

# Lead Contamination in Soil at Outdoor Firing Ranges



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## Introduction

Over the past several years, issues have been raised regarding the potential environmental impact of outdoor firing ranges. The main concern has been the fate and transport of heavy metals from bullets and bullet fragments accumulating in soil. Of these metals, lead is the predominant contaminant.

Most outdoor firing ranges are used for small arms, using munitions that are 50 caliber or less. Pistols, shotguns, skeet shooters, rifles and machine guns all fit into this category.

Lead is the most prevalent contaminant at Superfund sites across the country. It is considered the top environmental threat to children's health, associated with development delays and reduced IQ.<sup>1</sup>

The U.S. military alone has cleaned up more than 700 fire ranges across the country over the past several years. There are currently 1813 commercial outdoor firing ranges registered with the National Shooting Sports Foundation.<sup>2</sup>

According to estimates by the Environmental Working Group, outdoor firing ranges put more lead into the environment than any other industry in the U.S., with the exception of metals mining and manufacturing.<sup>3</sup> Civilians, the Department of Defense, the Department of Energy and law enforcement agencies combined use tens of billions of rounds of ammunition each year, translating to hundred of tons of lead per day.

## The Outdoor Firing Range

A typical outdoor firing range (Figure 1) is comprised of a series of targets in front of an impact berm. The targets may be made of paper, wood or metal and the impact berm may be equipped with bullet traps.

The distance from the firing line to the target may be as much as 2,000 feet for some military operations, providing a very large area for potential contamination.

The bullet will likely move through the target and will strike the impact berm, penetrating, fragmenting, agglomerating, smearing or ricocheting.

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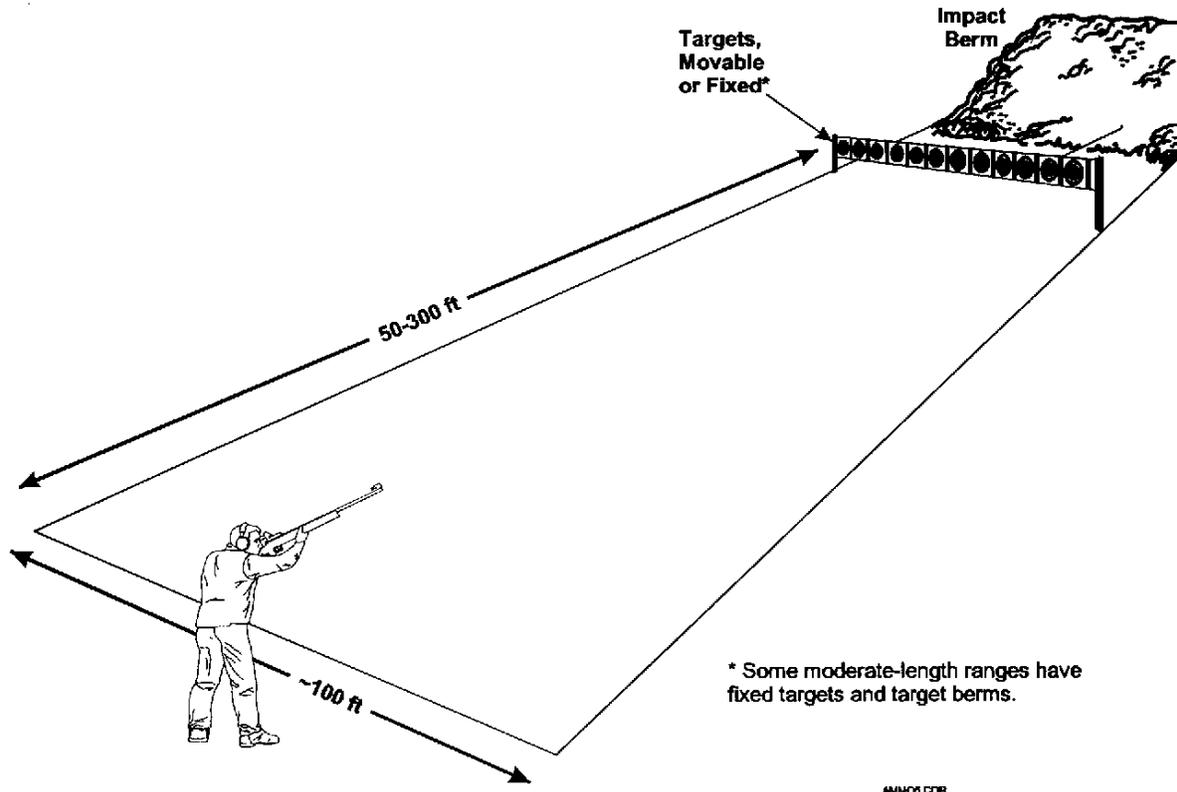


Figure 1. Typical outdoor firing range.<sup>4</sup>

### Lead Bullets

Lead has been the material of choice because of its low cost, easy availability, versatility and excellent performance. Many bullets are jacketed with copper, as illustrated in Figure 2, making them more environmentally sensitive in wet soils due to the galvanic corrosion potential.

