Environmental Impacts of Lead from Paper-Insulated Lead-Covered Cable

1009513

Technical Update

Environmental Impacts of Lead from Paper-Insulated Lead-Covered Cable

1009513

Technical Update, April 2004

EPRI Project Manager

Naomi Goodman

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Exponent

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520. Toll-free number: 800.313.3774, press 2, or internally x5379; voice: 925.609.9169; fax: 925.609.1310.

CITATIONS

This document was prepared by

Exponent
4940 Pearl East Circle, Suite 300
Boulder, CO 80304

Principal Investigator or Author
T. Gauthier

This document describes research sponsored by EPRI.

The publication is a corporate document that should be cited in the literature in the following manner:

Environmental Impacts of Lead from Paper-Insulated Lead-Covered Cable, EPRI, Palo Alto, CA, 2004, 1009513.

ABSTRACT

Paper-Insulated Lead-Covered (PILC) cables have been used in medium-voltage underground power distribution applications in the United States (U.S.) since the late 1800s. When installed in the U.S., most PILC cable was placed in conduit or duct systems; very little PILC cable was direct-buried in contact with soil. Prior to 1960, most PILC cable was installed with a bare lead sheath, and unsheathed cables were common until the 1970s. Corrosion of the lead sheath on PILC cable is a mechanism that could potentially result in lead being released to the environment. Corrosion of the lead sheath is common but usually not severe, due to formation of passivating films on the surface of the lead. If lead were to be released, transport in soil would be quite limited because of sorption and precipitation reactions that cause lead to be of low mobility in soils. Although the initial by-products of corrosion would likely represent the more bioavailable forms of lead, alteration of these forms to more stable soil mineral forms would reduce lead bioavailability over time. In addition, exposures to the general population would be limited due to the fact that any lead released from PILC would be trapped at depth in the soil column, in proximity to the PILC. Thus, potential risks to human health and the environment are considered to be extremely low.

Lead may also be released to sediment and water accumulated in manholes and ducts. In a limited survey of utility vaults and manholes, some concentrations of lead in water and sediment collected in these structures were elevated. Installation and maintenance practices involving hot lead work during soldering and wiping may have contributed to the high lead levels. Although none of the sediment samples tested was classified as a hazardous waste, many of the vault water samples exceeded ambient water quality criteria for lead, and the samples with the higher lead concentrations may have exceeded sewer use criteria in some regions. Water and sediment pumped from vaults and manholes could result in additional routes of exposure to lead if not disposed of responsibly. In addition, discharges to surface waters and sewers could pose regulatory compliance concerns.

Overall, the risks from exposure to lead in lead-sheathed cable are very low, and replacing cable for reasons of environmental protection alone isn't justified at this time. There are no current or proposed U.S. regulations restricting the use of PILC cable or requiring its removal. However, there is a chance that future regulation in the U.S. will restrict PILC cable usage or require its replacement if the U.S. decides to follow the European approach. Therefore, it makes sense for utilities to be proactive in PILC cable removal, where economic or operational factors favor cable replacement.

CONTENTS

1

INTRODUCTION

Background

Paper-Insulated Lead-Covered (PILC) cables have been used in medium-voltage underground power distribution applications in the United States (U.S.) since the late 1800s [1]. Much of this cable was installed in the mid-20th century and is gradually being replaced as it nears or exceeds its designed 30- to 50-year lifespan [2]. However, some of this cable is still in service even after more than 90 years [3].

Prior to 1950, most PILC cable was installed with a bare lead sheath. Protective outer jackets were introduced in the 1950s, but not all applications adopted this configuration. Goodwin suggests that jackets may have been used as early as the 1940s [4]. In the early 1960s, high-molecular-weight polyethylene (PE) was introduced as an alternative to impregnated paper insulation, and new installation of medium-voltage PILC cable was slowly phased out. However, some utilities continue to install PILC in urban areas and central business districts because of its proven long-term reliability and ability to fit in older conduit-manhole systems where other cables will not [5].

When installed in the U.S., most PILC cable was placed in conduit or duct systems; very little PILC cable was direct buried in contact with soil. While offering protection from mechanical stress, conduit/duct systems are not watertight and do not prevent corrosion of the outer lead sheath.

The potential for lead contamination of soil or groundwater from PILC cable has been addressed only recently, and limited research has been done on this topic. Corrosion of the lead sheath on PILC cable is a mechanism that could potentially result in lead being released to the environment. Corrosion of the lead sheath is common but usually not severe, due to formation of passivating films on the surface of the lead. A mid-1960s review of lead-sheathed power cable usage in Germany noted that the number of cable faults due to corrosion was "extraordinarily small," so small that it was not tracked in fault statistics [6]. Anstey found "very little or no evidence of significant corrosion of the lead sheathing apart from two instances of stray d.c." in a survey of PILC cables excavated recently in the UK [7]. However, in this survey, most of the cables had an outer jacket of polyvinyl chloride (PVC) covering the lead sheath. At Public Service Electric & Gas (PSE&G) in New Jersey, Blew reported that corrosion is not a big problem, and the number of corrosion failures has decreased in the past decade—from 32 in 1992 to only 1 in 2002 [8].

Lead may also be released by hot lead soldering and wiping during installation and maintenance of PILC cable. If the PILC cable employs a PVC protective jacket, the PVC jacket may contain lead stabilizers that could conceivably leach out of the PVC and enter the environment. However, this process does not appear to be a significant source of lead to the environment [75].

Recent legislation in the U.S. and abroad has focused increased attention on the use of lead in commercial applications. Lead-free initiatives are underway in the U.S., Europe, and Japan, particularly in the area of consumer electronics. Lead has already been banned, or greatly reduced, in a number of consumer products (gasoline, paint, solder), and Denmark is the first country to ban lead in low- to medium-voltage power cables [9, 10]. Alternatives to PILC cable are available, and many countries have begun to phase out its use on a voluntary basis. With recent legislation in Europe advocating principles of precaution and substitution, it is only a matter of time before other countries follow the lead of Denmark and ban the use of lead in applications where a viable alternative is available. However, there is no current or proposed legislation of this type in the U.S. at this time.

Project Objective

The objective of this technical update is to assess the potential for lead from PILC cable to contaminate soil and groundwater, and to evaluate the potential effects from such a release considering the transport, fate, and bioavailability of lead in the environment. In addition, the document reviews the current and proposed regulations potentially affecting future use of PILC cable in medium-voltage power applications, in both the U.S. and European Community (EC).

2

PILC CABLE CONSTRUCTION, INSTALLATION, AND MAINTENANCE

In this chapter, the basic construction of PILC cable and the installation practices and typical environments of installed cable are reviewed.

Typical PILC Cable Construction

The basic components of a single conductor PILC cable are illustrated in Figure 2-1. The central conductor (A) may be solid or multi-stranded, and is made of copper or aluminum. The insulation (C) is made of multiple layers of paper tape impregnated with a dielectric fluid. The paper is applied in multiple tape layers over the cable conductor, and the paper-insulated conductor is then immersed into a dielectric impregnant to give dielectric properties. The composition of the oil has changed over the years from a rosin oil to a naphthenic or paraffinic oil, and later to synthetic materials such as polybutene oil [11]. The paper insulation is covered by an extruded lead sheath (E), which may be protected by an outer polymer jacket (F). Layers (B) and (D) are semi-conducting shields, and are used to control electric stress in the cable.

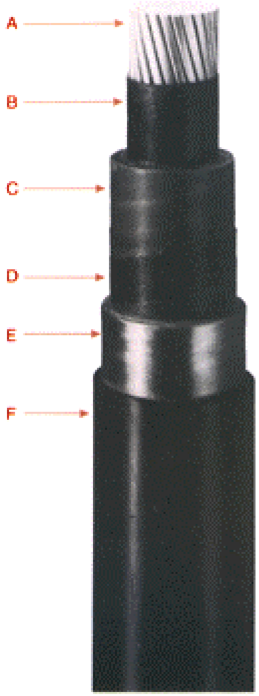

Figure 2-1
Typical PILC Cable Construction (www.okonite.com)

PILC cable is also supplied in a three-conductor configuration, as shown in Figure 2-2. The conductors (A) are individually wrapped and shielded (layers B, C, D, and E), packed with impregnated paper filler (F), bound together (layer G), and encased in a lead sheath (H) with a polymer jacket (J) [1].

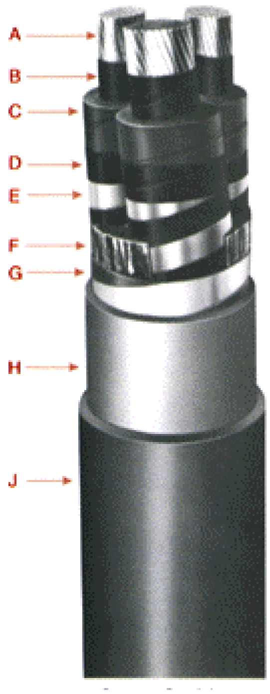

Figure 2-2
Three-Conductor Configuration of a Typical PILC Cable (www.okonite.com)

Lead and Lead Alloys Used in Sheathing

The lead sheath in PILC cable serves four primary functions: 1) it serves as a moisture barrier, 2) it provides mechanical protection of the paper insulation, 3) it serves to contain the impregnating fluid, and 4) it carries leakage current from the insulation and any possible short-circuit current. The lead sheath was initially constructed of pure lead, using a ram-type lead press. In 1939, an arsenic alloy (designated F-3) was developed to improve mechanical properties and corrosion resistance [1]. Development of the Hansson Robertson continuous lead extruder, which became commercially available in 1949, resulted in a significant increase in lead sheath quality and allowed the use of various lead alloys that were difficult to process using a ram-type press [3]. More uniform cable sheaths could be produced using the continuous extrusion process, and because of that, reduced alloying levels could be tolerated, leading to the use of ½ concentration alloys (*e.g.* ½ F3 or ½ C; compositions given in Table 2-1) [12].

Typical alloying elements used in lead cable sheathing are antimony, tin, and cadmium, although as indicated in Table 2-1, various other elements have also been used, including calcium, copper, arsenic, and bismuth [13]. These alloying elements are added primarily to improve mechanical properties. Pure lead has low tensile strength and is susceptible to creep (slow deformation under low stress). Alloying with calcium or antimony can strengthen lead and help minimize creep. According to Goodwin, alloys B, ½ C, E, and F3 are the most commonly used in North America [4]. Renka Corporation identifies lead Alloy E as the "most common and popular alloy" used for PILC cable sheathing [14].

