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Viability of Bismuth as a Green Substitute for Lead in Jacketed .357 Magnum Revolver Bullets

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Viability of Bismuth as a Green Substitute for Lead in Jacketed .357 Magnum Revolver Bullets

by

Joel Jenkins

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering
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ABSTRACT

In seeking to develop environmentally friendly lead-free non-toxic bullets, the research ballistically evaluated the performance of copper-jacketed handgun bullets containing a pure bismuth core. The lead was first removed from 140 grain Hornady™ XTP® bullets of 38 caliber (.357 diameter) by melting. The empty jackets were then refilled with pure bismuth, including the forming of a correctly sized hollow-point cavity. Due to the lower density of bismuth as compared to lead, the bismuth-cored bullets consistently weighed 125 gains. Conveniently this allowed direct comparison to commercially available 125 grain Hornady™ XTP® lead-cored bullets of 38 caliber. Both bismuth-cored and lead-cored versions of the 125 grain bullets had identical nose dimensions and jacket material, the only dimensional difference being the bullet length below the cannelure. Shooting took place at an outdoor range using a 357 Magnum Ruger™ SP101® revolver with 3” barrel as the test weapon. FBI protocols were followed when firing through clothing, wallboard, plywood, steel plates and laminated glass. Wound paths and bullets were captured in ballistic gelatin, with data collected for velocity, penetration, expansion, and weight retention. Bismuth compared favorably with lead in all but the laminated glass test, where it under penetrated due to jacket separation.

CHAPTER 1: RESEARCH OBJECTIVE

Firearms fundamentally derive their destructive capability from kinetic energy. This energy is delivered to the target via a projectile or bullet. To maximize kinetic energy the bullet must be propelled at a high rate of speed (velocity) and possess a large mass. However, the bullet must also be rather compact so as to reduce drag during flight, facilitate penetration of the target, reduce weapon size and maximize magazine capacity. This combination of large mass with compact dimensions inevitably demands that bullets be constructed of dense materials. Such materials must also satisfy other demands such as cost constraints, obturation to adequately engage the rifling, expansion during terminal ballistics to avoid over penetration, and formability during high volume production.

Historically lead has been the material of choice for bullets. These are often jacketed with a thin copper overlayer to avoid barrel fouling, but lead remains the metal of choice for the bullet core. Lead has served as a near ideal bullet material for centuries, but it has now come under scrutiny because of one of its less desirable traits – toxicity.

Because of its known toxic nature, lead has now been banned in the US for shotgun cartridges used in the sport of waterfowling. It is perhaps only a matter of time before the use of lead in rifle or handgun ammunition also becomes more tightly regulated or even banned altogether.

Some manufacturers already offer “green” bullets as an alternative to lead, but these are usually made of pure copper throughout, which is 20% lighter than lead. The US military has explored the use of tungsten in bullets, but their work was discontinued following an accumulation of tungsten detected in groundwater in the vicinity around their testing range. The implications of this are poorly understood with very few studies having been undertaken to determine whether tungsten is benign or not.

The research presented here investigates the viability of the metal bismuth as a green substitute for lead in pistol bullets. Bismuth is not prohibitively expensive, has a low melting point, is only slightly less dense than lead (14% lighter), and is generally regarded as completely non-toxic. However it is harder and more brittle than lead.

The research goal was to evaluate bismuth’s suitability as a pistol bullet material by adopting it as a core material in jacketed revolver projectiles, and by ballistically comparing it to lead-cored bullets of equivalent weight using established FBI protocols.

CHAPTER 2: BACKGROUND

2.1 Lead and its Effects on the Environment

Lead is a heavy metal that has been known and used for centuries. It has been used in a variety of application including: solder, water pipes, roofing and flashing, as a paint additive, and for weights in fishing or scuba diving. It is now known to be an accumulative neurotoxin which the body has difficulty in excreting. It can affect the cardiovascular system, the immune system, the nervous system and more [1], [2]. In young children any source of lead can cause severe health effects [1], [2], [3]. For this reason lead is no longer used in paint and water pipes, and it is slowly being replaced in solder. Lead has been used for projectiles since the very first firearms were developed, but because of the health effects of lead shot on birds, the United States made a ban in 1991 on the use of lead shot for waterfowling [1], [3]. Lead based bullets used in rifles and handguns present less of an environmental threat, but shooting ranges have high volumes of lead exposure because numerous rounds are consistently shot at these locations. One research tested the soil from a Florida shooting range and found all samples had high levels of lead which exceeded the minimum acceptable limit [4]. When ammunition is fired and hits an object, it can fragment or expand, thereby exposing a high surface area to the elements, see Figure 1. These exposed rounds, if not removed and recycled, will decay over time contaminating the environment by leaching into soil and groundwater. Hunting for animals, as opposed to birds, usually involves few rounds over a very large area, and so the hazards are far less acute than at ranges. However it is not likely that legislators will distinguish between range shooting and

hunting, and so a comprehensive ban seems inevitable. For these reasons there is a need for non-toxic lead free options in ammunition [1].



Figure 1: 125 Grain Lead Hollow Point Bullet after being Shot

2.2 Lead Free Technology

Since the waterfowling ban on lead shot in 1991, there have been multiple lead free options developed [1]. Some lead free shots that are available are Hevi Shot™, bismuth, steel, and other metals. For solid rounds of the type used in rifles and handguns there are no restrictions as yet so lead still dominates the market. Recently, new solid copper bullets have started coming out with reasonable performance, no doubt in anticipation of future regulatory action.

2.2.1 Hevi-Shot™

Hevi-Shot™ is made from a proprietary alloy developed to comply with lead-free waterfowling requirements. Each shotgun shell contains many small typically round metal balls

inside of the hull. A typical shotgun shell has a metal base and a plastic hull that houses the shot, see Figure 2. Hevi-Shot™ alloy consists of tungsten, iron and nickel, is considered non-toxic and is approved for waterfowling use [5]. Studies found in 2003 that Hevi-Shot™ shot had no adverse effects on mallards (ducks) that were fed the shot for a thirty day trial [6]. In contrast the mallards exposed to the same dose of lead shot showed a 90% mortality rate with the first bird dying within just six days [6].



Figure 2: Hevi-Shot™ Shotgun Shells

2.2.2 Copper Bullets

Some companies, such as Barnes Bullets®, produce and sell pure copper bullets. Barnes™ was one of the first companies to make pure copper lead-free ammunition [7]. The Barnes™ VOR-TX® brand are pure copper bullets that are completely lead free, see Figure 3. Their 45 caliber 185 grain DPX™ bullet is another pure copper round which is a hollow point. Pure copper bullets are offered to take the place of lead since the environmental effects of copper are reasonably well known and considered non-toxic. However, copper is lighter than lead and

requires a deep hollow point construction in order to ensure expansion. Both facts result in longer bullets than their lead equivalent to achieve the same weight [8]. For example, a 140 grain .357 Barnes® pure copper hollow point bullet is 0.776 inches long. A lead Hornady™ 140 grain .357 hollow point bullet has a length of 0.600 inches.



Figure 3: Barnes™ VOR-TX® Pure Copper Bullets

2.2.3 U.S. Military's Tungsten-Nylon Bullet

Back in 1999 the United States military developed a new supposedly “green” (environmentally friendly) bullet, see Figure 4 [9]. This bullet was a tungsten-nylon bullet (tungsten powder in a nylon matrix) [9]. The military spent \$12m to develop a tungsten-nylon bullet along with a tungsten-tin bullet [9]. The caliber was 5.56x45mm NATO for use in the M16

platform standard issue rifle. This new green round was claimed to work as well as its lead counterpart [10]. By the year 2003 over half a million of these tungsten-nylon bullets were fired on ranges [9]. At that time people began to question the safety of the tungsten-nylon bullets. It was subsequently discovered that the tungsten powder used to make the bullets was breaking down [9]. Tungsten was measured in the water supply beneath the Cape Cod range, and it was found to have elevated and increasing levels due to the shooting of the tungsten-nylon bullets. Due to potential but unknown health risks from the increase in the tungsten levels, the tungsten-nylon bullet is no longer used by the military [11]. The manufacturing of these bullets also stopped which left many unused rounds in storage. In 2006 the military's supposedly green tungsten-nylon bullet stopped being used because of evidence of it effecting groundwater [9], [12].



Figure 4: U.S. Military's Tungsten-Tin Bullets

2.2.4 Military's M855A1 Bullets

Following the failure of their tungsten-based bullets, the US military tried to develop a bismuth-tin version in 2008, using an alloy similar to that used in green shot [13]. Unfortunately this material proved difficult to swag due to its low ductility, resulting in voids between the core and jacket. Since the 5.56x45mm NATO is a high-speed rifle bullet used over a relatively long range, the voids resulted in a loss of stabilization during flight [13]. Despite this setback, the use of bismuth in short-range, low-speed pistol rounds remains an untested possibility, especially if cast rather than swaged.

The United States military finally developed its first successful green bullet, designated the M855A1 Enhanced Performance Cartridge, by adopting a copper core and a steel penetrator [14]. The copper bullet weighs the same as the lead version at 62 grains [14]. Although, since copper is lighter than lead the bullet itself is longer by about 1/8 inch [14]. Even with an increased size of the bullet it can be pushed further into the brass case to make the overall cartridge length the same as the lead version [14]. Although this green round has proved successful for the military, it is destined to be banned for civilian use by BAFTE (Bureau of Alcohol, Firearms, Tobacco and Explosives) on the pretense that it is armor piercing and therefore a threat to law enforcement.

CHAPTER 3: MATERIAL OPTIONS

Lead is the current most common type of metal found in hollow point pistol bullets. To find a viable replacement, many materials were looked at with similar densities to that of lead. Lead has a density of 11.35 g/cm^3 [15]. Several heavy elements from the periodic table were examined, but many were eliminated due to toxicity, radioactivity, etc. The following is a list of possible elementary metals that could be considered as contenders.

- Tin density 7.31 g/cm^3
- Iron density 7.87 g/cm^3
- Copper density 8.96 g/cm^3
- Bismuth density 9.75 g/cm^3
- Silver density 10.5 g/cm^3
- Gold density 19.32 g/cm^3
- Tungsten density 19.35 g/cm^3
- Platinum density 21.45 g/cm^3

Obviously metals such as platinum, gold and silver are currently too costly to be a viable replacement for lead. That left some common materials such as tin, iron, copper, bismuth, and tungsten. Tungsten has a very high melting point, thereby limiting its use to powders. The possibility of making a tungsten bullet out of powdered tungsten and adhesive was looked into, but the apparent density of the tungsten powder became an issue. Since the U.S. military had already abandoned green ammunition using tungsten-nylon and tungsten-tin [9] it was not

considered further. Since bismuth is heavier than that of iron, copper, and tin it was decided to focus on and test the performance of a hollow point bismuth pistol bullet. Also, besides the density of bismuth (at 9.75 g/cm^3) being close to that of lead (at 11.3575 g/cm^3), it is also currently approved as a non-toxic shot [15], [16].

CHAPTER 4: BISMUTH

4.1 What is Bismuth

Bismuth is the 83rd element on the periodic table. Bismuth is obtained typically as a byproduct of refining lead, copper, and tin [17], [18]. Bismuth is considered a heavy metal. It has a silvery metal appearance as can be seen in Figure 5. It is a hard and brittle metal that has low thermal conductivity [14]. Many of bismuth's properties are summarized in Table 1 [15]. Bismuth has been used in many applications. One of these uses has been for solder as a non-toxic replacement for lead. Bismuth is also sometimes used to replace lead in fishing weights [19]. Also, bismuth can be used in making low melting temperature alloys. These low melting temperature alloys are used in products such as fire sprinklers and some fire alarms [17]. It is sometimes used for fuses because of the low melting temperature of the alloy [17]. There are other uses in pharmaceutical applications such as the product Pepto-Bismol™, which contains bismuth. Pepto-Bismol™ contains bismuth oxide salicylate as an active ingredient. Pepto-Bismol™ is used to relieve stomach problems [17]. Bismuth oxychloride is used in some cosmetic products for its coloration. Bismuth has also been used in shot as a replacement for lead shot [17].



Figure 5: Chunk of Solid Bismuth

Table 1: Properties of Bismuth

Atomic number	83
Atomic mass	208.9 g/mol
Ionic Radius	$0.74 \times 10^{-8} \text{ cm}^{-3}$
Density	9.8 g/cm^3 at 20°C
Melting Point	271°C
Boiling point	1420°C
Young's Modulus	$4.6 \times 10^6 \text{ psi}$

One interesting property of bismuth is how its oxide takes on an iridescent color. An example of this iridescent color of bismuth oxide can be seen in Figure 6. This iridescent color is

quite interesting and unique. Bismuth also has an interesting crystal structure. As bismuth cools from a liquid to a solid it starts forming square like structures as it solidifies. This phenomenon can be seen in Figure 6. If bismuth is cooled properly it can create very distinct shapes. Some people use these bismuth crystals as jewelry or decorations.



Figure 6: (Left) Oxidized Bismuth Iridescent Color, (Right) Square like Structure Forming in Bismuth

4.2 Bismuth Shot

Bismuth shot was invented in the 1980's in Canada by J. Brown [20]. This bismuth shot was advertised as an alternative shot to that of lead and steel shot [20]. In 1993 the Bismuth Cartridge Company™ started [20]. They made bismuth shot that consisted of 97% bismuth and 3% tin [20]. In 1997 the Canadian Wildlife Services approved bismuth shot as a non-toxic ammunition [21]. In 2007 the Bismuth Cartridge Company™ went out of business [22]. Companies such as Rio Ammunition™ (a Spanish based company) currently manufactures bismuth shot [22]. Rio Ammunition™ produced a shot that contains 94% bismuth and 6% tin [22]. The cost of these bismuth shells is \$19-\$21 per ten shells where a box of lead shot costs

around \$6 [22]. Currently in the United States bismuth based shot is a legal non-toxic shot. This shot is 97% bismuth and 3% tin. Other approved non-toxic shots are iron-tungsten shot, iron-nickel-tungsten shot, tungsten-bronze, copper clad iron, tungsten-tin-bismuth shot, along with quite a few more [16].

4.3 Bismuth Effects on the Environment

The effects that bismuth has on the environment has been looked into by multiple researchers over the years. Most of this research was testing bismuth shot, because bismuth shot is one of the main ways that this material would be left in the environment. Many of these studies have found bismuth to have low health risks for animals and the environment. In 1992 a study by Sanderson was conducted on the effect of bismuth shot on the health of mallards (ducks) [21]. This study of bismuth shot found that it did not provide any acute health risks to mallards [21].

Research was done in 1993 to test the effects of ingested tungsten-bismuth-tin shot on mallards [23]. This shot that was tested was 39.05% tungsten, 44.49% bismuth, 16.46% tin [23]. The test used a sample size of 40 mallards, half female and half male [23]. Radiography was used on one of the mallards and showed there was a reduction in shot inside the mallard between day 1 and 11. This test found on day 1 there were 258 countable pellets and on day 11 found only 114 pellets remained in the bird, this is a reduction of 56% between day 1 and 11 [23]. This research concluded that the tungsten-bismuth-tin shot was initially absorbed and then excreted by the bird and had no detrimental effect [23]. This along with other earlier research suggested at that time metal shot such as tungsten based shot and bismuth based shot were not harmful to the environment.

A study in 1996 took shot that was a metal alloy containing bismuth and placed it into water birds surgically [24]. This was done to investigate if birds were hit by this shot, would it cause any negative health effects on the test animals. This test was done over eight weeks. At the end of the study it was found that the shot had no toxic effect and did not create any lasting health impacts on these birds [24].

In 2003, a research study was conducted to find the background level of bismuth in wild birds [25]. There had not been much research on bismuth effects on the environment. In some past research they had a detection limit of 3.00 ppm or 5.00 ppm, which could skew data, modern detection levels of bismuth are closer to 0.05 ppm [25]. This study found no significant difference between bismuth build up in the muscles or in the liver. This research concluded that more research needs to be done on the topic of bismuth and its effect on the environment [25].

In Norway there was a hunting accident where a hunter got shot with bismuth pellets which were 93% bismuth [26]. Although doctors removed as much of the bismuth shot as possible they could not remove all of the shot. Doctors detected high levels of bismuth in the man's blood and urine following the accident. The hunter's maximum blood bismuth level was 38 nmol/L and the urine bismuth level was 1,300 nmol/L [26]. After several years the bismuth levels had decreased to 19 nmol/L in the blood and 720 nmol/L in the urine [26]. Normal bismuth levels are less than 0.05 nmol/L [26]. One conclusion that can be made from this accident is bismuth can become mobile if implanted in the body [26].

Another study consisted of implanting bismuth into rats which resulted in no significant elevation of bismuth in the first 2-4 months [21]. Although, after longer exposure of 12 months they observed increased levels of bismuth in the rats along with some health issues. Most former

studies had only observed animals for a couple of months, and so there is now a need to research the long term chronic effects of bismuth and to run tests for 12 months or longer [21].

Currently bismuth shot is still classified as a non-toxic shot because of its minimal toxicity and health risks. Bismuth is still found in products that are used on people such as Pepto-Bismol™ and cosmetics without causing any significant health risks. Bismuth shot is doing well as an alternative to lead shot for waterfowling. Overall, the research on bismuth has shown it to be much safer for humans and the environment than lead.

CHAPTER 5: MAKING THE BISMUTH BULLETS

5.1 Firearms Usage

Firearms use in the US falls generally into the following categories: Military, Law Enforcement, Hunting, Competition, Recreational, and Personnel Protection. The vast majority of weapon types used outside of the military are either: Shotguns, Long guns or Handguns. It is likely that any future ban on lead will be applied to all the above categories, with the possible exception of the military. In reality it is unlikely that bullets (as opposed to shot) present any real harm to the environment, as most shooting takes place at ranges where the lead is recovered from traps (indoor ranges) and berms (outdoor ranges) and subsequently recycled. When outside of a range, say during hunting, the number of rounds discharged is very small. Most game, such as deer, are taken with a single shot with the bullet generally remaining in the carcass prior to eventual recovery during butchering and dressing of the meat. Any future ban on lead will therefore more likely be politically motivated and introduced as a thinly veiled encroachment by certain anti-gun interests on second-amendment rights.

5.1.1 Choosing Test Weapon and Caliber

When it comes to developing a green substitute for lead, performance is of critical importance during situations where human life-or-death is involved, i.e. for law enforcement and personal protection. For this reason it was decided to concentrate the research on handguns, rather than rifles, and with weapons of modest barrel length. A 38 caliber hand gun was chosen

as the test weapon, because it is commonly used for home self-defense and carried by law enforcement as a reliable backup weapon. The specific test weapon was a Ruger™ SP101® double action revolver in .357 Magnum. This test weapon has a barrel length of three inches. This caliber is a popular weapon for self-defense and provides good stopping power.

5.1.2 Copper Jackets and Bullet Choice

A copper jacketed bismuth bullet was desired because of the following. First, bismuth has a higher Mohs hardness than that of lead. The Mohs hardness of bismuth is 2.5 compared to 1.5 for lead. Bismuth is also more brittle than that of lead. Having a copper jacket would protect the bismuth bullet from potentially breaking in the gun barrel, in turn protecting the barrel of the test weapon from undue wear or metal fouling.

Copper jackets are often drawn out from blanks of copper. This process works by first punching out a copper blank, which is a round disk of copper. The next step is to place the copper blank into a die and a press. The press forces the copper blank into the die which has a slightly smaller diameter than that of the blank. This draws out the copper creating the walls of the copper jacket. This process is repeated using dies with slightly smaller diameters. Over a many step process the walls of the copper jacket are drawn out till the copper blank transforms from a round circular disk to a cup like shape. This copper cup would then have a lead, or other metal, core placed in the copper jacket. The jacket would then be swaged so that it fits tightly against the metal core, often locked in place by a cannelure.

