THE
Water
Research
FOUNDATION

PROJECT NO.
4693

Lead Service Line Identification Techniques

Lead Service Line Identification Techniques

Prepared by:

Zia Bukhari, Shaoqing Ge, Suzanne Chiavari, and Peter Keenan
American Water

2020

THE
Water
Research
FOUNDATION

The Water Research Foundation (WRF) is a nonprofit (501c3) organization that provides a unified source for One Water research and a strong presence in relationships with partner organizations, government and regulatory agencies, and Congress. WRF conducts research in all areas of drinking water, wastewater, stormwater, and water reuse. The Water Research Foundation's research portfolio is valued at over $700 million.

WRF plays an important role in the translation and dissemination of applied research, technology demonstration, and education, through creation of research-based educational tools and technology exchange opportunities. WRF serves as a leader and model for collaboration across the water industry and its materials are used to inform policymakers and the public on the science, economic value, and environmental benefits of using and recovering resources found in water, as well as the feasibility of implementing new technologies.

For more information, contact:
The Water Research Foundation

1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445
P 571.384.2100

6666 West Quincy Avenue
Denver, Colorado 80235-3098
P 303.347.6100

www.waterrf.org
info@waterrf.org

WRF ISBN: 978-1-60573-469-9
WRF Project Number: 4693

Prepared by American Water

Acknowledgments

The project team contacted numerous vendors and utility partners to gather information on their technologies or procedures and these materials were used to develop example case studies and prospective methods in this report. All these individual's openness and willingness to share experiences and provide insights are appreciated.

The authors gratefully acknowledge the support provided by Emily Hoing (Civil Engineering, Drexel University) and Matthew Waligorski (Geoscience, Drexel University) while interning in the One Water Engineering group in American Water. Both Emily and Matthew were instrumental in getting the literature collated and helping with the preparation of all aspects of the report.

The project team also acknowledges Chandan Venkatesh, David Hughes, and Kurt Sjoblom, PhD. for their initial contributions to this project.

Research Team

Principal Investigator:
Zia Bukhari, PhD
American Water

Project Team:
Shaoqing Ge, PhD, PE
American Water

Suzanne Chiavari, PE
American Water

Peter Keenan, PE
American Water

WRF Project Subcommittee or Other Contributors

Whit Wheeler
City of Raleigh, North Carolina

Benjamin Klayman
Medford Water Commission

Frank Grablutz
Aqua America, Inc.

WRF Staff

John Albert, MPA
Chief Research Officer

Jonathan Cuppett
Research Program Manager

Abstract and Benefits

Abstract:

The Water Research Foundation has developed an extensive knowledge base on lead in drinking water systems. However, recent high-profile events have generated significant media attention, and have solidified the opinion for some that the only safe option is to remove lead service lines (LSLs) completely from drinking water systems. This is consistent with the U.S. Environmental Protection Agency's (EPA) maximum contaminant level goal (MCLG) of zero for lead in drinking water. The most significant challenge for water utilities has been to develop an accurate inventory of the 6 to 10 million LSLs that are estimated to exist in the US. Since the implementation of the Lead and Copper Rule (LCR; EPA 1991), the industry has relied on indirect methods that use historical records, such as tap cards, to develop inventories of customer locations thought to have LSLs. However, in some instances, this approach has produced low accuracy rates (i.e., 70%). Without an accurate inventory of LSLs, the exploratory excavation costs can become cost-prohibitive.

Accurate and cost-efficient identification of LSLs continues to be a challenge for water utilities in the US

In this project, reviews of the literature and industry practices were conducted to identify detection technologies that are fast, portable, economical, user-friendly, minimally invasive, and sufficiently sensitive to identify lead pipes buried in soils of various types. Additionally, indirect screening techniques used by utilities to gather information on the likely presence of LSLs were explored and discussed using case studies to substantiate the usefulness of promising approaches.

This study concludes that no convenient methodology is currently commercially available that is capable of directly identifying buried LSLs. In addition, while some promising technologies exist, no vendors appear to be actively developing products that would provide reliable, cost-effective, and easy-to-use solutions. The literature and case studies highlight numerous utilities that are leveraging historical information in conjunction with GIS mapping to develop spatial inventories of their LSLs. However, the accuracy of this historic information is key in accurately predicting the presence of LSLs.

Utilities need to adopt a multipronged approach to develop robust inventories to facilitate future LSL replacement strategies

Benefits:

- Based on literature reviews and industry reconnaissance conducted in this study, a variety of physical detection methods exist for potentially identifying LSLs. Unfortunately, most of these technologies were considered developmental, commercially unavailable, or unlikely to be commercialized in the foreseeable future.
- In the absence of convenient physical detection methods for LSLs, the only definitive method for establishing their presence is through physical inspection (e.g., excavation).
- As extensive physical inspection efforts are likely to be cost-prohibitive, utilities should focus on supplementing their intelligence around LSL presence in their service areas with information gathered through indirect methods. Examples of indirect data sources include:
    - tap cards
    - service/repair tickets

    - construction records
    - plumbing permits
    - water quality data
- Given various data sources could contribute to understanding the likely presence of LSLs and contribute to inventory development, utilities should consider digitizing all of their historic sources of data that can yield information on LSLs.
- The usefulness of data to predict the likelihood of LSLs will be dependent on the number of data sources, their accuracy, and completeness of information from each source. Accordingly, water utilities should validate the information from each data source and, where possible, leverage advanced analytics (i.e., machine learning) to improve the confidence in predicting the presence of LSLs.
    - Validation of LSL presence would require physical inspection, which should be adjusted according to the level of confidence in historic data (i.e., perform more validation where lower confidence)
    - Utilities should verify through the current LCR regulation to ensure replacement rates meet compliance at a minimum.

Keywords: Lead Service Lines, LSL, Methods, Tap Card, Identification, Case Studies, GIS.

Contents

Acknowledgments iii
Abstract and Benefits iv
Figures viii
Acronyms and Abbreviations ix
Executive Summary xi

Chapter 1: Introduction 1
- 1.1 Background 1
- 1.2 Problem 3
- 1.3 Prior Research and Future Needs 4
- 1.4 Objectives 5

Chapter 2: Locating LSLs Using Direct Methods 7
- 2.1 Introduction 7
- 2.2 Pothole/Vacuum Excavation 7
- 2.3 CCTV Inspection 8
- 2.4 Scratch and Magnet Test 8
- 2.5 Disclosures 9

Chapter 3: Locating Lead Service Lines Using Indirect Methods 11
- 3.1 Introduction 11
- 3.2 Historical Information to Create an Online Inventory 11
- 3.3 Geostatistics and Machine Learning 13
- 3.4 Water Sampling 14

Chapter 4: Case Studies- LSL Replacement Strategies 17
- 4.1 Case Study Identification and Selection 17
- 4.2 Madison, Wisconsin (Scratch Test and Historic Data) 17
- 4.3 Green Bay, Wisconsin (Historic Data Online Inventory and CCTV Inspection) 18
- 4.4 Lansing, Michigan (Historic Data Online Inventory) 19
- 4.5 Tucson, Arizona (Historic Data Inventory and CCTV Inspection) 19
- 4.6 Denver, Colorado (Historic Data Online Inventory) 20
- 4.7 Indiana American Water- Northwest (Historic Data Online Inventory) 20
- 4.8 DC Water (Water Quality) 21

Chapter 5: Prospective Methods for Lead Service Line Detection 23
- 5.1 Metal Detectors 23
  - 5.1.1 Very Low Frequency (VLF) Technology 24
  - 5.1.2 Terahertz Technology 24
  - 5.1.3 Three-Dimensional Electromagnetic Induction 25
  - 5.1.4 Pulse Induction 25
  - 5.1.5 Multi-mode Electromagnetic Target Discriminators 25
  - 5.1.6 Polyharmonic Metal Detectors 25
- 5.2 Magnetometers and Gradiometers 26
- 5.3 Ground-Penetrating Radar 26

5.4 Stress Wave Propagation 27
5.5 Acoustic 27
5.6 Electrical Conductivity Object Locators 28
5.7 Field Portable X-ray Fluorescence Spectrometry 28

Chapter 6: Conclusions and Recommendations 29
6.1 Conclusions 29
6.2 Recommendations 29

References 31

Figures

1-1 Human Health Effects Associated with Exposure to Lead 2
1-2 Property Line Dividing the Public (Utility) Side and the Private (Customer) Side 3
3-1 Historical Tap Card Showing Location Specific Information 12
4-1 Application of the Potholing Technique for LSL Exposure at the Curb Stop 21
5-1 Working Principle of Metal Detector 24

Acronyms and Abbreviations

ALE	Action level exceedance
ASV	Anodic stripping voltammetry
CCTV	Closed-circuit television
dL	Deciliter
DNA	Deoxyribonucleic acid
ECOL	Electrical conductivity object locator
EDF	Environmental Defense Fund
EM	Electromagnetic
GSL	Galvanized service lines
GIS	Geographic information system
GPR	Ground-penetrating radar
ICP/MS	Inductively coupled plasma/mass spectrometry
LBWL	Lansing Board of Water and Light
LCR	Lead and Copper Rule
LSL	Lead service line
LSLRC	Lead Service Line Replacement Collaborative
LSLRP	Lead Service Line Replacement Program
MCL	Maximum contaminant level
MCLG	Maximum contaminant level goal
METD	Multi-mode electromagnetic target discriminator
NPR	National Public Radio
PWD	Philadelphia Water Department
ROV	Remotely-operated vehicle
3AMFG	Three-axis magnetic field generator
3D EMI	Three-dimensional electromagnetic induction
3DSMF	Three-dimensional steerable magnetic field
UXO	Unexploded ordinances
EPA	United States Environmental Protection Agency
VLF	Very low frequency
WLL	Water lead level
XFR	X-ray fluorescence

Executive Summary

ES.1 Key Findings

- At this time, there is not a commercially available method to detect the material composition of buried service lines, except for physical excavation and verification.
- As extensive physical inspection efforts are likely to be cost-prohibitive, utilities should focus on supplementing their intelligence around lead service line (LSL) presence in their service areas with information gathered through indirect methods such as tap cards, service/repair tickets, construction records, plumbing permits, and water quality data.
- Utilities should take the time to determine which techniques are most practical and effective for their unique circumstances.
- Utilities with good quality tap card records should invest the time and effort to digitize those records and add them to their GIS systems to help organize and manage their LSL replacement programs.

ES.2 Objectives

The primary objective of this project was to document the methods and technologies that water utilities are currently using to identify buried lead service lines (LSLs) within their service areas. In addition, the study provides a review of new technologies that may have the potential to improve the effectiveness of LSL location and identification in the future.