Table 2-1
Common Lead Alloys Used in Construction of PILC Cable

Lead Alloy	Elemental Composition (Weight %) in Addition to Lead	Reference
F3	0.15% As; 0.1% Sn; 0.1 % Bi	[3]
½ F3	0.07% As; 0.05% Sn; 0.05 % Bi	
½ C	0.17 – 0.23 % Sn; 0.06 – 0.09 % Cd	[7]
B	0.80 – 0.85 % Sb	
E	0.35 – 0.45 % Sn; 0.15 – 0.25 % Sb	
½ E	0.17 – 0.23 % Sn; 0.08 – 0.12 % Sb	
Copper bearing lead	0.02 % Ag; 0.04 – 0.08 % Cu; < 0.025% Bi ; <0.002% As, Sb, Sn, Zn and Fe	[15]
Kb-Pb Sb 0.5	0.5 – 0.6 % Sb	[12]
Kb-Pb Te 0.04	0.04% Te; 0.04% Cu	

The addition of some alloying elements can increase susceptibility to corrosion, but the difference is slight. Wesson and Littauer note that "the specialized alloys used in the cable industry which contain less than 1% total of antimony, tin, copper, and cadmium … exhibit desirable mechanical features and, although their corrosion resistance is reduced by these additions, are adequate for underground environments which are less aggressive than those found in the chemical industry" [16]. In a series of soil corrosion field tests, the National Bureau of Standards (NBS) found no difference between the corrosion of pure lead and three different lead alloys containing copper, antimony, tellurium, and tin in various amounts [17]. Overall, Goodwin states that the corrosion resistance of lead alloys used in cable sheathing is similar to that of pure lead [4].

Use of Protective Outer Jackets

Protective outer jackets were introduced in the 1950s, but were not necessarily used in all applications. For example, several U.S. and Canadian utilities supplied various field-aged cables for an investigation of diagnostic techniques to evaluate the condition of medium-voltage PILC cable. Eight of the 16 cables were unjacketed and manufactured between 1931 and 1961; four of the eight were manufactured in the 1950s. The earliest jacketed cable sample was manufactured in 1956 [69].

The outer jacket provides mechanical protection during installation and inhibits corrosion of the lead sheath. Early jackets were made of thermoplastic black polyethylene, thermoplastic black PVC, or a thermoset neoprene [1]. With the presence of a protective outer jacket, the lead sheath thickness could be reduced. Linear low-density polyethylene offers superior moisture resistance relative to PVC; but PVC has superior flame resistance and is often used if damage due to fire is a concern [18].

Lead stabilizers are commonly used in PVC applied as outer jackets for power cables. White lead, tribasic lead sulfate, dibasic lead phthalate, dibasic lead stearate, and lead stearate are some of the forms of lead used as stabilizers [19]. The lead stabilizers increase the thermal stability of the PVC and limit dehydrochlorination reactions during processing.

There is some concern that PVC outer jackets may be a source of lead to the environment; however, a recent review of PVC leaching studies concluded "the general view expressed in studies investigating the release of stabilizers from PVC products is that as the stabilizers are encapsulated in the PVC matrix, the migration rate is expected to be extremely low and would only affect the surface of the PVC but not the bulk of the material" [75]. This suggests that PVC outer jackets are not a significant source of lead to the environment. In addition, any lead released to soil will be quickly immobilized in the soil matrix.

History of Use in the U.S. and Abroad

Goodwin summarized PILC cable usage in the U.S. and other countries [4, 24]. All of the countries surveyed currently use XLPE (cross-linked polyethylene), TRXLPE (tree-resistant cross-linked polyethylene) or EPR (ethylyene propylene rubber) insulated cable in most new installations. Existing PILC cable systems are gradually being replaced on an as-needed basis or as part of a formal program to replace all existing PILC cable. In Sweden, PILC cable replacement began in the 1960s. In France, PILC cable was used exclusively in medium-voltage applications until the mid-1970s. Now all 15-kV PILC cable in France is being phased out. In the UK, the transition away from PILC cable did not occur until the mid-1980s. In Canada, Toronto Hydro began a program to phase out the use of PILC cable in its 13.8-kV system in 1988.

Kal Sarker, of Toronto Hydro Electric System, reported that Toronto Hydro began installing PILC cable in the early 1900s. The switch from lead to lead alloy occurred in 1959, and PE jackets were introduced in 1960 [5]. At Consolidated Edison, the use of XLPE-insulated cable began in the early 1970s. This cable also employed a lead sheath. The switch to an EPR-insulated cable with no lead sheath occurred in the 1980s [20].

Baltimore Gas & Electric uses XLPE and EPR cables, direct-buried in soil, to distribute electric power in residential areas. In urban areas, a combination of PILC and extruded dielectric cables installed in ducts is used in medium-voltage power distribution [21]. Blew reported that PSE&G is no longer installing any PILC cable but still has a lot of PILC in the ground [8].

Although there is a general overall trend away from PILC cable usage, many utilities continue to install PILC cable in traditional urban areas because of its proven long-term reliability and their ability to fit it into older conduit-manhole systems. Dyba reports a 67% decline in lead use for cable sheathing in the U.S., from 60,000 tons in 1962 to 20,000 tons in the 1970s, with a leveling off to this level in the 1980s and early 1990s [5]. A similar size decline of about 60% has been cited for Organization for Economic Co-Operation and Development (OECD) countries' demand for lead used in cable sheathing between 1970 and 1990 [22].

The majority of respondents to a 1992 survey of Association of Edison Illuminating Companies (AEIC) members indicated that they are continuing to install some PILC cable in traditional urban areas and central business districts [5]. In addition, lead-sheathed cable is still used in high-voltage and submarine applications. For example, in September 2000, Colorado Springs utilities completed the underground installation of 13.5 miles of 115-kV power cable. The XLPE-insulated cable, with an outer lead sheath and polyethylene-silicone jacket, was installed in concrete-encased PVC pipe. [23].

Installation and Maintenance of PILC Cable

In Holland, France, and Germany, most medium-voltage PILC cable was direct-buried in soil. The same is true for Canada and the U.K., with the exception of urban networks and some suburban locations where PILC cable was placed in ducts. At BC Hydro, most PILC cable is installed in ducts, and the ducts are placed in concrete [24]. In Switzerland, most medium-voltage cable is installed in dry ducts. Korea installs their PILC cable in ducts and then seals the ducts to prevent water intrusion. In the U.S., most PILC cable is installed in ducts, but it is not uncommon for parts of these duct systems to fill with water [4].

The first underground residential distribution (URD) systems in the U.S. were installed in the 1920s in exclusive subdivisions only. Lead-covered rubber or PILC cable was installed in ducts with manholes, but the cost for installation was expensive [11]. When direct burial of URD systems became common in the early 1960s, PE-insulated cable with no lead sheath was used, to keep the price competitive with overhead distribution systems, which were falling out of favor [25]. Thus, very little PILC was direct-buried in the U.S.

Installation and maintenance practices involving hot lead work during soldering and wiping can lead to emissions of lead. Lead wiping or soldering is necessary for splicing and terminating cables, to prevent moisture intrusion and provide a low-resistance connection between the sheath and the splice that can withstand the cyclic expansion and contraction of the cable [12]. These types of operations typically take place in underground manholes and vaults. The lead may be released in the form of shavings, solder drippings, or dust. New techniques for splicing and terminating lead-sheathed cable that avoid hot lead work have been developed, such as pre-assembled solder joints, spring-loaded gaskets, mechanical glands, adhesive bonding resins, and heat-shrinkable tubing [12]. Several of these designs have been tested, but more research is needed for evaluating their effectiveness.

3

CORROSION OF LEAD IN PILC CABLE

Although lead offers superior protection from moisture intrusion, lead will slowly corrode when exposed to the environment, and this can eventually result in perforation of the outer lead sheath under certain conditions. The rate of corrosion depends on a number of factors, but overall, the corrosion of lead is a very slow process due to the formation of a protective film that coats the metal and limits further corrosion. In this section, we provide a brief discussion of corrosion processes and the types of corrosion that are important for lead-sheathed cable that is installed underground.

Corrosion Basics

Corrosion is a term used to describe the deterioration of a material caused by exposure to the environment. It is generally used to describe an electrochemical process but may also refer to a chemical process that does not involve generation of an electric current, such as the dissolution of a material by an acid. The four basic components required for establishing an electrochemical corrosion cell are the anode (where oxidation takes place), the cathode (where reduction takes place), a conducting medium in contact with the anode and cathode to facilitate the movement of ions (an electrolyte solution), and an electrical connection between the anode and the cathode to allow the flow of electrons between the two.

The overall reaction that is taking place in the basic corrosion cell consists of two half-reactions. The half-reaction taking place at the anode is called an oxidation reaction and involves a loss of electrons. The half-reaction taking place at the cathode is called a reduction reaction and involves a gain of electrons. The electrons lost at the anode must be balanced by a gain of electrons at the cathode; thus, one reaction cannot proceed without the other. Either reaction then can serve as the limiting step that controls the rate of corrosion.

For all metals except gold, the metal oxide is more thermodynamically stable than the elemental form of the metal. For this reason, pure metals exposed to air become coated with an oxide film. When placed in aqueous solution, the oxide layer will tend to dissolve, leaving an active metal surface. Dissolution of the oxide layer is enhanced in an acidic solution but limited in near-neutral solutions where the solubility of the oxide is lower. When the oxide layer dissolves and exposes the active metal surface, the metal tends to dissolve, releasing metal ions into the solution and retaining electrons on the surface of the metal. For example, metallic lead [Pb] will dissolve to yield the lead ion [Pb^{2+}] and two electrons [e^-] as shown in reaction (1). Because there is a loss of electrons, this reaction is called an oxidation reaction.

$$Pb \rightarrow Pb^{2+} + 2e^- \qquad (1)$$

This separation of positively charged ions in solution and negatively charged electrons on the metal surface establishes an electric potential (measured in volts) at the surface of the metal. A number of factors can affect the magnitude of the potential established at the metal surface, including solution properties (pH, ionic strength, temperature, and concentration of solution constituents), as well as microstructure and composition of the metal. Eventually, as the electrons (and negative charge) build up on the surface of the metal, the positively charged lead ions will be attracted to the metal, and the reverse reaction will occur until equilibrium is reached. At equilibrium, there is no further net dissolution of the metal.

If a dissimilar metal such as copper is placed in the same electrolyte solution, a similar reaction takes place, as shown in reaction (2).

$$Cu \rightarrow Cu^{2+} + 2e^{-} \qquad (2)$$

However, because copper is a less active metal and less prone to dissolve in solution, the potential generated at the surface of the metal is lower, and the charge buildup on the surface of the copper is less. If the two metals are connected electrically, then the electron buildup on the metals will tend to equilibrate, and electrons will flow from the metal with the higher potential (lead) to the metal with lower potential (copper). The shift in equilibrium caused by the flow of electrons results in an increase in the rate of dissolution (corrosion) of the lead and a decrease in the rate of dissolution of the copper. The oxidation of lead occurs at the lead electrode (the anode), and if there is a sufficient supply of Cu^{2+} ions in solution, copper will be reduced at the copper cathode. The electrolytic cell established by two dissimilar metals is referred to as a galvanic cell, and the reaction occurring at the anode is called galvanic corrosion.