The idea of creating a custom copper jacket was considered, but another simpler way was devised. It was decided to take a premade copper jacketed lead bullet and melt the lead out of the copper jacket. By doing this it would not require using dies or a press. Also, by using a standard

commercially available copper jacket the test bismuth bullet would have the same size and shape as the original jacketed lead round. This would allow comparison between a manufactured jacketed lead-cored bullet and the custom fabricated bismuth-cored bullet. Therefore, it was decided to melt the lead out of a copper jacket. The XTP® jacketed hollow point lead-cored bullet manufactured by Hornady™ was chosen, as this is one of the most widely used revolver bullets in the U.S. It also has a proven performance.

5.1.3 Determining Weight of the Test Bullets

First a decision on what bullet weight to use was needed, some available XTP® bullet weights that work with the .357 magnum are 110, 125, 140, and 158 grain bullets which are the most common. Looking at the densities of bismuth at 9.8 g/cm^3 and lead at 11.34 g/cm^3 gives a conversion ratio from lead to bismuth of about 0.86. To determine the mass of lead that is in the copper jackets the weight of an empty jacket was subtracted from the overall bullet weight. After melting out the lead the average weight of a copper jacket for a 140 grains Hornady™ XTP® jacketed lead-cored bullet was 32.5 grains. This average was based on five measurements.

By knowing the weight of the copper jacket the lead weight can be determined easily. For the 140 grain the jacket weighs 32.5 grains so the weight of lead is approximately 107.5 grains (i.e. $140 - 32.5$).

Next the weight of replacing the lead core with a bismuth core was calculated by using the weight of the lead and the previously determined density ratio. The ratio between converting a mass of lead to an equivalent sized mass of bismuth is 0.86. Therefore, replacing the lead with bismuth in a 140 grain lead bullet with 107.5 grains of actual lead would give about 92.5 grains

of weight by bismuth (i.e. 107.5×0.86). A bismuth filled jacket from a 140 grain lead bullet would weigh a total weight of approximately 125 grains (i.e. $92.5 + 32.5$).

It was nothing more than fortuitous that a bismuth filled jacket from a 140 grain lead bullet weighed 125 grains. This coincidence allowed a direct comparison to a 125 grain XTP® lead-cored bullet because the lead and bismuth bullets both had the same overall weight. Both bullets had the same diameter and nose profile, and fit into the same brass casing. The bismuth bullet is just slightly longer than that of the lead 125 grain bullet since bismuth has a lower density. Figure 7 shows the size comparison between a 125 lead bullet and a 125 grain bismuth bullet.



Figure 7: (Left) 125 Grain Copper Jacketed Lead-Core Hollow Point XTP Bullet, (Right) 125 Grain Copper Jacketed Bismuth-Cored Hollow Point XTP Bullet

5.2 Getting the Copper Jacket

First a new Hornady™ XTP® 38 caliber (.357 inch diameter) 140 grain copper jacketed lead bullet was obtained, see Figure 8. Then the best method to remove all the lead was determined so that the 140 grain bullet's copper jacket is the only remaining part. Multiple methods were devised and tested to see which would work the best to remove the lead and leave a clean copper jacket, which would later be filled with bismuth to form the copper jacketed bismuth bullet.



Figure 8: New Hornady™ XTP® 140 Grain Lead Bullets

The first method that was tried was to set the bullet on an electrically heated hot plate, which is designed to melt bullet lead, with the hollow point facing up. After a few minutes of heating on the plate the lead became molten. While the lead was molten the copper jacket was gripped using pliers and then turned upside down and tapped on its side. This method was tried

and found that it got most of the lead out. One problem was as the lead melted and expanded the molten lead ran down the sides of the copper jacket and stuck there.

To stop the lead from dripping down the jacket it would need to be heated upside down, with the hollow point facing down. So a second method was devised to remove the lead from the jacket. One way to stop the lead from dripping down the sides of the case was to make an aluminum stand so that the bullet was held with the open end facing down, see Figure 9. This stand was designed so that the bullet rests in the top of the stand. As can be seen in the figure the stand had grooves at the base so that lead can flow out. Upon trying this method it was found the lead was clogging in the grooves and sticking to the sides of the interior walls and still leaving some lead in the jacket.



Figure 9: Aluminum Stand to Hold Hollow Point for Melting the Lead Out

A third method was to use a heat gun to heat up the bullet and to melt the lead out. A 1000 watt heat gun was used to heat up the bullet, see Figure 10. The bullet was held by a piece of metal wire wrapped around the cannellure and strung between bricks with reflective aluminum

foil in-between, see Figure 11. With this method it would take about 30-60 seconds to liquefy the lead and with a couple of taps against the back of the bullet the molten lead would run out leaving a clean empty jacket. This method kept the bullet clean and was quicker than the other methods. Therefore this method was selected.



Figure 10: 1000 Watt Wagner Heat Gun



Figure 11: (Left) Bullet Held by Metal Wire, (Middle) Bullet in Place Wire Held by Bricks, (Right) Full Heating Setup

5.3 Casting Bismuth Bullets

The method of getting the bismuth into the empty copper jacket had to be determined. Different methods were tried to ensure a consistent bismuth bullet. The bullets needed to be filled evenly with bismuth so that no voids form. If voids form it would create an unbalanced bullet. If an unbalanced bullet was shot it would greatly reduce accuracy and precision of the round. Therefore, a method that would allow for easy casting of the bismuth into the bullet and that would create a reasonably consistent result needed to be determined.

5.3.1 Methods to get Bismuth into the Jacket

After the bullets were heated and the lead removed the next step was to get the bismuth inside of the empty copper jackets. There were multiple ways considered. The first method was to pour the molten bismuth directly into the jackets by hand. It was decided that this method would require too much hand eye coordination and the fact that most likely bismuth would spill.

A second method considered was to use a metal funnel to guide the molten bismuth directly into the jacket. This method had similar issues to the first. A funnel would have to be held carefully over the opening of the jacket. When pouring the bismuth into the funnel it would have to be held in place until the bismuth cooled and turned into a solid. This posed problems one being that once the bismuth cooled there would be hardened bismuth in the funnel, which could prove difficult to remove. Another issue was there would need to be a tight seal between the funnel and jacket so that no liquid bismuth would leak out.

Another idea was to use plaster of paris to make a mold around the jacket. This mold would create a static funnel into the casing. This method would solve the issues of the second

method. Also, upon testing these methods, this method gave the most consistent results. Therefore this method was chosen because it would allow for easy casting of the bismuth bullet.

5.3.2 Bullet Casting Aluminum Funnel Tool

To create the mold for casting the bismuth a conical shape tool was made, see Figure 12, to create a funnel in the top of the mold. This tool was machined on a lathe. First a conical shape was cut in the aluminum shaft reducing it to a size a little larger than the opening of the copper jacket. Then a stepped cut was turned on the tip so that it would just fit into the opening of the jacket. With this cut it created a shoulder that rests on the lip of the jacket that can be seen below in Figure 12.



Figure 12: Ruler Measures Centimeters, (Left) Cone Casting Tool, (Middle) Top View of Cone Tool, (Right) Cone Tool Resting on Copper Jacket

5.3.3 Making Plaster Molds

The empty copper jacket, which is from a Hornady™ XTP® .357 140 grain bullet, was placed into a disposable plastic cup with the opening of the jacket facing up. The metal funnel was placed on the jacket so it plugs the opening in the copper jacket, see Figure 13. At this point

it was ready for plaster of paris to be poured around the bullet to encase the bullet and create a mold so that casting the bismuth is easier.

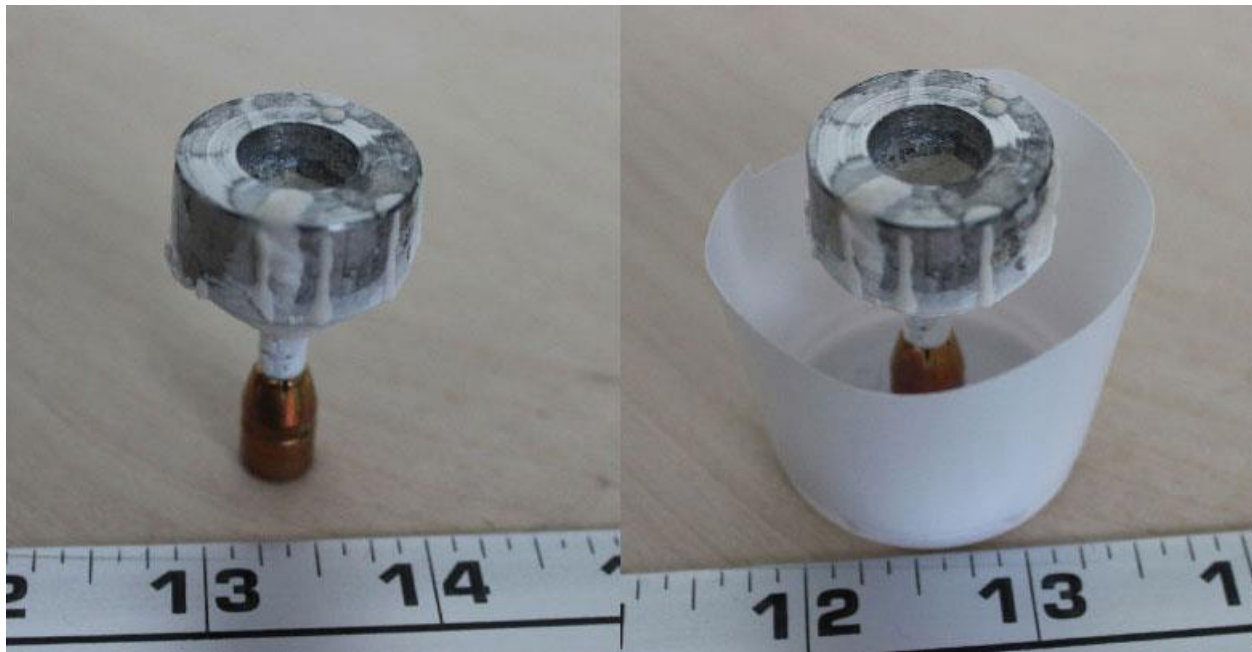


Figure 13: (Left) Metal Cone Tool Resting on Jacket, (Right) Jacket and Cone Tool Assembled in Plastic Cup

The plaster of paris was mixed following the instructions provided by the manufacturer. The plaster was mixed using two parts plaster of paris powder and one part water. This was mixed until the powder thoroughly mixed with the water leaving no clumps. Then the liquid plaster mix is poured around the bullet and metal cone, the level of the plaster comes up to the edge of the cone portion of the metal cone tool.

The plaster was left to dry for 12 hours. After the 12 hours the plaster is fully hardened. The metal funnel was removed from the plaster mold by pulling it up and out of the plaster. The next step was to bake the mold to remove the remaining moisture from the mold, if all moisture is not removed from the plaster it could cause the mold to crack or break upon coming into contact with liquid metal. The plaster mold was baked at 275°F for two hours. Once the two

hours had past, the temperature was turned up by 25°F and left to heat for an additional five minutes. This process of turning the temperature up by 25°F and waiting five minutes was repeated until the temperature reached 500°F. Once the heating was done the mold was allowed to cool and was then ready for casting metal see Figure 14.



Figure 14: Plaster Mold with Jacket Entombed Inside

5.3.4 The Heating Crucible

To heat and melt the bismuth a 120 volt, 500 watt Lee Precision Melter™ was used, see Figure 15. This heating crucible is designed to melt bullet lead. Since bismuth melts at a similar temperature to lead the Lee Precision Melter™ worked to melt the bismuth. This crucible does not have exact temperatures, it was numbered from low to high with numbers in-between. Therefore, any references to temperature of the heater will be given in numbers from one to ten.



Figure 15: Lee Precision Lead Melter™

5.3.5 Hollow Point Tool

A custom tool was made to create the hollow point in the end of the bullet. This tool was machined from a rod of aluminum, see Figure 16. First a cut was made to reduce the lower portion of the tool to slightly larger than that of the copper jacket's opening, so that it would rest on the top of the jacket without falling into it. Then the tip of the tool was reduced to a size that would just fit into the jacket's opening. This portion that would fit into the jacket was then shaped into a dome shape of the hollow point. This was done by using emery cloth and a lathe to slowly remove material until it was the right shape. The shape of the hollow point was determined by taking a 125 grain Hornady™ XTP® .357 bullet, cutting it in half and comparing the tool shape to the cavity of the actual bullet, until they matched. Then two cuts were made on

the sides of the tool near the tip. This was done to let bismuth run out while the bismuth was cooling. It should be noted that bismuth has the unusual property of reverting to a smaller volume when molten. It therefore expands upon solidification in a similar manner to water.



Figure 16: Hollow Point Tool Shown With Sectioned Bullet

5.3.6 Bismuth Casting Procedure

Equipment needed for the casting process is as follows Lee Precision Melter™, plaster mold with bullet copper jacket inside, solid bismuth metal, a ladle or container for holding and pouring the liquid metal bismuth.

The first step was to take the mold turn it upside down and shake it to make sure the copper jacket is empty, because the dried plaster tends to flake off and fall into the jacket. After that the solid bismuth metal was placed into the ladle and the bismuth was heated in the crucible. The temperature on the heating crucible was set between five and six, which took about 9 minutes to melt the bismuth metal. Once the bismuth had melted into a liquid, it continued to be heated for an extra minute to make sure the bismuth was fully liquefied.

Once the metal was liquefied fully it was poured into the mold making sure to pour the molten bismuth slightly offset from the sprue to reduce possible air bubbles getting trapped in the cast metal. Immediately after pouring the molten bismuth into the mold, the side of the mold was tapped five to six times to help remove any air bubbles trapped in the bismuth. The mold was allowed to cool down, this took approximately 10 to 15 minutes.

Once cooled the plaster mold was split open and the bismuth bullet was removed from the plaster, see Figure 17. At that point the bullet had a bismuth neck that stuck out of the copper jacket (nicknamed a “mushroom” due to its characteristic shape). The neck portion of the bismuth that comes out of the bullet was cut off with a saw so that the bismuth was smooth with the top of the copper jacket. The weight of the bullet was checked to make sure it was clear of any voids. The bullet should weigh 125 grains or more if it weighs less than 125 then there are most likely voids in the bullet. These voids would be problematic if in the final bullet, because it would reduce weight and make the bullet unbalanced. One such bullet can be seen in Figure 18.



Figure 17: Split Plaster Mold Showing Freshly Cast Bismuth Bullet with “Mushroom”



Figure 18: Bismuth Bullet with Voids

Once the neck of bismuth was cut off the bismuth bullet was ready for a hollow point. The bismuth bullet was placed into the crucible with the nose of the bullet facing up. The hollow point tool was held in a drill press to make sure it was stable. The Lee Precision Melter™ with the bismuth bullet was placed below the hollow point tool, see Figure 19. The heating crucible temperature was set between six and seven. It took about 3.5 minutes to become pliable. The bismuth was checked frequently to see if it was pliable by tapping the top of the bismuth with the hollow point tool. Once pliable the hollow point tool was pushed into the bullet. If the bullet was heated too long the bismuth would bubble up and run out of the bullet making it too light.



Figure 19: Starting Hollow Point Procedure

Once the hollow point tool was in place the heat was turned off and the bullet was left to cool. Some of the bullets ended up cracking because bismuth expands upon cooling. These cracked bullet were not used. Once the hollow point was added the new 125 grain bismuth bullet was complete. 40 such bismuth bullets were successfully created with each given a unique ID number, see Table 2. Every bullet was inspected, measured for accurate sizing and carefully weighed to ensure no voids were present. Light and swollen bullets were rejected. Generally the bismuth bullets had a diameter within $\pm.0005$ of the desired .357 dimension.

Table 2: All Bismuth Bullets Made with their ID Numbers

Bullet ID #	bullet weight (grain)	comment	Bullet ID #	bullet weight (grain)	comment
1	no hollow point		21	no hollow point	
2	122.5	too light	22	125.3	
3	125.5		23	125.7	
4	124.4		24	no hollow point	
5	125.5		25	124.7	
6	124.3		26	124.2	
7	124.6		27	124.9	
8	125.6		28	125.3	
9	124.9		29	125.8	
10	124.2		30	127.7	Bulging
11	125.5		31	125.8	
12	117.4	voids	32	125.2	
13	120.4	too light	33	125.5	
14	123.5	too light	34	126.6	
15	118	too light	35	126.5	
16	116.3	too light	36	126.6	
17	122.3	too light	37	125.8	
18	124.1		38	125.4	
19	125.5		39	125.5	
20	no hollow point		40	127.2	Bulging

CHAPTER 6: RELOADING BULLETS INTO CARTRIDGES

To be able to shoot the newly made bismuth bullets they must be loaded into brass casings with gunpowder. First an empty .357 magnum brass casing was obtained. These were Winchester™ brand. Then the proper equipment was needed to reload the bullets such as a press, dies, priming tool, scale, gunpowder and more [27]. The first main piece of equipment is a press. In this research a Lee Precision™ press was used, see Figure 20. This press uses dies to make it work. There are four dies that are used in reloading which are the sizing die, expander die, seating die, and the crimping die. These dies need to be designed for the right caliber, in this case the dies were for .357 magnum rounds, see Figure 21 [27].

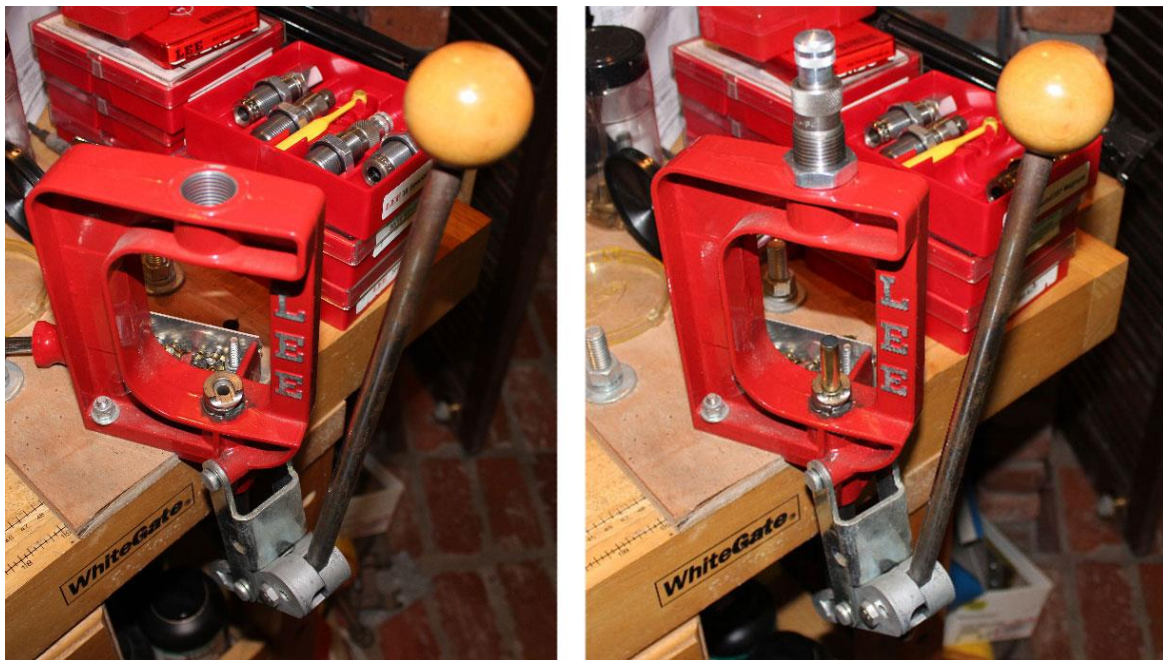


Figure 20: Lee Precision™ Press (Left) Empty Press, (Right) Press with Brass Case and Die



Figure 21: (Left to Right) Crimping Die, Seating Die, Yellow Gunpowder Scoop, Sizing Die, Expander Die

The first die used was the sizing die. This die was used to size the diameter of the brass casing, which is a Winchester™ .357 magnum brass case, see Figure 22 , along with removing any used primer from the brass casing [27]. This was done by setting the brass casing into the press, see Figure 20, and then the lever was pulled down accomplishing both these steps at one time. After the primer was removed from the brass the next step was to use the expander die to flair the neck of the brass. This was done so that the bullet can rest in the brass case preparing the bullet to be set. A trimming tool was used to trim the brass casing. This was done to make the brass the proper length because firing a cartridge can result in the internal pressers stretching the casing slightly, that is why trimming is necessary [27].



