Lead Mobility in Soil: A Refresher

By Eric Morton, M.P.H.
Tetra Tech EM, Inc., Chicago, Illinois

Background

Outdoor shooting ranges, including small arms ranges and shotgun ranges, are under increasing public and regulatory scrutiny because of perceived human health and environmental risks posed by metal components of ammunition used. As the principal component of traditional ammunition formulations, lead has received the greatest amount of public attention. Based on the potential for exposure to lead by ecological receptors and the potential adverse health effects associated with such exposure (both exposure to lead and the toxicity of lead are addressed in detail in other presentations), various federal and state regulations have been instituted. In particular, lead shot use for waterfowl g and upland game hunting in areas where waterfowl may be exposed to lead has been prohibited by federal and state authorities (see 50 Code of Federal Regulations Part 20 [Migratory Bird Hunting] and Part 32 [Hunting and Fishing]).

Appropriately, exposure to, risks from and remediation of lead at outdoor shooting ranges have been the primary concern and focus of research efforts organized by the Sporting Arms and Ammunition Manufacturers' Institute (SAAMI) and the National Shooting Sports Foundation (NSSF).

In 1996, SAAMI published the report "Lead Mobility at Shooting Ranges" (referred to as the lead mobility report). This report, which was prepared by EA Engineering, Science and Technology, Inc., is Volume 1 of the Facility Development Series published by NSSF. The lead mobility report details the many factors affecting and controlling the mobility of lead in the environment and particularly at outdoor shooting ranges.

Introduction

A better understanding of lead mobility in soil at shooting ranges by their managers, employees and users will significantly facilitate assessment of potential lead-related problems at individual ranges, and the need for and application of preventive and remedial options. Therefore, the primary purpose of this presentation is to provide a refresher on the principles associated with and factors affecting lead mobility at outdoor shooting ranges.

Eric Morton has more than 15 years of professional experience in environmental health planning and toxicology. He has managed, led and participated in preparation and review of numerous human health and ecological risk assessments at a variety of hazardous waste sites and industrial facilities throughout the country. Mr. Morton assisted EPA in developing human health and ecological risk assessment guidance documents, and recently participated in a project for the Sporting Arms and Ammunition Manufacturers Institute to research and prepare a guidance document on the risks and mobility of heavy metals at shooting ranges.

Fate and Transport of Lead at Outdoor Shooting Ranges

The primary features of an outdoor shooting range are the firing point (line) and impact area. Metals are deposited from the primer, propellant and cartridge cases in the vicinity of the firing point, while projectiles (bullets and shot) are deposited in the impact area. Impact areas consist largely of soil and may be relatively flat (this is typical for shotgun ranges, including trap and skeet fields) or built up (backstops and berms normally are present at rifle and pistol ranges). However, impact or shot fall areas at shotgun ranges also can include water, wetlands, forested areas or steep hillsides. This presentation focuses on the mobility of lead deposited in impact areas.

Upon striking an impact berm, bullets may penetrate the berm, ricochet, fragment or behave in other ways. Most of the projectile mass deposited in the impact area is in the form of intact projectiles or large fragments. However, small lead particles also are present. These large and small lead fragments and particles are subject to various physical and geochemical processes that control lead mobility in the environment.

Physical Processes

The three primary physical processes controlling the mobility of lead at outdoor shooting ranges are: 1) surface water runoff; 2) leaching to and transport in groundwater; and 3) generation of fugitive dust. These processes are illustrated in the conceptual site model presented in Figure 1.

Of the three physical processes, surface water runoff is the primary mechanism by which lead is transported within and off a range. Surface water may transport lead dissolved in the water, bound to soil and sediment particles, or as small, metallic fragments. As discussed below under Geochemical Processes, lead binds tightly to soil particles. As a result, the potential for and extent of lead leaching to and being transported in groundwater usually are not significant. Likewise, generation of fugitive dust at outdoor ranges is expected to be insignificant because of vegetative cover and the likelihood that remedial actions will be taken if dust becomes a nuisance.