Rainwater will act as an electrolyte, stimulating electron exchange between the two metals, initiating galvanic corrosion. Since lead has a significantly lower electromotive force (-0.126) than copper (-0.337), these metals together are prone to galvanic corrosion and the lead will be more soluble than copper and creating more of an environmental concern.<sup>4</sup>

Munitions from skeet shooting are less likely to promote soil contamination. Most bullets used for this purpose do not break into fragments. The bullets usually have an oxide coating, which gives the bullet an added layer of protection from the elements. Water and acidic conditions would first have to break down the oxide coating before attacking the lead. In this way, the oxide coating helps to prevent the material from being mobile.

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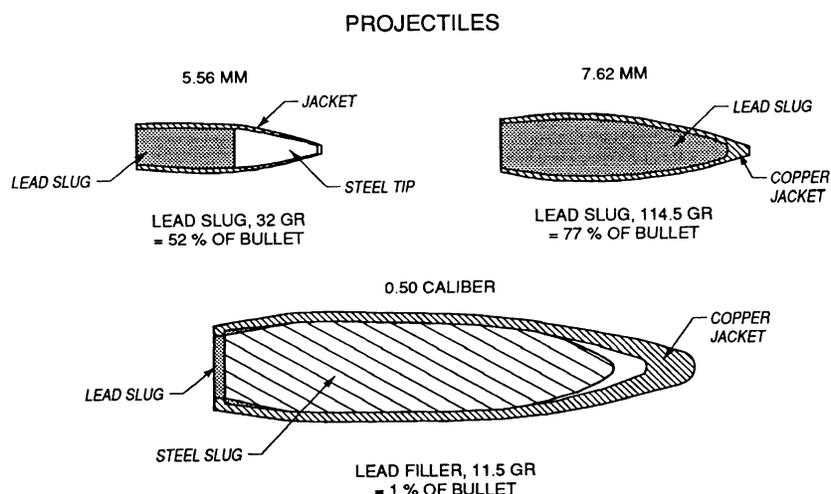


Figure 2. Most bullets are comprised of a copper jacket with a solid lead core.<sup>5</sup>

Pistols normally fire at a lower velocity than rifles; thus, the bullets tend to remain intact. The amount of fracturing will depend on the composition of the target material. Steel targets, for example, will cause more fragmentation and airborne particulate generation than wood or paper targets.

Rifles pose the largest risk for contamination. Typically, the projectiles exit at a very high velocity and the bullet breaks apart into small fragments. Smaller fragments provide a much larger surface area reacting with materials in the soil or atmosphere.

## Lead Mobility

Once the lead bullets and debris settle on the soil, a number of factors will determine the extent of the actual hazard it might pose. The more easily the lead moves through the soil, the more of an impact it will have. The total soil concentration of lead alone has little or no bearing on lead mobility or bioavailability. In order to become mobile, it must dissociate into pore water and migrate via mass transport.

Solubilization of lead depends on a number of factors including

- metal speciation
- soil chemistry
- water chemistry
- bullet composition and condition

## Metal Speciation

Lead speciation is dependent on pH and pE (redox potential). Figure 3 illustrates that divalent lead ions are predominant at a low pH and a high pE. A high pE is indicative of low electron activity, favoring oxidation.

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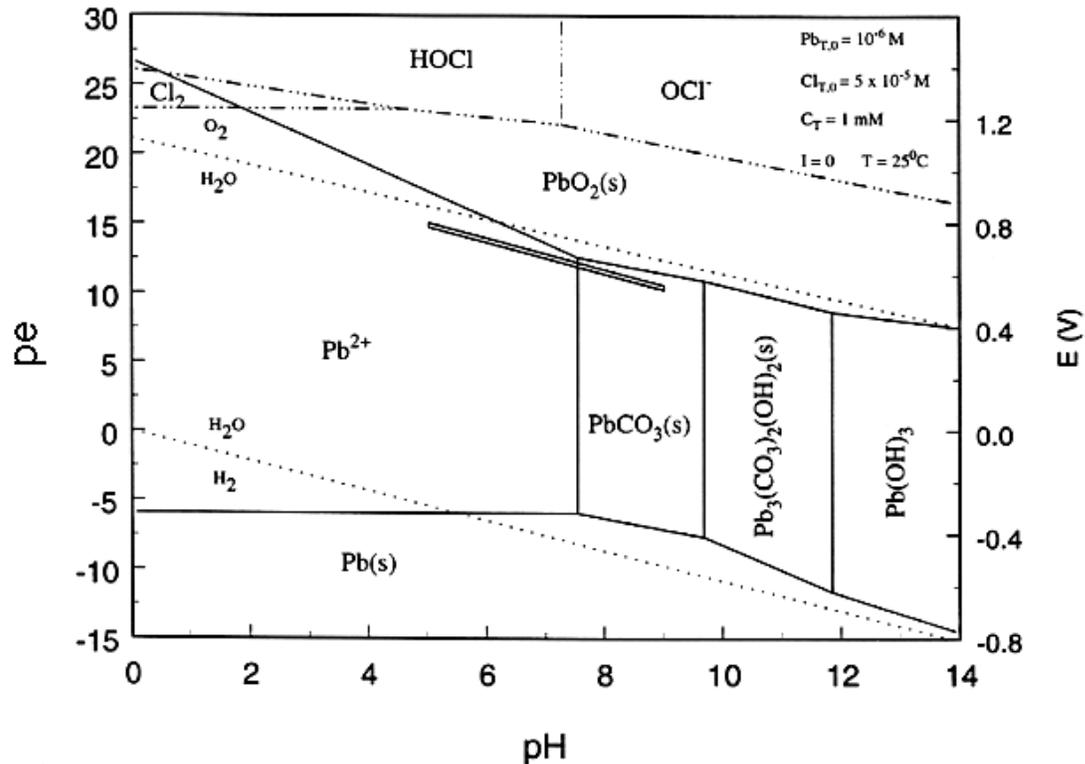