Figure 22: Winchester™ .357 Magnum Brass Casing

Next a new primer was inserted into the primer pocket using the priming tool, see Figure 23. This was done by placing the brass case and the primer in the tool then squeezing the lever to push the primer into the primer pocket of the brass casing. The primer's purpose is to ignite the powder when the primer is hit by the firing pin [27]. For this research the Winchester™ small pistol magnum WSPM primers were used on all test rounds, see Figure 24. Setting the primer can be dangerous because it is reasonably easy to set the primer off [27]. For this reason the primer was always set before any gunpowder was placed in the case [27].



Figure 23: Priming Tool for Adding a Primer to the Brass Casing

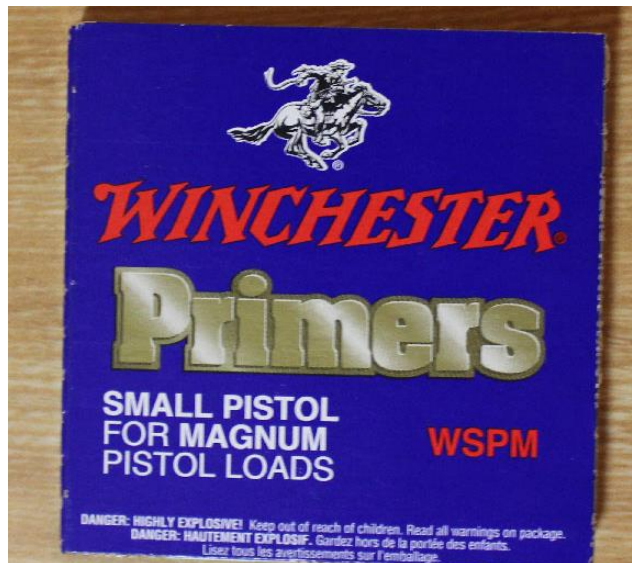


Figure 24: Winchester™ Pistol Primer for Magnum Pistols

The next step was to add powder into the brass casing. Since the 125 grain lead bullet is being compared to a 140 sized bismuth bullet which weighs 125 grains it was desired to find a powder amount that would fit in the brass case for both bullet sizes and have sufficient speed.

For a bullet to mushroom it is ideal to have a velocity greater than 1000 fps. To determine what

powder and amount to be used the Hodgdon™ 2009 Reloading magazine was reviewed [28]. It was decided to use 9.1 grains of Hodgdon™ Longshot® powder see Figure 25. This volume of powder was chosen because a 140 grain lead XTP .357 magnum bullet only leaves enough spacing in the casing for 8.0 to 9.1 grains of Longshot® powder [28]. While a 125 grain lead bullet can successfully be propelled by 8.7 to 9.7 grains of Longshot® powder [28]. Therefore, 9.1 grains of gunpowder was safe to use for the 125 grain lead bullet but would still fit in the reduced casing volume below the longer 125 grain bismuth bullet. The 9.1 grains of Longshot® powder is capable of propelling a 125 grain bullet to around the speed of 1500 fps out of a ten inch barrel [28].



Figure 25: Hodgdon™ Long Shot® Gunpowder

After the powder was poured into the brass casing the next step was to set the bullet to the correct depth. The brass was set in the press and the bullet was placed on top of the casing mouth. The seating die was screwed into the press and the bullet was then seated into the brass casing so that the cannellure groove was aligned with the top of the brass casing [27]. The final

step was to use the crimping die to crimp the top of the brass case into the cannelure groove so that the bullet is firmly in place and will not fall out of the brass [27].

CHAPTER 7: TESTING PROCEDURE AND EQUIPMENT

7.1 Ballistics Testing

A method for testing the performance of the new bismuth bullet was needed. The ballistics performance of a bullet is separated into three main sections which are interior ballistics, exterior ballistics and terminal ballistics. Interior ballistics is the behavior of the bullet while it's still in the gun including when the bullet is traveling down the barrel. Exterior ballistics is the behavior of the projectile while traveling through the air. Finally terminal ballistics is how the projectile performs upon impacting a target. Tests were devised to evaluate the latter two types of ballistics.

Some of the key factors of bullet performance are the speed of the bullet, the stability of the bullet while flying through the air, and how far it penetrates and damages the target upon impact. To test how the bismuth bullet performs while flying through the air a group of bismuth bullets were fired into paper targets. If the group of bullets had a tight grouping this would suggest the bullets are stable while in flight. Although to find exactly how the exterior ballistics behave would require high speed video, which was not available.

To test the terminal ballistics of the bismuth bullets a standard method was needed. One such method is the FBI's standard ballistics test. This test was designed to consistently test the terminal ballistic performance of rounds as used by law enforcement. The FBI standard ballistics test has been adopted by industry because of its effectiveness in predicting the behavior and performance of bullets under real world situations.

7.2 FBI Standard Ballistics Test

To test the effectiveness of the bismuth bullets the FBI standard ballistics protocol was used. This includes six different tests [29], [30]. These involve shooting through various barriers and on into ballistic gelatin over a range of 10 feet. For a bullet to be considered reliable it must have a minimum of 12 inches of penetration in all tests at any angle [29], [30]. A penetration of 18 inches is preferred [29], [30].

The first test is shooting into “bare” 10% ballistic gelatin with no barrier [29], [30]. The crown of the muzzle must be positioned at 10 feet from the front face of the gelatin block. This is done to gather baseline information and to provide a reference to all the other tests [29], [30].

The second test is shooting at gelatin with thick clothing over it. This thick clothing consists of one layer of cotton t-shirt material (5.25 oz/yard), one layer of cotton shirt material (3.5 oz/yard), one layer of fleece (such as Malden Mills™ Polartec® 200 fleece), and one layer of denim (14.4 oz/yard) [29]. These materials are placed directly onto the front of the gelatin [30].

The third test is to shoot through two pieces of 20 gauge galvanized steel which are hot rolled [30]. The two plates are set 3 inches apart from each other. There must be 10 feet from the muzzle crown to the front of the first steel sheet. Three inches behind the first plate is the second plate of steel. Finally the gelatin block with light clothing is placed 18 inches behind the second plate [29].

The fourth test uses two pieces of 1/2 inch thick gypsum wallboard set 3.5 inches apart. The gelatin is again covered with light clothing [29]. The gel is 18 inches in back of the rear

piece of wallboard. The end of the muzzle of the gun is 10 feet from the front of the first board [29], [30].

The fifth test uses one piece of 3/4 inch thick AA Fir plywood. The gelatin is covered in light clothing [29], [30]. The gelatin is 18 inches from the back of the wood. There is 10 feet from the front of the wood to the muzzle of the gun [29], [30].

The sixth test is to shoot through one layer of auto glass which is 1/4 inch thick laminated glass. The glass is placed at 45° from the horizontal and the glass is turned 15° to the side. The gelatin covered with light clothing is 18 inches in back of the glass [30]. The muzzle is 10 feet from the center of the glass plate [29], [30]. The layout of the six tests can be seen in Figure 26.

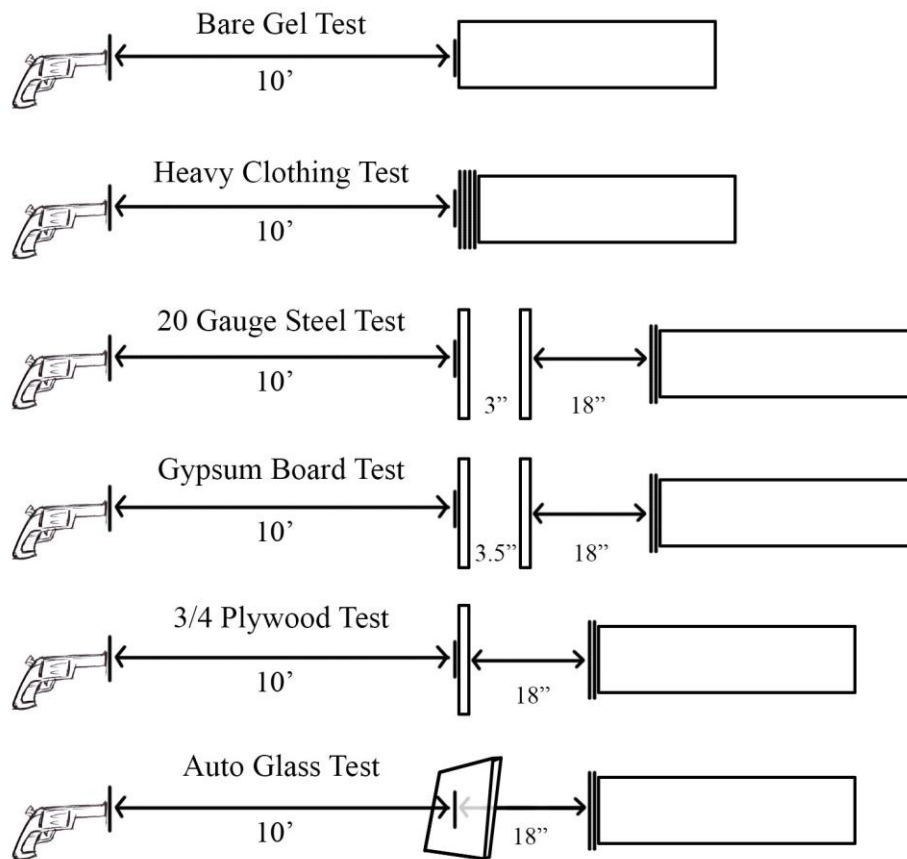


Figure 26: FBI Ballistics Test Setup

7.2.1 Measurement of Ballistics Data

Penetration depth was measured by measuring the distance from the front of the ballistic gelatin, where the bullet entered, to the end of where the bullet stopped [29], [30]. Also once the bullet was recovered the retained weight was measured, and the expansion of the bullet was measured by averaging the maximum and minimum diameters of the bullet [29], [30]. Finally the velocity of each bullet was measured and recorded [29], [30].

7.3 Ballistic Gelatin

To test the penetration of bullets and other projectiles often they are shot into a type of gelatin that simulates human flesh. The FBI has developed standard testing procedures to test ballistics, which are used to test the effectiveness of weapons. The FBI uses a ballistic gelatin block that is made of 10% weight gelatin (90% water) with dimensions of 16 inches long by 6 inches high by 6 inches wide [31]. The FBI protocol uses an organic gelatin, but this is known to be sensitive to heat. The company Clear Ballistics™ sells a synthetic block that is equivalent to the FBI standard ballistics block, see Figure 27 [31]. According to Clear Ballistics™ their 10% ballistic gelatin is calibrated with a .177 caliber bb that is shot at 590 fps plus or minus 15 fps and penetrates the block 2.95 inches to 3.74 inches [31]. According to the FBI standard this is the same calibration of the 10% organic gelatin that is used for the FBI standard ballistics test [29], [31]. This Clear Ballistics™ gelatin was used in this research to determine the effectiveness of the bismuth bullet [31].



Figure 27: Clear Ballistics™ 10% Gelatin

One advantage of using Clear Ballistics™ 10% ballistic gelatin was that the gel is reusable [31]. After shots have been fired into the block, the block can be melted down and reformed. Once reformed the block can be used again. Although according to Clear Ballistics™ the block can only be melted so many times before it begins to discolor. The gelatin was reformed by first cleaning the surface of the ballistic gelatin with soap and water. After the gelatin dried it was cut into pieces and any debris was removed from the ballistic gelatin, discarding any gel that was highly contaminated. The cut up pieces were washed to further remove any remaining residue. All the pieces were thoroughly dried before moving on, because if the pieces were not dry the extra moisture could change the calibration of the block. After most of the debris was removed it was ready to be re-melted. The ballistic gelatin was heated to 270°F, making sure not to exceed 280°F or the block will discolor. Once the gelatin was completely liquefied, the liquid was poured into the mold (obtained from Clear Ballistics™), which is sized to reform the gelatin block, see Figure 28. Next the bubbles were removed from the gelatin by heating the mold with the gelatin at 265°F for 2 to 4 hours. The final step was to let it cool for at least 12 hours and then it was ready to be removed from the mold and used.



Figure 28: Clear Ballistics™ Gelatin Reforming Mold

7.4 The Test Weapon

The test weapon which all shots were fired from was the Ruger™ .357 Magnum SP101®, see Figure 29. This gun is an all stainless steel double action revolver with a five shot capacity and a 3 inch barrel. This gun has a robust design to handle .357 magnum loads. The SP101® is a little too large and heavy for concealed carry, but it is commonly kept in the home for self-defense, and carried by law enforcement as a reliable backup weapon. This model has solid side walls (no removable plate), an offset cylinder lock and crane latch, all of which make the SP101® very durable.



Figure 29: Ruger™ SP101® .357 Magnum Revolver

7.5 Ransom Rest®

A rest was used to hold the gun for the target shooting. The rest used in this research was the Ransom™ Master Series® rest, see Figure 30. This rest is designed to securely hold the gun while allowing recoil motion. After shooting the gun can be returned back to its original position for the next shot. This is done to ensure all shots are fired at the same angle and position.

This rest is designed to mimic a shooter, but with more consistency. The rest is designed with a pivot so that when the gun is fired it will pivot with the recoil. This is done to simulate the wrist of a shooter. It also has an adjustable screw that controls the angle from the horizon where the gun is aiming. This type of rest is standard equipment and practice when assessing the accuracy of firearms and their associated ammunition.



Figure 30: Ransom Rest®

7.6 PVC Holding Stand for Materials

In addition to the FBI standard protocol it was felt that additional insight might be gained by supplementary water bag testing. This involved shooting into a row of water filled zip-lock bags. A universal rig was designed to hold the water bags as well as the targets, and the various materials that would be involved in the FBI testing, see Figure 31. The rig was made of 1.25 inch PVC tubing, 0.25 inch steel rods to hold the targets, PVC joints, and various clamps to hold up the materials, see Figure 32. The overall size of the rig was 5 feet long by 19 inches tall by 15 inches wide. The long PVC side pieces had holes drilled along them at a 3 inch spacing over a length of approximately 28 inches. These holes were drilled to hold the 0.25 inch steel bars. Two other zones were incorporated that provided attachment points for the various barriers required with the FBI standard ballistics test.



Figure 31: PVC Holding Rig Holding Water Bags



Figure 32: PVC Rig for Holding Target Materials (Left) Front View, (Right) Side View

7.7 Chronograph

To measure the speed of the bullets a ProChrono™ digital chronograph was used, see Figure 33. This chronograph is designed to measure the speed of projectiles with high accuracy. This chronograph can measure speeds from 21-7000 fps. Accuracy of the chronograph is plus or minus one percent of the velocity that was measured. This chronograph has internal memory that can store nine strings and each string can have up to 99 data points. The FBI testing protocol requires that the chronograph be positioned at 5 feet from the muzzle crown. This avoids false reading due to rapidly expanding propellant gasses escaping the barrel muzzle.



Figure 33: ProChrono™ Digital Chronograph

7.8 Targets

For testing the accuracy of the bullets Dirty Bird™ 8 inch bull's eye paper targets were used. This target is an 8 inch disk on a square background which provides enough space to easily

hit the target. The target can be seen in Figure 34. This target has a white splatter effect to make seeing where the bullet hit easy. These targets were chosen because of the clear contrast they have between where the bullet hits the target and the surrounding area. This in turn made it easier to see and analyze the accuracy.



Figure 34: Dirty Bird™ 8" Target

7.9 Laser Bullet Bore Sight

A laser bullet bore sight was used during the test to increase accuracy of the shots, see Figure 35. The laser is designed to fit into a gun and has the same dimensions as a .357 magnum cartridge. Once loaded in the chamber, the laser will shine directly down the barrel of the weapon. This shows exactly where the gun is aiming.



Figure 35: Laser Bullet Bore Sight

7.10 Shooting Apparatus Setup

The outdoor shooting setup for performing the standard ballistics test is shown in Figure 36. For the FBI standard test two blocks of ballistic gelatin were set on a table. Double blocks were used instead of a single block to guarantee bullet capture should penetration exceed 16 inches. The chronograph was placed centrally, 5 feet from the muzzle of the gun and 5 feet from the front of the gelatin or material that was to be shot through. For shooting through steel, wood and gypsum board the PVC materials holding rig was set in front of the gelatin to hold the various materials that were to be shot through. The rig was not necessary for bare gelatin and clothing tests. For heavy clothing the layers of clothing were draped over the front of the gelatin block. The auto glass required extra setup because the glass needed to be 45° up from the horizontal and 15° to the side. This was accomplished by connecting two angular-cut wooden blocks to the tabletop and attaching the glass in place with adhesive tape, see Figure 37.



Figure 36: Shooting Apparatus Setup



Figure 37: Auto Glass Setup

7.11 Scales

All bullets, gun powder, and other various components needed to be accurately weighed.

For this research two different scales were used. One was the Lee Safety Powder Scale®, see

Figure 38. This scale was used to measure out the powder when reloading the bullet. This scale is designed to precisely measure gunpowder. The Lee scale has a sensitivity of 1/20 of a grain. Its scale is capable of measuring values form 0 to around 100 grains of weight.

For everything else the Frankford Arsenal™ digital reloading scale was used, see Figure 39. The Frankford Arsenal digital scale is capable of weighing up to 750 grains and has accuracy of ± 0.1 grain. This scale was used for measuring all bullet weights, retained weights and to double check the powder weight.



Figure 38: Lee Safety Powder Scale®



Figure 39: Frankford Arsenal™ Digital Reloading Scale

7.12 Distance Measurements

To measure distances a variety of yard sticks, rulers, and tape measurers were used for apparatus setup and penetration data. A digital caliper was used for measuring the expansion of the bullets and finer more detailed measurements, see Figure 40.



Figure 40: Digital Calipers

CHAPTER 8: RESULTS

8.1 Accuracy Test of Bismuth Bullets Compared to Lead Bullets

There were four bismuth bullets and four lead bullets fired into targets. There was 10 feet between the gun and the targets. Figure 41 shows the grouping of both lead and bismuth bullets. Figure 42 shows a close up of the holes in the targets created by the bullets. The radius of the grouping can also be seen.