The reduction of metal at the cathode is not commonly encountered in soils and natural waters. The more common reactions are the reduction of hydrogen ion [H^+] to generate hydrogen [H_2], as shown in reaction (3);

$$2H^{+} + 2e^{-} \rightarrow H_2 \qquad (3)$$

the reduction of dissolved oxygen [O_2] to form hydroxide ion [OH^-] at neutral or alkaline pH, as shown in reaction (4);

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \qquad (4)$$

or the reduction of oxygen to form water [H_2O] at low pH, as shown in reaction (5).

$$O_2 + 4H^{+} + 4e^{-} \rightarrow 2H_2O \qquad (5)$$

Reactions (3), (4), and (5) can occur simultaneously at the cathode; however, at neutral pH, the concentration of hydrogen ion is low, and reaction (4) is the primary reaction. If the rate of corrosion is controlled by the rate of reaction at the cathode, then a decrease in pH (increase in hydrogen ion concentration) can accelerate the rate of corrosion. If the solution is anoxic, the corrosion rate will be reduced by about a factor of ten [26].

In some cases, corrosion leads to the formation of a protective film that limits further corrosion. For example, aluminum is a highly reactive metal that readily corrodes; however, in the initial stages of corrosion, a thin passivating film of Al_2O_3 is formed at the surface of the metal, which limits further corrosion. The green patina that is formed on copper protects the underlying metal from further corrosion.

The corrosion rate of lead is usually controlled by the reaction occurring at the anode, because many of the corrosion by-products formed at the anode are relatively insoluble and can limit further attack [28].. Common products formed at the anode that are capable of acting as a protective layer include lead sulfate [$PbSO_4$], lead chloride [$PbCl_2$], lead chromate [$PbCrO_4$], lead oxide [PbO], lead tetroxide [Pb_3O_4], and basic lead carbonate [$2PbCO_3 \cdot Pb(OH)_2$] [16]. These protective layers or films can serve to limit diffusion of metal ions away from the metal at the anode, to limit diffusion of oxygen toward the cathode, or if the protective layer has electrical insulating properties, to limit cathode reactions occurring at the surface of the film [27]. Thus, the growth of the film depends in part on its conductivity. If the conductivity is low, the film will tend to grow laterally and remain thin.

The corrosion rate of lead in natural waters depends in part on the hardness of the water. Hard waters containing calcium and magnesium salts form films on the lead that protect it against corrosive attack [28]. In contrast, lead corrodes more readily in soft, aerated natural waters. The concentration of the relevant anion in solution can also affect the nature of the film, with low concentrations often leading to imperfect films [16]. Miyata reports that passivation of lead occurs at carbonic acid concentrations greater than 20 mg/L [29]. Lead carbonate islands begin growing at random and eventually coalesce within 10–30 minutes.

Whether the lead by-product forms in solution as a precipitate that subsequently adheres to the surface of the metal, or forms on the metal surface by solid state, will determine its effectiveness as a protective layer. Loosely adhering precipitates are much less effective at limiting diffusion and are easily subject to mechanical disturbance. Disruption of the protective film can lead to an increase in the rate of corrosion. The process of creep can accelerate the corrosion process by disrupting the protective layer and continually exposing a fresh surface to the environment [28]. Thus, use of alloys to improve strength and reduce creep can also increase corrosion resistance.

Corrosion generally occurs at the anode; however, some metals like aluminum and lead can corrode at the cathode as well, if the chemical reaction occurring at the cathode creates a strongly alkaline environment. For example, hydroxide ions are generated in reaction (4). The reaction of lead(II) ion with hydroxide yields the insoluble precipitate lead hydroxide.

$$Pb^{2+} + 2OH^- \rightarrow Pb(OH)_2 \qquad (6)$$

The lead hydroxide is amphoteric and reacts with both acids and bases. In acid solution, the lead hydroxide dissolves to regenerate lead(II) ions, as shown in reaction (7).

$$Pb(OH)_2 + 2H^+ \rightarrow Pb^{2+} + 2H_2O \qquad (7)$$

Alternatively, in the presence of additional hydroxide ion, the lead hydroxide dissolves to form the soluble lead tetrahydroxide complex [$Pb(OH)_4^{2-}$].

$$Pb(OH)_2 + 2OH^- \rightarrow Pb(OH)_4^{2-} \qquad (8)$$

Thus, the solubility of lead is increased at both low and high pH. The increased solubility of lead at high pH discourages formation of a protective layer on the surface of the lead and results in increased corrosion rates.

General Corrosion

The anode and cathode can be dissimilar metals, as described above for lead and copper, or dissimilar regions of the same metal. When the corrosion results in an apparent uniform wasting away of material, it is referred to as general corrosion. General corrosion occurs when multiple closely spaced anodic and cathodic regions are present on the surface of the same metal. These anode and cathode sites may be established because of inhomogeneities in the metal caused by inclusions, stress variations, or differences in temperature leading to slight variations in electrical potential at the surface of the metal [28]. These areas will shift with time so that the surface corrodes evenly.

The corrosion of lead in moist air is a form of general corrosion. Lead is quickly oxidized in moist air, forming a thin protective layer of lead oxide. This lead oxide layer further reacts with carbon dioxide [CO_2] to form a thin protective film of basic lead carbonate and eventually lead carbonate [30]. In the presence of sulfur dioxide [SO_2], the lead carbonate is converted to lead sulfate. The corrosion of lead in coarse soils that permit free circulation of air is similar to the corrosion of lead in moist air.

Local Cell Corrosion

Local differences in the electrolyte environment can also create anodic and cathodic sites on the same metal. These are referred to as local corrosion cells. Corrosion cells can be formed by variations in soil composition, including differences in aeration, water content, chemical composition, and bacteria [16]. The area of more dilute ion or oxygen concentration will be the area that becomes anodic and undergoes attack. Variations in oxygen concentration result in formation of a differential aeration cell, also known as an oxygen concentration cell. Any process resulting in higher concentrations of oxygen in one area and lower concentrations of oxygen in another area will cause the oxygen-rich area to become cathodic and the oxygen-poor area to become anodic. For example, underground lead-sheathed cable passing through gravel and clay regions will be exposed to different oxygen concentrations. Oxygen concentrations will be higher in the permeable gravel regions and lower in the less permeable clay regions. The section of cable buried in the clay becomes anodic and corrodes faster than the section in gravel. Oxygen concentration cells can also be formed in poorly ventilated cable ducts or water-filled ducts where the cable is partially submerged. At the air/water interface, oxygen concentrations are higher near the surface of the cable exposed to air, and lower at the surface of the cable submerged in water or wet sediment.

The rate of corrosion is determined by the potential difference between the two areas of the metal. Even splicing a new cable onto an older, dirty cable can result in corrosion [31]. Fresh scratches exposing shiny new metal on an old cable can also result in corrosion where the exposed metal, generating the higher potential, is the anode.

Stray Current Corrosion

Goodwin recently reviewed the corrosion of lead-sheathed power cable and identified stray current corrosion as the leading cause of corrosion damage [32]. At PSE&G in New Jersey, Blew reported that most corrosion problems occur in metropolitan areas near electrified rails [8]. The main source of corrosion in lead-sheathed telecommunication cable in Taiwan is stray current from direct-current-operated rail transit [33]. Experience at British Telecom indicates that corrosion of the outer lead sheath is caused primarily by stray DC currents, usually from electric trolley systems, or “aggressive” soils [34]. A mid-1960s review of lead-sheathed power cable usage in Germany noted that the number of cable faults due to corrosion was “extraordinarily small” and that stray current corrosion was the primary cause of the cable faults observed [6]. Anstey found “very little or no evidence of significant corrosion of the lead sheathing apart from two instances of stray d.c.” in a survey of PILC cables excavated recently in the UK [7]. However, most of the cables had an outer jacket of PVC covering the lead sheath.

Stray-current corrosion occurs when electrical current flows through a path other than that intended. Because the generally accepted concept for the flow of current is opposite to the direction of electron flow, if a lead-sheathed cable constitutes part of the unintended path, then the lead sheath becomes cathodic where the stray current enters the cable and anodic where the stray current leaves the lead sheath and re-enters the soil. Corrosion is enhanced in the anodic region and suppressed in the cathodic region. The sources of stray current are not always obvious, but common sources cited by Goodwin are cathodic protection systems, electric welders, and grounded direct-current electricity supplies [32].

Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals are placed in an electrolyte and are electrically connected to each other. An electrical potential is established, and the less reactive metal serves as a cathode and the more reactive metal acts as an anode. The rate of corrosion in a galvanic cell depends on the magnitude of the potential difference between the two metals. The relative surface areas of the two metals also affect the rate of corrosion. The rate of corrosion at the anode increases as the relative area of the cathode to anode increases.

The relative tendency for metals to corrode is represented in the form of a galvanic series, as shown in Table 3-1.

Table 3-1
Galvanic Series of Metals in Soils [32]

Metal	Potential (V) versus Copper Sulfate Reference Electrode
Pure magnesium	- 1.75
Magnesium alloy	- 1.60
Zinc	- 1.10
Aluminum alloy	- 1.05
Pure aluminum	- 0.8
Mild steel (clean and shiny)	- 0.80 to - 0.50
Cast iron	- 0.50
Lead	- 0.50
Mild steel (rusted)	- 0.50 to – 0.20
Mild steel in concrete	- 0.20
Copper, brass, bronze	- 0.20
Mill scale on steel	- 0.20
High-silicon cast iron	- 0.20
Carbon, graphite, coke	+ 0.30

Pure magnesium is the most reactive metal in the table. When electrically connected to lead and placed in an electrolyte, the magnesium will corrode preferentially to the lead and function as a sacrificial anode. However, when lead is in contact with copper, lead is the more reactive metal and undergoes galvanic corrosion as described above. Rusty steel in contact with lead can also cause galvanic corrosion. Some PILC cable may be encased in a steel armor or supported by steel structures in vaults or manholes. If the steel rusts, then it can be cathodic to the underlying lead sheath. In some cases, steel may initially be anodic to lead, undergo oxidation, and then become cathodic to lead [35, 36]. Serious galvanic corrosion can occur if the PILC cable is buried in an area containing coke or cinders [31].

Biological Corrosion

The growth of biological organisms on or near metal structures can influence corrosion in a number of ways. Biological metabolism can affect pH, oxygen concentration, and other environmental variables and help establish local concentration cells [37]. The formation of biofilms on the surface of the metal can prevent diffusion of oxygen to areas of the metal and set up oxygen concentration cells, particularly if the biofilm coverage is sporadic. Some bacteria produce acidic or corrosive by-products of metabolism that can assist in corrosion of metals. One example is sulfate-reducing bacteria that generate corrosive hydrogen sulfide [H_2S]. Others can produce or consume hydrogen and shift the equilibrium of cathodic reactions [37]. Sulfate-reducing bacteria, which thrive under anoxic conditions, can assist in the corrosion of lead by consuming hydrogen produced at the cathode.

An investigation of medium-voltage power cable failures in Spain revealed lead sheath corrosion in cables having an outer protective layer of steel sandwiched between layers of bitumen-impregnated jute fiber [38]. Each of the conductors in the three-phase cable was contained in a lead sheath, but only one of the sheaths was visibly corroded with an efflorescing corrosion product that was later determined to be basic lead carbonate and traces of lead tetroxide. The formation of lead carbonate was attributed to diffusion of water and carbon dioxide through the protective outer layers of the cable.