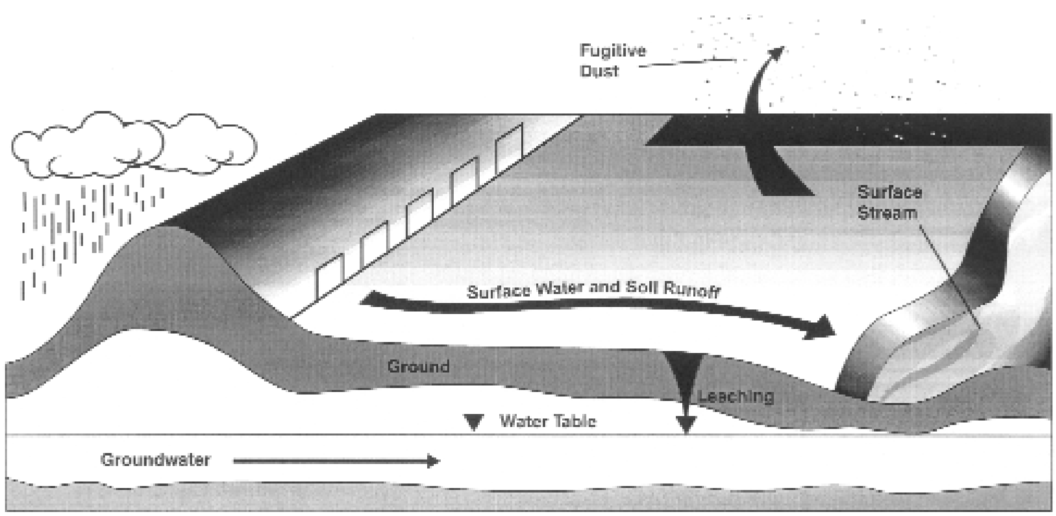

Figure 1. Conceptual site model.

Geochemical Processes

The basic geochemical processes that control lead mobility in the environment include oxidation/reduction, adsorption/desorption, precipitation/dissolution, oxidation/reduction and complexation/chelation. For each of these process pairs, the first process is defined below; the second process basically is opposite of the first process.

- Oxidation/reduction*: Oxidation is the process by which metallic lead is converted into more soluble forms (e.g., Pb^0 to Pb^{2+} and Pb^{4+}).*
- Adsorption/desorption*: Adsorption is the process by which dissolved lead ions are taken out of solution through their binding to the surfaces of soil and sediment particles.*
- Precipitation/dissolution*: Precipitation is the process that removes lead from solution as a discrete, solid form (e.g., lead and sulfate may combine to form lead sulfate, $PbSO_4$).*
- Complexation/chelation*: Complexation is the process by which dissolved lead associates with other dissolved materials, resulting in higher dissolved lead levels.*

Before these processes are discussed further, it is important to point out that soil chemistry is very complex and range-specific. The overall mobility of lead at individual ranges is the net result of a variety of processes and factors. Figure 2, which is drawn from the lead mobility report, illustrates the complex interaction of the various factors influencing lead mobility in the environment. Figure 2 also serves to illustrate the significant variety of compounds that may form in a system containing only lead, carbon dioxide and sulfur under a variety of oxygen and pH conditions. The soil at individual outdoor shooting ranges may contain an even greater variety of compounds and be even more complex.

Of the four major geochemical processes impacting the mobility of lead in soil, adsorption/desorption and precipitation/dissolution are dominant. As a generalization, the relative influence of adsorption/desorption is about one order of magnitude (10 times) greater than that of precipitation/dissolution. In turn, the influence of precipitation/dissolution is more than one order of magnitude greater than that of the other two processes. However, before either of the two dominant processes can influence the mobility of lead, the metallic lead introduced to an impact area must be oxidized.

Oxidation/Reduction

Oxidation is the process that converts the metallic lead deposited in the impact area into positively charged ionic forms. For example, metallic lead (Pb^0) may be oxidized into either of two positively charged forms of lead, Pb^{2+} or Pb^{4+}. Once lead has been oxidized, the dominant process pairs, adsorption/desorption and precipitation/dissolution, can begin to exert their influence.