Figure 41: (Left) Four Bismuth Bullets Shot into a Target from Ten Feet, (Right) Lead Rounds Shot under Similar Conditions

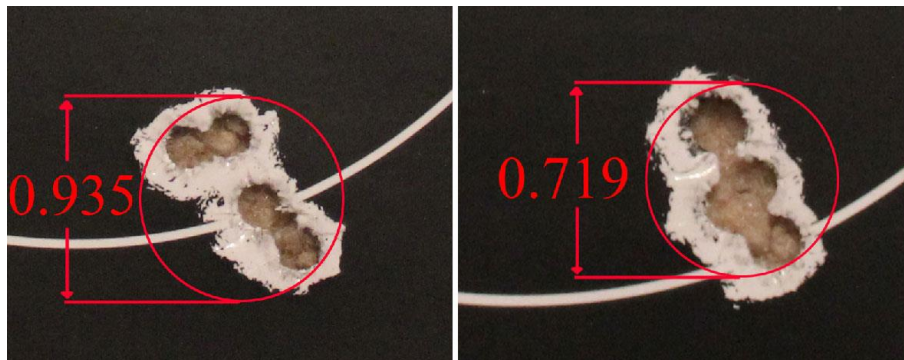


Figure 42: (Left) Bismuth Bullets Grouping, (Right) Lead Bullets Grouping

Table 3: Weather Data for Target Shooting

Weather data	
Date	6/2/2014
Condition	Overcast
Temperature	84°F
Humidity	45%
Wind	E 7 mph
Barometer	30.1 in-Hg
Visibility	10 miles
Bearing of gun	126° South East

Table 4: Bullets Shot into Targets

Bullet speed & weight		
Bullet type and ID	Bullet weight (grains)	Speed in (fps)
Bismuth bullet #3	125.4	1249
Bismuth bullet #5	125.4	1235
Bismuth bullet #11	125.2	1236
Bismuth bullet #19	125.2	1234
Lead bullet #1	125	1239
Lead bullet #2	125	1176
Lead bullet #3	125	1177
Lead bullet #4	125	1167

Table 3 has a list of all the weather conditions for the day of shooting into targets along with the bearing of the gun.

Table 4 shows the data for the eight bullets fired into targets on June 2, 2014. This table contains each bullet's velocity along with the original weight of all the bullets.

8.2 Shooting into Water Bags

Four bismuth bullets and one lead bullet were fired into water bags. This was done to get preliminary information on the general behavior of the bismuth bullet along with penetration. The lead bullet was fired to have a comparison to the bismuth bullets. Table 5 shows the weather data for the day of shooting into water bags along with the bearing of the gun. Table 6 contains the initial weight, velocity, and the penetration of the bullets.

Table 5: Weather Data when Shooting into Water Bags

Weather data	
Date	5/20/2014
Condition	Mostly sunny
Temperature	80°F
Humidity	66%
Wind	NE 4 mph
Barometer	30.2 in-Hg
Visibility	10 miles
Bearing of gun	126° South East

Table 6: Bullet Penetration into Water Bags

Bullet speed, weight, penetration			
Bullet type	bullet weight (grains)	Speed in (fps)	Penetration (inches into water)
Lead bullet #5	125	1135	21
Bismuth bullet #4	124.2	1259	33
Bismuth bullet #7	124.5	1195	30
Bismuth bullet #25	124.5	1218	27
Bismuth bullet #27	124.5	1223	21

8.3 FBI Ballistics Test Results

To test the overall penetration effectiveness of the 125 grain .357 bismuth bullet the FBI standard ballistics test was done. This test is designed to measure the penetration of bullets through many common materials. This test was developed by the FBI to standardize how ammunition is tested.

8.3.1 Bare Ballistic Gelatin

This test consisted of shooting bullets into bare ballistic gelatin from 10 feet away. There was one bismuth bullet fired along with one lead bullet. Table 7 contains the weather conditions on the day of shooting along with the bearing of the gun. Table 8 contains the weight of the bullets before and after shooting, along with penetration, average expansion and the velocity of the bullets.

Table 7: Weather Data for Shooting into Bare Ballistic Gelatin

Weather data	
Date	1/16/2015
Condition	Mostly sunny
Temperature	63°F
Humidity	63%
Wind	NW 6 mph
Barometer	30.14 in-Hg
Visibility	10 miles
Bearing of gun	95° East

Table 8: Ballistics Data for Lead and Bismuth Bullets into Bare Gelatin

Bullets shot into bare gelatin		
	Bismuth bullet #32	Lead bullet #6
Bullet weight before shooting	125.2 grains	125 grains
Bullet weight recovered	111.8 grains	116.4 grains
Velocity	1221 fps	1125 fps
Penetration (where bullet stopped)	19.50"	17.50"
Expanded diameter of bullet	0.453"	0.454"

Figure 43 is a side view of the ballistic gelatin which contains both bullets. Figure 44 shows a top view of the ballistic gelatin with both lead and bismuth bullets inside.

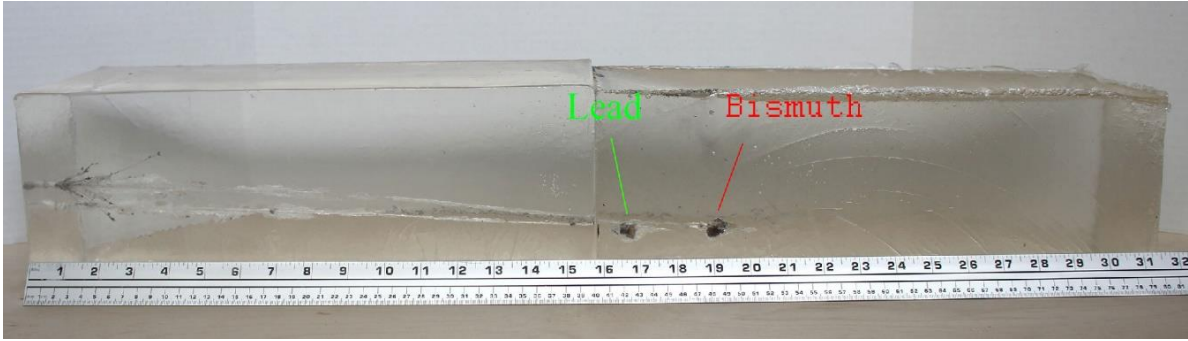


Figure 43: Side View of Bullets Shot into Bare 10% Gelatin

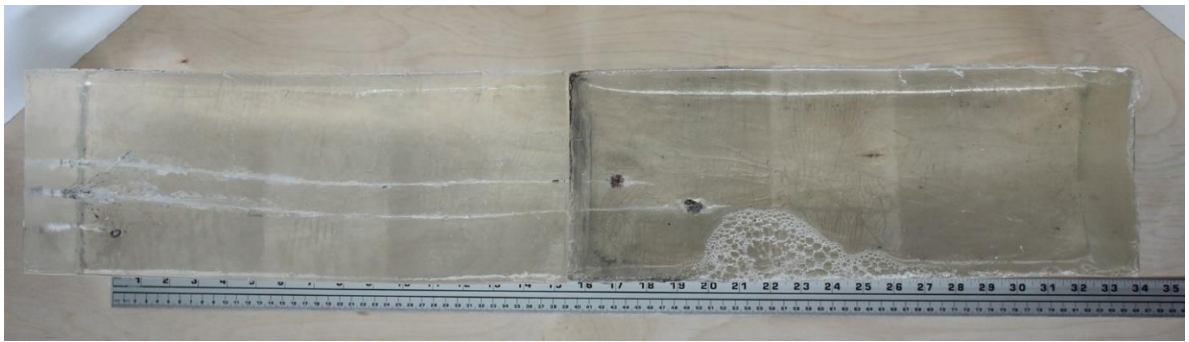


Figure 44: Top View of Bullets Fired into Bare Gelatin, (Top) Lead Bullet, (Bottom) Bismuth Bullet

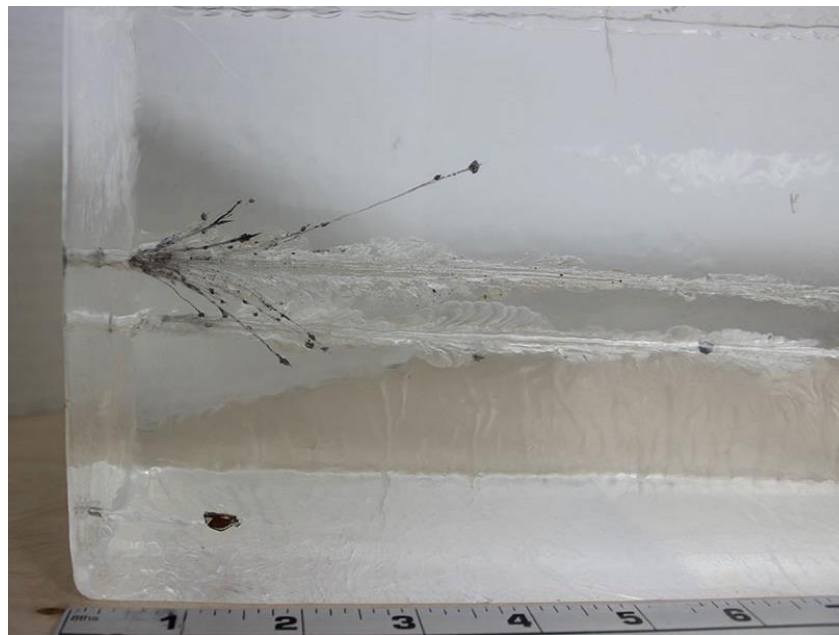


Figure 45: Entrance Wounds in Bare Gelatin, (Top) Bismuth Bullet Entrance, (Middle) Lead Bullet Entrance, (Bottom) Detached Jacket

Figure 45 shows a close up view of the entrance wounds in the gelatin. The bismuth bullet's nose fragmented. The base of the copper jacket can be seen in the lower part of the gelatin. Figure 46 shows the resting place of both bullets in the gelatin.

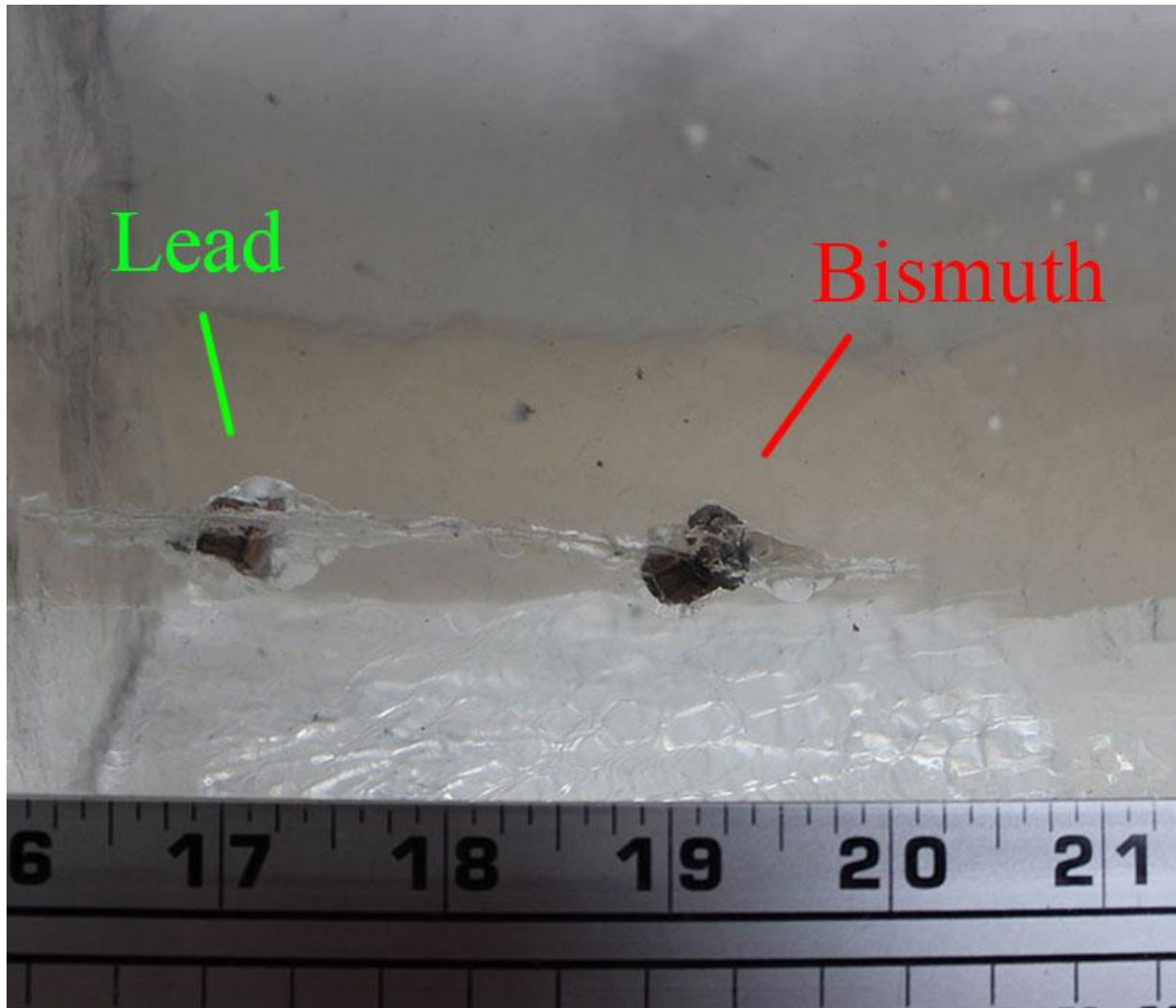


Figure 46: Terminal Location of Bullet Fired into Bare Gelatin

Figure 47 shows both bullets after they were extracted from the gelatin. The base of the bismuth copper jacket can be seen on the right of the image. Figure 48 shows the base of the bullets. It can be seen in this image the base of the bismuth bullet's jacket did indeed break off.



Figure 47: Bullets Shot Into Bare Gelatin, (Left) Lead Bullet, (Middle) Bismuth Bullet, (Right) Jacket Base



Figure 48: (Left) Lead Bullet, (Right) Bismuth Bullet with Missing Base

8.3.2 Heavy Clothing

This test consisted of shooting bullets into ballistic gelatin covered by heavy clothing from 10 feet away. The heavy clothing test consists of four layers of fabric laid over the ballistic gelatin. The first layer of clothing against the ballistic gelatin was a layer of cotton t-shirt material. The next layer was cotton dress shirt material. This was followed by a layer of Malden Mills™ Polartec® 200 fleece and finally one layer of denim.

There was one bismuth bullet fired along with one lead bullet. Table 9 contains the weather conditions on the day of shooting along with the bearing of the gun. Table 10 contains the weight of the bullets before and after shooting, along with penetration, average expansion and the velocity of the bullets.

Table 9: Weather Data for Shooting into Heavy Clothing

Weather data	
Date	1/21/2015
Condition	Mostly sunny
Temperature	77°F
Humidity	44%
Wind	ENE 3 mph
Barometer	30.06 in-Hg
Visibility	10 miles
Bearing of gun	95° East

Table 10: Ballistics Data for Shooting through Heavy Clothing

Bullets shot through heavy clothing		
	Bismuth bullet #23	Lead bullet #7
Bullet weight before shooting	125.7 grains	125 grains
Bullet weight recovered	119.8 grains	123.1 grains
Velocity	1256 fps	1183 fps
Penetration (where bullet stopped)	19.75"	19.5"
Expanded diameter of bullet	0.452"	0.465"

Figure 49 shows the four layers of fabric that were used in the heavy clothing test. The fabric in order from top to bottom are denim, fleece, dress shirt and t-shirt material.



Figure 49: Heavy Clothing, Top Layer Denim, Second Layer Black Fleece, Third Blue Dress Shirt, Fourth Gray T-Shirt

Figure 50 shows a side view of the ballistic gelatin that contains both bullets after they were shot through heavy clothing. Figure 51 is a top view of the bullets contained in the gelatin from shooting through heavy clothing. Figure 52 is a close up view of the entrance wounds of both lead and bismuth bullets.



Figure 50: Side View of Bullets Shot into Heavy Clothing



Figure 51: Top View of Bullets Fired through Heavy Clothing, (Top) Bismuth Bullet, (Bottom) Lead Bullet

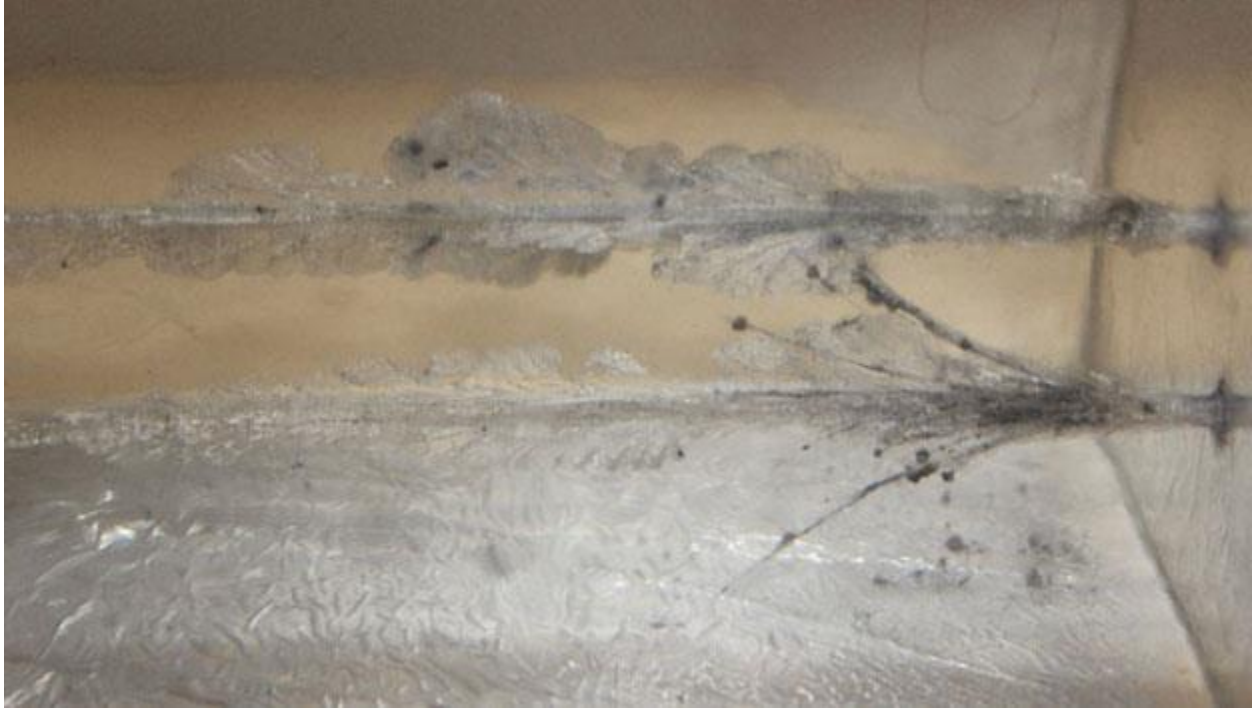


Figure 52: Entrance of Bullets Shot through Heavy Clothing, (Top) Lead Bullet Entrance, (Bottom) Bismuth Bullet Entrance

Figure 53 shows a close up of the bismuth bullet in the gel after it was shot through heavy clothing. Figure 54 shows a close up of the lead bullet after being shot through heavy clothing.

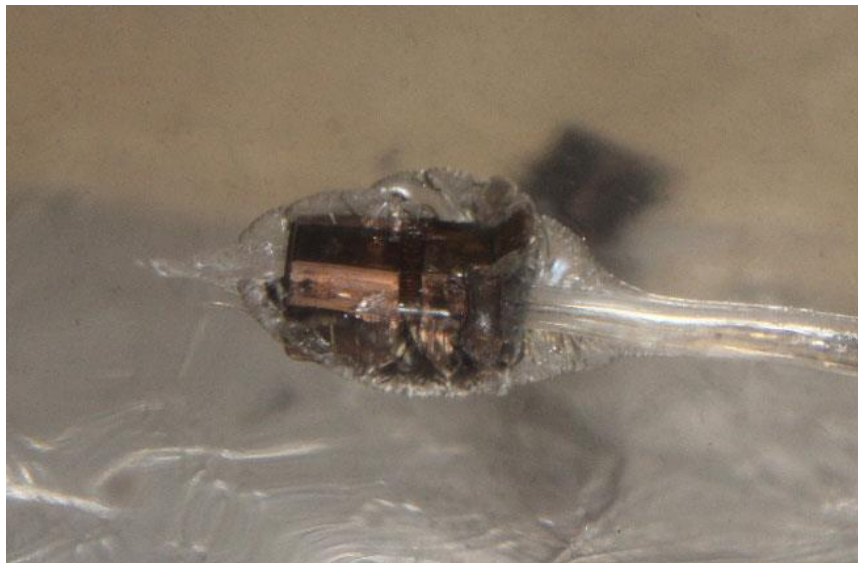


Figure 53: Bismuth Bullet Shot through Heavy Clothing



Figure 54: Lead Bullet Fired through Heavy Clothing

Figure 55 shows the bismuth and lead bullets after extraction from the ballistic gelatin.