Microbial contamination of the cable constituents (jute, paper, and bitumen) was confirmed, and strains of bacteria and fungi were identified. Fungal growth was correlated with degradation of the outer bitumen layer. Laboratory experiments with lead disks inoculated with bacteria showed pitting attack in areas where bacterial colonies were established. Inoculation with fungi showed random blisters of lead carbonate but no attack under fungal mycelia [38]. The bacterial colonies were likely responsible for establishing local oxygen concentration cells on the surface of the lead, while CO_2 production from fungal metabolism likely assisted in formation of lead carbonate.

Factors Affecting the Rate of Corrosion

The rate of corrosion of lead-sheathed cable will be determined by the metallurgical properties of the lead, the characteristics of the surrounding environment, and most importantly, the presence or absence of a protective film layer. Slight inhomogeneities in the metal structure can contribute to variations in potential and form anodic and cathodic regions across the metal surface. The inclusion of alloying elements can be a source of these inhomogeneities, but also serves to strengthen the lead, limit grain growth, and improve resistance to creep. Overall, the corrosion resistance of lead alloys used in cable sheathing is similar to that of pure lead [32].

Much greater variability is observed in the local environment surrounding the lead sheath than in the lead sheath itself. PILC cables can be found direct-buried in soil or installed in conduit/duct systems. The ducts may be constructed of concrete, steel, PVC, vitrified clay, or even wood. Vaults or manholes provide access to the cable at intervals. Dry ducts are unlikely to cause corrosion of lead because of the stable lead carbonate or lead sulfate film layers formed in air. However, most duct/manhole systems are not watertight and frequently contain some water.

Lead-sheathed cables in water-filled concrete ducts or conduit encased in concrete may be subject to corrosion by calcium hydroxide [39]. The calcium hydroxide (hydrated lime) may be present if the concrete was not allowed to cure completely prior to cable installation. Upon curing, the calcium hydroxide is converted to calcium carbonate and becomes part of the concrete structure. In the fully cured state, concrete has little effect on the corrosion of lead. However, when incompletely cured, pH levels in water-filled concrete ducts can reach as high as pH = 12 and cause lead to corrode [39]. Corrosion has also been observed where lead-sheathed cables pass directly through masonry walls and where fresh cement is used to seal around the cable [31].

Water and silt collected in low-lying sections of conduit can result in formation of oxygen concentration cells where the cable intersects the air/water interface [36]. Areas of PILC cable immersed in water closest to the air/water interface are cathodic, while submerged areas furthest from the air and lower in oxygen content, become anodic and undergo attack. Corrosion is favored in low-pH and high-conductivity solutions. Thus, in the northern climates, where de-icing salts may affect conduit/manhole systems, corrosion may be enhanced. In one case, where cables were installed in creosoted wood ducts, acetic acid leached from the wood led to rapid failure of the lead sheath [31]. Lead oxide coatings are soluble in acetic acid, and the acid most likely inhibited the formation of a protective surface layer.

A number of factors can affect the rate of corrosion in soil, including moisture content, pH, redox potential, organic matter content, oxygen content, temperature, and concentration of ionic species in solution. Water is required for electrochemical corrosion reactions and affects soil resistivity. In general, soil resistivity decreases with increasing moisture content and increasing ionic strength. Low soil resistivity will enhance corrosion.

In a series of soil corrosion field tests, the National Bureau of Standards (NBS) found that the corrosion of lead was greatest in poorly aerated soils, which tend to retain moisture [17]. In the NBS study, specimens of lead and lead alloys were installed at 14 different sites representing a wide range of soil properties. Soil resistivity ranged from 62 to 17,800 ohm-cm; pH values ranged from 2.6 to 9.4; and soil types included clays, loams, cinders, and peat. The rate of corrosion (maximum pit depth and weight loss) was monitored over a period of 11 years. The field tests revealed no effect of lead alloy elements on the rate of corrosion. In general, corrosion was greatest in poorly aerated soils, including the soil containing cinders. High concentrations of sulfate, chloride, and bicarbonate ions had an inhibitory effect on corrosion, even in poorly aerated soils. Except for several of the poorly aerated soils, the rate of corrosion decreased markedly over the 11-year duration, presumably due to build-up of sparingly soluble corrosion products.

Lead is highly susceptible to corrosion in weak organic acids like acetic acid, and waters sampled from peaty moorlands are corrosive to lead [16, 31]. Corrosion of lead-sheathed cables in some areas of the UK has been attributed to peaty soils with a high organic matter content.

Simple systems with a limited number of components at known concentrations are often represented in the form of an Eh-pH diagram, also known as a Pourbaix diagram. Eh-pH diagrams can be used to predict the thermodynamic stability of lead species in solution and whether or not lead will corrode under a specific set of conditions. Eh-pH diagrams for lead-water systems show that metallic lead is unstable and will tend to form the thermodynamically more stable oxidized forms [*e.g.,* PbO, $PbCO_3$, $Pb(OH)_2$, $Pb(CO_3)_2(OH)_2$] under most soil conditions. The oxidized form is determined primarily by pH.

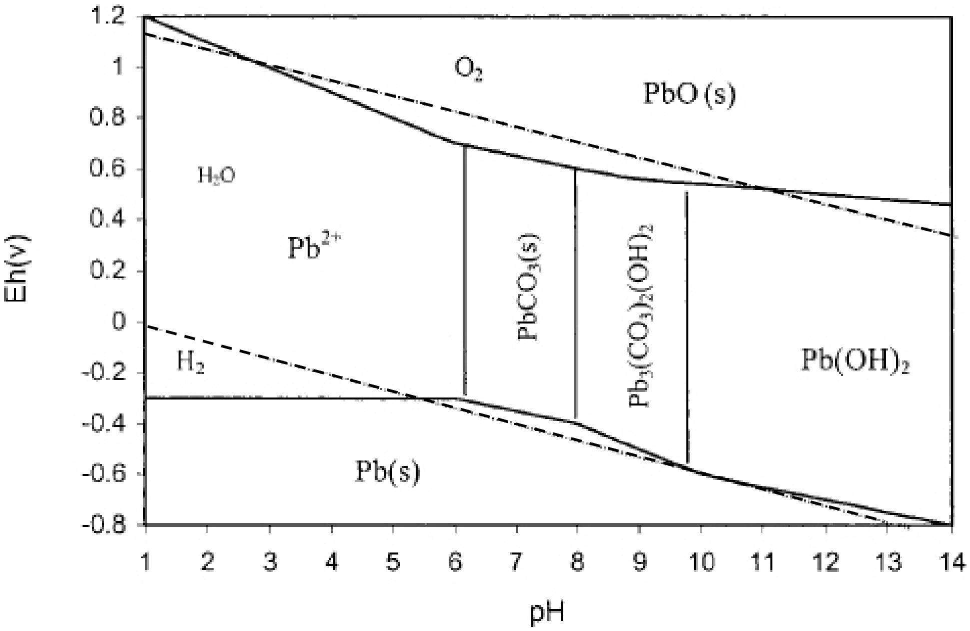

Figure 3-1
Eh-pH Diagram for Pb-CO_2-H_2O System [40]

The simplified Eh-pH diagram presented in Figure 3-1 shows regions where lead is stable in an aqueous system containing 1×10^{-6} M Pb and 1×10^{-3} M CO_2. The dotted diagonal lines beginning at Eh values of 0 and 1.1 at pH = 1 represent the stability lines for water. Water is stable at Eh-pH values inside these dotted lines, but in areas below the lower dotted line, water is reduced to hydrogen gas, and in areas above the upper dotted line, water is oxidized to oxygen gas. As indicated in Figure 3-1, metallic lead, $Pb_{(s)}$ is stable only at very low redox potentials in the pH range of about 6–10. In all other regions, lead will corrode. However, it should be noted that Eh-pH diagrams reveal no information about kinetics and cannot predict whether precipitate formation will result in an adherent film layer that limits the rate of corrosion.

Reported By-Products of Corrosion

Corrosion of lead can result in formation of oxides, carbonates, hydroxides, and chlorides, including some compound forms such as $PbCl_2{\cdot}Pb(OH)_2$ and $PbCl_2{\cdot}6PbO{\cdot}2H_2O$ [16]. Alkaline soils can cause lead to corrode by forming soluble lead hydroxides, which then decompose to form red lead oxide [16].

Lead oxide [PbO] has two forms: litharge, which is red in color and has a layer structure, and massicott, which is yellow in color and has a chain structure [41]. Lead dioxide (plattnerite)

[PbO_2] contains lead in the +4 oxidation state and is formed only at high Eh (greater than about 1V) and outside the region of most natural environments. Therefore, detection of lead dioxide among lead corrosion products usually indicates that a stray current is responsible for corrosion [16].

Hymes reports that by-products of corrosion at the anode are white in color and usually consist of lead chloride and lead sulfate [42]. Under severe conditions, lead peroxide, a chocolate brown precipitate, may be found. Under cathodic conditions, the final corrosion product is reported to be a bright orange-red lead monoxide product.

Concern over lead in the environment has led to increased interest in the corrosion of lead shot and lead bullets in firing range soils [40, 43–45]. The literature describing these reactions may be useful for predicting lead sheath corrosion products. Lead shot consists of mostly lead (97%) with small amounts of antimony, arsenic, and sometimes nickel [45]. Thus, lead shot and lead sheath compositions are similar. However, one difference may be that the lead shot fired into a soil berm has a much higher ratio of surface area to volume compared to a lead sheath. Also, the lead shot likely enters the soil environment with a freshly exposed lead surface, as opposed to lead-sheathed cable, which has likely built up a passive corrosion layer in air prior to installation in soil.

In one study, lead oxide, cerussite, and hydrocerussite were detected as weathering products on the surface of lead bullets in firing range soils with pH near 5.7; but only hydrocerussite was detected at a higher pH of 7.4 [43]. Others have reported the presence of anglesite [$PbSO_4$] in addition to lead carbonates [45]. Lead minerals detected in soil may differ from those present as surface crusts on weathered bullets. For example, at one site, hydroxypyromorphite [$Pb_5(PO_4)_3(OH)$] was detected in soil where cerussite and hydrocerussite were the primary species detected in bullet surface layers [43]. In another study, higher corrosion rates were reported in soils with higher organic matter content. The authors estimated that 4.8% of the lead was released from lead shot over a period of 20–25 years in low organic matter (OM) soil compared to 15.6% in higher OM soil over the same time period [45]. The primary transformation products in soil were anglesite at low pH and cerussite at near-neutral pH.

4

LEAD TRANSPORT AND FATE IN THE ENVIRONMENT

The lead sheathing on buried PILC cable can contribute lead to the surrounding environment only where there is direct contact between the lead sheathing and soil or water. If the cable conduit is dry, or an intact jacket protects the cable, no contamination would be expected. However, cables that are direct buried in soil, or installed in ducts that contain water, could potentially result in a release of lead corrosion products into the surrounding media. Lead may also be released to vaults or manholes from cable repair procedures and could be transferred to surface waters or soils during routine cleaning and dewatering of the vaults.