Figure 3. pH-pE diagram for lead species.<sup>6</sup>

### Soil and Water Chemistry

The chemistry of the soil and groundwater or nearby water sources will affect the fate and transport of the lead. Some examples include:

- Acidic conditions favor solubilization of lead, while basic conditions decrease the concentration of dissociated lead, based on the pH-pE diagram above. Likewise, a shift in redox potential will either increase or decrease lead concentrations by shifting metal speciation either toward the divalent lead ion or a more stable lead compound.
- The presence of protonated ligands, such as NTA, and chelating agents, such as EDTA, will likely promote complexation by causing a shift in oxidation-reduction equilibria strongly to the right by binding to the product ion:<sup>7</sup>



- High concentrations of humic substances, such as fulvic acid or humic acid can increase lead concentrations due to their chelating capabilities.
- Insoluble organic matter and clays can decrease lead concentrations by sorbing the lead or forming stable complexes.
- Sandy soils are less likely to bind to lead and do not retain water, reducing the lead concentration.

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- Phosphate or sulfide lead compounds are generally less soluble than carbonate or hydroxides.

Thus, one might expect more of a problem with lead solubilization in the northeastern U.S. where acidic conditions are more prevalent due to the effects of acid rain and the absence of large amounts of limestone. Areas around industrial processes releasing chelating agents into groundwater or soil would be more susceptible to lead contaminations problems as well.

### Mass Transport of Lead

While the mere presence of solubilized lead in soil can pose a hazard to wildlife, movement of the lead into groundwater is more of an environmental concern. Mass transport of lead into groundwater is influenced by a number of factors including:

- Amount of normal precipitation
- Topography of the fire range area
- Distance (depth) to groundwater from the soil surface

Rainwater acts as a carrier for solubilized lead. If there is little or no precipitation, the lead is less easily transported to groundwater. If there is a great deal of precipitation, infiltration is probable, but the concentration of lead might be too dilute to be of environmental concern.

A flat terrain favors infiltration to groundwater. If the range is on a hilly area, where the topography is sloped, runoff is more likely, which can be particularly problematic based on what is downhill from the range.

If the lead must travel a long distance to groundwater, lead concentrations may be dilute or the lead might never reach the groundwater. Where the water table is high, the traveling distance will be much shorter and pore water concentrations are likely to be higher.

Another factor to consider is that copper and lead in soil can limit the growth of plants and grasses, leading to soil erosion, particularly in areas that receive a fair amount of precipitation. Eroded soil may be more easily infiltrated and the distance to groundwater may be reduced, both possibly resulting in higher lead concentrations.

## Remediation

EPA Region VIII recently developed draft guidelines for remediation of outdoor firing ranges.<sup>8</sup> Their approach proceeds in several steps:

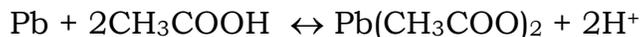
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1. Sift munitions fragments from the soil. The fragments can be recycled and doing so makes them exempt from hazardous waste reporting and management requirements.
2. Sample and analyze the remaining soil to determine if the leachable level is at or above the EPA limit of 5 mg/L. If it does not exceed the limits, the soil can be disposed or reused or left in place with no further action needed. If it exceeds the limit, proceed.
3. Analyze the soil in layers to determine the extent of the contamination. Layers that do not exceed the limit need no further action.
4. Treat or dispose of the soil. There are numerous options, including placement in a hazardous waste landfill, onsite stabilization and solidification and soil washing.

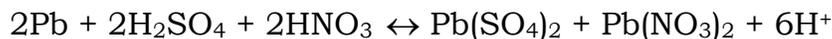
When analyzing the soil, it is important to choose the right test methods. One common problem has been the use of the Toxic Characteristic Leachate Procedure (TCLP) to determine lead concentrations in soil. TCLP is designed to simulate conditions in a landfill and is used to determine whether a waste material must be handled as hazardous waste. However, the soil at a working firing range is not usually not subject to those conditions.<sup>9</sup>

A more accurate test is the Synthetic Precipitation Leaching Procedure (SPLP), which is almost identical to TCLP, but simulates acid rain, rather than landfill conditions. Since SPLP uses a higher pH, it is much less efficient at solubilizing lead from the soil than TCLP and results are typically 5 to 100 times lower than TCLP.