Figure 56 shows the base of both bullets shot through heavy clothing.



Figure 55: Bullets Extracted from Gelatin after Being Shot through Heavy Clothing, (Left) Lead Bullet, (Right) Bismuth Bullet



Figure 56: Base of Bullets Shot through Heavy Clothing, (Left) Lead Bullet, (Right) Bismuth Bullet

8.3.3 Gypsum Board

This test consisted of shooting bullets into ballistic gelatin covered by light clothing, with an intermediate barrier of two layers of 1/2 inch gypsum board. The two pieces of gypsum board were separated by 3.5 inches. The gelatin was 18 inches behind the rear piece of gypsum board. The gun was 10 feet from the first piece of gypsum board.

There was one bismuth bullet fired along with two lead bullets. Two lead bullets were fired because the first lead bullet hit the gelatin and swerved out the top of the block. Table 11 contains the weather conditions on the day of shooting along with the bearing of the gun. Table 12 contains the weight of the bullets before and after shooting, along with penetration, average expansion and the velocity of the bullets.

Table 11: Weather Data for Shooting through Gypsum Board

Weather data	
Date	1/26/2015
Condition	Mostly sunny
Temperature	63°F
Humidity	48%
Wind	NW 17 mph
Barometer	29.96 in-Hg
Visibility	10 miles
Bearing of gun	95° East

Table 12: Ballistics Data for Shooting through Gypsum Board

Bullets shot through gypsum board		
	Bismuth bullet #29	Lead bullet #8
Bullet weight before shooting	125.8 grains	125 grains
Bullet weight recovered	110.3 grains	124.5 grains
Velocity	1154 fps	1195 fps
Penetration (where bullet stopped)	16.00"	16.25"
Expanded diameter of bullet	0.530"	0.495"

Figure 57 shows both pieces of gypsum board that were shot through in this test. The bismuth bullet hole is the lowest out of the group of holes. The right most hole was from the lead

bullet that stayed in the gel. The top hole was from the lead bullet that was lost. The detached jacket base from the bismuth bullet impacted slightly below and to the left of the group.

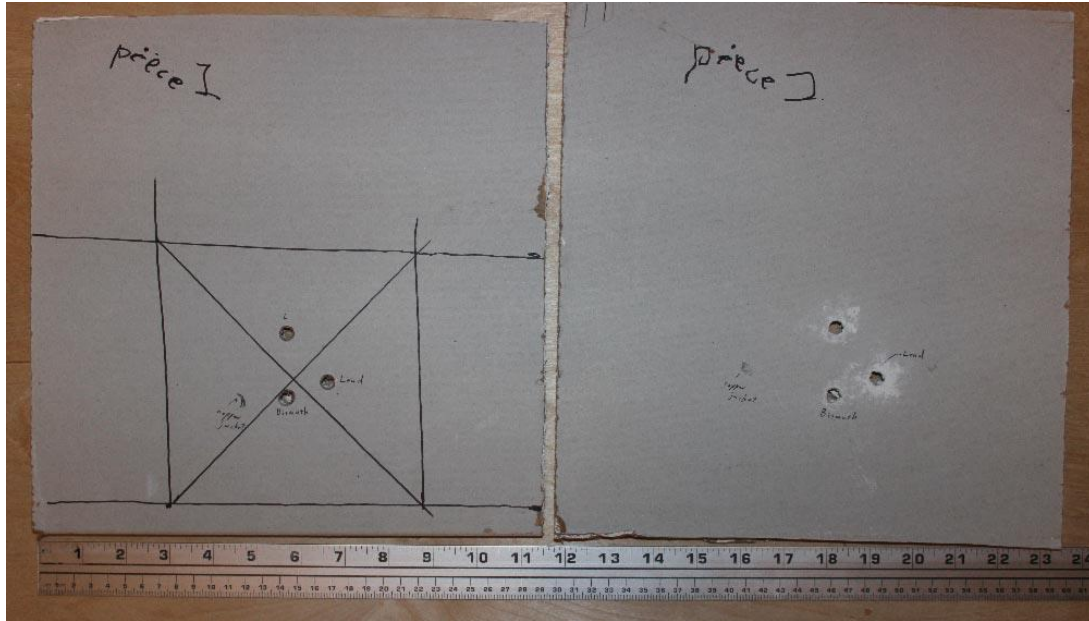


Figure 57: (Left) Front Piece of Gypsum Board, (Right) Second Piece of Gypsum Board

Figure 58 shows a side view of the ballistic gelatin that contains both bullets after they were shot through two layers of gypsum board. Figure 59 is a top view of the bullets contained in the gelatin for shooting through two layers of gypsum board. Figure 60 is a close up view of the entrance wounds of both lead and bismuth bullets.

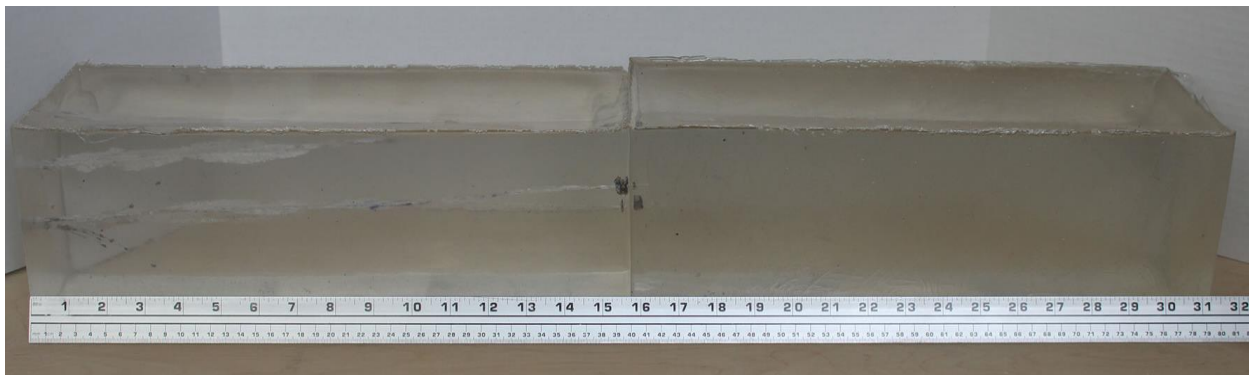


Figure 58: Side View Bullets Fired through Gypsum Board

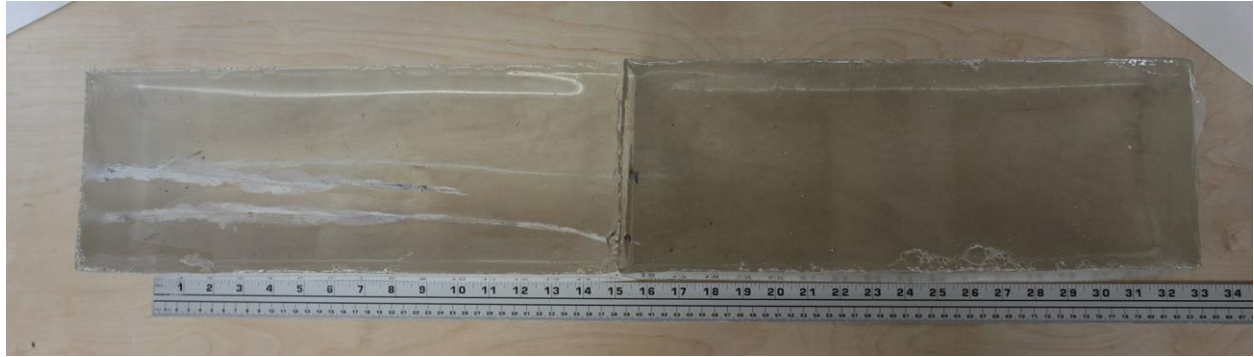


Figure 59: (Top) Bismuth Bullet, (Bottom) Lead Bullet

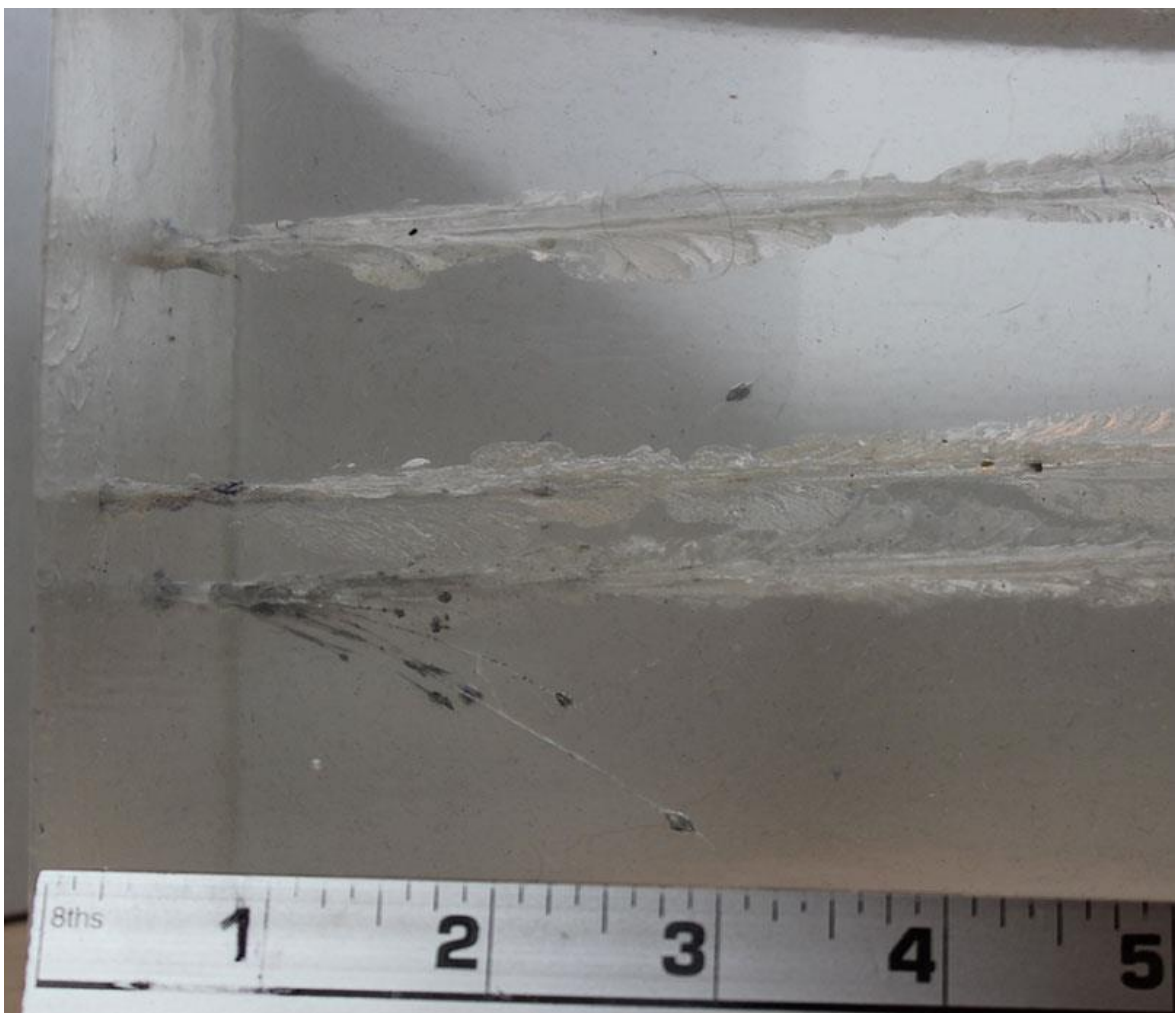


Figure 60: (Bottom) Bismuth Entrance, (Middle) Lead Bullet Track, (Top) Lost Bullet

Figure 61 shows the bismuth and lead bullets after extraction from the ballistic gelatin.

Figure 62 shows the base of both bullets shot through gypsum board.



Figure 61: Top View of Bullets Shot through Gypsum Board, (Left) Lead Bullet, (Right) Bismuth Bullet



Figure 62: Base View of Bullets Shot through Gypsum Board, (Left) Lead Bullet, (Right) Bismuth Bullet

8.3.4 Plywood

This test consisted of shooting bullets into ballistic gelatin covered by light clothing, with an intermediate barrier of a 3/4 inch piece of plywood. The ballistic gelatin was 18 inches in back of the wood. The gun was 10 feet from the front of the plywood.

There was one bismuth bullet fired along with one lead bullet. Table 13 contains the weather conditions on the day of shooting along with the bearing of the gun. Table 14 contains the weight of the bullets before and after shooting, along with penetration, average expansion and the velocity of the bullets.

Table 13: Weather Data for Shooting through Plywood

Weather data	
Date	1/28/2015
Condition	Mostly sunny
Temperature	52°F
Humidity	54%
Wind	NNE 9 mph
Barometer	30.27 in-Hg
Visibility	10 miles
Bearing of gun	95° East

Table 14: Ballistics Data for Shooting through Plywood

Bullets shot through plywood		
	Bismuth bullet #39	Lead bullet #9
Bullet weight before shooting	125.5 grains	125 grains
Bullet weight recovered	117.7 grains	124.8 grains
Velocity	1239 fps	1155 fps
Penetration (where bullet stopped)	20.25"	19.75"
Expanded bullet of bullet	0.381"	0.383"

Figure 63 shows both pieces of plywood. The bismuth bullet was fired into the left piece of plywood and as can be seen in the figure there is a second hole where the base of the copper jacket hit the wood. The lead bullet was fired into the right piece of plywood in the figure.



Figure 63: (Left) One Bismuth Bullet Shot through 3/4 Inch Plywood, (Right) Lead Bullet Shot into Plywood

Figure 64 shows a side view of the ballistic gelatin that contains both bullets after they were shot through one layer of plywood. Figure 65 is a top view of the bullets contained in the gelatin for shooting through one layer of plywood.

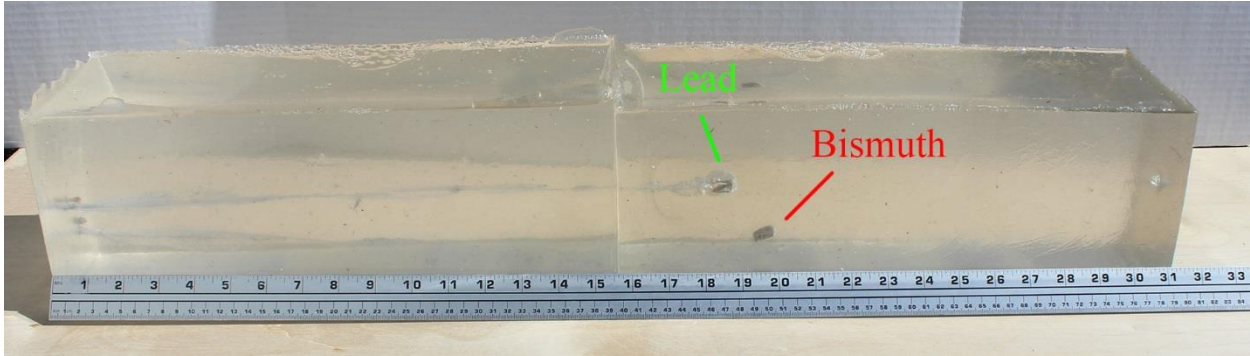


Figure 64: Side View of Bullets Shot through Plywood, (Top) Lead Bullet, (Bottom) Bismuth Bullet

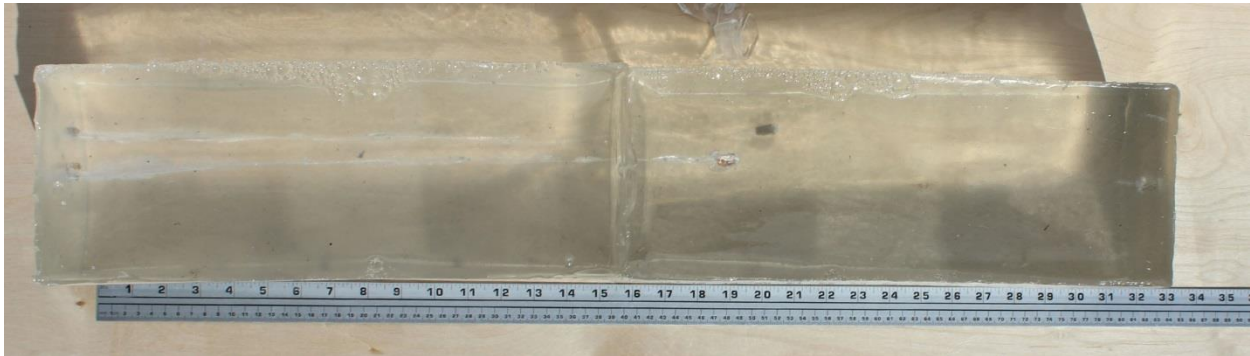


Figure 65: Top View of Bullets Shot through Plywood, (Top) Bismuth Bullet, (Bottom) Lead Bullet

Figure 66 is a close up view of the entrance wounds of both lead and bismuth bullets. Figure 67 is a close up view of the resting place of both bismuth and lead bullets in the ballistic gelatin.