Lead corrosion results in formation of Pb^{2+} ions at the anode. Once formed, these lead ions can react with anionic species at the surface of the lead sheath to form a passivating layer, remain in solution as free metal ions or soluble inorganic complexes (*e.g.* $Pb(OH)^+$, $PbCl^+$, $PbHCO_3^+$, or $Pb(CO_3)_2^{2-}$), sorb to dissolved organic matter (DOM) or solid mineral phases in soil, or form relatively insoluble precipitates. Most of the lead reacts to form a passivating film layer on the surface of the metal that limits further corrosion. If formation of a competent film layer is prevented, lead ions can migrate away from the lead sheath. However, transport is limited, because lead is strongly sorbed by soil mineral phases and forms relatively insoluble precipitates with a variety of inorganic ligands.

Lead mobility in soil is affected by a number of factors, including pH, cation exchange capacity (CEC), iron and manganese concentrations, organic matter content, and redox conditions. Common anionic species like phosphate, carbonate, sulfate, sulfide, chloride, and hydroxide can form relatively insoluble precipitates with lead. Lead may also co-precipitate or sorb to various mineral phases that result from soil weathering, such as iron and manganese oxides and hydroxides. Dissolved organic matter (DOM) can also participate in reactions with lead and increase apparent solubility and enhance mobility in soil. Conversely, organic matter bound to soil is an efficient sink for lead. As a result, lead transport in soil is generally quite limited.

Similar reactions control the fate of lead released to surface waters. Lead will form relatively insoluble precipitates with phosphate, carbonate and sulfate ions; lead will sorb to particulates and form complexes with dissolved organic matter; and some lead will remain in solution as free metal ions and soluble inorganic complexes. Solution pH is a controlling factor. Dissolved lead concentrations are higher in low pH (acidic) surface waters while neutral and high pH (basic) waters favor sorption and precipitation reactions. In general, most of the lead released to surface waters would be deposited in sediments.

Sorption to Solid Mineral Phases

In general, lead immobilization in soil is directly related to the CEC and inversely related to soil pH. Soil pH was determined to be the principal controlling factor affecting the vertical migration of lead in soil-rock cores collected from five historical lead smelting sites varying in age between 220 and ~1900 years [46]. The authors recorded depths at which lead concentrations reached background levels and calculated average lead migration rates of 0.07 to 0.75 cm/yr. The highest rate was found in soils with a lower pH, lower CEC, and lower calcium content. The presence of carbonate species at higher pH was associated with formation of insoluble precipitates, increased adsorption on soils, and decreased lead migration rates.

Hawkins *et al.* collected soil cores from the dripline of an 800-year-old Danish church constructed with a lead roof [47]. Most (99.5%) of the lead was detected in the top 18 cm of the soil column. Sequential extraction of the lead indicated that most of the lead was bound to carbonates in the top 10 cm of soil, associated with a mixture of carbonates and iron and manganese oxides between 10 and 24 cm, and primarily associated with iron and manganese oxides below 24 cm.

Lead is strongly retained by specific adsorption and cationic exchange in soils. In a study involving montmorillonite and kaolinite clay solutions, lead removal by cation exchange-adsorption reactions was affected by pH and ionic competition [48]. At pH values less than 6, adsorption decreased with decreasing pH, apparently due to an increase in competition for adsorption sites by hydrogen ions. At pH values greater than 6, adsorption increased sharply due to formation of lead hydroxyl complexes and precipitation of lead carbonate.

Martinez and Motto added soluble lead nitrate to soils and measured the solubility of lead after 40 days equilibration and after subsequent additions of hydrochloric acid to lower pH [49]. Lead solubility increased with decreasing pH below about pH = 5.2 in calcareous soils, and below pH = 6.0 in non-calcareous soils, suggesting that some of the added lead was associated with the calcium carbonate phase in calcareous soils.

Aqueous lead complexes like $PbCl^+$, $PbNO_3^+$ and $PbCH_3COO^+$ also participate in sorption reactions. Papini *et al.* investigated the effect of lead speciation on the adsorption capacity of "Red Soils" common to Italy by varying the pH and electrolyte solutions to generate a variety of aqueous lead complexes [50]. Lead retention in soils was strongest in sodium perchlorate solutions, which generated the highest free lead ion (Pb^{2+}) concentration, whereas lead mobility was greatest in sodium acetate solutions where the predominant forms of dissolved lead were $PbCH_3COO^+$ and $Pb(CH_3COO)_2$ (aq).

In a low-pH soil (pH < 4.5), Wang and Benoit found that dissolved lead decreased with depth in soil. Total dissolved lead was less than predicted by equilibrium speciation models, suggesting that solubility was not controlled by precipitation of lead carbonates, sulfates, or phosphates but rather adsorption to solid mineral phases [51].

Phenolic and carboxylic acid groups are believed to be the most active heavy metal adsorption sites on humic and fulvic acids [52]. Ionic strength and pH can affect the conformation of the humic and fulvic acids, as well as the number and nature of active adsorption sites. An increase in pH results in an increase in lead adsorption; adsorption is greater at lower ionic strength [52].

Precipitation and Complex Ion Formation

Except for lead nitrate [$Pb(NO_3)_2$] and lead acetate [$Pb(CH_3CO_2)_2$], most lead salts are sparingly soluble or insoluble in aqueous solution. The solubility product constant (K_{sp}) describes the equilibrium between a solid salt and a saturated aqueous solution of the salt. Log K_{sp} values for some lead compounds are presented in Table 4-1.

As indicated in Table 4-1, the lead phosphates are among the most insoluble lead compounds found in soils. The less soluble $PbHPO_4$ and hydroxypyromorphite may control lead solubility in soils with sufficient phosphate levels [55].

Table 4-1
Log Solubility Product Constants for Various Lead Compounds

Lead	Log Solubility Product Constant
PbO	12.9
$PbCl_2$	-4.8
$PbBr_2$	-6.0
$PbSO_4$	-7.9
PbI_2	-8.1
$PbCO_3$	-12.8
$PbCrO_4$	-13.7
$Pb(OH)_2$	-14.4
PbS	-28.2
$Pb_3(PO_4)_2$	-32.0
$Pb_5(PO_4)_3OH$	-76.8
$Pb_5(PO4)_3Cl$	-84.4

Source: [53,54]

Dissolved Organic Matter Effects

The presence of a dissolved organic matter phase can increase the apparent solubility of lead and enhance vertical migration through the soil column. "Soluble organic matter…has a sufficiently strong affinity for metals such as Cu, Ni, Hg and Pb that it promotes dissolution of these metals from adsorption sites on clay minerals" [56]. Small organic compounds (oxalate, citrate, and pyruvate) can form soluble complexes with lead and may serve to release lead bound to manganese oxides in soil via reductive dissolution of the manganese oxide phase [57].

The data of Bolter *et al.* indicate that lead complexed with naturally occurring organic acids "…is much less easily adsorbed than ionic Pb. This should increase the mobility of complexed Pb in soils and aquatic systems" [58]. The enhanced transport of metals by soluble organic compounds "…may occur either as soluble metal-organic complexes, stabilized mineral colloid particles with adsorbed contaminants, or particulate matter-metal associations" [59].

Jordan *et al.* found that the retardation of lead in soil column experiments decreased by a factor of 4–8 in the presence of dissolved humic and fulvic acids [60]. Although the apparent solubility of lead was greater in the presence of the fulvic acid compared to humic acid in batch equilibration studies, facilitated transport was greater with dissolved humic acid, presumably due to size exclusion effects associated with the larger humic acid molecule.

Lead Released to Surface Waters

In general, most of the lead released to surface water bodies will deposit in sediments. The factors affecting lead mobility in soil (*i.e.* pH, CEC, iron and manganese concentrations, organic matter content, and redox conditions) also control sorption to sediments. Dissolved lead concentrations may also be affected by formation of relatively insoluble precipitates with carbonate, sulfate and phosphate ions depending upon pH and ligand concentrations [78]. High pH favors sorption and precipitation reactions; while mobility of lead is enhanced at low pH. Dissolved organic matter can also enhance the solubility and mobility of lead; but sediment-bound organic matter can act as a sink for lead.

Concentrations of Lead in the Vicinity of Lead-Sheathed Cable

A comprehensive literature search revealed few studies documenting the release of lead from corrosion of lead-sheathed cable, and/or the subsequent transport of lead away from the cable.

Forsberg and Björkman measured lead in soil samples collected from above and beneath lead-sheathed telecom cables at seven different sites in Sweden [61]. The seven different sites were characterized by four different soil types. Three of the sites were characterized as acid sandy soils (pH = 4.8–5.7), two sites consisted of alkaline boulder clay soils (pH = 7.7–8.0), one was a neutral clay soil (pH = 7.6), and one site was characterized as an acid sulfate soil (pH = 4.3). The telecom cables were installed 30 to 45 years prior to sampling.

Samples were collected at 5-cm intervals from above, below, and diagonally below the cables at two locations for each site, approximately 2 meters apart. Concentrations of lead were highest in the 0–5 cm interval directly surrounding the cable, and occurred at levels between 100 and 4,000 mg/kg. The authors report that 83%–98% of the lead in soil is retained in this 0–5 cm interval. The highest lead concentrations were detected in the acid sulfate soil and the lowest concentrations were detected in the calcareous soil.

Acetic acid–extractable levels of lead were also determined at each site. Lead concentrations ranged from 23 to 201 mg/kg in the 0–5 cm interval of the calcareous soils but as high as 2,684 mg/kg in the low-pH soils. However, even in low-pH soils, lead concentrations decreased dramatically to below 60 mg/kg in the 5–10 cm interval. Therefore, any lead released from the cable was quickly immobilized within 5 cm from the surface of the cable.

Jaspers *et al.* measured concentrations of lead in soils surrounding 13 different lead-sheathed telecom cables [62, 63]. The lead sheath on these telecom cables is protected by a layer of paper followed by two layers of bitumen paper, two layers of steel foil, and finally by a layer of bitumen jute. Only three of the cables showed appreciable degradation of the bitumen layer and four cables showed rust on the underlying steel tape. Five cables were installed in sandy soil, five were installed in neutral to alkaline clayey soils, and three were installed in acidic peaty soils. Samples were collected at 5- and 10-cm intervals above, below, and horizontally and diagonally away from the cable. Cables varied in age from 24 to 68 years.

Concentrations of lead were generally below the national background concentration of 85 mg/kg. Concentrations exceeded this level at only two locations (a value of 240 mg/kg at one site, and values of 250 and 340 mg/kg at another site). These three samples were collected away from the cable and were deemed unlikely to have been affected by the cable. Only two sites showed a slight gradient of decreasing lead concentrations with distance away from the cable.