ES.3 Background

A comprehensive study was conducted and published by the Water Research Foundation to examine various direct and indirect approaches for determining the presence of LSLs (Deb et al. 1995). The study concluded that methods available at the time were hampered by several challenges, but most significant were the general inaccessibility of buried service lines and complexities created by split ownership responsibility between the utility and the customer. Therefore, a number of new technologies were identified that could have the potential to overcome the accessibility challenge, but the study concluded that additional research and development would be necessary to determine if any of the prospective technologies would be cost-effective and practical for use by water utilities.

The most problematic challenge for locating and identifying LSLs is that most of the service line is concealed underground. In the absence of direct detection methods that do not require excavation, utilities have adopted indirect strategies, such as information captured from tap cards, date of service line installation, records from recent repairs, water quality data, or even institutional knowledge, to ‘predict’ the likely presence of LSLs. These indirect methods provide intelligence to help locate LSLs, but challenges like incomplete records or inconsistent record formats reduce the reliability of this approach. Nonetheless, the 1995 study reported that the Chester Water Authority and the Water and Sewer Utility Administration of Washington, D.C. (now DC Water) achieved a 92.2% and a 73.7% success rate, respectively, for identifying LSLs in their service areas using indirect methods.

Currently, corrosion control continues to be a cost-effective option for managing lead levels in highly optimized systems, but lead-related incidents are encouraging an increasing number of utilities to seek to eliminate all LSLs in their drinking water systems. It is estimated that between 6 and 10 million LSLs remain in active service across the US (Cornwell et al. 2016). Given a range of unit costs, the total cost to replace all LSLs in the US could tally between \$20 billion and \$80 billion. A key to managing these costs is the ability of the utility to directly and expeditiously identify the location of LSLs in their system. Without practical and cost-effective direct methods, utilities need to use indirect methods to gather information on the presence of lead service lines; however, it has been suggested that exclusive use of such approaches can significantly underestimate (i.e., by approximately 30%) the number of LSLs in a system. Given that the Deb et al. (1995) study was conducted over two decades ago, the thrust of this project was to understand what advances were made in both the direct and indirect methodologies that could help utilities expedite the detection of LSLs.

ES.4 Approach

Since the principal goal of this research was to identify practical and cost-effective technologies or procedures/approaches that can help water utilities locate LSLs, the ideal methodologies need to be fast, portable, economical, user-friendly, and, importantly, they should be minimally invasive and sufficiently sensitive to identify the target materials buried in soils of various type, without the need for extensive excavation. Therefore, the project scope included the following elements:

- Identify physical detection methodologies that are capable of rapidly and directly establishing the presence of LSLs.
    - To avoid duplication of efforts, this study focused on the recent evolution of the technologies originally discussed in Deb et al. (1995). The goal was to identify features/advances in those technologies or their recent iterations that may improve their capability for identifying LSLs.
- Examine indirect screening techniques that are being effectively used by utilities to gather evidence that allows highly accurate predictions of where LSLs are likely to be present in a given water system.
- Discuss case studies to substantiate the usefulness of promising techniques or approaches for identifying LSLs.

ES.5 Conclusions

The limited accessibility to buried service lines, the age and condition of records, and complications of utility versus private property owners make it difficult to locate LSLs. Unfortunately, the development of new portable tools to directly screen for LSLs, without excavation, has been limited over the past 20 years. Thus, existing direct LSL identification methods remain inadequate and cumbersome. For example, using a “pothole” excavation method may be more cost-effective than excavation to expose the entire service line, but the pothole method only provides information on a portion of the line. It does not guarantee that the service line material is the same over its entire length. Inserting cameras into the service line can provide details on the service line materials, but scale build-up inside the line may still prohibit definitive identification of the pipe material.

Several prospective direct methods were identified, all of which rely on some form of electromagnetic radiation or seismic waves. However, none of these prospective non-invasive technologies is currently able to reliably or cost-effectively confirm the presence or absence of LSLs. Therefore, utilities will need to rely on one or more indirect methods to help assess the probability that a customer is served by an LSL. Quality assurance of the various data sets and verification of the predictive capabilities of the indirect method through some form of physical inspection is essential to assure adequate reliability.

The most commonly used indirect method is reviewing tap cards that the water utility used to log information at the time of service line installation. Unfortunately, because most LSLs were installed 80 or more years ago, tap cards may be missing, incomplete, or difficult to read, or they may not have been updated to reflect more recent repairs/replacements.

Ensuring multiple verified data sources are used will likely improve the robustness of predictive methods. Other parameters to assist with LSL inventory development may include:

- Age of property or construction time frame
- Physical location relative to other confirmed LSL locations
- Service or repair tickets
- Construction or plumbing permit records
- Water sampling data for lead

ES.6 Recommendations

Identifying LSLs continues to be a significant challenge for many utilities. Without direct identification methods, utilities should consider using a multipronged approach for inventory development to facilitate their LSL replacement strategies. To ensure that a utility's LSL replacement program can proceed as effectively and efficiently as possible, utilities should:

- Take the time to determine which techniques are most practical and effective for their unique circumstances.
- Invest the time and effort to digitize tap card records and add them to their GIS systems to help organize and manage their LSL replacement programs.
- Gather additional intelligence for the presence of LSLs by:
    - Developing or accessing databases for various parameters (property age, service or repair tickets, construction and plumbing permit records, water sampling data for lead, etc.)
    - Conducting quality assurance review of the data for completeness and accuracy
    - Exploring the use of GIS-based systems for spatial distribution
    - Leveraging the use of advanced statistical and machine learning tools
    - Developing record keeping methods to capture service line material data that is usually readily available during water main replacement activities
- Validate data gathered using indirect methods with one or more direct methods. Options may include:
    - Customer requests to conduct a magnet and scratch test that are reported back to the utility
    - Visual inspections (potholing, camera or full excavation) of representative locations based on the utility's degree of confidence with the inventory.
    - Data gathered from routine inspections, main replacement or emergency response events.
- Proactively communicate experience (successes, failures, etc.) in conference proceedings, trade and journal articles, and webinars to help utilities identify the LSL detection methods that may best suit their unique circumstances.

ES.7 Related WRF Research

- Evaluating Key Factors That Affect the Accumulation and Release of Lead from Galvanized Pipes (project 4910)
- Evaluation of Lead Pipe Detection by Electrical Resistance Measurement (project 4698)
- Full Lead Service Line Replacement Guidance (project 4713)

CHAPTER 1

Introduction

1.1 Background

Lead is a toxic heavy metal with an atomic weight of 82 and is represented by the symbol Pb (Latin *plumbum*) in the periodic table. Often described as a soft malleable metal, lead has several stable isotopes (^{208}Pb, ^{207}Pb, ^{206}Pb, ^{204}Pb) and is estimated to be the 38th most abundant element on the planet, comprising 13 mg per kg in the earth's crust (Nordberg et al. 2007). Relatively high availability in conjunction with its unique properties (high density, low melting point, ductile and inert nature) and ease of extraction have afforded opportunities for its wide and varied use in history. While not intended as an exhaustive list, lead has been used as an additive in eye and facial cosmetics, for sound dampening, and in manufacturing of church organ pipes, X-ray shielding plates, lead-acid batteries, plastic stabilizers, and pigments. It was once used for adulterating wine to provide additional sweetness, and excessive imbibing was known to have caused poisoning and madness in some historically renowned musicians and artists. Less melodramatic but just as profound may have been the health effects from exposure to lead which was used as an antiknock agent (i.e., tetraethyl and tetramethyl lead) in gasoline until that was phased out in the United States in the 1970s (Walsh 2007).

The lead was first used for the construction of water pipes beginning in Roman times, and eventually became a popular choice for plumbing materials in the US, with more than 70% of larger cities (populations >30,000) using lead for buried customer service lines by 1900 (Rabin 2008). While most lead service lines (LSLs) were installed before 1940, mounting evidence of exposure-related health effects ultimately led to a ban on its future use by the US Congress in 1986 (EPA 1989). Presently, it is estimated that more than 6 million, and possibly as many as 10 million LSLs are still in use in the US today (Cornwell et al. 2016). Leaching of lead can occur from several possible components or sources within customer premise plumbing, such as the lead or lead-lined iron service piping, lead-tin plumbing solder, or lead-bearing brass valves and faucets. The release of lead from such components can be influenced by various factors, including the age and type of material, workmanship, size of the pipe, water quality, and degree of stagnation. The United States Environmental Protection Agency (EPA), as a regulator for the drinking water industry in the US, has established a maximum contaminant level goal (MCLG) of zero for lead. While this is an aspirational goal, it highlights there is no known safe level for lead in drinking water.

Excessive exposure through ingestion can result in lead poisoning, where transport of lead from the intestines to various bodily organs occurs through binding of the beta, delta and especially fetal gamma chains of red blood cells (Harewood and Azevedo 2019). Absorption rates can be significantly higher in children than adults, so children can be most significantly impacted with neurological, gastrointestinal and/or developmental deficiencies (Bathla and Jain 2016). Symptoms may be wide and varied but can include intellectual impairment or memory problems, headaches, stomach and kidney issues, anemia, seizures and high blood pressure (Figure 1-1). In the US, normal blood lead levels in adults are estimated to be less than 10 µg per deciliter (dL). Occasional exposure can increase these levels into the range of 25 µg per dL, while "regular" exposure can yield blood lead levels as high as 40 µg per dL and frequent exposure can increase blood lead levels to 80 µg per dL. While moderately elevated blood lead levels (i.e., 10 to 40 µg per dL) may show some evidence of physiological effects, frequent exposure to levels greater than 40 µg per dL is likely to have serious health effects, even in the absence of any noticeable symptoms (Wani et al. 2015).

Figure 1-1. Human Health Effects Associated with Exposure to Lead.
Source: Aquasana 2019.

The significant health effects associated with lead prompted the establishment of drinking water regulations, known as the Lead and Copper Rule (EPA 1991), under the Safe Drinking Water Act. As the US regulatory framework at the federal level relies on a variety of factors (i.e., availability of treatment, tangible health benefits, costs) in establishing drinking water standards, human health effects from public exposure to contaminants in water can be managed by defining maximum contaminant levels (MCLs) or through prescribed treatment techniques. The LCR, which applies to community and non-transient-non community public water systems and is currently undergoing revisions, focuses on the treatment techniques to help reduce exposure to lead in drinking water. According to the LCR, utilities are required to take action if more than 10 percent of lead samples at the customers' tap exceeds 0.015 mg per L (or 15 µg per L) from the first draw following 6 hours of stagnation. As indicated earlier, the MCLG for lead is zero, which suggests the action level is indicative of effective corrosion control and not reflective of public health protection.