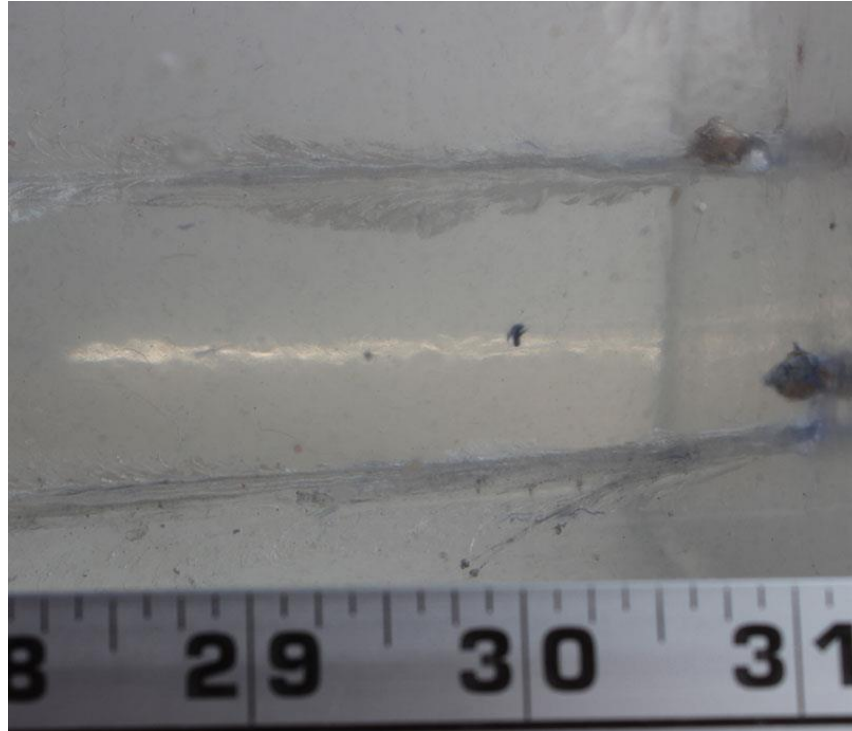


Figure 66: Plywood Test, (Bottom) Bismuth Entrance Wound, (Top) Lead Entrance Wound

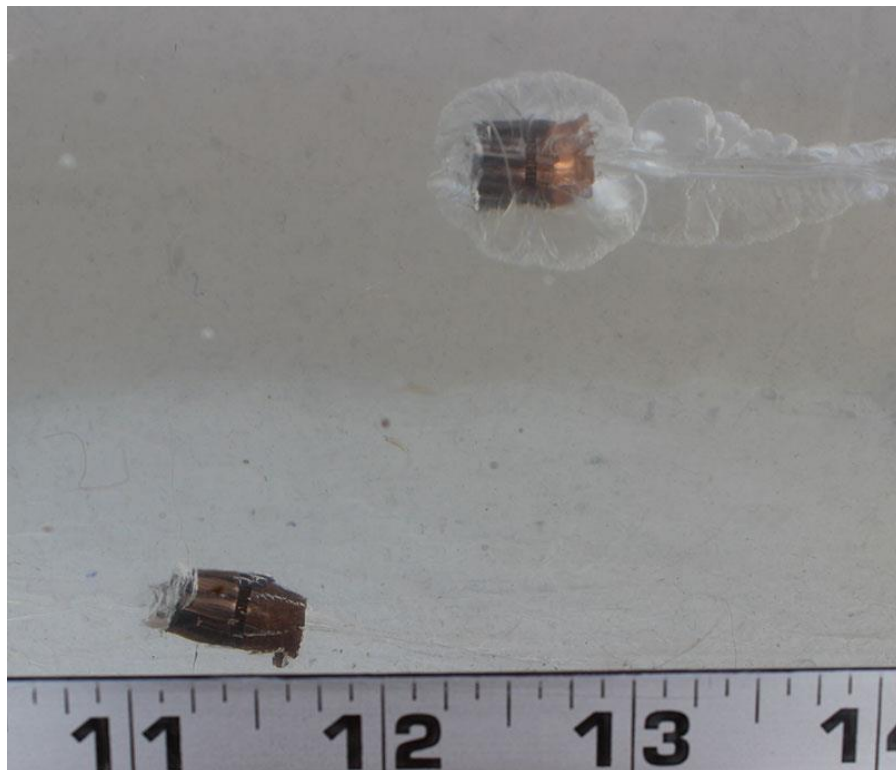


Figure 67: Both Bullets Tumbled in Plywood Test, (Bottom) Bismuth Bullet, (Top) Lead Bullet

Figure 68 shows the bismuth and lead bullets after extraction from the ballistic gelatin.

Figure 69 shows the base of both bullets shot through plywood.



Figure 68: Side View, (Left) Lead 125 Grain Bullet Shot into Plywood, (Right) Bismuth 125 Grain Bullet

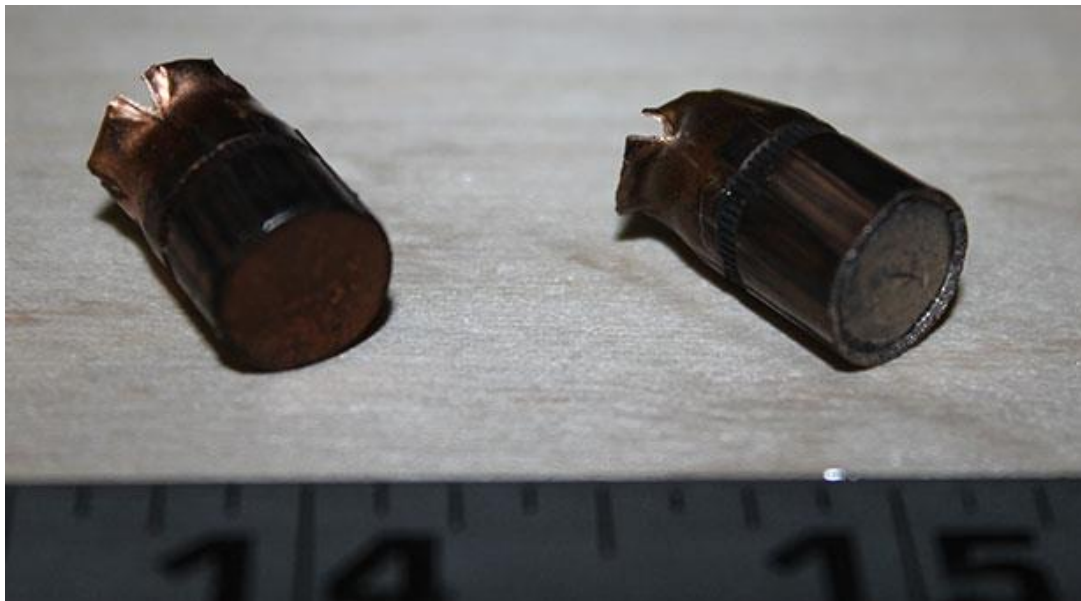


Figure 69: Base View (Left) Lead 125 Grain Bullet Shot into Plywood, (Right) Bismuth 125 Grain Bullet

8.3.5 Galvanized Steel

This test consisted of shooting bullets into ballistic gelatin covered by light clothing, with an intermediate barrier of two layers of 20 gauge galvanized steel. The two pieces of steel were separated by 3 inches. The gelatin was 18 inches behind the rear piece of 20 gauge steel. The gun was 10 feet from the first piece of steel.

There was one bismuth bullet fired along with one lead bullet fired in this test. Table 15 contains the weather conditions on the day of shooting along with the bearing of the gun. Table 16 contains the weight of the bullets before and after shooting, along with penetration, average expansion and the velocity of the bullets.

Table 15: Weather Data for Shooting through 20 Gauge Steel

Weather data	
Date	1/30/2015
Condition	Cloudy
Temperature	63°F
Humidity	77%
Wind	WSW 9 mph
Barometer	30.25 in-Hg
Visibility	10 miles
Bearing of gun	95° East

Table 16: Ballistics Data for Shooting through 20 Gauge Steel

Bullets shot through 20 gauge steel		
	Bismuth bullet #37	Lead bullet #10
Bullet weight before shooting	125.8 grains	125 grains
Bullet weight recovered	111.5 grains	122.9 grains
Velocity	1299 fps	1104 fps
Penetration (where bullet stopped)	18.25"	18.50"
Expanded diameter of bullet	0.434"	0.472"

Figure 70 shows both pieces of 20 gauge galvanized steel. The left piece of steel in the figure is the front piece of steel. The bismuth bullet shot through the left hole and the lead shot through the right hole. The right plate is the second piece of steel that was positioned three inches behind the first. The holes left by the lead and bismuth bullets can be seen along with a dent caused by debris from the lead bullet.

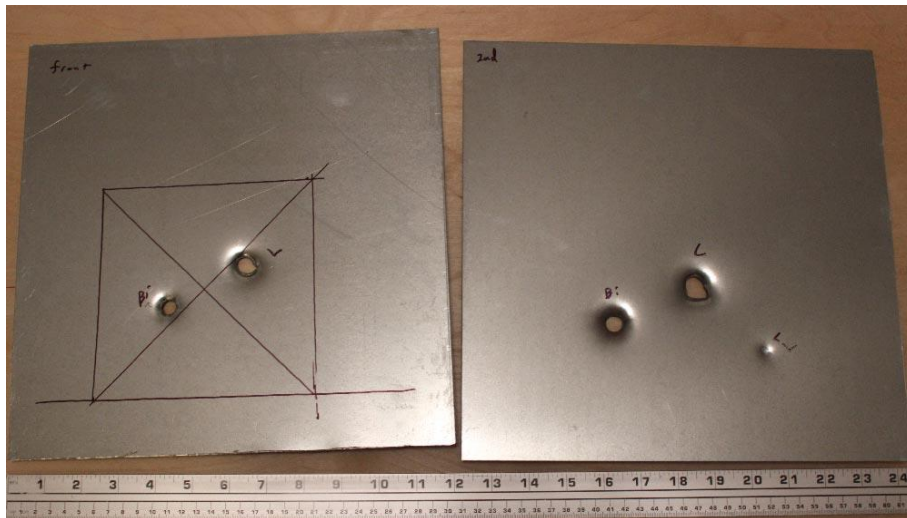


Figure 70: (Left) Front Plate of Galvanized Steel, (Right) Second Plate of Steel

Figure 71 shows a side view of the ballistic gelatin that contains both bullets after they were shot through two layers of 20 gauge galvanized steel. Figure 72 is a top view of the bullets contained in the gelatin for shooting through two layers of steel.

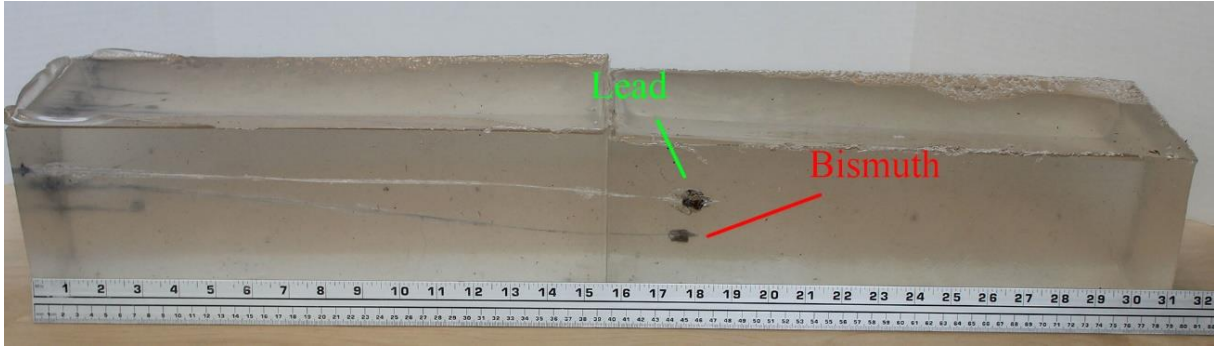


Figure 71: Side View of Lead and Bismuth Bullets Shot through Two Layers 20 Gauge Steel

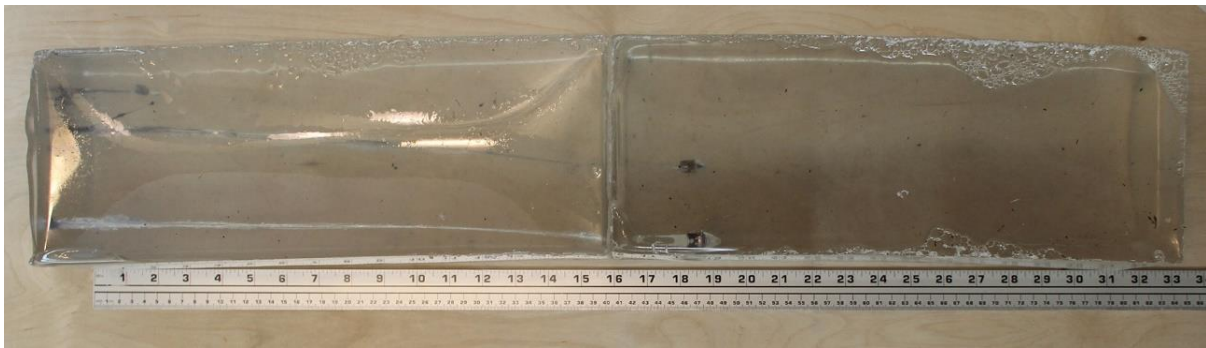


Figure 72: Top View Bullets Shot through 20 Gauge Steel, (Top) Bismuth Bullet, (Bottom) Lead Bullet

Figure 73 is a close up view of the bismuth bullet entrance wound after being shot through two layers of 20 gauge galvanized steel. Figure 74 is a close up view of the entrance wound of the lead bullet after being shot through two pieces of 20 gauge steel. Figure 75 is a close up view of the resting place of both bismuth and lead bullets in the ballistic gelatin after being shot through two pieces of 20 gauge galvanized steel. The base of the bismuth bullet's copper jacket and two disks of 20 gauge steel were extracted from the gelatin see Figure 76.

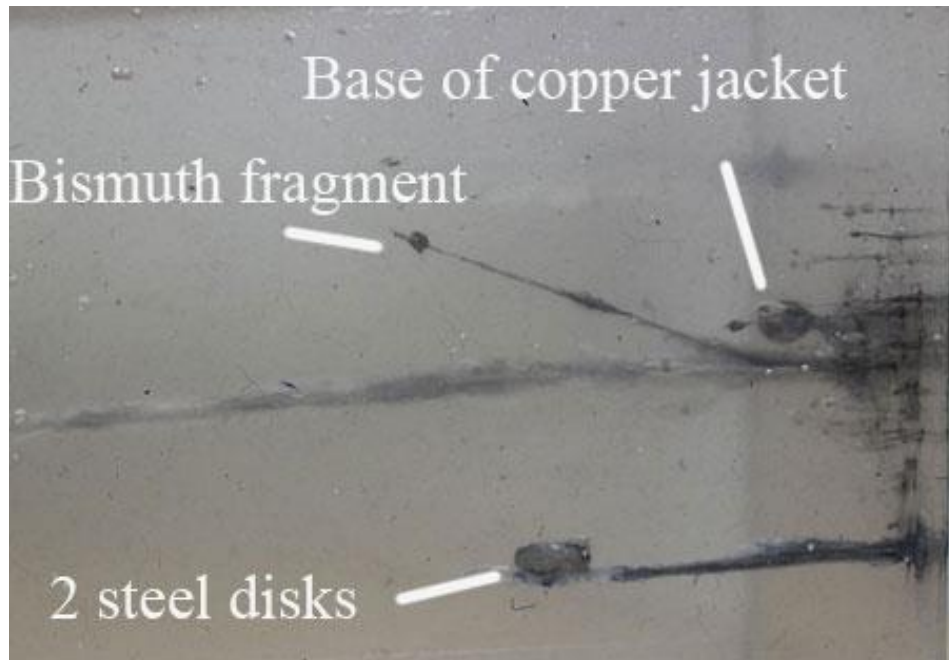


Figure 73: Bismuth Entrance Wound – Lower Fragment is Disk Punched from Steel Plate

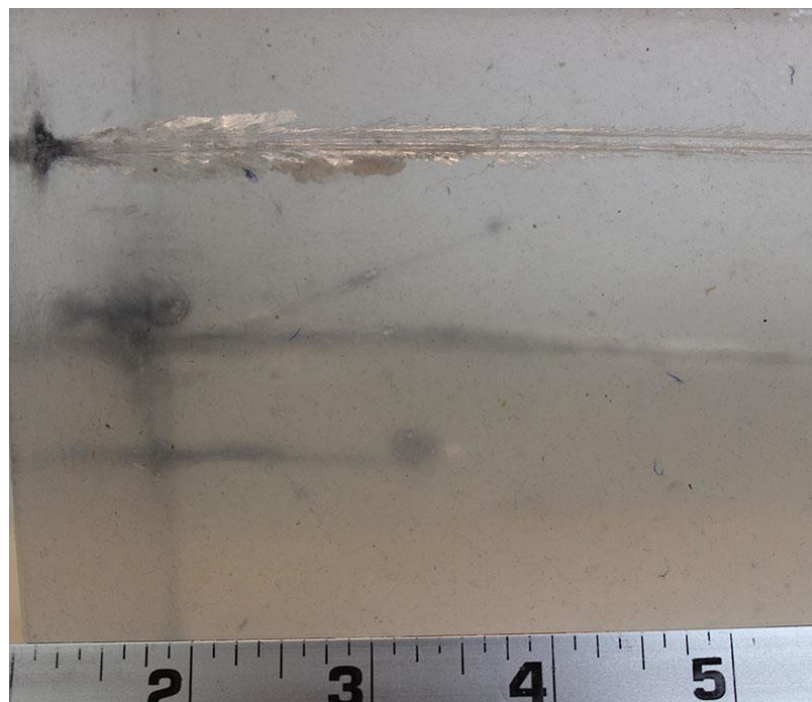


Figure 74: Steel Test, (Top) Entrance Wound of Lead Bullet

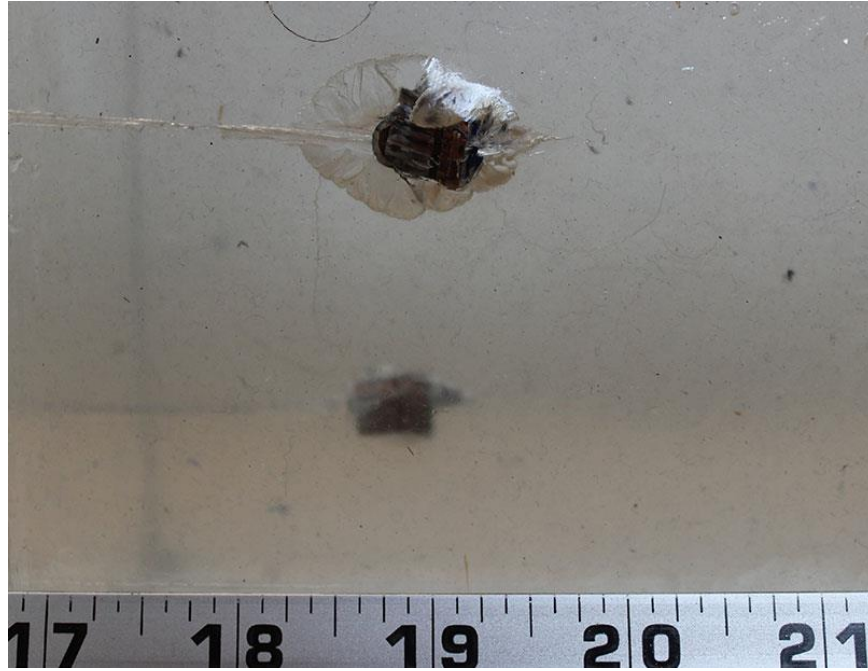


Figure 75: Steel Test, (Top) Lead Bullet, (Bottom) Bismuth Bullet



Figure 76: Fragments Pulled from the Ballistic Gelatin after Firing through Steel, (Left) Base of the Copper Jacket, (Right) Two Disks of Steel

Figure 77 shows the bismuth and lead bullets after extraction from the ballistic gelatin.

Figure 78 shows the base of both bullets shot through steel.



Figure 77: Bullets Shot through Steel (Left) Lead 125 Grain Bullet, (Right) Bismuth Bullet



Figure 78: Base View of Bullets Shot through Steel, (Left) Lead Bullet, (Right) Bismuth Bullet

8.3.6 Auto Glass

The auto glass test was performed twice. This test was repeated because the penetration distance of both bismuth and lead bullets were lower than expected. Both tests showed very similar penetration within 1/2 inch of each other. Both tests consisted of shooting through one layer of auto glass into ballistic gelatin covered by light clothing. The auto glass was at 45° to the horizontal then turned 15° to the side.

There was one bismuth bullet fired along with one lead bullet fired in each test. Table 17 contains the weather conditions on the days of shooting along with the bearing of the gun. Table 18 contains the weight of the bullets before and after shooting, along with penetration, average expansion and the velocity of the bullets.

Table 17: Weather Data for Shooting through Auto Glass

Weather data		
	Test 1	Test 2
Date	2/2/2015	2/13/2015
Condition	Cloudy	Mostly sunny
Temperature	74°F	50°F
Humidity	81%	47%
Wind	S 5 mph	NNE 7 mph
Barometer	30.00 in-Hg	30.30 in-Hg
Visibility	10 miles	10 miles
Bearing of gun	95° East	95° East

Table 18: Ballistics Data for Shooting through Auto Glass

Bullets shot through auto glass				
	Test 1		Test 2	
	Bi bullet #31	Lead bullet #11	Bi bullet #30	Lead bullet #12
Bullet weight before shooting	125.8 grains	125 grains	124.7 grains	125 grains
Bullet weight recovered	Shattered*	81.9 grains	36.3 grains	87.1 grains
Velocity	1195 fps	1283 fps	1313 fps	1064 fps
Penetration (where bullet stopped)	8.25"	11.50"	8.50"	11.75"
Expanded diameter of bullet	Shattered*	0.440"	0.447"	0.462"

* Data of shattered bismuth pieces in Table 19

Figure 79 shows all four pieces of auto glass that were shot through for both test 1 and 2.