In a limited survey, lead concentrations were measured in water and sediment collected from underground electric utility distribution manholes, vaults, and service boxes [64]. The average concentration of lead detected in 217 water samples collected from four different utility systems was 1.2 mg/L. However, more than 75% of the samples were collected from a single utility system that was prone to infiltration from tidal sources. The maximum concentration detected was 130 mg/L, but only three samples exceeded 10 mg/L, and 95% of the samples were less than 2.8 mg/L. The 50th percentile concentration was 0.1 mg/L.

These concentrations are somewhat higher than lead levels detected in lead drinking water pipes. In a 12-month pilot study designed to test the effect of chlorine on leaching of lead from lead pipes in drinking water systems, lead concentrations averaged about 0.3 mg/L in untreated controls. Only 3 of 46 samples exceeded 1.0 mg/L and no sample exceeded 10 mg/L [77]. Lead leached from PILC cable submerged in water-filled ducts could reach similar levels; however, if the ducts are made of concrete, the neutral to alkaline pH would tend to limit dissolved lead concentrations.

The lead concentrations in many of the vault water samples exceed the national recommended water quality criteria maximum concentrations for lead (0.065 mg/L for freshwater and 0.21 mg/L for saltwater assuming a water hardness of 100 mg/L as $CaCO_3$) [76]. These levels represent the highest concentrations to which an aquatic community can be exposed briefly without resulting in an unacceptable effect. Therefore, discharge of vault waters to surface water may be a concern in some cases. The highest concentrations detected may also exceed sewer use criteria in some regions. Only five sediment samples (from two of the utility systems) were analyzed for lead. The average lead concentration was 330 mg/kg, and the maximum concentration was 1,300 mg/kg. The source of lead in these samples is unknown. Vault waters may originate from groundwater seepage, stormwater runoff, or even surface-water flooding. Sources of sediment include stormwater, surrounding soils, and grouting materials as well as wastes from cable repair and maintenance operations. Because these manholes and vaults are typically dewatered and cleaned prior to electrical repairs or as a preventative maintenance practice, sediment and water accumulations may represent only recent input.

The ultimate disposition of lead in sediment and water collected in vaults and manholes will depend in part on disposal practices employed during routine cleaning and dewatering. Any lead entrained in exfiltrating water will be quickly tied up in soils and is unlikely to be a threat to ground water or nearby drinking water supplies. Lead concentrations in vault waters prone to infiltration from tidal sources will be subject to mixing and dilution effects. Therefore, any increase in the volume of vault waters should be offset by lower lead concentrations.

5

BIOAVAILABILITY OF LEAD

Lead bioavailability refers to the extent to which a biological receptor could absorb lead were it to come into contact with it; candidate biological receptors for lead from PILC could range from earthworms to humans. However, as described above, lead from PILC corrosion exhibits very limited migration in soils, which is consistent with studies from other lead sources. Lead bioavailability will become an issue only when the potential biological receptor comes into direct contact with the lead. As a result, lead bioavailability would be an issue only for direct-contact exposures to soils within 5–10 cm of PILC cable, or to lead in sediment and water collected in vaults and manholes during routine cleaning and dewatering, and disposed of in a manner that allows direct contact with a receptor. Given the vast array of exposure scenarios and potential receptors, the remainder of this discussion is limited to the potential for human exposures to lead from PILC. For humans, dermal absorption of lead does not occur, and inhalation of lead-contaminated soil or sediment could occur only under rare conditions. As a result, the exposure pathway of general concern for humans is incidental ingestion of lead-contaminated material (particularly for children who are more susceptible to the health effects associated with lead exposure).

As discussed above, lead from PILC corrosion may occur in soil as a complex mixture of solid-phase chemical compounds. These compounds include discrete mineral phases, coprecipitated and adsorbed lead species associated with soil minerals or organic matter, and dissolved species that may be complexed by a variety of organic and inorganic ligands. The occurrence and relative distribution of lead among these various phases, and the physical relation between the phases and the soil, control lead's dissolution properties, and hence, its bioavailability (in general, lead must be dissolved to be absorbed). Changes in the distribution of lead among these various phases over time, resulting from physical and chemical weathering, biological processes, and anthropogenic disturbances, may change the bioavailability over time.

All of the lead forms in soil that can result from PILC corrosion, and the subsequent transport and weathering of lead in soil, exhibit different rates of lead dissolution, depending on their chemistry and particle size distribution, the mechanism by which they dissolve, and the geochemistry of the soils in which they are present. As indicated in Figure 5-1, lead mineral form, grain size, and particle morphology appear to be the most important factors controlling the bioavailability of lead from soil [65]. It has also been observed that lead mineral phases that form under acidic conditions (e.g., lead sulfate, iron-lead sulfate) tend to be more stable under acidic conditions, and thus are less bioavailable to humans (i.e., are more stable in the acidic gastric environment). Mineral phases that form under alkaline conditions (e.g., lead carbonate, lead oxide) are less stable in the acidic conditions of the stomach, and more bioavailable.

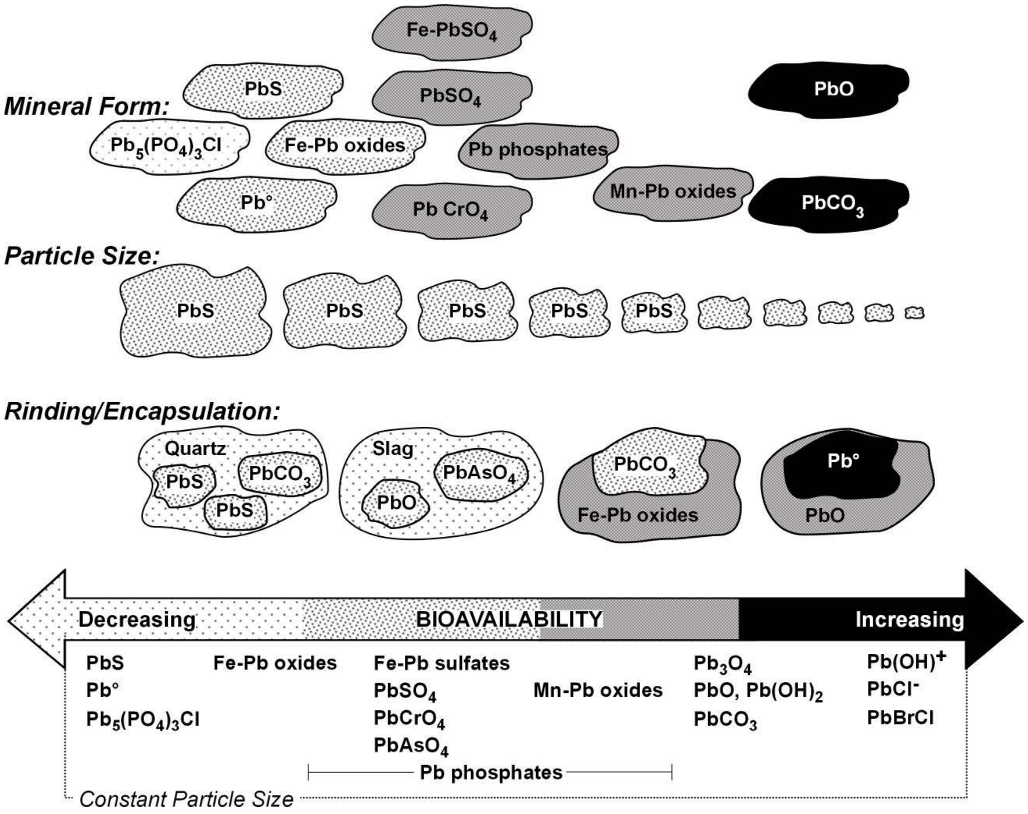

Figure 5-1
Schematic of How Different Lead Species, Particle Sizes, and Morphologies Affect Lead Bioavailability.

If direct-contact exposures were to occur to PILC corrosion products, the lead bioavailability would most likely be elevated due to the fact that these lead forms—oxides, carbonates, hydroxides, and chlorides—are soluble under acidic conditions [16]. However, as the lead from corrosion products began to migrate away from the PILC and to interact with the surrounding soil, lead bioavailability would likely decrease, because the resultant alteration phases (e.g., phosphates, sulfates, and lead in iron and manganese oxides) generally exhibit lower bioavailability than the parent lead forms in this case.

6

REGULATORY ISSUES

Existing and Proposed International Regulations

There is an ongoing, worldwide regulatory trend to restrict the use of heavy metals such as lead in commercial products. Additionally, manufacturers and importers in Europe are being required to reduce waste and improve the recyclability and reuse of product components. A number of countries already have bans on the use of lead in certain products such as gasoline, lead shot, lead solder in cans, lead in house paint, lead fishing weights, and lead in packaging [67]. Other voluntary initiatives are underway in the international community to reduce lead use (Table 4-1). Currently, Denmark is the only country that has banned the use of lead in medium- and low-voltage power cables [9, 10]. The Danish Ministry of Environment and Energy (Statutory Order No. 1012 of November 13, 2000) bans the import and marketing of lead (at concentrations greater than 100 mg/kg) in a variety of products, including "mantles for electrical underground cables under 24 kV." The ban for underground cables began on December 1, 2002 [10].

Other European countries are advocating a voluntary phase-out of lead use in power cable applications. In Sweden, the general policy for lead established in the Swedish Government Bill (1990/91:90) states that all uses of lead should be phased out in the long term, primarily through voluntary measures. In the new Environmental Bill (1997/98:145), which focuses on ecologically sustainable development, a phase-out within 10–15 years has been set as a target for the use of certain hazardous substances, including lead. In February 2001, the Swedish Government put forth a bill called "A Chemicals Policy for a Non-toxic Environment" that calls for all new products to be as free as possible from lead by 2010 [74]. As yet, there are no good alternatives to lead-sheathed submarine cable; however, cable producers are working to find alternatives, and Swedish users have committed to phasing out the use of lead in cables within this period [66].

Utilities in other countries have elected to phase out the use of PILC cable in medium-voltage power applications on a voluntary basis. All installations of new 15-kV PILC cable were stopped in 1977 in France, and Toronto Hydro is phasing out the use of PILC cable in its 13.8-kV system in Canada. Toronto Hydro is using a tree-resistant XLPE cable with a linear low-density PE jacket as a substitute for PILC in all new installations [5]. The voluntary phase-outs are being driven by economics, a lack of workers skilled in PILC cable installation and maintenance, and anticipation of future regulations due to the increasing awareness of the potential environmental and human health effects from the use of lead.

Table 6-1
Some International Commitments to Reducing Exposures to Lead

Basel Convention, 1989	Regulates trans-boundary movements of hazardous materials and wastes.
Organization for Economic Cooperation and Development (OECD) Declaration on Risk Reduction for Lead, 1996	OECD member countries pledge to raise the issue of lead exposure at an international level by monitoring levels of lead in the environment, working with industry to support voluntary risk reduction activities, and sharing information on lead exposures among all countries.
The World Summit on Sustainable Development (WSSD) Implementation Plan	Calls for a renewed commitment to the sound management of chemicals, using science-based risk assessment and risk management procedures, and taking into account the precautionary principle, to minimize adverse effects on human health and the environment.
The Miami Declaration, 1997	The G7/G8 Environment Leaders agree to promote the OECD Declaration on Risk Reduction for Lead on an international level, with the goal of reducing blood lead levels in children to below 10 µg/dl.
National Electronics Manufacturing Initiative (NEMI); Institute for Printed Circuits (IPC); International Tin Research Institute; Japan Electronics and Information Technology Industries Association (JEITA).	Various non-governmental organizations are supporting lead-free manufacturing initiatives.