TCLP uses acetic acid to adjust to a pH of 2.8:



SPLP uses 60:40 mix of sulfuric and nitric acids to adjust to a significantly higher pH of 4.2 for areas east of the Mississippi and 5.0 for western areas.



### Physical Separation and Acid Leaching

The objective of the physical separation/acid leaching method is to recover particulate and ionic lead from the soil. The advantages of this method are that it can be conducted on-site and that the recovered lead can be recycled. Figure 3 provides a simplified schematic for this process.

The first step in the process is physical separation of particulate lead from the soil. There are numerous methodologies available for this purpose, based on the size and composition of the particles. For munitions, there has been

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success using metal screens to separate coarse particles from fine particles, followed by gravity separation to filter the metal fragments from the bulk soil based on size and density. The finer, lighter particles consist of sands, silts, and clay and may contain very fine metal particulates and bound molecular or ionic metals.

The fine particles are subjected to acid leaching to dissociate the lead. Clean soil goes back to the range and the leachate is treated with precipitants to precipitate out the solubilized lead for recovery.

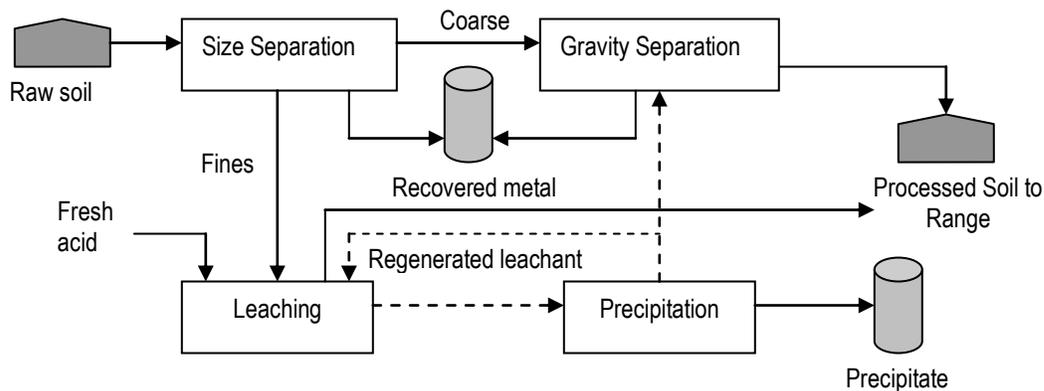


Figure 4. General schematic of the separation-leaching procedure.

The acid leaching proceeds as a continuous process. The first step is to subject the soil to an acid solution in a leaching tank. Contact time will vary depending on the type of soil and the contaminants. Usually, bench-scale testing of the process is conducted first to determine how effective the method will be and to choose the acid and determine contact time.

The soil slurry is pumped into a clarifier tank to allow the solids to settle out and discharge. A flocculant may be added to enhance settling of any colloidal masses. The overflow from the clarifier is the leachate containing the solubilized metals. The leachate is pumped into another tank where the solubilized metals are recovered either by precipitation or by electrowinning.

Bench-scale testing is necessary to determine which precipitants will be most effective, based on the composition of the leachate. For example, the leachate may contain other materials that were in the soil, including chelating agents, other metals, etc. A number of precipitants can be used, such as hydroxides, carbonates, phosphates, sulfates and sulfides. Once a precipitant is chosen, it is important to control the pH in the precipitation tank, since lead (like many metals) has an optimum pH for precipitation. The pH-pE curve in Figure 3 illustrates this for lead. Figure 5 shows the theoretical precipitation curves for other metals as hydroxides and illustrates the need for pH control.

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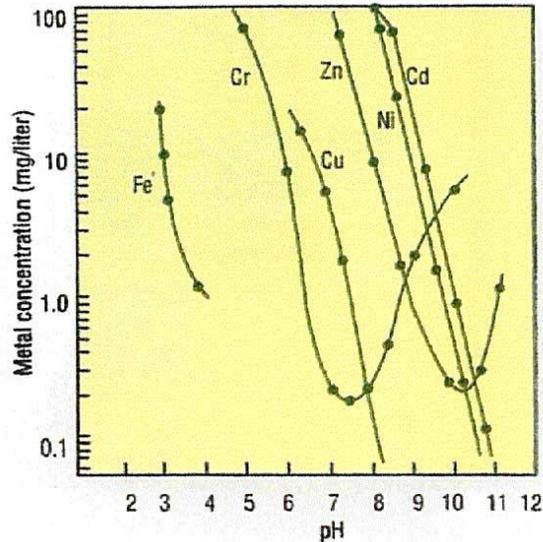
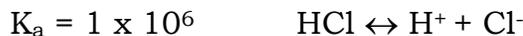


Figure 5. Precipitation of heavy metals as hydroxides

The two acids that can be used for the leaching process are acetic acid and hydrochloric acid. Both have their advantages and disadvantages. The same molar concentration of acetic acid ( $\text{CH}_3\text{COOH}$  or HOAc) and hydrochloric acid has equal neutralizing ability, but HCl is a much stronger acid than HOAc. HCl is an aggressive, highly corrosive leachant and HOAc is more selective and less corrosive.