Each bullet was shot through its own piece of auto glass.



Figure 79: (Top Row) Left Test 1 Lead Bullet Hole, Right Test 1 Bismuth Bullet Hole, (Bottom Row) Left Test 2 Lead Bullet Hole, Right Test 2 Bismuth Bullet Hole

Figure 80 shows the side view of the ballistic gelatin for both bismuth and lead bullets from both test one and test two for shooting through auto glass. The first two bullets were shot into different gelatin blocks. In the second test both bullets were fired into the same block.

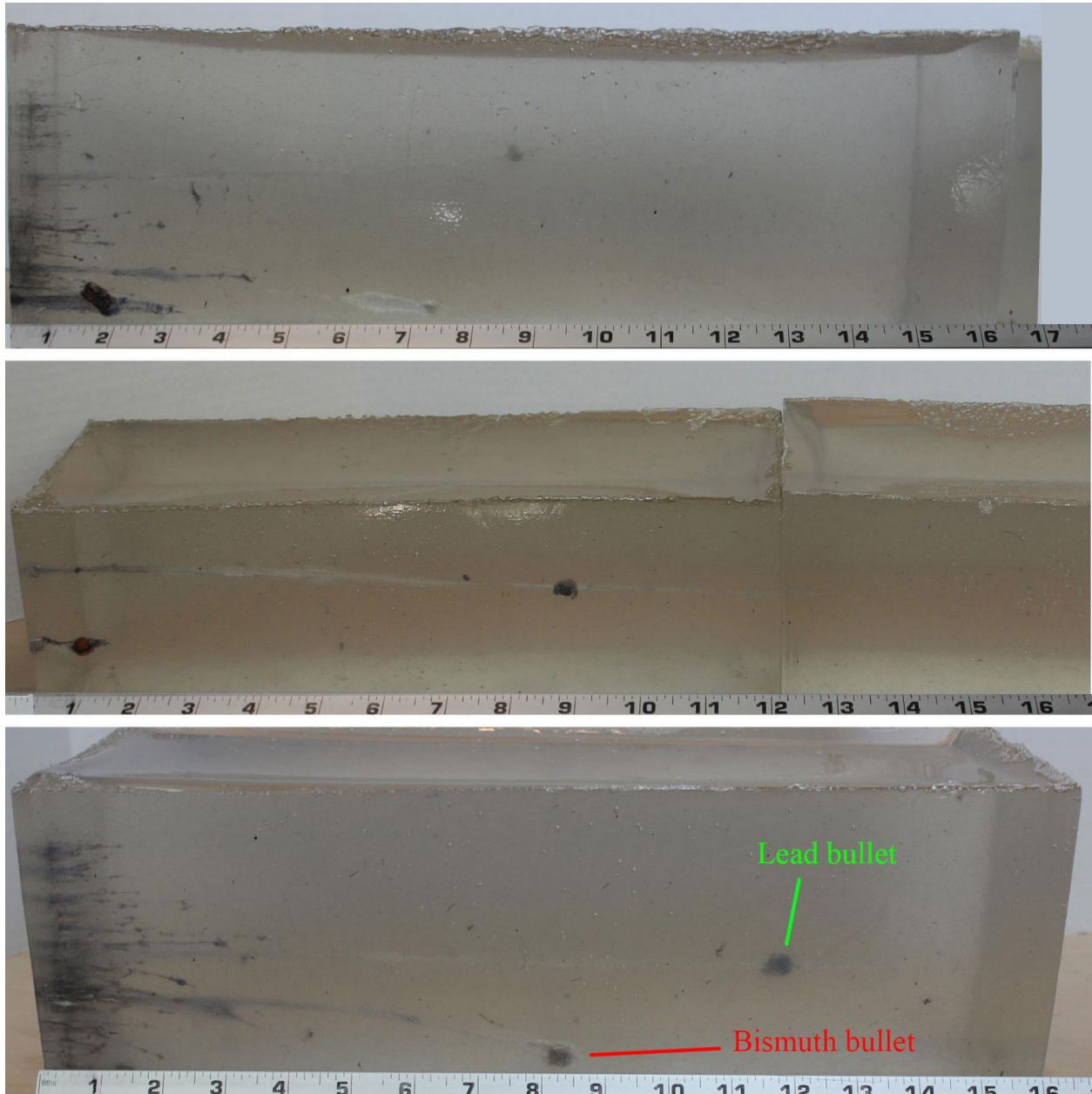


Figure 80: Side Views of Bullets Shot through Auto Glass, (Top) Bismuth Bullet Test 1, (Middle) Both Pieces of Lead Bullet Test 1, (Bottom) Lead and Bismuth Bullets Test 2

Figure 81 shows the top view for both bismuth and lead bullets from both tests shooting through auto glass.

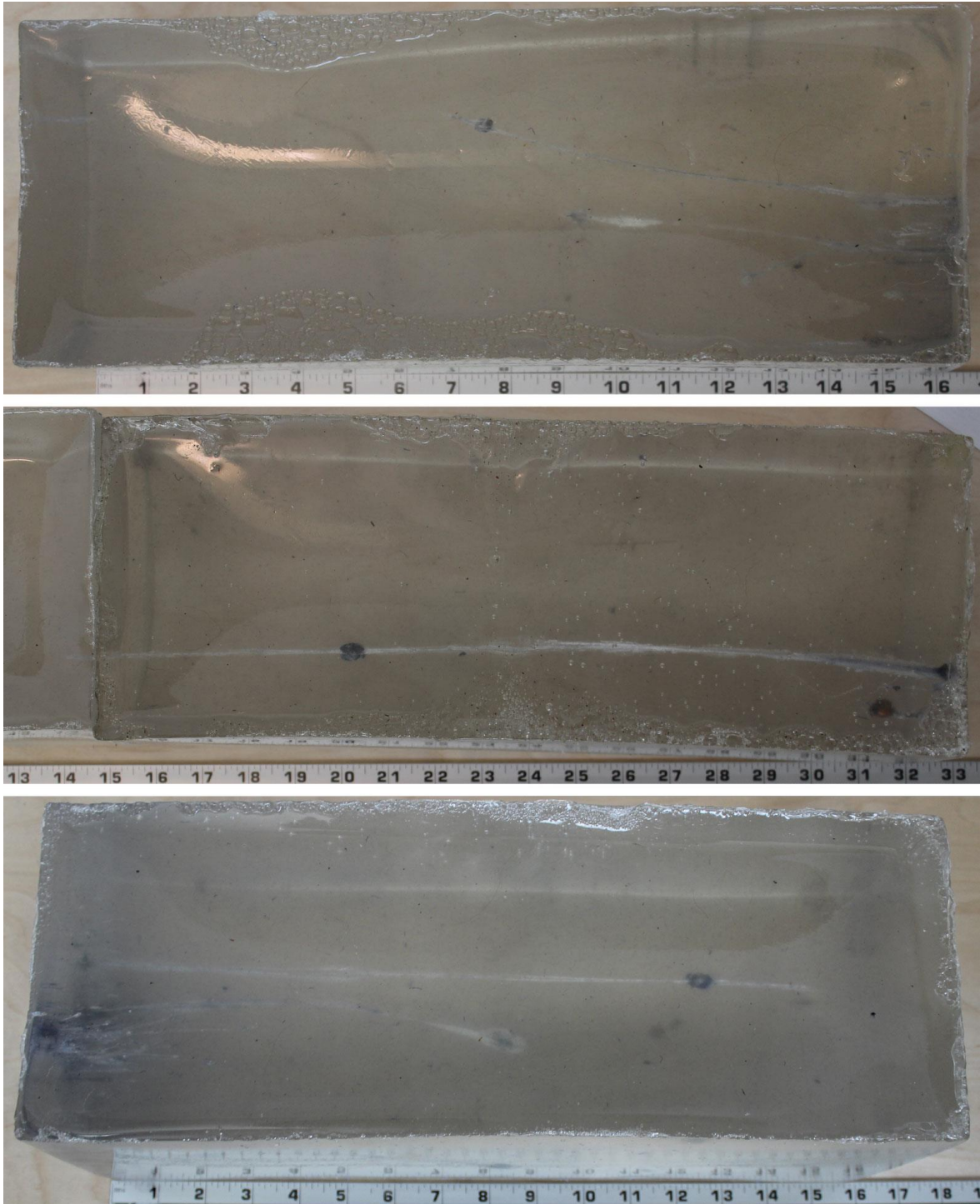


Figure 81: Top View of Bullets Shot through Auto Glass, (Top) Bismuth Bullet Test 1, (Middle) Lead Bullet Test 1, (Bottom) Lead and Bismuth Bullets Test 2

Since the bismuth bullet on test 1 shattered into many small fragments the four main observable chunks were collected. Figure 82 shows the four main fragments of the bismuth bullet that were observed. Table 19 contains the penetration and mass of each of the four chunks in test 1.

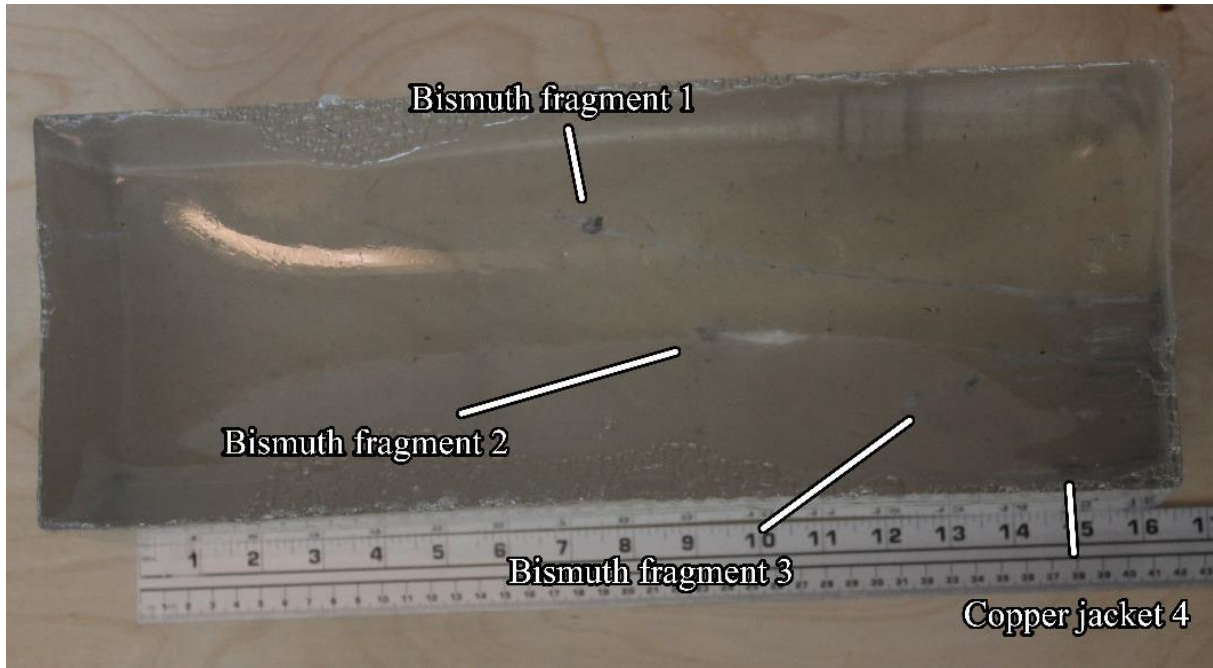


Figure 82: Four Main Observable Bismuth Fragments

Table 19: Bismuth Bullet Fragments Penetration Shot through Auto Glass Test 1

Bismuth bullet test 1 shot through auto glass		
	Penetration fragment	Mass
Bismuth fragment 1	8.25"	24.6 grains
Bismuth fragment 2	7.00"	10 grains
Bismuth fragment 3	3.75"	7.3 grains
Bismuth copper jacket 4	1.75"	20.8 grains

Figure 83 shows a close up view of the bismuth bullet's entrance wound in ballistic gelatin after it was shot through auto glass.



Figure 83: Bismuth Entrance Wound, Bullet Fragmented upon Going through the Auto Glass Test 1

Figure 84 shows the extracted bullet fragments from test 1 for shooting through auto glass. Figure 85 shows the remnants of the bullets shot on the second test shooting through auto glass.



Figure 84: (Starting from the Left Going Right) Copper Jacket of Lead Bullet, Lead of the Lead Bullet, Bismuth Fragment 1, Bismuth Fragment 2, Bismuth Fragment 3, and Bismuth Copper Jacket 4

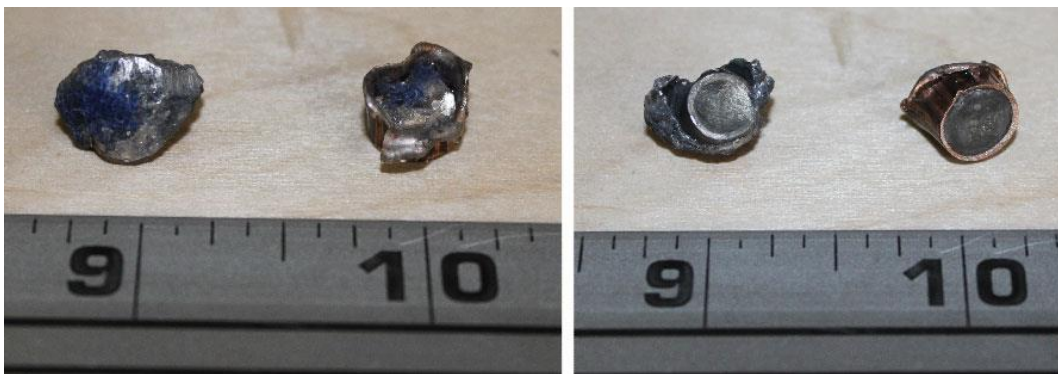


Figure 85: Bullets Shot into Auto Glass Test 2, (Left) Both Bismuth and Lead Bullets Top Side, (Right) Under Side of the Bullets in Test 2

Figure 86 shows the location of the copper jacket from the lead bullet fired in test 2.

Figure 87 shows the front of the entrance wound from both tests 1 and 2.

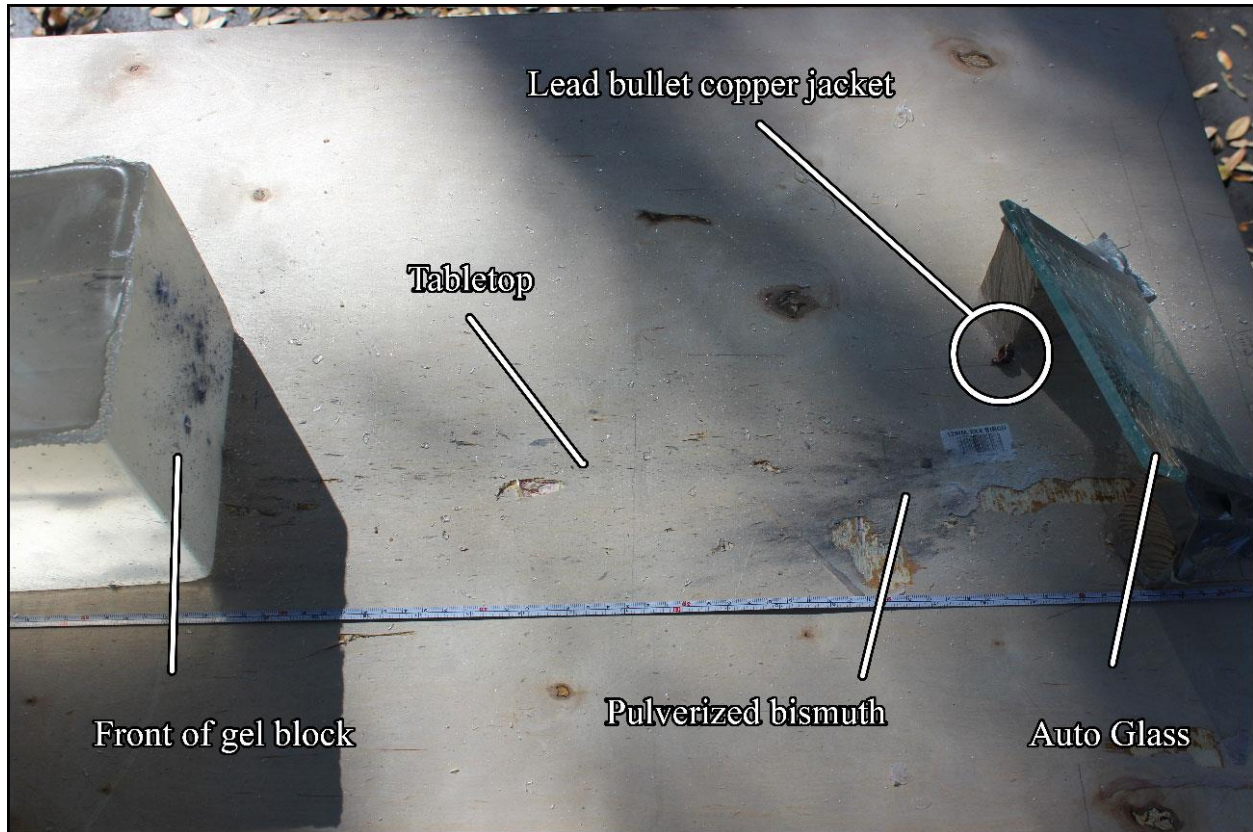


Figure 86: Lead Bullet Copper Jacket Bounced off of the Gelatin Test 2

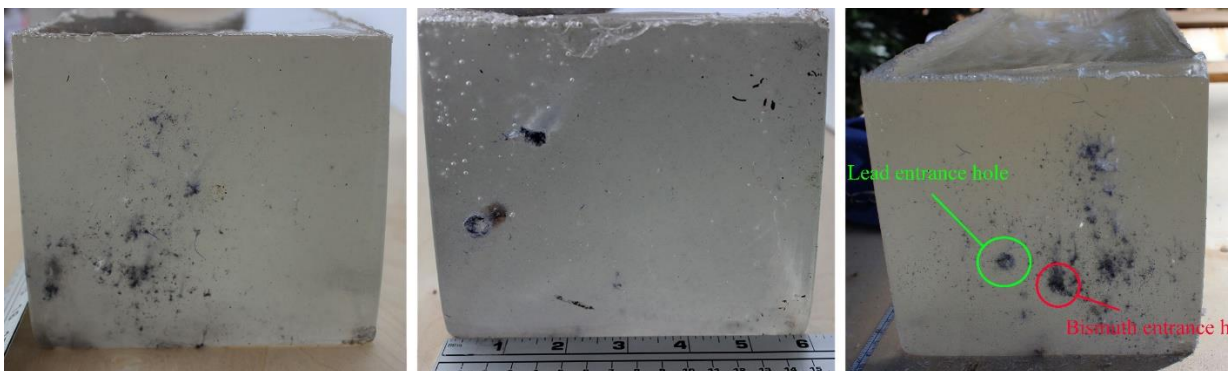


Figure 87: Front of the Ballistic Gelatin of Bullets Shot through Auto Glass, (Left) Bismuth Bullet Test 1, (Middle) Lead Bullet Test 1, (Right) Lead & Bismuth Bullets Test 2

8.4 Average Speed of the Bullets

Table 20 shows the average velocity of all bullets shot over the course of this research. This table also includes the maximum speed and the minimum speed of all the bismuth and lead bullets that were fired. The standard deviation was also calculated.