Plentiful peer-reviewed information exists on various aspects of lead control or management in drinking water infrastructure to assist utilities in meeting the lead action level. The Water Research Foundation website hosts a multitude of resources concerning lead including 119 project papers, 86 webcasts, 64 projects, 29 web tools, 20 special reports, 18 case studies, and 10 presentations. With this wealth of information, many utilities in the US have effectively used corrosion control techniques (i.e., pH, alkalinity adjustment to reduce the corrosivity of water or addition of ortho/polyphosphates as treatment techniques) to avoid Action Level Exceedance (ALE). Where ALE occur, utility action involves increasing the number and frequency of sampling, education of the customers, monitoring the entry point to the distribution system, developing a better understanding of the water quality at the source and customer taps, and developing strategies for source water treatment in concert with optimal corrosion (Cantor 2017) control. The complexity of maintaining optimized water chemistry and corrosion control can be challenging in drinking water distribution systems; especially systems with inadequate staffing, lack of financial resources, variable water demands and/or variable water quality characteristics. When coupled with inconsistencies in the source water or quality of corrosion control chemicals, exacerbation of this situation can occur. Systems that continue to experience persistent or recurring ALE must take steps to optimize corrosion control treatment or explore LSL replacement at a minimum required rate (i.e., 7% per year).

In the recent past, several high-profile incidents in the Midwest, along with persistent ALE in large systems along the east coast, have highlighted the balancing act utilities have had to perform in managing the risk of action level exceedances for lead. Source water changes, treatment chemical changes or disinfectant level/type changes, either individually or collectively can set off a cascade of downward spiraling events that can expose communities to the risk of ingesting elevated lead levels.

1.2 Problem

LSLs are typically found in older water systems where distribution mains were installed before the 1940s (Boyd et al. 2001). Customer service lines are typically divided along the property line (Figure 1-2) into sections in the public space (utility-owned) and on private property (customer-owned). The inventory of service lines, in general, is often incomplete, inaccurate, and undermanaged, perhaps because utilities placed greater emphasis on inventorying mains, valves, and hydrants (NJDEP 2016). Factors contributing to this may be many, but likely include one or more of the following: general lack of financial resources, shared ownership of the service line between the utility and the end-user/customer, general neglect arising from a low failure rate of the service line, and limited accessibility.

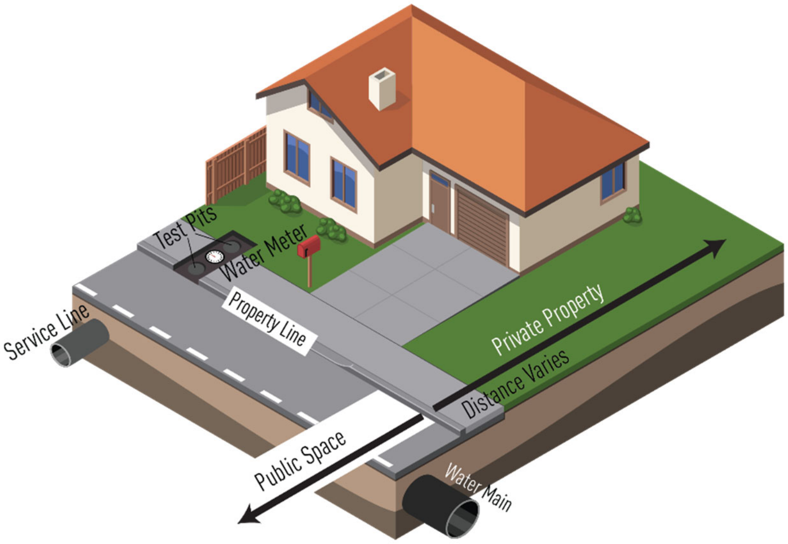


Figure 1-2. Property Line Dividing the Public (Utility) Side and the Private (Customer) Side.
Source: Adapted from Welter et al. 2013.

When service line replacements have been necessary, historically they have only been replaced up to the property line (Cartier et al. 2012). However, partial LSL replacement has not been an effective strategy for managing the exposure risk from lead (Triantafyllidou and Edwards 2010). Partial replacements, where a section of the LSL has been replaced with another metal (e.g., copper), can cause corrosion through galvanic action that occurs at the interface between the two dissimilar metals, and can adversely influences lead levels in drinking water (Welter et al. 2013, Brown et al. 2015). Further contributions to lead levels in water can occur from the physical disruption of lead-bearing scales that occurs during and following a partial LSL replacement. While the effects of the latter can also be observed for some time after complete replacement of LSLs (both utility- and customer-side), currently this seems to be the most reliable approach for reducing the likelihood of persistent lead exposure in the future.

There may be numerous impediments to proceeding with complete LSL replacement, including who will be responsible for funding the work. However, a fundamental question that needs to be addressed is where exactly LSLs are located within a water utility's infrastructure. Customer service lines may consist of many pipe materials, including cast iron, lead, galvanized steel, copper, polybutylene, high-density polyethylene, polyvinyl chloride and a variety of composite tube types (Ryan 2008, Rabin 2008). To ensure LSLs have been identified accurately, it is important to develop an inventory of service line materials on both the public and private sides of a service connection.

An accurate and cost-effective method for identifying buried lead pipe is needed to accomplish this task. Variations in soil type, soil moisture, depth of installation, presence of pipe shutoffs and bends, limited access points, and even seasonal changes can individually or collectively impact the ability to discriminate pipe materials. In addition, many LSLs that have been removed from service may have been abandoned in place. Thus, detection methods may need to ascertain whether the pipe of interest is still in use.

1.3 Prior Research and Future Needs

Previously the Water Research Foundation conducted a comprehensive study to examine approaches capable of detecting buried lead pipes (Deb et al. 1995). Several direct and indirect approaches were identified and evaluated through bench-scale and field studies. The investigators also conducted a comprehensive literature review (400 databases using keywords like *metal, detect, ground-penetrating radar, lead, pipe, remote sensing*), extensive patent searches, and communications with various vendors to identify non-destructive direct approaches that may be used to ascertain information on pipe materials while avoiding the need for complete excavation. The study found that fiber optic image capturing systems and eddy current technology could assist in the identification of service lines, but they were difficult to deploy and required direct access to the pipe section to determine its characteristics. Therefore, the study concluded that additional research and development would be necessary before a practical non-destructive direct method for identifying LSLs would be available.

Because of the limited number of direct detection methods and numerous obstacles to their use, utilities are increasingly using “indirect” strategies, such as institutional knowledge, water quality data, information captured from tap cards, date of service line installation, records of recent repairs, etc., to ‘predict’ the likely presence of LSLs. Indirect methods (Chapter 3) can help utilities identify customers that are most likely to have LSLs, but Deb et al. (1995) noted there are often challenges, such as incomplete records or inconsistent formats, that can affect the accuracy of indirect methods. Despite such challenges, however, that study documented how the Chester Water Authority and the Water and Sewer Utility Administration, Washington, D.C. (now DC Water) achieved a 92.2% and 73.7% success rate respectively for identifying LSLs in their utilities using indirect methods.

Based on the recent events associated with lead in drinking water, the heightened media attention, increased public awareness, the future introduction of more stringent regulations, and the compelling evidence on health effects from increased blood lead levels, various water utilities are exploring proactive approaches to the management of lead in drinking water. Evidence to date demonstrates that lead levels can be managed effectively through corrosion control strategies; however, this is a complex process in a constantly changing environment. Deviations in corrosion control can allow system upsets that can yield exceedances, which can occasionally become persistent. When this occurs, it may be challenging for utilities to recover expeditiously; especially where resources or trained personnel are in limited supply.

While corrosion control continues to be a cost-effective option for managing lead levels in optimized systems, an increasing number of utilities are seeking a long term or permanent solution, which includes LSLs removal from drinking water systems. In 1990 estimates for mandatory replacement, which included service line identification and administrative costs in addition to actual LSL replacement costs, were estimated to be $4.4 billion (Weston and Economic and Engineering Services, Inc. 1990). At the time of this analysis, the utility cost burden for pipe replacement relative to the associated health benefits in the exposed populations was determined to have a 30- to 35-fold disparity, meaning optimized corrosion control was the most cost-effective management strategy. However, recent events have changed that perception significantly. Currently, estimates indicate that between 6 and 10 million LSLs remain in active use in the US, with an estimated average replacement cost of around $5,800 per service line. Given a range of unit costs, the total cost to replace all LSLs in the US could tally between $20 billion and $80 billion. A key to managing these costs would be the ability of the utility to directly and expeditiously identify the location of LSLs in their system. Without direct methods, utilities need to rely on indirect methods (i.e., tap card records, meter repair/replacement notes, service line maintenance, water main replacement notes, etc.) to gather information on the presence of LSLs. However, it has been suggested that the exclusive use of such approaches can significantly overestimate or underestimate the number of LSLs in a system. Given that the Deb et al. (1995) study was conducted over two decades ago, the thrust of this project was to understand what advances have been made in both the direct and indirect methodologies that can help utilities expedite the detection of LSLs.

1.4 Objectives

The principal goal of this project was to identify cost-effective detection technologies or procedures/approaches that could help water utilities identify the presence of LSLs between the water main and the customer dwelling or building. Ideal methodologies need to be fast, portable, economical, user-friendly, and, importantly, they need to be minimally invasive and sufficiently sensitive to identify the target materials buried in soils of various types, without the need for extensive excavation.

Specifically, the project objectives were as follows:

- Identify physical detection methodologies that rapidly and directly establish the presence (or absence) of LSLs.
    - To avoid duplication of efforts, this study focused on any recent evolution or improvement of the technologies originally discussed in Deb et al. (1995). The goal was to identify features/advances in those technologies or their recent iterations that improve their ability for identifying LSLs.
- Examine the use of indirect screening techniques being used by utilities to accurately predict where LSLs are likely to be present in their systems.
- Present case studies to substantiate the usefulness of promising techniques or approaches for identifying LSLs

CHAPTER 2

Locating LSLs Using Direct Methods

2.1 Introduction

Direct methods are defined here as those that a water utility can perform to definitively ascertain the presence of an LSL without the need for major excavation. These are differentiated from indirect methods, discussed in Chapter 3, which rely on various sources of data to identify buildings that have a high probability of being served by an LSL. It is important to note that since indirect methods only give a probability, utilities cannot be certain LSLs are present unless a direct method is used for confirmation.

There has been little advancement in the development of direct methods since publication of *Innovative Techniques for Locating Lead Service Lines* (Deb et al. 1995) and the direct methods described in this section have been available, and in many cases, have been in use for decades. Nonetheless, the associated equipment that is required for these direct methods has evolved, which may help make certain direct methods somewhat more efficient and effective than they were in the past.

2.2 Pothole/Vacuum Excavation

Potholing and vacuum excavation by themselves are a relatively safe and efficient way to expose underground utilities for observation by comparison to “potholing,” which entails using a backhoe or hand tools to dig a hole to expose a service line or other pipe segment. Vacuum excavation uses high velocity, high-pressure air or water to break up the soil so it can be removed easily through an integral high-powered vacuum (Super Products 2019). The term “hydro-excavation” is sometimes used when water is used instead of air to loosen the soil.