Adsorption/Desorption

Adsorption results from a difference in electrical charge between molecules and solid soil and sediment surfaces. Specifically, positively charged molecules (referred to as cations) are *attracted and bind to negatively charged soil and sediment surfaces. The strength of a molecule's attraction to particle surfaces, as compared with its tendency to remain in solution, is measured by its adsorption coefficient (Kd). Different cations compete for binding sites on soil and sediment particles. Molecules that bind strongly to particles can displace less tightly bound molecules. Lead binds very strongly to soil and sediment particles and, thus, is unlikely to be displaced by other cations.*

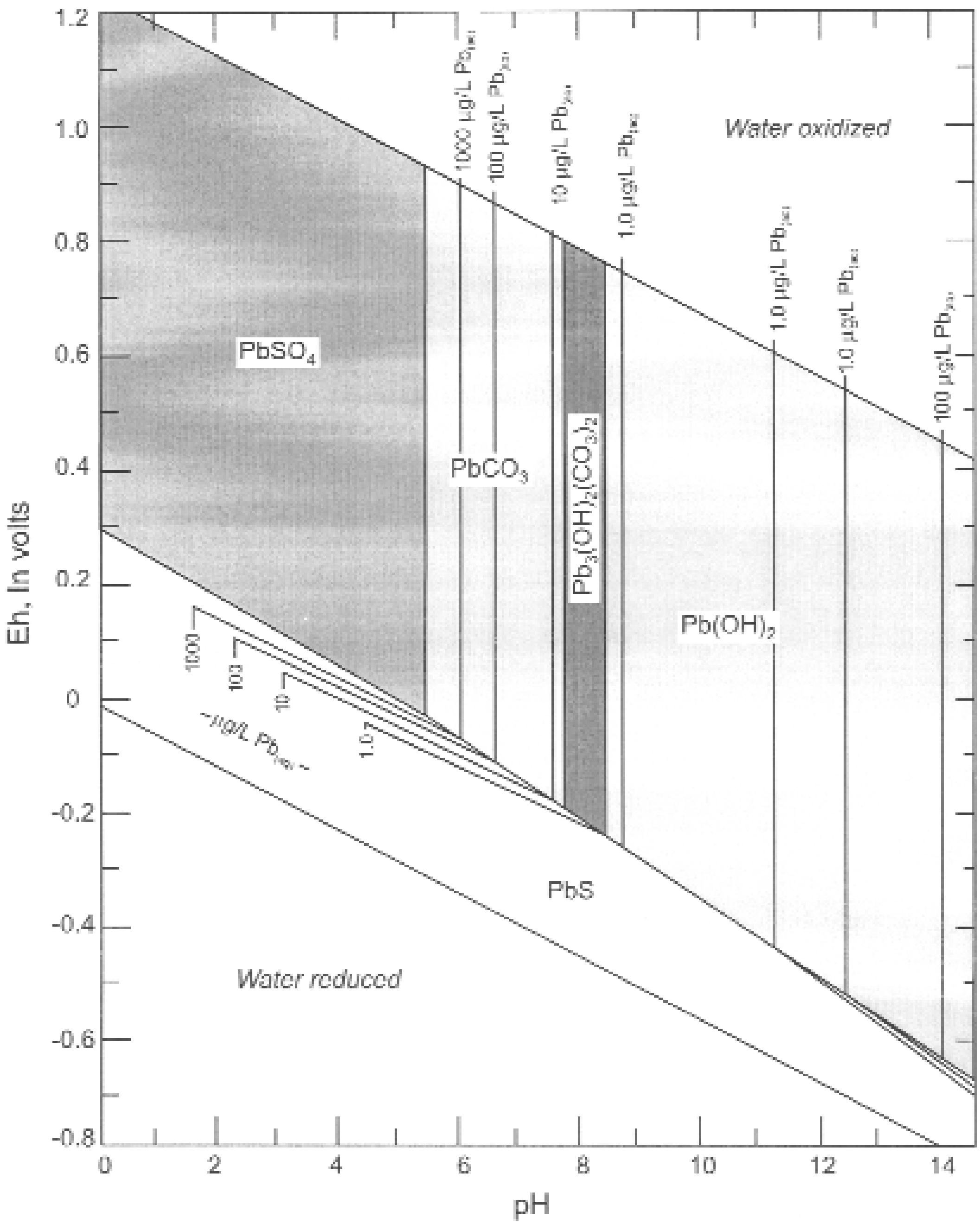

Figure 2. Equilibrium stability field diagram for solids and dominant solute species in a lead/water system Pb+CO_2+S+H_2O at 25 degrees Celsius and 1 atm pressure. This diagram shows which species are likely to form as a function of pH and Eh when ionic strength = 0.005. (Total dissolved CO_2 = 0.001 molar.) (Total dissolved S = 0.001 molar.)