The acid dissociation equilibrium constant for HCl is very large compared to that for HOAc. In water, almost 100% of the HCl will dissociate, making the  $\text{H}^+$  ion available.



The equilibrium lies so far to the right that it is almost appropriate to change to a one-way arrow.



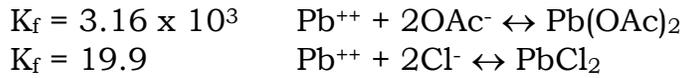
The equilibrium constant for HOAc is very small, several orders of magnitude below that for HCl. While HCl will dissociate almost entirely at any pH more than zero, the  $\text{H}^+$  concentration from HOAc will always be relatively small. Using the equation

$$K_a = \frac{[\text{OAc}^-][\text{H}^+]}{[\text{HOAc}]} = 1.8 \times 10^{-5}$$

one can calculate the concentration of HOAc needed to achieve a high percent (at least 15%) dissociation of acetic acid to  $\text{H}^+$ . The optimum acid activity ( $\text{H}^+$

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availability with the lowest concentration of HOAc) occurs with dilute concentrations of HOAc ( $\sim 1 \times 10^{-3}$  M) with a pH 3.3-3.8.



Although the formation constant for the acetate is more than 100 times that of the chloride, one must keep in mind that the amount of available OAc<sup>-</sup> ion is likely less than the abundance of available Cl<sup>-</sup> ion.<sup>10</sup>

However, if the lead is already solubilized, lead complexation to form soluble acetate complexes can occur at a higher pH range. Another advantage to using acetic acid is that the acetate complexes are stronger than chloride complexes. Indeed, PbCl<sub>2</sub> is still relatively soluble, with a K<sub>sp</sub> of  $2.4 \times 10^{-4}$ .<sup>10</sup>

Based on projects completed by Battelle, Inc. involving remediation of outdoor military firing ranges, the physical separation and acid leaching method removed 93% of the total lead (based on TCLP) using acetic acid and 96% of the lead using hydrochloric acid.

### Metal Stabilization

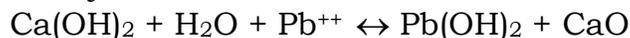
Another common method for remediating lead in soil is stabilization or solidification of lead in soil. The objective is not to remove the lead, but to reduce its mobility by having it bind to a chemical reagent. Portland cement and sodium silicate, lime and fly ash, manganese or iron oxides, and phosphate have been used for this purpose.

Depending on the material used, the chemical reagent reduces mobility by:

- Controlling pH and/or pE (lime and fly ash)
- Chemical binding by precipitation as carbonates (lime and fly ash), silicates (sodium silicates) or phosphates.
- Micro and macro encapsulation (Portland cement and silicate)
- Adsorption (Portland cement)
- Oxidation (iron or manganese oxides)

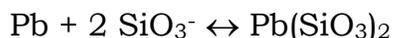
Contaminated soil is first collected and screened to remove bullet fragments. The soil is mixed with the chemical reagent and enough water to catalyze the reaction. The treated soil may need to pass through conveyers to capture any hazardous off-gases (e.g., hydrogen sulfide, when sulfides are used), which then pass through either a wet scrubber or activated carbon.<sup>11</sup>

Lime and fly ash



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### Silicates



One of the most promising stabilizing techniques for lead involves the use of phosphates. There are a number of different techniques using several types of phosphate compounds. It appears that the best stabilizer is apatite,  $\text{Ca}_5(\text{PO}_4)_3\text{Cl}$ .



The solubility constant for the resulting lead pyromorphite is  $3.98 \times 10^{-85}$ , making it extremely insoluble. Table 1 lists solubility products of other compounds as a means for comparison.

Table 1. Solubility products of various compounds.<sup>12</sup>

Name	Formula	$K_{sp}$
Salt	NaCl	0.0
Quartz	$\text{SiO}_2$	$1.0 \times 10^{-4}$
Galena	PbS	$3.16 \times 10^{-28}$
Chloropyromorphite	$\text{Pb}_5(\text{PO}_4)_3\text{Cl}$	$3.98 \times 10^{-85}$
Corkite	$\text{PbFe}_3(\text{PO}_4)(\text{SO}_4)(\text{OH})_6$	$3.98 \times 10^{-113}$

To test the effectiveness of the stabilization process, treated soil samples are subjected to the Multiple Extraction Procedure (MEP). This procedure is similar to TCLP, but involves ten separate extractions using ten different acids. While TCLP is designed to simulate 100 years of stability, MEP simulates 1,000 years of stability.<sup>11</sup> Several projects have boasted of great success in using the phosphate stabilization process, based on MEP results.