Table 20: Average Velocity for All Bullets Tested

	Bismuth Bullets	Lead Bullets
Average Speed (fps)	1235	1167
Maximum Speed (fps)	1313	1283
Minimum Speed (fps)	1154	1064
Standard Deviation	38.1	55.8

CHAPTER 9: DISCUSSION

9.1 Accuracy Test of Bismuth Bullets Compared to Lead Bullets

When shot from a Ransom™ rest over a range of 10 feet both the lead and bismuth bullets grouped on the targets in about the same location, see Figure 41. This would suggest that the general trajectory was not affected by the bismuth bullets being slightly longer. The four bismuth bullets formed a group that fit into a circle of 0.935 inches diameter, see Figure 42. The lead bullet group fell within a circle of 0.7189 inches diameter, see Figure 42. Both bullets had a grouping under 1 inch when shot from 10 feet. This is excellent accuracy for the case of self-defense using a short barreled firearm. The bismuth bullets were clearly engaging the rifling correctly and exhibited stabilized flight without tumbling. This is indicated by the clean circular holes punched into the paper targets.

The speed of each round was recorded by the chronograph which can be seen in Table 4. Velocities greater than 1000 fps are generally associated with bullet expansion during penetration, which is desirable in transferring maximum energy from bullet to target.

9.2 Shooting into Water Bags

A preliminary penetration test was done by shooting bismuth bullets into water bags. This was done to establish the general shootability of bismuth bullets before committing to a full investigation. The PVC holding rig was loaded up with water bags and these were shot through. Each water bag was filled with 1/2 a gallon of water and its width was 3 inches per bag. Table 6

shows the penetration along with the weight and speed of the bullets shot into the water bags. This preliminary data was used to justify the comprehensive study that was to follow.

9.3 FBI Ballistics Tests

The following sections discuss the findings revealed by the FBI testing protocol on bare gelatin, heavy clothing, gypsum board, 3/4 inch plywood, 20 gauge galvanized steel and auto glass.

9.3.1 Bare Gelatin

The ballistics data for the bare gelatin test are summarized in Table 8. It was found that the bullets had penetrations of 19.00 inches and 17.50 inches for the bismuth and lead bullets respectively. Both bullets had greater penetration than the minimum 12 inches that the FBI standard test indicates as reliable penetration. Upon removing the bullets from the gelatin it was found the lead bullet lost 8.6 grains of weight. The bismuth bullet had lost 13.4 grains of weight. Both bullets had a similar average expanded diameter of approximately 0.453 inches.

As can be seen in Figure 43 and Figure 44 both bullets traveled fairly straight in the gelatin. An up-close of the entrance wound of both bullets can be seen in Figure 45. For the bismuth there is approximately a 1/2 inch deep circular hole at the beginning of the gelatin. Since this hole is the same diameter of the bullet it can be assumed the bullet hit the front of the gelatin flying straight. As the bullet went further into the gelatin the hollow point began to expand. At around the 1/2 inch mark, the nose of the bismuth bullet shattered sending a spray of small bismuth pieces into the gelatin. These pieces that broke off had penetrations of 1 to 2.5 inches. The rest of the track shows signs of the expanded bullet penetrating further into the gelatin. The

base of the copper jacket of the bismuth bullet can be seen in the gelatin. The jacket base had a separate entrance wound hole than the main bullet. This would suggest that the base of the copper jacket of the bismuth bullet broke off during flight. The lead bullet also started expanding around the half inch mark but unlike bismuth its nose did not shatter. The lead bullet track shows signs of the expanding bullet traveling through the gelatin.

In Figure 46 the bullets' resting place in the ballistic gelatin can be seen. Both bullet tips are roughly facing forward. Figure 47 and Figure 48 show both extracted bullets. From these images it can be seen clearly the bismuth bullet's nose shattered. The bismuth metal did not expand like the lead. The only expansion of the bismuth bullet is from the copper jacket. The lead bullet on the other hand plastically deformed. The front of the lead bent back with the copper jacket upon going through the gelatin. These images show the bismuth bullet copper jacket base clearly broke off. The probable cause of the bismuth bullet's copper jacket breaking off in many of the FBI standard ballistics tests is that bismuth expands upon solidifying. When the bullet was cast and cooled this would put stress of the copper jacket. The same thing happens a second time when the bismuth bullet is heated to create the hollow point. It was observed when putting the hollow point in the bismuth bullet, molten bismuth sometimes would force its way out of the base of the copper jacket. This occasionally would leave a crack around the base of the bullet. Although any bullets with visible cracks were not used for testing.

9.3.2 Heavy Clothing

The ballistics data for the heavy clothing test are summarized in Table 10. It was found that the bullets had a penetration of 19.75 inches and 19.50 inches for the bismuth and lead bullets respectively. Both bullets had greater penetration than the minimum twelve inches that

the FBI standard test indicates as reliable penetration. Upon removing the bullets from the gelatin it was found the lead bullet lost 1.9 grains of weight. The bismuth bullet had lost 5.9 grains of weight. The average expanded diameter of the lead and bismuth bullets were 0.465” and 0.452” respectively.

As can be seen in Figure 50 and Figure 51 the bismuth bullet path in the gelatin was fairly straight. The lead bullet had a curved path in the ballistic gelatin. A close up view of the entrance wound of both bullets can be seen in Figure 52. The bismuth bullet entrance wound on the front of the gelatin is the same diameter as the bullet, this would suggest the bullet was flying straight upon impact. Both bullets quickly started to expand upon entering the ballistic gelatin. The tip of the bismuth bullet once again shattered sending small bismuth pieces into the gelatin with penetration of a couple of inches. The wound track of the lead bullet appears larger than the bismuth bullet’s track.

Figure 53 and Figure 54 shows the bullets’ resting place in the ballistic gelatin. The front of the bismuth bullet was facing backwards in the ballistic gelatin. This would indicate the bismuth bullet tumbled also. Tumbling is not necessarily a bad characteristic provided there is adequate penetration. Tumbling can increase energy exchange and tissue damage. The lead bullet’s front is facing downward and appears to have tumbled as it traveled through the gelatin.

Figure 55 and Figure 56 show both extracted bullets. From these images it can be seen clearly the bismuth bullet’s nose shattered. The bismuth metal did not expand like the lead. The only expansion of the bismuth bullet is from the copper jacket. Two of the copper jacket flaps did not bend all the way back. The lead bullet on the other hand plastically deformed. The front of the lead bent back with the copper jacket upon going through the gelatin.

Both lead and bismuth bullets had comparable performance in shooting into ballistic gelatin covered with heavy clothing.

9.3.3 Gypsum Board

In this test three bullets were shot through two pieces of gypsum board, one bullet was bismuth and the other two were lead. The reason two lead bullets were fired was, when the first lead bullet hit the front of the gelatin it swerved up and exited out of the top of the gelatin. With the bullet exiting the gelatin the penetration data could not be properly gathered on that bullet and that is why the second lead bullet was fired. This second lead bullet successfully stayed within the gelatin block after initial penetrating. The ballistics data is summarized in Table 11. It was found that the bullets had a penetration of 16.00 inches and 16.25 inches for the bismuth and lead bullets respectively. Both bullets had greater penetration than the minimum 12 inches that the FBI standard test indicates as reliable penetration. Upon removing the bullets from the gelatin it was found the lead bullet lost 0.5 grains of weight. The bismuth bullet had lost 15.5 grains of weight. Generally it was found that bismuth bullets always lose more weight compared with lead bullets. This is due partly to the detached jacket base and partly due to the characteristic tendency for nose shattering with bismuth. The average expanded diameter of the lead and bismuth bullets were 0.495” and 0.530” respectively.

As can be seen in Figure 51 and Figure 52 both bullets traveled fairly straight in the gelatin. A close up view of the entrance wound of both bullets can be seen in Figure 53. The bismuth bullet entrance wound on the front of the gelatin is the same diameter as the bullet, this would suggest the bullet was flying straight upon impact. Both bullets quickly started to expand upon entering the ballistic gelatin. The tip of the bismuth bullet characteristically shattered

sending small bismuth pieces into the gelatin with penetration from around 1 to 3 inches. Both bullets were found to be facing backwards in the gelatin. This would indicate the bullets tumbled during penetration.

Figure 54 and Figure 55 show both extracted bullets. From these images it can be seen clearly the bismuth bullet's shattered nose. The only expansion of the bismuth bullet is from the copper jacket. The base of the bismuth bullet's copper jacket broke off. The copper jacket base went through the first piece of gypsum board and left a dent in the second. This means the base of the copper jacket broke off during flight.

Both lead and bismuth bullets had comparable performance in shooting into ballistic gelatin with an intermediate barrier of gypsum board.

9.3.4 Plywood

The ballistics data for the 3/4 inch plywood test are summarized in Table 13. It was found that the bullets had a penetration of 20.25 inches and 19.75 inches for the bismuth and lead bullets respectively. Both bullets had greater penetration than the minimum twelve inches that the FBI standard test indicates as reliable penetration. Upon removing the bullets from the gelatin it was found the lead bullet lost 0.2 grains of weight. The bismuth bullet had lost 7.8 grains of weight. The average expanded diameter of the lead and bismuth bullets were 0.383" and 0.381" respectively. The minimal expansion observed in both bullets probably accounts for the deep penetration seen in this test.

As can be seen in Figure 57 and Figure 58 the bismuth bullet path in the gelatin was fairly straight. The lead bullet had a curved path in the ballistic gelatin. A close up view of the

entrance wound of both bullets can be seen in Figure 66. The bismuth bullet entrance wound on the front of the gelatin is the same diameter as the bullet, this would suggest the bullet was flying straight upon impact. Both bullets quickly started to expand upon entering the ballistic gelatin. A few pieces of bismuth broke off. Figure 67 shows the bullets' resting place in the ballistic gelatin. Both bismuth and lead bullets were facing backwards. This would indicate both bullets tumbled while traveling through the gelatin. Figure 61 and Figure 62 show both extracted bullets. It can be seen that the base of the bismuth bullet copper jacket broke off. The base of the bismuth bullet broke off and struck a little to the right of the bismuth bullet hole. This suggests the base detaches during flight before reaching the plywood. Neither bullet expanded much. In this test the bismuth bullet nose stayed intact. This is because the bullet did not expand enough. It remains unclear as to why both lead and bismuth bullets failed to expand when traveling through plywood.

Both lead and bismuth bullets had comparable performance in shooting into ballistic gelatin with an intermediate barrier of plywood.

9.3.5 Galvanized Steel

The ballistics data for 20 gauge galvanized steel is summarized in Table 16. It was found that the bullets had a penetration of 18.25 inches and 18.50 inches for the bismuth and lead bullets respectively. Both bullets had greater penetration than the minimum 12 inches that the FBI standard test indicates as reliable penetration. Upon removing the bullets from the gelatin it was found the lead bullet lost 2.1 grains of weight. The bismuth bullet had lost 14.3 grains of weight. The average expanded diameter of the lead and bismuth bullets were 0.432" and 0.434" respectively.

As can be seen in Figure 64 and Figure 65 both bullets traveled fairly straight in the gelatin. A close up view of the entrance wound of the bismuth bullet can be seen in Figure 66. It can be seen that there are many entrance wounds. This is because upon going through the two pieces of 20 gauge steel the bismuth bullet's nose shattered spraying the front of the gelatin with many pieces of bismuth. Also in this image there are two larger disk like objects. The closer disk which had a penetration of about 2 inches was found to be two disks of steel. These disks were punched out of the steel when the bismuth bullet went through. This propelled the disks forward into the ballistic gelatin. Figure 67 shows the entrance wound of the lead bullet. The lead bullet expanded as it went through the gelatin. Figure 68 shows the resting place of both bullets in the gelatin. By observing the gel it appeared that the bismuth bullet did tumble in the gelatin.

Figure 70 shows both pieces of 20 gauge galvanized steel that were shot through. As can be seen in this figure both bullets hit the front plate and went through. On the second plate when the lead bullet was shot through the steel something was propelled, hitting the second steel plate and leaving a dent. This dent is believed to have been caused by a steel disk punched out by the lead bullet and propelled into the second piece, the dent can be seen on the right of the second plate in Figure 70. Figure 76 shows the base of the bismuth bullet's copper jacket along with the two disks of steel that the bismuth bullet punched out. The two pieces of steel were stuck together and could not be easily separated.

Figure 77 and Figure 78 show both extracted bullets. The tip of both bullets have a silvery coat on the top of both bullets. This is believed to be a thin layer of zinc used in galvanized coating. The base of the bismuth bullet's copper jacket broke off.

Both lead and bismuth bullets had comparable performance in shooting into ballistic gelatin with an intermediate barrier of 20 gauge steel.

9.3.6 Auto Glass

The auto glass test was performed twice. This was done because the penetration distance of both bismuth and lead bullets were disappointingly low. A second test was performed to confirm the first. Both tests had very similar penetration within 1/2 an inch between both tests. Both tests consisted of shooting through one layer of auto glass set at 45° to the horizontal then skewed 15° about the vertical.

Both tests were performed within a two week period the weather data for both tests are summarized in Table 17. The ballistics data is summarized in Table 18. The two tests agree very closely. Unfortunately all of the bullets shot through auto glass had penetration less than the 12 inches the FBI standard suggests.

Both the bismuth and the lead bullets had most of their copper jackets ripped off upon going through the auto glass. The lead-core stayed together as a chunk of metal and plastically deformed upon going into the gelatin. In contrast the bismuth-core displayed its brittleness and shattered into many small pieces. This can be seen by the recovered fragments from the tests. In test 2 the chunk of lead that penetrated 11.75 inches had a weight of 87.1 grains. In comparison the main piece of bismuth which penetrated 8.5 inches was only 36.3 grains. For test 1 the lead bullet once recovered weighed 81.9 grains. The bismuth bullet in test 1 shattered into many pieces of which 3 were significant in size, plus the detached copper jacket, see Figure 82. The fragment of bismuth that penetrated the furthest at 8.25 inches weighed 24.6 grains. The other two fragments of bismuth had weight and penetration of 10 grains and 7.00 inches, 7.3 grains

and 3.75 inches. The data for the bismuth fragments from test 1 are summarized in Table 19, and see Figure 82, Figure 84, and Figure 85 for the remnants of the bullets.

The side and top view of both tests can be seen in Figure 80 and Figure 81. These figures show that the bullets had a fairly straight path in the gelatin. Figure 83 is a close up view of the bismuth bullet entrance wound in test 1. As can be seen there are many small pieces of bismuth and many of them created their own wound holes. This is confirmation the bismuth bullet almost completely shattered upon going through the auto glass. Figure 84 and Figure 85 show the extracted pieces of the bullet after they were fired through auto glass.

Figure 86 shows the copper jacket of the lead bullet on the second test. It is believed that upon going through the glass the lead and the copper jacket got separated. The copper jacket then would have hit the front of the gelatin and rebounded back, landing by the base of the auto glass. Figure 87 shows the front of the entrance wound from both tests. In contrast to the second test the first test showed the detached jacket entering the gelatin rather than rebounding. This created two holes in the front of the gelatin. The bismuth on the other hand had a shotgun effect on the front of the gelatin leaving many small holes.

Figure 79 shows the pieces of auto glass that were shot through in both tests. Each bullet had its own piece of glass. This was done because when one bullet is fired through the auto glass it leaves cracks that would interfere with a second shot into the same piece of glass.

For this test the bismuth bullet had a significantly different performance from that of the lead bullet. The lead bullet had deeper penetration and the core stayed together. The bismuth bullet shattered into many small pieces. Each of these smaller pieces would have less kinetic energy than that of the larger single piece of lead. That is the reason why the lead bullet had

deeper penetration than the bismuth bullet for this test. Technically both the lead and the bismuth bullets failed the auto glass test. But the performance of the lead bullet was clearly superior and only failed the penetration test by 1/2 inch. The bismuth bullet clearly had inadequate penetration and underwent severe fragmentation.

9.4 Average Speed of the Bullets

Upon observing the velocities of all the bullets shot in this research it was found the bismuth bullets on average traveled at higher speeds than the lead bullets, despite the use of the same quantity and brand of propellant, see Table 20. The average speed for the bismuth bullets was 1235 fps. The average speed for the lead bullets was 1167 fps. Giving an average difference between the bullets of 68 fps. A t-test was done on the velocities of the lead and bismuth bullets using Microsoft Excel. A p-value of 0.0026 was found. Therefore, since $0.0026 < 0.05$ there is a significant difference between the velocities of both bullet types. Although both bullets weighed about the same, the bismuth bullets were a little longer than lead bullets. Bismuth bullets had to be seated further into the brass casings thereby reducing the volume available for containing the gunpowder.

9.1 grains of gunpowder were used for both the bismuth cartridge and the lead cartridge, but since less space was available inside the cartridge when using the bismuth bullet a more rapid increase of pressure likely occurred. This higher pressure would inevitably lead to increased velocities in the case of bismuth bullets as compared to lead bullets.

CHAPTER 10: CONCLUSION

In the FBI standard ballistics test a bullet must reliably penetrate 12 inches into 10% ballistic gelatin. Apart from the auto glass test, the 125 grain bismuth and lead bullets performed similarly, achieving a penetration of between 16 to 20 inches. The bismuth bullet typically had a little more penetration than that of the lead bullet.

One interesting behavior of the bismuth bullet is the tendency for the nose of the bullet to shatter. This sends out a spray of bismuth particles upon entering the gelatin. This spray adds an interesting dynamic to the bismuth bullet. This spray happens because bismuth is more brittle than lead. When the bullet hits a target the copper jacket bends back. With the more ductile copper no longer supporting the tip of the bismuth hollow point it shatters. This behavior is an interesting property that could be investigated further in future research.

Shooting into paper targets demonstrated that bismuth bullets were stable and able to achieve similar accuracy to bullets constructed with a lead-core.

Unfortunately both lead and bismuth bullets underperformed when shooting through auto glass. Although both lead and bismuth bullets penetrated less than the recommended 12 inches, the bismuth bullet performed the worst. The bismuth bullet shattered and fragmented into multiple components achieving a penetration of only 8.5 inches. This penetration might still be adequate for self-defense, but is less than ideal.

The advantage of bismuth is that it is non-toxic and can be incorporated into copper jackets relatively easily. Copper jacketed bismuth can be reloaded into existing cartridges without the need for any special equipment. It also appears to function in existing firearms without damaging the bore or disintegrating prematurely.

Bismuth is however more expensive than lead or pure copper as used in current bullets. Typically bismuth costs \$9 per pound compared to \$0.80 and \$2.70 for lead and copper respectively. However bismuth is less toxic than lead and heavier than copper, making for green bullets that more closely match the dimensions of existing lead bullets.

Overall, bismuth has been shown to be a viable alternative to lead in green bullets. It is regarded as non-toxic but able to perform similarly to lead if constructed using copper jacketing. Should the government decide to ban lead for bullets, this study has demonstrated that bismuth could be substituted in 125 grain 38 caliber rounds which are widely used for self-defense.

CHAPTER 11: FUTURE WORKS

The bismuth bullet tended to be more brittle than lead, causing negative effects on performance when shot through auto glass. Therefore an area for future research would be to add an additional material to the bismuth to increase its ductility. If the bismuth was more ductile it would display similar behavior to that of lead. Bismuth shot used for shot guns is typically 3-10% tin. The added tin would increase the ductility of the bismuth. Although, the addition of tin to bismuth would slightly reduce its density. There is also the potential of adding other material to the bismuth to increase the ductility.

Also a high speed camera could be used to observe the total behavior of the bullet in exterior and terminal ballistics. High speed footage would allow for complete evaluation of the bullet behavior during flight. This would show if the bullet was stable and flying straight. It would also show if any part of the bullet broke off during flight. For terminal ballistics it would show exactly how the bullet expanded, deformed, and traveled through the ballistic gelatin.

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