Both techniques create a test hole, which allows for direct observation so piping material can be identified. In vacuum excavation, the debris is stored in an internal holding container until ready to be placed back into the excavation, which can minimize the amount of debris stockpiled in the vicinity (MARC 2003) and make it less disruptive for parking or passing traffic (Vactron Equipment 2019). This technique for excavating has advantages over the backhoe digging method. The vacuum excavation method is considered to be safer because high-pressure air or water is less likely to disrupt or damage existing piping or other buried utilities, which are always a risk associated with potholing, especially with a backhoe. Additional extension tools are available that allow vacuum excavators to reach confined or restricted spaces (Pullin 2019).

Vacuum excavation is also used in numerous places because of its cost advantage over more traditional means of pothole excavation. According to Eric Schwartz in the Declaration of the Lawsuit against the City of Flint, the average price for one hydro-excavation is about $285, while the price of a traditional excavation ranges from $1,780 to $2,600 (Abernethy et al. 2018).

An important limitation of using this method are situations where a pipe was already partially replaced. Creating a hole to test the pipe could land on the section where the lead had been upgraded and result in a false assumption that the pipe was not lead. The mayor of Flint, Michigan banned the use of vacuum excavation because a concern arose that the method was missing lead pipes due to partial repairs (Ahmad 2019).

2.3 CCTV Inspection

Closed-circuit television (CCTV) is widely used in the wastewater industry to inspect the interior of gravity sewer lines. There are numerous CCTV cameras and associated devices on the market with various sizes and features ranging from rigid or flexible insertion style probes to self-propelled, remotely-operated vehicles (ROVs). ROVs are currently only available for inspection of larger diameter water or sewer lines, but smaller probe or insertion style CCTV cameras have been used by several water utilities to visually identify service line materials. CCTV inspections generally fall into one of two categories, with one being to inspect the exterior of the service line and the second being to inspect the interior.

Exterior inspections normally involve inserting the CCTV camera into the curb box where the service line may be partially exposed on each side of the shut-off valve. There are a variety of curb box styles on the market, but in cold climates, they usually consist of a telescoping pipe that extends vertically from the ground surface down to the shut-off valve, which is typically situated 3 to 5 feet below grade. In warmer climates, curb stop boxes may be larger plastic or fiberglass enclosures buried at shallower depths. The bottom of the curb box is frequently arched so the service line passes through the arch without the valve box resting on the line itself. The top of the valve box is fitted with a lid that can be removed to allow the insertion of a long-shaft valve wrench or key that fits over the nut on the top of the valve to allow it to be operated. Some valve boxes are equipped with an integral actuator stem so just the top of the curb box lid needs to be rotated to open or close the valve.

Often it is necessary to first vacuum soil or other debris out of the curb box to expose the valve and the two sides of the service line that connect to it. Assuming this can be accomplished, a small-diameter CCTV camera can be inserted into the curb box to visually examine the service line connections to the curb stop valve. LSLs often feature a uniquely characteristic bulb-shaped “wipe joint” connection to the curb stop valve, which can help facilitate external identification. Utilities have had mixed success with being able to determine service line materials using this technique. Sometimes the curb box cannot be adequately cleared of soil or debris or the service line may simply be too heavily coated with mud or oxidation deposits to allow visual confirmation. In some cases, simply locating the curb stop can be the primary obstacle. The Pittsburgh (PA) Water and Sewer Authority used CCTV cameras through the curb box to identify piping materials for several hundred service lines, but the characteristic of about 43% of the inspected services remained undetermined due to difficulties locating the curb stops or obtaining clear enough imagery of the service line (Conway 2017).

Some utilities have successfully used fiber optic CCTV camera technology to visually inspect the interior of service lines. A major benefit to this approach is that more of the service line can be visually inspected, rather than just the segments connecting to the curb stop valve. As such, it may be possible to confirm where lead segments occur within the service line, such as cases where the gooseneck is lead but the service line extension to the curb box is copper, or where a repair was made previously but lead piping still remains further down the line. However, this approach may also become ineffective where the interior of the service line is coated with corrosion or scale deposits that conceal the pipe surface. The City of Tucson uses internal CCTV inspections to help determine if either the utility side or private side of service lines contain any lead segments.

2.4 Scratch and Magnet Test

The scratch and magnet test is a simple and effective way to determine pipe material. As the name implies, the test combines two elements to verify if an exposed pipe segment has lead. The order that the elements of the test are performed is unimportant. The “scratch” portion of the test entails using a key, coin, or other sharp metal objects to scratch the outer surface of the pipe. If the pipe scratches easily and the scratches appear silver in color and shiny in luster, the pipe material may be lead. If the scratches appear orange in color, the line is probably made of copper.

The magnet portion of the test involves checking to see if a simple kitchen magnet sticks to the pipe. If the magnet sticks to the pipe, the service line is made of galvanized steel or iron. If the magnet does not attach, the pipe could be lead or copper, in which case the scratch test should be able to discriminate between the materials.

There are a number of resources available to help customers perform a scratch and magnet test on the portion of their service line that enters their dwelling or building. National Public Radio (NPR) has an informative, interactive webpage (NPR 2019) that guides the customer through all the steps, from finding the water meter, scratching the pipe, and testing to see if the pipe is magnetic (Bichell and Pupovac 2016).

One challenge to the scratch and magnet test is that independent access may need to be made to both the public side and private side of a service line if the water utility does not have adequate records to confirm if the gooseneck and/or utility-portion of the service line is lead. In some cases, it may be possible to access both the public (utility) side and the private side of the service line at the curb stop valve box. However, in most cases, the valve box is not large enough to permit effective inspection and testing of the service line materials at this location.

2.5 Disclosures

Disclosures refer to requirements in real estate transactions wherein the seller is legally required to disclose to prospective home buyers information about "defects" that may have an impact on the value of a property. When a prospective home buyer is looking to purchase a property, they "expect to be informed about deficiencies, defects, or environmental hazards on the property" (McCormick et al. 2017). In 1996, it became a Federal Law to require that property owners disclose the presence of lead-based paint to a prospective home-buyer for residences that were built before 1978 (Lu et al. 2019). However, this Federal disclosure requirement does not extend to LSLs or potential lead solder or plumbing fixtures that may be found in homes.

The majority of real estate disclosure requirements are established at the state level, so there is significant variability in the number and type of "defective" issues that must be disclosed to potential homebuyers in each state. In 2017, the Environmental Defense Fund (EDF) graded each state on their required disclosures to home buyers regarding lead piping or plumbing fixtures. The results of their study found that only four states (CT, DE, NY, PA) required mandatory disclosure of lead pipes or fixtures (McCormick et al. 2017). These disclosures specifically asked if lead-bearing materials are known to be present in the plumbing system. For example, Pennsylvania asks "Type of Plumbing," and the seller checks either copper, galvanized, lead, PVC, unknown, or other (PA 2010). Meanwhile, seven states (DC, IL, MI, NM, NC, SC, WI) require mandatory disclosure of pipe material, but lead is not listed as an option. For example, North Carolina's *Residential Property and Owners' Association Disclosure Statement* asks, "The dwelling's water pipes are made of what type of material?" and the seller can check copper, galvanized, plastic, polybutylene, or other (NC 2020). Another example is California, where a seller can check yes, and specify plumbing when asked if the seller is "aware…of any of the following substances, materials, or products that may be an environmental hazards such as, but not limited to, asbestos, formaldehyde, radon gas, lead-based paint, fuel or chemical storage tanks, and contaminated soil or water on the subject property?" (State of California 2005).

By requiring a more transparent, upfront disclosure policy, homeowners would be more aware of the potential risks of lead exposure associated with a property (SimpleWater 2019), and EDF predicts that over time, market pressures would result in the increased replacement of LSLs and lead in household plumbing systems. “An informed buyer can decide how to value the property and take appropriate precautions. If the property has an LSL, the buyer can decide to add the cost of replacement to the mortgage, deduct the estimated cost from the sale price, demand replacement prior to purchase, or plan to replace it later” (McCormick et al. 2017). It is important to note that none of the questions on the disclosure address the presence of LSLs specifically, but rather lead pipes or plumbing in general. Another EDF study, performed in conjunction with researchers at Cornell University, found that potential homebuyers with access to a seller’s disclosure indicating presence of an LSL on the property perceived a higher risk and a greater willingness to negotiate with the seller to replace or compensate for LSL replacement prior to closure of the sale (Lu et al. 2019). It would appear that strengthening requirements for identifying and disclosing the presence of lead plumbing materials to prospective homebuyers would incentivize a higher rate of LSL and lead plumbing replacement than is the case presently.

CHAPTER 3

Locating Lead Service Lines Using Indirect Methods

3.1 Introduction

In the absence of easy, cost-effective methods to directly identify buried LSLs, the only option for 100% accurate determination of LSL presence is through ground excavation followed by physical inspection. However, with an estimated 6 to 10 million LSLs still in use in the US, the financial burden and practicality of such a proposition are not viable. Given this, reliance on indirect methods, which serve to provide a preponderance of evidence for the presence of LSLs, will likely be necessary for many utilities. Deb et al. (1995) discussed a pragmatic approach that culminated in a flow diagram to help utilities navigate the process of identifying LSLs. The key components of this framework were inputs from a multitude of data sources (e.g., installation, maintenance and billing records like tap records, year of installation, addresses, block or other subdivision info) and programs (e.g., street and/or meter replacement) to develop a database of records.

At the time of the 1995 study, major limitations included the lack of data conversion from physical to digital databases, as well as database functionality itself. In the quarter-century that has elapsed, the exponential increase in computer processing power, broad adoption of the internet, enhanced digitization, improved analytical algorithms, and incorporating the use of machine learning are all advancements that can be leveraged to improve the reliability of the indirect approach. An important component that is as relevant now as it was 25 years ago is data accuracy. Deb et al. (1995) stressed the need for quality assurance of databases to ensure accuracy of the gathered information before using data for various analyses (e.g., graphical trends to generate chronology of LSL installations, statistical probabilities of LSL occurrence, etc.). Wherever indirect methods can be augmented with direct evidence (i.e., from excavation and physical inspection to provide verification), the predictive confidence may be improved further. Additionally, utilities need to remember that historic insights from senior legacy staff can complement any or all of their indirect methods. It is possible that these individuals recall significant decisions or events around the use or discontinuation of LSLs that were not captured in any paper or electronic records, which can have a significant bearing on how expeditiously inventories are developed.