Apatite has the added advantage of acting as an excellent buffer for neutralizing acidity through  $\text{PO}_4^-$  and  $\text{OH}^-$  and promotes precipitation of oxide, hydroxide and carbonate metal phases. It is very stable over a large pH range (2-12), up to  $1000^\circ\text{C}$  and in the presence of aqueous and non-aqueous phase liquids. The bioavailability of ingested metal-apatite is greatly reduced, making it safe for consumption by most wildlife.<sup>11</sup>

Not much apatite is required. The greatest reduction in lead concentration occurs with only 1% addition of apatite.

Another study found that addition of manganese oxides to the phosphate additive even further reduces the bioavailability of lead in soil. Cryptomelane,  $\text{KMn}_8\text{O}_{16}$  acts as a strong oxidizer for phosphate and metals.<sup>13</sup>

## Phytoremediation

Using plants to extract lead from soils is an emerging technology. Researchers have found that certain plants accumulate and tolerate very high concentrations of certain heavy metals in their shoots. These “hyperaccumulators” theoretically should be able to reduce lead levels in contaminated soil to an acceptable level.

There are a number of challenges to this technology. First, some plants can release the compounds and their metabolites in to the atmosphere, which defeats the purpose of the remediation. Phytoremediation works by drawing the lead into the shoots, which requires the lead to be in a soluble form. This will not work if stabilization techniques have been employed, since the availability of solubilized lead should be minimal.<sup>14</sup> If the soil is acidified or otherwise treated to promote lead dissociation, many plants will not thrive.

For lead remediation, the plant must be capable of accumulating greater than 1% lead in shoots and must produce more than 20 tons of shoot biomass per hectare per year.<sup>15</sup>

One of the first plants identified that meets these qualifications is the Indian Mustard plant (*Brassica juncea*) shown in Figure 6. This plant is capable of accumulating 1.5% lead in plant tissue and has a high biomass.<sup>16</sup> Agronomic crops, such as corn and pea plants, have also been successful in accumulating significant lead concentrations.<sup>15</sup>

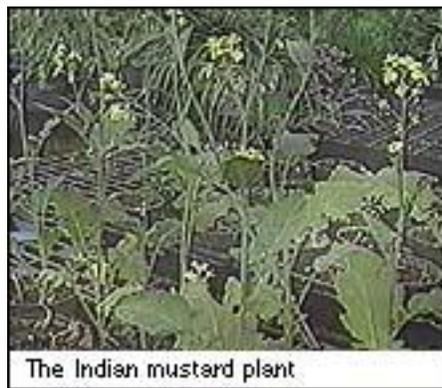


Figure 6. The Indian Mustard Plant (*Brassica juncea*)<sup>17</sup>

For most lead contaminated soil, only 1% of the lead is available in the solubilized form. Lead will rapidly be extracted into the roots and shoots of a plant if it is bioavailable in the plant growth media.<sup>15</sup> To promote solubilization of the lead, many researchers have studied the role that chelates may play in phytoextraction.

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Studies have shown that amending soil with chelates will increase the concentration of solubilized lead in the soil, which directly correlates with an increase of lead accumulation in plants.

A number of chelates have been tested for this purpose. Generally, EDTA was superior to any other chelate tested. Figure 7 shows the results of experimentation with five different chelates in soil with pea and corn plantings. Not only does this illustrate that EDTA is the most efficient chelate, but it is apparent from these graphs that the amount of solubilized lead in the soil is directly related to the concentration of lead in the plants.

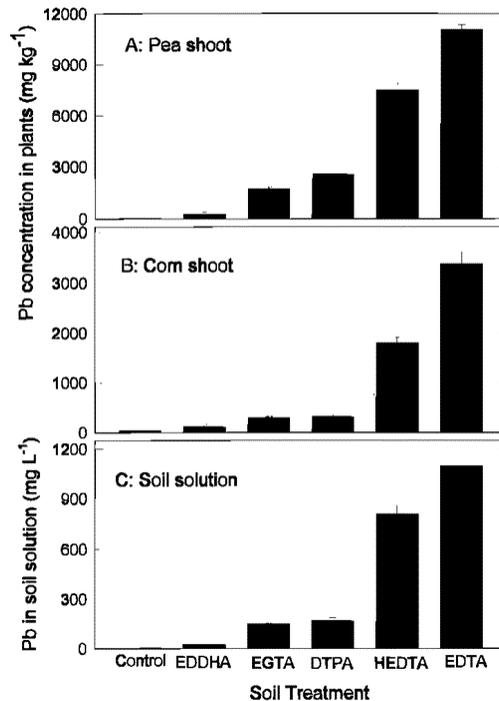


Figure 7. Relative efficiency of five synthetic chelates in enhancing Pb accumulation in shoots of pea (A) and corn (B) grown on the chelates treated Pb-contaminated soil and Pb desorption from soil to soil solution.<sup>15</sup>