Precipitation/Dissolution

Lead may be removed from solution through binding with various precipitation agents. These agents may include carbonates, phosphates and sulfates. For example, phosphate is added to range soils in order to increase lead precipitation. In addition, the extent to which lead dissolves in solution is significantly impacted by pH. As shown in Figure 3, lead mobility increases at both low and high soil pH. Lead mobility is lowest in the typical soil pH range (about 6 to 9). Lime is added to range soils in order to raise soil pH to within the normal range. Figure 3 is a generalization; the actual change in lead mobility with changes in soil pH is range-specific.

Complexation/Chelation

Complexation and chelation do not significantly impact lead mobility in range soils and will not be discussed further.

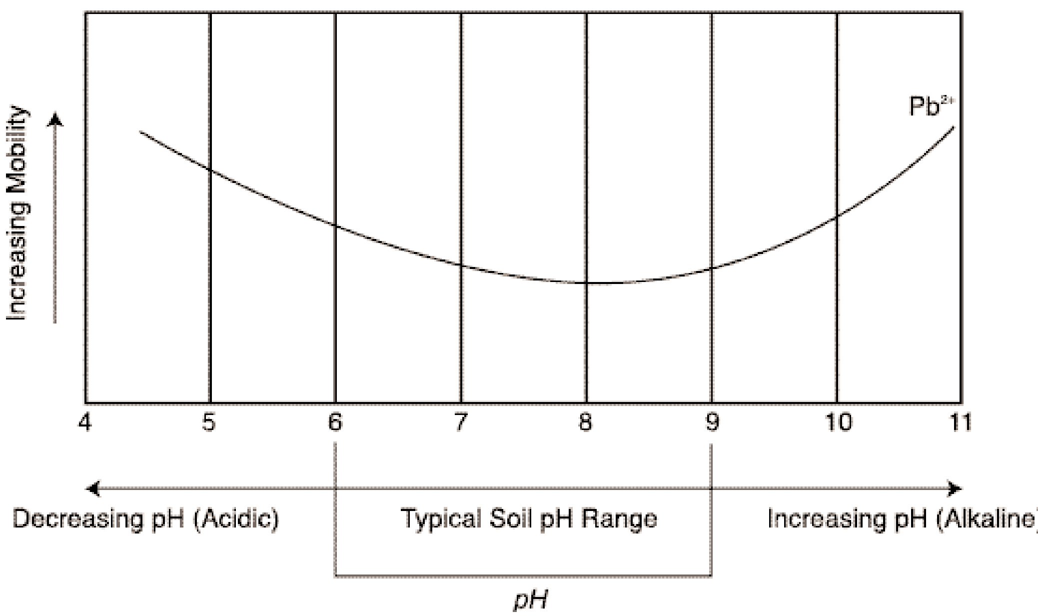

Figure 3. Generalized relationship between lead mobility and soil pH.

Remedial Options

Numerous potential and actual options for controlling lead mobility have been investigated and used with varying degrees of success at outdoor shooting ranges. Three of the most widely recognized options are recovery and recycling, control of surface water runoff, and addition of lime and phosphate. These and other options are discussed in great detail in the lead mobility report, as well as in Volume 2 of the Facility Development Series, "Environmental Aspects of Construction and Management of Outdoor Shooting Ranges."

Conclusions

Based on increased public scrutiny of the potential environmental impacts of outdoor shooting ranges, potential for exposure to and the toxicity of lead in the environment, processes and factors affecting the mobility of lead in the environment, and potential preventive and remedial options, the following general conclusions may be drawn:

- *Increased attention to the impacts of lead warrants that shooting range managers evaluate whether such impacts exist at their range.*
- *The basic processes controlling lead mobility at outdoor shooting ranges are well known; however, range-specific interactions of factors may need to be assessed.*
- *Range-specific lead mobility can be determined if certain site characteristics are known and appropriate site-specific evaluations are performed.*
- *Most outdoor shooting ranges probably do not have adverse environmental impacts caused by lead; however, conditions may exist that could result in such impacts.*
- *Outdoor shooting ranges can be proactive in evaluating the potential for adverse lead impacts and can minimize or prevent such impacts.*