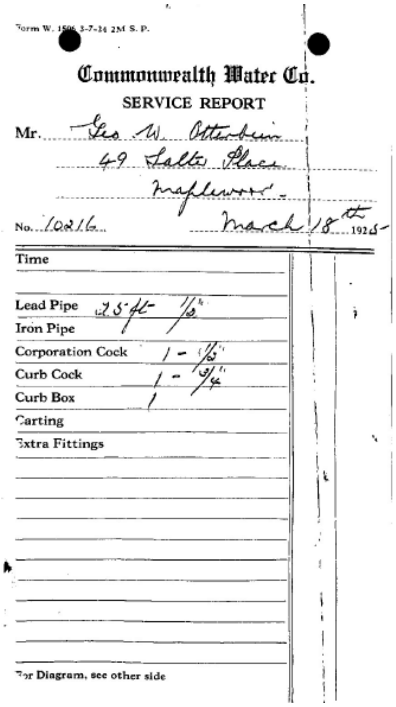
Any LSL replacement program developed using an individual or a combination of databases of indirect methods should be corroborated with a direct method (i.e., visual inspection) for a representative portion of the inventory before implementing any service line replacement programs. The following sections provide a recap of techniques and strategies that may be useful for utilities to develop their databases for indirectly deducing where LSLs may remain in service.

3.2 Historical Information to Create an Online Inventory

Utilities may have access to a number of historical records that may be helpful towards assessing the probability that a customer is served by an LSL. The Lead Service Line Replacement Collaborative (LSLRC), which is a joint effort of 27 national public health, water utility, environmental, labor, consumer, housing, state and local governmental organizations, identifies the following:

- Tap cards from initial service installation indicating the date, location and possibly pipe material installed.
- Plans from water main installation, rehabilitation, and replacement illustrating service line locations

and pipe materials;
- Historic water utility records, plumbing codes, and ordinances specifying materials and construction standards for service lines;
- Tax records indicating when a building was constructed, since LSLs were completely banned in new constructions as of June 1986 in the United States
- Plumbing permits indicating when existing structures were renovated and service lines were replaced; and
- Visual confirmation of pipe material by plumbers or utility crews during routine maintenance and renewal activities, like a meter or valve replacement and leak repairs.



Form W. 1506 3-7-24 2M S. P.

Commonwealth Water Co.

SERVICE REPORT

Mr. Geo. W. Otterbein
49 Salter Place
Maplewood

No. 10216 March 18th 1925

Time

Lead Pipe 25 ft 1/2"
Iron Pipe / /
Corporation Cock 1 - 1/2"
Curb Cock 1 - 3/4"
Curb Box 1
Carting
Extra Fittings

For Diagram, see other side

Figure 3-1. Historical Tap Card Showing Location-Specific Information.
Source: American Water 2019.

LSLRC recommends the first step in building an online inventory of LSLs is to digitally catalog historical information such as tap cards, service or repair tickets, construction records, or plumbing permits. A tap card was often a handwritten index card (Figure 3-1) that recorded information about a service line that 'taps' into the water main and connects the main to a house's internal plumbing system. This information may include the address, date of installation, pipe size, and/or pipe material. Using tap cards alone can be challenging since information can be inconsistent, unreliable or altogether absent. For example, there may be situations where a line was repaired or replaced, but the location-specific tap card was never updated. Without knowledge of the reliability or accuracy of a tap card as a data source, there may be a possibility of overestimating the presence of LSLs (Goovaerts 2017). Other complications also exist with relying on information from tap cards. Early versions of the tap card may have captured very limited information (i.e., address, pipe size) and may not have specified the service line material. Utilities may have also changed ownership over the years, and if tap cards were not digitized, they may have been misplaced.

Another source of information could be long-tenured staff, who may know the locations of LSLs because of their years of experience working within a water utility's system. Such individuals can help level set the expectations and expedite the inventory process.

Many cities, such as Washington D.C., Cincinnati, and Seattle, have created online Geographic Information System (GIS) maps with presumed locations of LSLs using historical information. This information is geocoded onto an online GIS map to make the utility staff and their customers aware of locations where LSLs may exist.

A study completed by the EDF found that the most useful online database to communicate information about LSLs to the public had four elements. First, they found that users wished to access information regarding their specific properties. This helps users identify whether any actions are necessary. This also helps potential homebuyers review specific areas that may have LSLs before making their purchasing decisions. Second, users wish to see information about both sides (i.e., public and private) of the line. Third, users are interested in understanding what is unknown. That is, users wish for transparency and frequent updates to the database as new information becomes available. Fourthly, users want judicious use of the colors for the legend and icons to clearly distinguish colors and shapes and what they denote (Hiltner et al. 2019).

3.3 Geostatistics and Machine Learning

Geostatistics refers to spatial data that can be analyzed to predict physical features or conditions in a specific geographic location. A geospatial approach to predict the likelihood that a residence has an LSL or galvanized service line (GSL) based on neighboring field data (i.e., house inspection) and secondary information (i.e., construction year and city records) was described by Goovaerts (2017). This geostatistical method was tested in Flint, Michigan where over-identification of LSLs was noted previously when using tap cards and construction drawings only. Ten zones were created, where zones represented various factors such as the concentration of lead and galvanized lines, the population density of children and the elderly, and the water lead levels determined by testing water from the tap (Goovaerts 2017). The ability to consider both the geographical location and spatial distribution of data allowed for improved prediction of LSL presence at unknown sites. Additionally, reliability of the geostatistical prediction, a process known as kriging, was feasible based on weight adjustments for clustered data that contained data redundancy.

A group from Google and the University of Michigan created machine-learning software to assist with an LSL replacement strategy for Flint, Michigan (Abernethy et al. 2018). Various inputs (i.e., property data such as location, age, value, water testing results, historical records, and service line physical inspection data) were examined statistically, in conjunction with active machine learning, to navigate the challenges of dealing with inconsistent, incomplete or inaccurate data, and to develop a holistic data-driven approach for determining the presence/absence of LSLs. To facilitate uniform collection of historic data, a python-based application was developed for capturing property-specific information (i.e., excavated pipe material, length, dates information on residents, etc.). A statistical model relying on Bayesian data analyses assigned probabilities on whether a service line was hazardous, and was combined with an unbiased and calibrated algorithm for the active learning framework. The authors found tree-based methods to be most successful and opted for gradient boosted trees in the XGBoost package. Based on historical data, the overall accuracy of the XGBoost model was determined as 91.6% with a 3% false-positive rate.

The investigators determined that for this specific system, where the majority of the properties were built between 1920 and 1960, and where most property values were below $100,000, the most significant predictive factors for the presence of a LSL were, in order of decreasing importance: age, property value, property location, utility records, and private service line inspection reports. The latter was based on plumbers inspecting the customer side of the service line where it was readily accessible in their basements.

To avoid bias in the selection criteria used for identifying properties for LSL verification, an Inspection Decision Rule was developed, which helped randomize the selection of residences for inspection using active learning. A Lead Service Line Replacement Decision tool was also developed to help prioritize a service line replacement strategy for the study area, which was based on high-risk populations (i.e., pregnant women, young children, or the elderly) and a high likelihood of success in finding lead pipe. Using the dataset for 200 homes with elevated water lead levels, it was determined that only 40% of the residences would have been selected for service line replacement according to conventional methods that rely on historic data. By comparison, the machine learning method allowed for the selection of 96% of the homes. While these investigators were examining a unique situation where political, financial and logistical factors needed to be considered in developing priority lists (i.e., replacement decision tool), the water industry, in general, may still garner useful insights from the statistical, machine learning, and inspection strategies described in this study.

3.4 Water Sampling

Water sampling may be a useful tool for some utilities as an indirect method for identifying locations where lead is present somewhere in a premise plumbing system. Lead and Copper Rule regulations stipulate that compliance samples should collect the first draw (1L) after an extended period of stagnation (min. 6 hrs.). One significant challenge with this approach is that a positive detection of lead in a customer sample does not reveal whether the lead originates from an LSL or from lead solder or leaded-brass fixtures elsewhere in the premise plumbing system. Another challenge is that the absence of lead in water samples does not necessarily mean an LSL is not present if utility corrosion control practices are highly effective. Given these challenges, water sample data collected for LCR compliance are primarily useful for survey purposes to identify the effectiveness of corrosion control strategies, possible lead hotspots and direct further location-specific investigations. Additionally, modified methods of tap sample collection that systematically conduct profile sampling (see case study in section 4.8 as an example), maximize stagnation periods and collect the 4th liter after a hard tap flush (3L) could potentially provide a more representative sample of water held within the LSL.

The LCR and its revisions focus on community water systems and non-transient-non community water systems for monitoring lead and copper at the customers' tap. Due to the complexities of the regulations and the analytical methods, which require advanced methods and technical skills, it is impractical to monitor every single customer using the framework outlined in the LCR. Therefore, sampling has been designed to gather representative information, with the number of grab samples and their sampling frequency being dependent on system size. Sites selection and sample collection methodology are designed to increase the probability that customers with lead services or lead solder within plumbing systems will be sampled, and that samples represent a “worst-case” for producing lead or copper corrosion products that can be detected. Large systems (population >50,000-100,000) may require sampling at 60-100 sampling sites for lead and copper analyses. Simultaneously analyses for various water quality parameters (pH, alkalinity, calcium, conductivity, corrosion inhibitor [orthophosphate or silica as appropriate] and temperature) occurs at a prescribed frequency, which also varies by the system size and historic results. The sampling burden is tiered down for medium (>3,300-50,000 population) and small systems (<3,300 population).

Information from LCR based compliance monitoring efforts can contribute a large data set on tap water lead levels, and the relationship between these metals and specific water quality parameters. LCR sampling data can, therefore, serve as an important first step to identifying potential problem areas for systems, and potential for developing insights into LSL replacement strategies. It is possible to gather additional information on customer lead levels by increasing the monitoring frequency or increasing the number of sampling sites, but doing so may become cost-prohibitive if the additional analyses are being conducted using EPA approved methods in accredited laboratories. This has created potential opportunities for innovative technologies to provide rapid and cost-effective field or laboratory lead measurements. However, to be useful, new lead detection methods would have to be reliable, repeatable, and effectively as accurate as EPA Method 200.8 Rev 5.4 (EPA 1994), which relies on inductively coupled argon plasma-mass spectrometry (ICP-MS) and has a method reporting limit of 1 µg per L.

For example, the city of Montreal launched a program in 2006 to replace its LSLs by 2026. With the absence of historic data and without an active corrosion control strategy, a plan was implemented to measure lead concentrations at the tap using portable Anodic Stripping Voltammetry (ASV). ASV is an electrolytic method utilizing a mercury electrode, which concentrates the metals in solution in the mercury amalgam under reducing conditions (Song et al. 2018), followed by an increase in electrical potential yielding metallic oxidation for determining the metal concentration (Baron-Jaimez et al. 2013). This process only requires a small sample volume (5 mL) and has a reported method sensitivity range of 2-100 µg per L. In addition, the field procedure can usually be completed in approximately 20 min (Goldcamp et al. 2008). A comparison of ASV with the standard ICP-MS method was conducted and revealed an excellent (R^2=0.991) correlation (Cartier et al. 2012) for dissolved or soluble lead. However, an important limitation of detecting particulate or colloidal lead existed with this method (requiring acid digestion). The advantages of the ASV method include its speed and its preconcentration step at the electrodes, which can help enhance method sensitivity for measuring low levels of the targeted metals. However, besides difficulties measuring particulate lead, it was also reported that test performance may be impacted by factors such as water temperature, household plumbing configuration, and length and diameter of the service line (Cartier et al. 2012).