Chelating agents like EDTA (Figure 8) have multiple binding sites. The lead will react with the chelating agent to form a Pb-EDTA complex. It is not well understood why the Pb-EDTA complex is as readily absorbed as ionic lead, but several studies confirm this to be the case.<sup>16</sup>

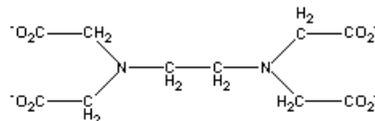


Figure 8. Ethylenediamine triacetic acid (EDTA)

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Slight adjustment to the soil pH using a buffer such as acetic acid also appears to enhance lead uptake by the plants, particularly in combination with a chelating agent. Acetic acid alone will increase lead uptake by a small degree, but one study found that by decreasing the pH slightly (from 8.3 to 7.8) using a buffering acid like acetic acid and applying EDTA simultaneously doubled the lead uptake compared to EDTA alone.<sup>16</sup> One theory for this is that the decreased pH helped to create more  $Pb^{++}$  ions available, some complexing with EDTA and other simply taken up in the ionic form by the shoots.

Phytoremediation is certainly promising. One New Jersey based company, Edenspace (formerly Phytotech), has documented successes with a few Brownsfields projects in New Jersey using the Indian mustard plants in soil amended with EDTA and acetic acid. A number of projects in Europe have also been successful, but much more research and demonstration projects are needed before this technology is universally accepted and the appropriate applications are identified.<sup>14</sup>

## Pollution Prevention

There are a number of methodologies for reducing lead pollution from outdoor firing ranges.

### Green Bullets

Probably the most promising pollution prevention strategy for both indoor and outdoor firing ranges is the development of the “green bullet”. Rather than lead, this new bullet is a slug made from tungsten and tin (Figure 9). Tungsten is an environmentally non-toxic metal with a higher density than lead. In a powder form, it is mixed with a softer, lighter metal like tin to produce a high density material, without the need for heating (thus without the possibility of volatilizing the metal). The material can easily be pressed into shape to replace many small caliber bullets.<sup>18</sup>



Figure 9. Tungsten-Tin Bullet<sup>18</sup>

The ballistic performance of the green bullet is equivalent to that of lead bullets, but boasts additional properties, such as ease of varying impact properties by altering the composition of materials, that make its overall performance superior to that of lead bullets.<sup>18,19</sup>

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The tungsten and tin are also completely recyclable. The metals can be reclaimed from the scrap collected at the firing ranges

A team of researchers at Oak Ridge National Laboratory, a Department of Energy (DOE) facility in Oak Ridge, Tennessee, used a decision methodology based on life-cycle analysis to help determine whether or not the use of “green bullets” is a significant pollution prevention strategy. The analysis took into consideration health and safety impacts, environmental impacts, life-cycle cost, schedule impacts, local economic impacts, institutional issues and stakeholder acceptance.<sup>19</sup>

Their analysis found tungsten-tin bullets to be superior in every category, including cost. While the “green bullets” are more expensive to produce, the overall cost is less when maintenance and cleanup activities associated with lead is considered. *Table 2* provides a breakdown of the estimated costs.

*Table 2.* Annual cost comparison for the DOE training facility outdoor firing range.

	Slug Composition	
	Lead	Tungsten-Tin
Ammunition	\$2,500	\$7,500
Maintenance and Cleanup	\$48,000	\$2,500
Total	\$50,500	\$10,000

Ammunition cost based on 10,000 rounds per year at \$0.25 each. “Cleanup” refers to periodic activities such as recovery of slugs from bullet traps.

U.S. Army officials plan to switch to the lead free bullets by 2005.<sup>20</sup> By that time, it may be less expensive to produce the tungsten-tin bullets. They are currently more expensive to produce due to the fact that lead is abundant in the U.S., while tin and tungsten must be imported from other countries. Since both metals are easily recyclable, our dependence on imported raw materials will be reduced once enough recycled metal is accumulated.

### **Bullet Trapping**

Bullet traps are a relatively expensive way to capture and contain lead from firing ranges. One type of trap constructed of a low-density, fiber-reinforced concrete effectively traps the lead bullet by allowing the bullet to bury itself in the concrete to avoid ricochet. The captured bullet debris undergoes a corrosion process to form a relatively insoluble oxide coating on the bullet fragments. The less soluble fragments reduce the leachability of the lead, thus reducing the potential for lead mobility from the firing range area.<sup>21</sup>

Rubber traps are less expensive and more popular. They are either made of a series of rubber strips or a steel box with a rubber front. The rubber absorbs

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the energy of the munitions, leaving the bullet intact and reducing airborne lead.<sup>8</sup>

A water trap consists of a funnel leading to a deceleration chamber containing water. Bullets will enter the chamber, deflect downward and spin until their energy is spent, wetting the chamber in the process, reducing the likelihood of airborne lead dust.<sup>8</sup>

Upward deflecting backstops reduce the velocity of munitions, providing the best method of ensuring that the majority of the bullet and fragments are trapped. The metal backstop does facilitate production of lead dust, which can contaminate adjacent soils.