Source: [68]

In August 2003, the NAFTA Commission for Environmental Cooperation released a draft decision document to determine whether lead should be the subject of a North American Regional Action Plan (NARAP) under the Sound Management of Chemicals initiative. NARAPs are developed for “persistent and toxic substances that the Parties agree warrant collective regional action because they pose a significant risk to human health and the North American environment” [68].

The European Parliament recently ratified two new laws pertaining to electrical and electronic equipment that could have significant implications for the future use of lead in lead-sheathed power cable. The Directives on Waste Electrical and Electronic Equipment (WEEE; directive 2002/96/EC) and the Restriction of the Use of Certain Hazardous Substances (RoHS; Directive 2002/95/EC) in electrical and electronic equipment will require companies to recycle waste electrical/electronic equipment and remove certain hazardous substances such as lead, mercury, and cadmium [69, 70].

The WEEE directive covers a broad range of equipment with voltages up to 1,000 volts ac and 1,500 volts dc. Beginning in August 2005, producers will be responsible for financing the collection and treatment of waste and meeting targets for re-use, recycling, and recovery. The Directive encourages a focus on sustainability to improve the environmental performance and end-of-life management of products.

Starting in July 2006, the RoHS Directive limits levels of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBBs), and polybrominated diphenyl ethers (PBDEs) in products. The target level for lead is 0.1%. A number of applications are exempted for these substances, including lead in electronic ceramic parts, lead in glass of cathode ray tubes, and lead in solders used for certain applications [69].

In the electronics industry, Japanese and European manufacturers have voluntarily begun to remove lead from new products before such action becomes mandatory [71]. Japanese manufacturers have viewed the challenge to produce lead-free products as a marketing opportunity to increase market share when regulations do take effect [71]. The goal is to remove lead from all electronic components and subassemblies by 2015.

The WEEE and RoHS directives do not currently affect medium-voltage lead-sheathed power cables. However, as in the case of Denmark, individual countries may establish regulations that are stricter than the directives. Thus far, with the exception of Denmark, lead-sheathed power cable has escaped governmental regulation. It is possible, however, that future European regulations will address the lead content in lead-sheathed power cables.

Existing and Proposed U.S. Regulations

The U.S. EPA currently regulates lead concentrations in the environment under the Clean Water Act (CWA), the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the Resource Conservation and Recovery Act (RCRA), the Superfund Amendments and Reauthorization Act (SARA), and the Safe Drinking Water Act (SDWA). In addition, the U.S. Occupational Safety and Health Administration (OSHA) has established a permissible worker exposure limit for lead in air of 50 $\mu g/m^3$ as an 8-hr time-weighted average and requires personal protective equipment and medical surveillance for workers exposed to lead.

There are currently no regulations in the U.S. governing the use of lead in lead-sheathed cable. Based on the trend in Europe, however, it is conceivable that similar legislation will be passed in the U.S. For example, the California Electronics Waste Recycling Act of 2003, which is similar in scope to the WEEE Directive, has become the first statewide electronics recycling law in the U.S. [72]. The law requires California retailers to collect a waste-recycling fee on cathode ray tube monitors, flat-panel screens, and television sets larger than four inches (10.2 cm) in size. California will use revenue from the fee to pay for the collection and recycling of the material. The Bill also includes measures to phase out the use of toxic materials in electronic products by 2007.

As in European countries, a voluntary phase-out of lead use in power cable applications in the U.S. appears likely. For example, PSE&G in the U.S. is no longer installing any PILC cable in their medium-voltage power system. The voluntary phase-out would likely be driven by economics and anticipation of future regulations that reflect increasing concern about the potential environmental and human health effects from the use of lead.

7
CONCLUSIONS AND RECOMMENDATIONS

The underground application of lead-sheathed power cable does not present a significant risk to human health and the environment. The lead sheath is susceptible to corrosion, but this mechanism for lead release is limited, because the corrosion by-products tend to form a passivating layer on the surface of the metal and inhibit further corrosion. Newer installations typically employ an outer polymer jacket, which provides additional protection from corrosion. Corrosion can be severe in extreme circumstances, leading to failure of the cable, but these cases are rare.

The few studies that have examined the distribution of lead in soil surrounding lead-sheathed cable find that most of the lead is either concentrated within 5 cm of the cable or found at background levels. This is consistent with other studies showing that the transport of lead in soil is limited, even after hundreds of years. The initial by-products of corrosion would represent the more bioavailable forms of lead, but the likely soil alteration phases would exhibit lower bioavailability than the initial corrosion products. In addition, exposures of the general population to lead are limited because the lead is trapped at depth in soil. Thus, potential risks to human health and the environment are considered to be extremely low.

Lead may also be released to sediment and water accumulated in manholes and ducts. In a limited survey of utility vaults and manholes, elevated concentrations of lead were found in some water and sediment samples. Although none of the sediment samples tested was classified as a hazardous waste, many of the vault water samples exceeded ambient water quality criteria for lead and the samples with the higher lead concentrations may have exceeded sewer use criteria. Installation and maintenance practices involving hot lead work during soldering and wiping may have contributed to lead levels. Water and sediment collected from vaults and manholes could result in additional routes of exposure to lead if not disposed of responsibly. In addition, discharges to surface waters and sewers could pose regulatory compliance concerns.

Overall, the risks from exposure to lead in lead-sheathed cable are very low, and replacing cable for reasons of environmental protection alone isn't justified at this time. There are no current or proposed U.S. regulations restricting the use of PILC cable or requiring its removal. However, there is a chance that future regulation in the U.S. will restrict PILC cable usage or require its replacement if the U.S. decides to follow the European approach. Therefore, it makes sense for utilities to be proactive in PILC cable removal, where economic or operational factors favor cable replacement.

8

REFERENCES

1. J. Dyba, "The Rise and Decline, in the United States, of Impregnated Paper-Insulated, Metallic-Sheathed Cable, Solid Type: Part I – The Rise," *IEEE Electrical Insulation Magazine.* Vol. 15, No. 4, pp.13 – 16 (1999).

2. V. Buchholz, M. Colwell, J.P. Crine, A. Rao, S. Cherukupalli, and B.S. Bernstein, "Condition Assessment of Distribution PILC Cables," *IEEE* pp. 877 – 881 (2001).

3. J. Dyba, and F.E. Goodwin, "New Developments in Lead-Sheathed Cables," Conference Record of the 1998 IEEE International Symposium on Electrical Insulation, Arlington, Virginia, June 7 – 10, 1998.

4. IEEE Power Engineering Society, "1425 - IEEE Guide fro the Evaluation of the Remaining Life of Impregnated Paper-Insulated Transmission Cable Systems," (March, 2002).

5. K. Bow, "Selected Panel Sessions: 1994 Transmission and Distribution Conference and Exhibition," *IEEE Electrical Insulation Magazine* Vol. 11, No. 3, pp. 44 – 51 (1995).

6. H. Bax and E. von Wiarda, "The Lead Sheath in German Power Cable Practice," Lead 65, Edited Proceedings of the Second International Conference on Lead Pergamon Press, New York, NY 1967, pp. 109–115.

7. *A Survey of Problems with Lead Sheathed, Paper Insulated, Oil Filled Cables and Reinforcing Tapes*. Southampton, SO31 7GA, England: Robin Anstey, Mantech Consulting Services, November, 2002.

8. *Aging PILC – Utility Viewpoint – Maintaining Reliability of PILC Cables*. Powerpoint Presentation presented by David S. Blew, Public Service Electric & Gas, Newark , NJ. December, 2002.

9. "Denmark Adopts its Ban on Products Containing Lead." Business Alert – EU, tdctrade.com Issue 26, 2000 (22 December). http://www.tdctrade.com/alert/eu0026b.htm

10. *Statutory Order No. 1012 of November 13, 2000 on Prohibition of Import and Marketing of Products Containing Lead*, 2000, Ministry of Environment and Energy, Danish Environmental Protection Agency, Translation AG/LK, November.

11. W.A. Thue, “History of Paper Insulated Power Cables,” Powerpoint Presentation, ICC Spring, (2003).

12. F.E. Goodwin and J.J. Dyba, “Recent Technological Developments for Lead Sheathed Cables,” *IEEE* (1994).

13. S.S. Sahay, S. Guruswamy, and F.E. Goodwin, “The Control of Intermetallics in Pb-Cu-Te Cable Sheathing Alloys,” *IEEE Electrical Insulation Magazine* Vol. 11, No. 3, pp. 12–25 (1995).

14. Renka Corporation, “Technical Guide – Selection of Power Cables,” (2003).

15. ASTM B29-79, Standard Specification for Pig Lead Chemical Requirements, http://www.maycoindustries.com/lead%20specs/refined_specs_5.htm

16. H.C. Wesson and E. Littauer, “Lead and Lead Alloys,” in *Corrosion, Volume 1, Metal/Environment Reactions* L.L. Shreir Ed., Newnes-Butterworth, Boston, MA 1976, pp. 4:68–4:85.

17. I.A. Denison, and M. Romanoff, “Soil-Corrosion Studies, 1946 and 1948: Copper Alloys, Lead, and Zinc,” *Journal of Research of the National Bureau of Standards* Vol. 44, 1950, pp. 259–275.

18. B.S. Bernstein, “Cable Testing: Can We Do Better?” *IEEE Electrical Insulation Magazine* Vol. 10, No. 4, pp. 33–38, (1994).

19. K. Mizuno, H. Hirukawa, O. Kawasaki, H. Noguchi, and O. Suzuki, “Development of Non-Lead Stabilized PVC Compounds for Insulated Wires and Cables,” *Furukawa Review* No. 18, pp. 111–118 (1999).

20. G. Murray, Consolidated Edison of New York, personal communication, (December, 2003).

21. B.E. Krpejs, and K. Wallace, “ARC Reflection Pinpoints Underground Cable Faults.” *The Electrical Tester,* Issue X, Winter 1998, p.1.

22. *Risk reduction Monograph No. 1 – Lead – Background and National Experience with Reducing Risk.* Organisation for Economic Co-Operation and Development, Paris, (1993). http://www.oecd.org/dataoecd/23/50/1955919.pdf

23. D. Warhola, and G. Dushan, “Colorado Springs Takes Transmission Underground,” *Transmission and Distribution World*, (March 1, 2001).

24. *PILC Cable Corrosion and Lead Condition Assessment.* Minutes of the EPRI Seminar held December 4 and 5, 2002 in Edison, NJ, prepared by International Lead Zinc Research Organization, Inc.

25. J.H. Lawson, "Utility URD Cable Experience," *IEEE Electrical Insulation Magazine* 1988, Vol. 4, No. 4, pp. 16–23.

26. "Lead: The Facts," Imperial College Consultants, Ltd., London, UK: 2001.