Another rapid test kit for lead measurements in water is manufactured by ANDalyze (ANDalyze 2019). This kit is based on an analyte-specific, fluorochrome-conjugated, deoxyribonucleic acid (DNA) molecules that can be cleaved in the presence of a specific analyte (i.e., lead) to generate a fluorescence signal that is directly proportional to the analyte concentration. This test has sufficient sensitivity (i.e., 2-100 µg per L of lead) and speed (completed within minutes) to have value as a preliminary screening tool. However, impacts of particulate versus dissolved metals (such as chromium, iron, zinc, manganese, etc.) and corrosion control inhibitors on its performance will need to be defined, as will its performance relative to standard methods. Despite these potential challenges, the ANDalyze test kit is being used by both Cincinnati, OH and Pittsburgh, PA, where significant analyses appear to have been performed (H_20 Connection 2018).

The purpose of LCR-based monitoring is to ensure that corrosion control measures being employed in systems with LSLs are effective for maintaining water lead levels below the action level of 15 µg/L. The sampling design for the LCR focuses on representative locations within the distribution system, so it does not provide data for all individual properties. The ICP-MS method used in the LCR is sufficiently sensitive to measure low lead levels in tap water, hence it provides useful information on either the presence of LSLs or lead solder in premise plumbing systems. However, the method is cumbersome, expensive and does not lend itself to field applications. Samples need to be collected, shipped overnight to laboratories with advanced analytical capabilities (i.e., ICP-MS equipment) where skilled staff may take several days to generate results. User-friendly methods that are specific for lead, sensitive, and portable to allow onsite lead measurements within minutes can be beneficial for rapid assessment of lead in customers' tap water. Additionally, to be effective for the purposes of ascertaining whether a building is supplied by an LSL, the accuracy of such methods needs to be established. Ideally, a high correlation needs to exist between the rapid method, at various lead concentrations (i.e., very low, low, medium and high lead levels in water) and the standard ICP-MS methods defined in EPA Method 200.8 Rev 5.4 (EPA 1994). In the future water quality information gathered using these rapid test methods can then be coupled with the various indirect methods discussed earlier and analyzed statistically through machine learning tools to bolster decisions on the likely presence of LSLs at specific locations. However, it is important to note that only direct methods can be deemed a ‘gold standard.’ In contrast, indirect methods can be prone to analytical limitations such as their inability to effectively measure particulate or colloidal materials. This can impact sensitivity and/or specificity for lead measurements, which can lead to high method detection thresholds and false negative data. Given this, utilities need to carefully weigh the pros and cons of each method, understand limitations of their preferred method and account for this during their data interpretation phase when selecting LSL monitoring technologies.

CHAPTER 4

Case Studies: LSL Replacement Strategies

4.1 Case Study Identification and Selection

Utility industry experience has underscored how difficult it is to locate LSLs and safely manage drinking water quality through those service lines. In 2017, the LSLRC launched an online tool kit designed to help communities across the US accelerate the removal of LSLs. The LSLRC website is also a clearinghouse for news articles and will include case studies from utilities that are pursuing the identification and replacement of LSLs. According to the LSLRC:

> “The number of LSLs and their geographic distribution within the community affects the scale of the task, budget implications, and the impacted population. The initiative must include plans intended to meet the needs of low-income and minority communities, target replacement efforts and coordinate with other infrastructure projects. The availability of information about the number of LSLs may differ considerably among utilities, particularly for older systems or where systems were acquired and complete records were not transferred.” (LSLRC 2019).

The EDF, a steering committee member of the LSLRC, has been tracking and actively helping to highlight utility success stories. The reader is directed to the EDF.org website for the most up to date case studies. Seven case studies with varying approaches are discussed in this report, including Madison, Wisconsin; Green Bay, Wisconsin; Lansing, Michigan; Tucson, Arizona; Denver, Colorado; Indiana American Water (Northwest); and DC Water. These case studies provide an overview of each utility’s or jurisdiction’s approach to their LSL replacement programs. Many other cities and utilities nationwide are also currently working towards removing all LSLs from active use.

4.2 Madison, Wisconsin (Scratch Test and Historic Data)

In 2000, Madison, Wisconsin became one of the first cities to launch a mandatory full LSL replacement program in the US (Schmidt 2016). The City used historical records of materials used on the public side of the service line and customer surveys to identify LSL locations. Records indicated that the City stopped installing lead service lines in the late 1920s. To determine what material existed on the customer side of the service line, the city distributed thousands of customer surveys, which asked customers to perform a scratch test on the segment of the service line that was exposed within the dwelling. Community meetings also complemented these efforts to help educate customers on how to perform scratch tests.

In 2001, the City passed Madison General Ordinance 13.18, which required homeowners to replace their portion of the service line if the material was lead. Over the next 12 years, the City replaced approximately 8,000 LSLs on the utility side and customers replaced about 5,600 LSLs. Schools and locations where water sampling exceeded the recommended amount of lead were prioritized for service line replacement. The City’s program cost about $15.5 million, which included a customer rebate program. To help offset the cost to affected customers, half of the costs for LSL replacement on the private side (up to $1,000) were reimbursable. The ordinance specified that customers who failed to comply could be fined $50 - $1,000 per day. According to the City’s website, only a small percentage of customers refused to comply with the ordinance and were referred to the City attorney’s office. Additionally, coordinating the public/private replacement efforts helped expedite the process and lower the replacement costs. The average cost on the public side was <$2,000 and on the private side was <$1,400.

While the utility considers their LSL replacement program to be complete, unknown legacy LSLs are found occasionally. However, LCR monitoring indicates 90th percentile lead levels have shown substantial improvements, declining from 16 µg per L at the start of the program to 3 µg per L after program completion.

The utility's website (City of Madison 2019) offers a helpful description of key aspects of its LSL replacement program to help other utilities learn from their experience.

4.3 Green Bay, Wisconsin (Historic Data Online Inventory and CCTV Inspection)

The Green Bay Water Utility provides water service to approximately 105,000 residents of the City of Green Bay and wholesales water to four neighboring communities. The utility is the 3rd largest supplier of drinking water in the state, using Lake Michigan as its source of supply and treating up to 42 MGD.

The utility started building its inventory by putting original service card records into a GIS system. The GIS records included service line attributes (date installed and material) and scanned images of the tap cards. Through queries on this data, the utility created its Utility Side Replacement candidate list, which identified services installed before 1945 and identified as lead. The utility then used its asset management system (Cityworks) to create work order templates to track costs on vacuum excavation and lead replacement costs. Staff then updated the records in GIS as service lines were replaced.

The LSLR program is tracked by running reports monthly and annually from the GIS system records. Progress is tracked using graphs, charts, and maps. The utility provides maps on their website indicating where lead lines exist on the utility side and where replacement work is being performed/planned. Information is shared with the local health department. The utility uses dashboards to track where LSLs remain. Green Bay Water has found that GIS and asset management systems have been effective in tracking and reporting the status of their replacement program. By using these tools, the information is more widely accessible to all users.

The utility construction crews utilize different tools to verify and locate LSLs in the field. First, they purchased two trailer-mounted Vacuum Excavators. This type of excavation allows them to pothole over the owner's service line at the property line or just beyond it. This can be done safely without having to set up a full excavation that would require four people, dump trucks, and backhoes, permit fees, and notifying Diggers Hotline. Typically they use two people per vacuum Excavator and can determine the owner's material on 6-8 services in an 8 hour day.

The utility also purchased an insertion camera (manufactured by Sub Surface) in 2018. They first used the camera to locate a blockage, and then found it could also be adapted for use in their Lead Service Replacement program. The camera approach can be especially beneficial when the water service follows the driveway or the sidewalk to the front of the home as cutting holes in concrete and sidewalk to vacuum excavate is time-consuming and messy. Typically inspection requires that the crew insert a high resolution camera equipped with a flexible fiber optic scope and a light source from the house to the water main. Alternatively, at the time of excavation, the camera may also be inserted from the utility end in the excavation to the house to visually inspect the type of service material.

4.4 Lansing, Michigan (Historic Data Online Inventory)

The Lansing Board of Water & Light (BWL) is a municipally owned utility that owns the entire service line from the water main to the meter. BWL began inventorying service line materials in the 1980s, so a relatively complete and organized set of service cards dating back to before the 1930s allowed the utility an accurate material inventory. If a record was marked as "*Unknown"* for the material of the pipe, it was assumed to be lead until it could be verified.

BWL's initial inventory identified 17,000 LSLs and unknowns (as of the early 1990s), and the replacement was originally planned to proceed on an as-needed basis. However, in 2004 BWL commissioners decided that 'in the best interests of its customers, these lead water service components should be voluntarily replaced in a timely fashion' and proceeded to implement an accelerated 10-year LSL replacement program. At the beginning of the program, BWL asked customers to self-identify their lines for verification of the service card files. Additionally, whenever the BWL completed any work on the service line, the type of material was noted to either clarify or verify the material.

The program successfully replaced approximately 12,150 LSLs by the winter of 2016 at a cost of $44.5 million. Factors used to prioritize replacement included lead lines that had been disturbed (excavation, leaks, etc.), lines supplying sensitive populations (i.e., schools, daycare), individual services in excess of the action level exceedances, and service lines in areas where multiple LSLs were located. Following replacement, customers were provided flushing instructions and, where requested, filters were made available with recommended use for up to 3 months.

Because the BWL owned the entire service line up to the meter, the customer did not pay for the replacement. To minimize costs, excavation and pipe replacements were scheduled along with Combined Sewer Overflow (CSO) Separation projects (Hamelink 2018) that the City of Lansing was undertaking.

LCR monitoring results have shown substantial improvements, with the 90th percentile lead level declining from 7.8 µg per L in 2014 to 1.1 µg per L in 2017 after completion of the program.

4.5 Tucson, Arizona (Historic Data Inventory and CCTV Inspection)

Tucson, Arizona is currently undergoing a replacement program entitled "Get the Lead Out." The city mandated LSLs be used from 1913 to 1929 (based on council minutes) and estimates that LSLs were used until 1949. As of 2016, the city had identified approximately 1,270 possible LSLs. The program's first step was to collect tap cards and other historical information from old construction drawings and vintage 1950s maps. The data were digitized, and an online interactive GIS map was created to keep the public informed about the findings of the study and the progress of the LSL replacements. Following the initial historical data collection, officials determined where to start inspecting service lines by prioritizing buildings where lead exposure would impact sensitive populations (i.e., schools, childcare facilities, hospitals, etc.).