### **Pretreatment of Soil**

Some firing ranges are experimenting with topical application of phosphate additives or iron to reduce lead mobility.<sup>5</sup> By applying these materials before the lead is introduced, it may be possible to prevent bioavailable lead from accumulating.  $\text{FeO}_4^{--}$ , for example, is a very strong oxidizer that will oxidize lead to a less soluble form.

## Conclusion

Lead from outdoor firing ranges has the potential to create significant environmental contamination requiring remediation. An enormous amount of lead is currently deposited at firing ranges across the country. There have been several firing ranges found to have high lead concentrations in soil. While in most cases, the lead is not very mobile (stays in metallic form), some ranges have had significant solubilized lead contamination requiring remediation.

By following prudent management practices and designing and maintaining the range in ways that minimize the potential for solubilized lead accumulation, it is possible to operate outdoor firing ranges in an environmentally responsible manner and to prevent or at least postpone the need for remediation.

## Bibliography

1. Environmental Protection Agency, *Fact Sheet on Common Contaminants at Superfund Sites*, <http://www.epa.gov/oerrpage/superfund/accomp/ei/contam.htm>
2. National Shooting Sports Foundation website, <http://www.nssf.org>
3. Houlihan, J. *Lead Pollution at Outdoor Firing Ranges*, Environmental Working Group, Washington, D.C., 2001.
4. US Army Corps of Engineers. Vertical Migration Potential of Metal Contaminants at Small Arms Firing Ranges, Camp Edwards Military Reservation, MA. Technical Report IRRP-98-3. March 1998.
5. Bricka, M. Soil Treatments to Limit Lead Mobility. *Fourth National Shooting Range Symposium*. 2000.
6. *Advances in Environmental Research*. <http://www.sfo.com/~aer/508-96f9.html>.
7. Manahan, S.E. *Environmental Chemistry*, 7<sup>th</sup> edition, Lewis Publishers, New York, 1999.
8. Environmental Protection Agency. Fact Sheet on Lead Contamination in Soil at Small Arms Firing Ranges. <http://es.epa.gov/program/p2dept/defense/airforce/2818.htm>. July 1995.
9. Cohen, S.Z. Testing Your Outdoor Range – Using the Right Tools. Fourth Annual National Shooting Range Symposium.
10. Nelson, B.. Implementation Guidance Handbook: Physical Separation and Acid Leaching to Process Small-Arms Range Soils. Battele Corporation. 1997.
11. Calabrese, E., P. KostECKI and M. Bonazountas. *Contaminated Soils*, Volume 3, pp. 289-290. Amherst Scientific Publishers, Amherst, MA. 1998.
12. Ruby, M.V., Davis A. and A. Nicholson. In Situ Formation of Lead Phosphates in Soils as a Method to Immobilize Lead. *Environmental Science and Technology*. Volume 28, pp. 646-654. 1994.
13. Hettiarachchi, G., G. Pierzynski and M. Ransom. In Situ Stabilization of Soil Lead Using Phosphorus and Manganese Oxide. *Environmental Science and Technology*. Volume 34, pp. 4614-4619. 2000.
14. Van der Lilie, Daniel, Jean-Paul Schwitzguebel, David Glass, Jaco Vangronsveld and A. Baker. Assessing phytoremediation's progress in the United States and Europe. *Environmental Science and Technology*. Volume 35, pp. 446A-452A. November 2001.

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15. Huang, J.W., J. Chen, W.R. Berti and S.D. Cunningham. Phytoremediation of Lead-Contaminated Soils: Role of Synthetic Chelates in Lead Phytoextraction. *Environmental Science and Technology*. Volume 31, pp. 800-805. 1997.
16. Blaylock, M.J. et al. Enhanced Accumulation of Pb in Indian Mustard by Soil-Applied Chelating Agents. *Environmental Science and Technology*. Volume 31, pp. 860-865. 1997.
17. McRae, M.A. Flower Power, CNN Interactive, <http://www.cnn.com/EARTH/9604/27/flower.power/>, 1996.
18. Mikko, D. U.S. Military “Green Bullet”, *Association of Firearm and Tool Mark Examiners Journal*. Volume 31, number 4, Fall 1999.
19. Bogard, J.S. et al. Application of life cycle analysis: the case of green bullets. *Environmental Management and Health*. October 5, pp. 282-289, 1999.
20. ABCNEWS.com: U.S. Army to Use “Green Ammo”, <http://more.abcnews.go.com/sections/scitech/DailyNews/greenbullets010503.html>
21. Environmental Security Technology Certification Program. Shock-Absorbing Concrete (SACON) Bullet Traps for Small-Arms Ranges. <http://www.estcp.org/projects/pollution/199609v.cfm>