controversy," James Fender, *Guns*, September 1988, pp. 38-40, 58-65.

5. "Why Steel Shot Opposition is Growing," Kevin E. Steele, *Guns & Ammo*, October 1989, pp. 76-80.

6. "Non-Toxic Shot Breakthrough!," Ross Seyfried, *Gun & Ammo*, December 1992, pp. 94-99, 107.

7. "The New Bismuth Non-Toxic Shot," Ron Forsyth, *The Double Gun Journal* 4(3), Autumn 1993, pp. 9-15.

8. "Experiences with Zincon, A Useful reagent for the Determination of Firing Range with Respect to Lead-Free Ammunition," Reginus Beijer, Journal of Forensic Science 39[4], 981-987 (July 1994).

9. "Ordnance Applications," S. Isserow, pp. 679-695 in the Metals Handbook, Ninth Edition, *Volume 7: Powder Metallurgy*, American Society for Metals, Metals Park, Ohio (1984).

10. "Kinetic Energy Penetrators," Thomas Penrice, Metals Handbook, Volume 7: Powder Metallurgy, *Powder Systems and Applications: Ordnance*, pp. 688-691, American Society for Metals, Metals Park, Ohio (1984).

11. Delta DFA, Lead-free frangible ammunition, tungsten and copper in Nylon, Delta Frangible Ammunition, 1235 Jefferson-Davis Highway, Suite 710, Arlington, VA 22202

12. GREEN SHIELD , lead-free frangible ammunition, tungsten and copper in Nylon, US Patent #5,237,930 issued August 24, 1993, Simunition Technologies, 366 Bruyere Street, Ottawa, Canada K1N 5E7

13. Vihtavuori Reloading Manual, Second Edition, Vihtavouri Oy, Gummerus Kirjapaino, Finland (1995).

MATERIALS SUPPLIERS

Tungsten: Osram Sylvania, Towanda, PA
Contact: David Vine

Tin: Pyron Metal Powders, Greenback, TN
Contact: Betty McNabb

Jackets: Berger Bullets, Glendale, AZ
Contact: Eric Stecker

Bullet Swaging Lubricant: Corbin Manufacturing, White City, OR
Contact: David Corbin

Die Lubricant: Stearic acid, Fisher Scientific

INVENTIONS MADE OR REPORTED

No inventions were made or reported.

COMMERCIALIZATION POSSIBILITIES

There are no plans to commercialize the results of this CRADA.

PLANS FOR FUTURE COLLABORATION

None

CONCLUSIONS

A powder metal composite simulant for lead was used to fabricate bullets, which were subsequently tested, and results compared to those for the lead-containing analogs. Powdered metals were blended and cores pressed at room temperature without further treatment. Swaging procedures identical to those used for lead bullets were employed to fabricate pistol and rifle bullets. Unjacketed, soft-point, full-metal jacket, and open-tip designs were readily produced.

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M98004585

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Report Number (14) Y/AMT--477

Publ. Date (11) 19970530

Sponsor Code (18) DOE/DP, XF

UC Category (19) UC-704, DOE/ER

DOE