Meter box inspections were performed and if anything other than lead was discovered, a CCTV camera inspection was used to confirm if partial LSLs were present. This was done by locating and turning off the shut off valve, disconnecting the meter and then inserting a camera into the pipe to ascertain that the service line material was the same throughout and confirm that the section of the non-leaded service line was not spliced onto the end of a lead service line. Tucson Water's website includes their procedural flow chart (City of Tucson 2019). After completing this work, the utility identified approximately 530 locations where LSLs may still be present. Once Tucson Water verifies that there is an

LSL on the private side, they offer to replace the line on the private side at the customer's expense while reimbursing them up to a maximum of $4,341 (Tucson Water 2018).

4.6 Denver, Colorado (Historic Data Online Inventory)

Denver Water is responsible for drinking water services to approximately 1.4 million people in the metro Denver area. This utility is adopting innovative approaches to deal with the complexities of managing lead in drinking water. Rather than opting for a corrosion control strategy using orthophosphate, Denver Water opted for LSL replacement because the utility considers this an opportunity for developing a holistic management strategy that is environmentally sustainable. Although corrosion control strategies are often effective for managing water lead levels such practices can contribute additional phosphorous loading to rivers and lakes, which in turn can act as a nutrient to promote the growth of harmful algal blooms or other negative environmental impacts.

By ramping up their LSL replacement rate to an annual average of 7%, Denver Water expects to provide a "multi-generational benefit of significantly reduced lead exposure." To facilitate this, Denver Water undertook an extensive effort to build an accurate inventory of LSL locations throughout its system. However, like many other utilities in the US, Denver Water also realized the challenges of developing an accurate inventory. Their plan has been to use both direct (visual inspection in homes, water quality testing, and potholing to observe pipes) and indirect (historical records, construction dates, and customer feedback) methods to develop interactive online maps for increased public engagement and communications. Despite such efforts, uncertainty on LSL presence will remain in some cases. Therefore, Denver Water plans to categorize residences into the following groupings: known LSL, suspected LSL, possible LSL, unlikely LSL, and non-lead. Using these designations, Denver Water anticipates an LSL replacement rate of approximately 4,500 LSLs per year. A priority matrix will be used that considers various risk-based factors, such as health considerations for children, critical customers, areas with low socioeconomic status, or where the adoption of utility-supplied lead filters is low.

4.7 Indiana American Water- Northwest (Historic Data Online Inventory)

Indiana American Water provides water and wastewater services to approximately 1.3 million people in more than two dozen service areas throughout the state of Indiana. Although lead monitoring results under the LCR have routinely remained below the 90th percentile action level, the company has committed to replacing all LSLs within its service territories across the state in an effort to reduce the risk of lead exposure to its customers. One area with a concentration of LSLs in the region in and around the City of Gary, IN. Historic tap card records, in conjunction with home construction date records, were used to develop an inventory, which was then used to create a GIS map of possible LSL locations. This was followed by potholing techniques to expose the service line on both the public and private side of the curb stop shut-off valve to verify the service line materials (Figure 4-1). The GIS map was then updated to reflect the confirmed materials. The company then proceeded to develop a plan for LSL replacement that seeks to optimize construction crews to minimize construction costs. One part of that optimization effort is to replace the LSLs in conjunction with other water main replacement or infrastructure improvement projects whenever possible.

Figure 4-1. Application of the Potholing Technique for LSL Exposure at the Curb Stop.
Source: American Water 2019.

4.8 DC Water (Water Quality)

DC Water purchases treated water from the Washington Aqueduct, which has chloramine disinfectant and orthophosphate (2.4 mg per L) for corrosion control. Their service line material inventory has approximately 9% (10,771 of 126,205) of their service lines as lead on the public side and an additional 9% (11,241) with lead on the private side only (past-partial LSLR). The past LCR 90th percentiles declined from 15 ppb in 2005 to 2 ppb in 2019. historic lead samples collected at homes showing 90% lead levels below 5 µg per L. To assess the usefulness of water quality monitoring as a predictor of LSL presence, customers were asked to collect 10 x 1L consecutive samples for lead testing and also asked to examine and describe their service line at the point of entry as copper, lead, galvanized iron or not visible. Where possible customers also provided a picture of the pipe.

The lead concentrations from the ten consecutive samples gives a profile of lead from the tap through the service line. This profile trend can indicate if lead pipe is present in the service line. Based on their data analyses of 172 homes with unknown service lines at the time of sampling, they predicted half the homes to have lead pipe present. Further analyses of 30 homes that later had service line work revealed that 26 of 26 were correctly identified to have lead and 2 of 4 were correctly identified as non-lead. DC Water also determined that a total lead mass from 10 liters of 5 µg per L or greater indicated that lead pipe was likely in their water system during this study period. Recall, the lead levels declined over the past 15 years following the implementation of orthophosphate corrosion control treatment. This total mass threshold of 5 µg would have been higher in earlier years after the treatment change compared to 15 years. They also concluded that the water sample analyses cannot confirm the absence of lead pipe due to stagnation challenges (e.g., unknown dripping faucets, leaks, or water use).

These data demonstrate that monitoring lead levels can be a useful adjunct to estimating the presence of lead service lines; however, various factors may influence their levels and physical inspection of the service line will remain necessary. Verification will be especially necessary for their water system where lead levels measured in water are <4 µg per L.

CHAPTER 5

Prospective Methods for Lead Service Line Detection

A primary objective of this project was to identify and evaluate technologies that could specifically detect LSLs without significant excavation. In Chapter 2 existing direct methods for LSL detection were discussed, but all of the existing procedures require direct access to the service line to yield meaningful information on the material characteristics. This chapter focuses on prospective methods or technology platforms that may facilitate LSL detection in the future, following varying degrees of refinements and field validation. For the purposes of this study, American Water reached out to more than 20 metal detectors and pipe locating companies globally, requesting general information related to their product, as well as highlights of their specific materials discrimination capabilities. For metal detectors, a tradeoff exists between the metal detection sensitivity and the locational depth of the metal. Depending on the frost line, service lines may be installed 30 inches or more below the surface (International Plumbing Code 2018). Metal detectors that can discriminate between metal types appear only to be able to identify materials down to a maximum of 12 to 15 inches depth. Technologies that non-invasively penetrate deep into the soil profile, and characterize the metals specifically, are needed to meet the challenge of locating and differentiating LSLs. The following sections provide an overview of various prospective methods or technology platforms that might have this potential if further development is successfully pursued.

5.1 Metal Detectors

All metal detectors use coils to transmit and receive electromagnetic signals. Metal detectors are based on electromagnetic induction technology using beat-frequency oscillation, very low frequency, pulse induction, or other related technologies (Tyson 2001).

Beat-frequency oscillation metal detectors are considered the most basic type and are no longer in popular use (Moreland 1999). Typically, they use two oscillators with identical frequencies. An alternating current passes through the transmitter coil to create an alternating magnetic field (Moreland 2006a). When the coil passes over an electrically conductive metal object, eddy currents are induced in the object, which creates a magnetic field around it (Figure 5-1). The receiver coil detects the interaction between the magnetic fields as a change in the magnetic field due to the presence of the object. The magnitude of this change is dependent on multiple factors, such as the depth, shape, orientation, and material type of the object (Moreland 2006b).

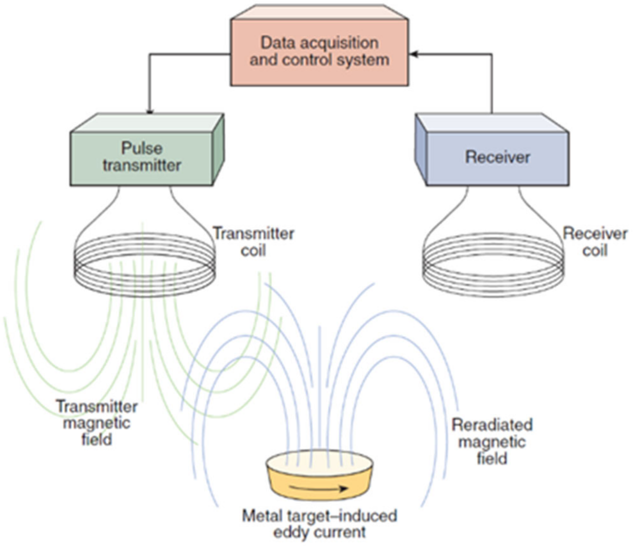


Figure 5-1. Working Principle of Metal Detector.
Source: Nelson 2004.

5.1.1 Very Low Frequency (VLF) Technology

Very low frequency (VLF), also called induction balance, is a common technology used to detect metals. A signal is transmitted from a transmitter coil and the reflected signals from the target (ferrous/non-ferrous metals) are received through a smaller, inner receiver coil (Tyson 2001). The received phase shift signals are delayed when compared to the transmitted signals due to differences in frequencies of the transmitter coil and the target object. The magnitude of the phase shift is dependent on the inductance or resistance of the target object. Highly inductive materials, such as metals, create large phase shifts while highly resistive materials create lower phase shifts.

The size of the coils impacts the effective depth range, with the technology being capable of locating and detecting metals buried below the frost line. However, the size of the buried object will also affect the size of the phase shift; larger objects will have a large phase shift (Tyson 2001). As different metal objects show signature phase-shift responses, it is expected that phase shifting has a potential for metal discrimination based on the inductance or resistivity characteristics of the metal (Rowan and Lahr 2019). However, no literature shows its ability to detect lead material or LSLs. It could potentially be used to identify ferrous pipes, which would theoretically rule out the existence of LSLs, but also copper and common non-ferrous service line materials. In addition, some iron service line piping may have been lead-lined, so utilities would need to have confidence that LSLs in their service territory were not of the lead-lined iron type.

5.1.2 Terahertz Technology

Terahertz technology, which uses a combination of spectroscopy and imaging technologies, has been a popular choice for military and security applications. Some examples of its application include military air survey, hand-held metal locators for landmines and unexploded ordinances (UXO), site investigation and monitoring of earth’s atmosphere, humidity and temperature. This technology has also been deployed to detect hidden subsurface objects (EARSC 2015, Federici et al. 2005), and has the capability to discriminate between ferrous, non-ferrous metal, and plastic materials. While this technology has not been used to discriminate lead, it has the potential to identify ferrous-bearing metals or plastic materials. If a system has a lot of galvanized service lines, it could be helpful to use a technology like this to verify that a service is not galvanized before more intrusive investigations are made.

5.1.3 Three-Dimensional Electromagnetic Induction

The three-dimensional electromagnetic induction (3D EMI) sensor system is a prototype technology developed at the Johns Hopkins University under U.S. Army defense funding to locate UXO. Apparently, this prototype has capabilities to measure multiple components of buried metal targets by exciting magnetic polarizability. The novel sensor, known as a three-dimensional steerable magnetic field (3DSMF) sensor system, consists of a broad bandwidth time-domain EMI system combined with a 3-axis magnetic field generator (3AMFG) and magnetic field receivers. The 3AMFG has the capability of generating a uniform magnetic field in space (Nelson et al. 2003, Black et al. 2004).