27. D.W. Shoesmith, "Kinetics of Aqueous Corrosion," in *Metals Handbook, Ninth Edition, Volume 13 – Corrosion,* Gulf Publishing Company, Houston TX 1987, pp. 29–36.

28. J.F. Smith, "Corrosion of Lead and Lead Alloys," in *Metals Handbook Ninth Edition, Volume 13, Corrosion* Gulf Publishing Company, Houston, TX pp. 784–792 (1987).

29. Y. Miyata, "Evaluation of Solution Corrosivity for Lead Alloy," *Corrosion Engineering,* Vol. 36, 1987, pp. 517–522.

30. L. Black and G.C. Allen, "Nature of Lead Patination," *British Corrosion Journal* Vol. 34, No. 3, 1999, pp. 192–197.

31. K.G. Compton, "Factors Involved in Corrosion of Lead Cable Sheath," *Corrosion* Vol. 17, 1961, pp. 409–412.

32. *Corrosion of Paper-Insulated Lead-Covered Cable*. Electric Power Research Institute, Palo Alto, CA: September, 2002. EPRI Project ID PID 008041.

33. Y.T. Horng, J.W. Hsu, H.C. Shih, J.H. Wang, H.P. Hsu, Y.C. Lin, and J.Y. Liu, "Cathodic Protection of Lead-Sheathed Telecommunication Cables in Manholes," *Materials Performance* Vol. 42, No. 5, pp. 22-25 (2003).

34. R. Tharby, "The Use of Lead Sheathed Cables by British Telecom," (undated).

35. K.K. Nikol'skiy, O.V. Chamkina, O.A. Lunev, and V.I. Mishchenko, "Corrosion of the Lead Sheathing of Armor of Communications Cable Due to the Action of Contact and Macrogalvanic Pairs," *Telecommunications and Radio Engineering (English translation of Elektrosvyaz, and Radiotekhnika)* Vol. 32-33, No. 3, 1978, pp. 11–14.

36. Nace Technical Committee Reports, Publication 56-9, "Cell Corrosion on Lead Cable Sheaths," *Corrosion* Vol. 12, 1956, pp. 257–259.

37. S.C. Dexter, "Appendix: Biological Effects," in *Metals Handbook, Ninth Edition, Volume 13 – Corrosion,* Gulf Publishing Company, Houston TX 1987, pp. 41–44.

38. J.L. Pintado and F. Montero, "Underground Biodeterioration of Medium Tension Electric Cables," *International Biodeterioration & Biodegradation* Vol. 29, 1992, pp. 357–365.

39. R.I. Perry, "Preventing Corrosion of Lead Sheathed Power Cables in Concrete Tunnels," *Corrosion* Vol. 12, 1956, pp. 207–212.

40. X. Cao, L.Q. Ma, M. Chen, D.W. Hardison Jr., and W.G. Harris, "Weathering of Lead Bullets and Their Environmental Effects at Outdoor Shooting Ranges," *Journal of Environmental Quality* Vol. 32, pp. 526–534 (2003).

41. F.Albert Cotton and Geoffrey Wilkinson. *Advanced Inorganic Chemistry – A Comprehensive Text.* John Wiley & Sons New York, NY 1980.

42. R.W. Hymes, "Lead Sheath Cable Corrosion – Cause and Prevention," Proc. 30th Appalachian Underground Corrosion Short Course, 1985, pp. 125–137.

43. X. Cao, L.Q. Ma, M. Chen, D.W. Harris, and W.G. Harris, "Lead Transformation and Distribution in the Soils of Shooting Ranges in Florida, USA," *The Science of the Total Environment* Vol. 307, pp. 179–189 (2003).

44. *A Review of the Environmental Impacts of Lead Shotshell Ammunition and Lead Fishing Weights in Canada.* Canadian Wildlife Service, 1995. Occasional Paper Number 88.

45. Z. Lin, B. Comet, U. Qvarfort, and R. Herbert, "The Chemical and Mineralogical Behaviour of Pb in Shooting Range Soils from Central Sweden," *Environmental Pollution* Vol. 89, No. 3, pp. 303–309 (1995).

46. J. Maskall, K. Whitehead, and I. Thornton, "Heavy Metal Migration in Soils and Rocks at Historical Smelting Sites," *Environmental Geochemistry and Health* Vol. 17, pp. 127–138 (1995).

47. J.L. Hawkins, M.I. Sheppard, and S.S. Jorgensen, "Predicting Soil Lead Migration: How Can Ancient Church Roofs Help?" *The Science of the Total Environment* Vol. 166, pp. 43–53 (1995).

48. R.A. Griffin and N.F. Shrimp, "Effect of pH on Exchange-Adsorption or Precipitation of Lead from Landfill Leachates by Clay Minerals," *Environmental Science & Technology* Vol. 10, No. 13, pp. 1256–1261 (1976).

49. C.E. Martinez and H.L. Motto, “Solubility of Lead, Zinc, and Copper Added to Mineral Soils,” *Environmental Pollution* Vol. 107, pp. 153–158 (2000).

50. M.P. Papini, A. Bianchi, M. Majone, and M. Beccari, “Equilibrium Modeling of Lead Adsorption onto a ‘Red Soil’ as a Function of the Liquid-Phase Composition,” *Ind. Eng. Chem. Res.* Vol. 41, 2002, pp. 1946–1954.

51. E.X. Wang, and G. Benoit, “Mechanisms Controlling the Mobility of Lead in the Spodosols of a Northern Hardwood Forest Ecosystem,” *Environmental Science & Technology* Vol. 30, No. 7, pp. 2211–2219 (1996).

52. A. Liu, and R. Gonzalez, “Modeling Adsorption of Copper(II), Cadmium(II), and Lead(II) on Purified Humic Acid,” *Langmuir* Vol. 16, pp. 3902–3909 (2000).

53. S.J. Traina and V. Laperche, “Contaminant Bioavailability in Soils, Sediments, and Aquatic Environments,” *Proc. Natl. Acad. Sci. USA* Vol. 96, pp. 3365-3371 (1999).

54. Therald Moeller and Rod O’Connor. *Ions in Aqueous Systems*. McGraw-Hill Book Company, New York, NY 1972, pp. 310–314.

55. M.V. Ruby, A. Davis, and A. Nicholson, “In Situ Formation of Lead Phosphates in Soils as a Method to Immobilize Lead,” *Environmental Science & Technology* Vol. 28, No. 4, pp. 646–654 (1994).

56. M.B. McBride, S. Sauve, and W. Hendershot, “Solubility Control of Cu, Zn, Cd, and Pb in Contaminated Soils,” *European Journal of Soil Science*. Vol. 48, 1997, pp. 337–346.

57. K.L. Godtfredsen, and A.T. Stone, “Solubilization of Manganese Dioxide-Bound Copper by Naturally Occurring Organic Compounds,” *Environmental Science & Technology* Vol. 28, No. 8, pp. 1450–1458 (1996).

58. E. Bolter, T. Butz, and J.F. Arseneau, “Mobilization of Heavy Metals by Organic Acids in the Soils of a Lead Mining and Smelting District,” 1975 pp. 107–112. In: Trace Substances in Environmental Health; Proc. University of Missouri’s Annual Conference. [P13242-13247].

59. R.D. Harter, and R. Naidu, “Role of Metal-Organic Complexation in Metal Sorption by Soils,” *Adv. Agron.*, 1995, Vol. 55, pp.219 – 263.

60. R.N. Jordan, D.R. Yonge, and W.E. Hathhorn, “Enhanced Mobility of Pb in the Presence of Dissolved Natural Organic Matter,” *Journal of Contaminant Hydrology* Vol. 29, pp. 59–80 (1997).

61. S. Forsberg and J. Björkman, “Release of Lead from Lead-Sheathed Telecom Cables in Soil,” Proceedings of the International Wire and Cable Symposium, 1994, pp. 478–482.

62. J.E. Jaspers and M.G.M. Megens, “Soil Pollution and Lead-Sheathed Telecom Cables,” *Wire Industry* Vol. 68, 2001, pp. 467–468.

63. H. Jaspers, M. Megens, and P. Matthijsse, “Investigation of Soil Pollution by Lead-Sheathed Cables,” Wire, Vol. 3, 2001, pp. 38-40.

64. *Survey and Characterization of Utility Vault Waters and Sediments.* EPRI: 1999. TR-113730.

65. M.V. Ruby, R. Schoof, W. Brattin, M. Goldade, G. Post, M. Harnois, D.E. Mosby, S.W. Casteel, W. Berti, M. Carpenter, D. Edwards, D. Cragin, and W. Chappell, “Advances in Evaluating the Oral Bioavailability of Inorganics in Soil for Use in Human Health Risk Assessment,” *Environmental Science & Technology,* Vol. 33, No. 21, pp. 3697–3705 (1999).

66. *Lead Risk Management Activities in OECD Member Countries (1993 to 1998) – Part One.* Organisation for Economic Co-Operation and Development, Joint meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology. ENV/JM/MONO(2000)1/PART1 February, 2000.

67. Nordic Council of Ministers. *Lead Review.* January, 2003.

68. NAFTA Commission for Environmental Cooperation (CEC), “Decision Document on Lead under the Process for Identifying Candidate Substances for Regional Action under the Sound Management of Chemicals Initiative,” June, 2003.

69. *Assessment of Paper-Insulated Lead-Covered Cable Condition – Electrical, Chemical, and Metallurgical Condition.* Electric Power Research Institute, Palo Alto, CA: March, 2003. 1001724.

70. Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment (WEEE). *Official Journal of the European Union* L 37/24–38, 13.2.2003.

71. Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment. *Official Journal of the European Union* L 37/19–23, 13.2.2003.

72. P.J.F. Le Fèvre, “Environmental Issues in Power Electronics (Lead Free)” APEC 2002.

73. "Davis Signs California E-Waste Bill," Recycling Today, September 26, 2003.

74. *Implementation of the HELCOM Objective with Regard to Hazardous Substances – Final Project Report*. Helsinki Commission, Baltic Marine Environment protection Commission, October, 2002.

75. *The Behaviour of PVC in Landfill – Final Report.* European Commission DGXI.E.3, February, 2000.

76. *National Recommended Water Quality Criteria: 2002*. U.S. EPA Office of Water, Office of Science and Technology, November 2002. EPA-822-R-02-047.

77. *The Effect of Chlorine on Corrosion in Drinking Water Systems – Final Report.* November 2000. http://mtac.sws.uiuc.edu/mtacdocs/CorrosionFinRpt/CorrosnFnlRpt00.pdf

78. *Understanding Variation in Partition Coefficient, Kd, Values, Volume II: Review of Geochemistry and Available Kd Values for Cadmium, Cesium, Chromium, Lead, Plutonium, Radon, Strontium, Thorium, Tritium (^{3}H), and Uranium.* U.S. EPA Office of Air and Radiation, August 1999, EPA 402-R-99-004B.

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case by case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

1009513

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com