There is no information available that indicates if this technology is capable of detecting LSLs, but its multiple component detection capabilities may mean that it has that potential. However, research would be required to determine if the technology is suitable for LSL detection. In addition, a device would have to be made commercially available since the current technology is still in the prototype stage.

5.1.4 Pulse Induction

Pulse induction metal detectors use high-powered, momentary pulses of current sent from a search coil instead of using a low-powered transmitter and receiver. Approximately 100 pulses are transmitted per second. With each pulse, the ground is briefly magnetized and after the pulse ends, the magnetic field reverses polarity, which creates an electrical spike that lasts for a short duration (30 milliseconds) that can be detected by the coil. If no metal is present, the induced magnetic field is detected by the coil and will decay at a uniform rate. The time it takes for the induced field to completely decay is used as a control measurement. However, if a metal object (either ferrous or nonferrous) is present, an eddy current is induced in the metal object which leads to a reduced decay rate of the induced magnetic field. An advantage of pulse induction is that it works well in soils containing high levels of metal-bearing minerals. This technology is suitable for metal detection down to the frost line, but the discrimination capabilities are not as effective as that of VLF with phase-shifting (PCTE 2019, Minelab 2019, Rowan and Lahr 2019, EPA 2006). Lead or other types of metal pipe may provide a distinct signature spike, but this has yet to be researched and confirmed. Even if pulse induction is not found to be capable of detecting lead specifically, it might still be useful for ruling out other types of metals.

5.1.5 Multi-mode Electromagnetic Target Discriminators

Multi-mode electromagnetic target discriminators (METD) work similarly to pulse induction. In both technologies, pulses are transmitted into the ground to generate eddy currents from a metal object. However, METD uses a separate coil as the receiver (Nelson 2005). METD is differentiated from other electromagnetic discriminators in that it uses both the time and frequency domain to measure the inductance response. Research and development has appeared to have stalled since 2004 (Black et al. 2004), so like pulse induction, its ability to discriminate lead has yet to be realized.

5.1.6 Polyharmonic Metal Detectors

Polyharmonic metal detectors use polyharmonic excitation signals coupled with signal processing in the detector to improve detection and the discrimination of the targeted metal (Svatos 2016, Svatos et al. 2018). This technology appears to be at the research level at this time, so research would be needed to determine if it is capable of locating and identifying LSLs, and commercial product development would be required.

5.2 Magnetometers and Gradiometers

Magnetometers measure the intensity of local distortions or anomalies in Earth's magnetic field that are caused by the presence of subsurface objects. Magnetometers can locate things like buried steel drums, underground iron or steel pipes, or other subsurface ferrous bodies (Marchetti et al. 2013). Steel tanks or drums can be detected as deep as 20 ft and larger mass objects can be detected down to 40 ft. A major limitation of magnetometers is their inability to detect non-ferrous metals such as copper, lead, aluminum or brass, and thus cannot be used to detect LSLs. They are also susceptible to interference from other ferrous materials (powerlines, fences, towers, and steel structures) or soil with a high concentration of ferrous minerals. Despite these challenges, magnetometers can still serve as a means of ruling out ferrous materials such as steel or ductile iron when searching for buried lead pipes.

Gradiometers are a more advanced type of magnetometer. Their probes consist of two or more magnetometers placed in a series, at a fixed distance to each other, to measure the difference in magnetic flux between the magnetometers. This technology can more accurately locate buried ferrous objects or disseminated ore bodies but shares the same limitations as magnetometers. Thus, gradiometers would only serve as a means of identifying ferrous pipe materials and cannot be used for direct identification of LSLs. Also, as was mentioned earlier, some iron-based service lines may be lead-lined, so utilities would need to have confidence that lead-line iron service lines were not historically used within their service area.

5.3 Ground-Penetrating Radar

Ground-penetrating radar (GPR) is a nondestructive, geophysical method that images the subsurface by detecting interfaces between materials of different relative permittivity or dielectric constants, such as interfaces between different strata or soil horizons or between buried objects and the surrounding soils. GPR transmits high-frequency pulses of electromagnetic (EM) radiation into the ground, which are then reflected, refracted, or scattered back after encountering a structure or interface. From the travel time and the known dielectric constants of the media, the depth to the object can be determined.

GPR has limitations due to the electrical conductivity of the subsurface media, the frequency of the EM pulses used, and the effective radiated power of the pulses. In highly conductive media, such as moist clay soils, the signal is attenuated more readily, and the effective penetration of the GPR is reduced. Using higher frequencies can provide a higher resolution at the expense of reducing the depth of radar penetration (Daniels 1989, Casas et al. 2000).

Based on the above, GPR is currently only capable of locating and determining, to some degree, the size of buried objects (Jaw and Hashim 2014). However, if GPR can be used to definitively determine the diameter of a buried pipe, it may be a useful tool to help locate LSLs. For example, the Philadelphia Water Department (PWD) believes that all ½-inch-diameter service lines in their system are exclusively lead. In this case, if a nondestructive direct method like GPR can reliably determine pipe diameter, PWD would at least be able to identify ½-inch LSLs (Deb et al. 1995).

Multiple studies have been conducted to test GPR's ability for estimating the diameter of the buried pipe. Windsor et al. (2005) successfully and accurately estimated the diameter of a concrete pipe using GPR. Jazayeri et al. (2018) developed a model using full-waveform inversion that could make an estimate of pipe diameter that was within 8% of the true diameter. Liu et al. (2017) also used full-waveform inversion and noted similar success. A separate study conducted by Jaw and Hashim (2011) used a different method to estimate pipe diameter using GPR backscatter data and found strong consistency between their diameter estimates and in-situ measurements. It should be noted that even though pipe diameter in some cases can be used to identify LSLs, it is not a dependable factor to identify LSLs in systems where pipe diameters are not uniquely associated with pipe materials.

To date, GPR has not been advanced to detect lead pipes directly. Hashim et al. (2011) used GPR backscatter data to determine the material type of buried pipes. GPR backscatter is the radiation that is diffusely reflected back and scattered after encountering a buried object or interface. Different materials will have unique backscatter amplitude ranges, so the amplitude of the backscatter can vary as a function of the pipe material. The materials tested in this study were Polyvinyl chloride, medium/high-density polyethylene, and mild steel, and each was distinguishable from their backscatters. The lead was not tested, but presuming it would also give a unique range of backscatter amplitudes, this method may recognize buried lead pipes. Future testing appears warranted to determine GPR's capabilities for identifying LSLs from GPR backscatter signatures.

5.4 Stress Wave Propagation

A patent submission for a device that uses the propagation of stress waves as a means of identifying the material of buried pipes was made by Drexel University. Typically stress waves travel at different speeds through different materials, suggesting that specific velocity measurements could reveal the presence of lead pipe. The speed for a wave traveling through lead pipes is significantly lower than for that of pipes made of other common service line materials. The probes in Drexel's experimental device used accelerometers to detect the substrate waves. When the waves travel through the buried service line, some of the energy from the wave is lost to the substrate. This loss of energy travels as waves through the substrate and can be detected by probes. The velocity of the wave traveling through the service line is the distance between any two probes divided by the difference in time for the substrate waves to reach those probes. A data acquisition unit receives and processes the information to remove outlier data that could be due to other buried objects or anisotropy of the substrate (Sjoblom et al. 2018).

The proof of concept developed by Drexel University has been successfully tested in the lab, and limited field trials were conducted as part of this study. Conclusions from the field trial were that additional field trials and data collection will be needed to fine-tune the algorithms for LSL recognition. In addition, the amount of equipment and setup required to conduct tests with the current system configuration limits its practicality for extensive use by water utilities. Future developments that improve the signal processing algorithms and achieve greater portability may offer promise.

5.5 Acoustic

Echologics developed and markets a pipe condition assessment technique that calculates the minimum average wall thickness of a segment of the pipeline by measuring the time it takes for a noise signal to travel through the pipeline segment. The key requirements of the technology are that the diameter and material composition of the pipeline must be known. Knowing the minimum average wall thickness for multiple pipe segments throughout a distribution system can allow a water utility to project the remaining life expectancy of its buried assets so an effective infrastructure renewal and/or replacement program can be budgeted.

It has been suggested that the same principles used in Echologics acoustic wall thickness measurement technology could potentially be applied to identifying LSLs. A key question around this would be whether the dense, typically substantial wall thickness of LSLs produces a discernible sound wave signature that could be recognized by an audio sensor. The concept is similar to the stress wave propagation technology described previously but would rely on acoustical waves rather than stress waves. Echologics initially indicated an interest in advancing acoustic monitoring technology for LSL detection, but it is unknown if and when research experimentation may begin.

5.6 Electrical Conductivity Object Locators

Electrical conductivity object locators (ECOLs) distinguish buried objects from surrounding soils using electrical conductivity mapping. The technique detects electrical conductivity differences between buried objects and the surrounding soil. Sensors are used to measure the electrical potential and magnetic fields that are created when an electrical current is injected into the ground at different locations. A finite element method is then used to calculate the subsurface conductivity profiles so a map of the area can be created which reveals the location of buried objects (Chin et al. 1999). This method is non-invasive and can reportedly discriminate between elements with high electrical conductivity. In theory, this method may be capable of discriminating lead, since it has a low conductivity compared to copper and galvanized steel and a high electrical conductivity compared to plastic pipes. However, it appears that no research has been conducted to date to test its potential for detecting LSLs.

5.7 Field Portable X-ray Fluorescence Spectrometry

X-ray fluorescence (XRF) spectrometry is currently utilized to screen soil for contamination with heavy metals such as arsenic and lead. The technology relies on atomic excitation principals. When X-ray beams are projected into soil samples, individual atoms are excited and photon emissions occur that have a characteristic energy or wavelength. Enumerating photons of energy from a sample can lead to the identification of the existing elements. Since atoms of different materials excite at different energy levels, XRF may be calibrated to specific metals (EPA 2015). This method may be able to identify LSLs by sampling the soil surrounding the service line to test for the presence of lead. However, one potential challenge is that the method could experience interference in situations where lead lines have been abandoned adjacent to the service line that is targeted (Shefsky 1997). Additional limitations with XRF include sample preparation error, spectral interferences, and chemical matrix interferences (EPA 2015). XRF may be refined in the future to detect LSLs, but it does not currently appear to be a practical choice for use by water utilities.

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The detection of high levels of lead in drinking water in Flint, Michigan has caused many North American water utilities to take a renewed interest in locating and eliminating LSLs. It was recently estimated that over 6 million buried LSLs may remain in active service across the U.S., most of which were installed before 1940. Because of the limited accessibility of buried service lines, the age and condition of records, and complications of utility versus private property ownership, it can be very difficult for utilities to know which customers are currently served from LSLs. Unfortunately, technology advances over the past 20 years have been limited, so the task of locating LSLs remains difficult and inefficient.

Direct LSL identification methods entail finding a way to access a small portion of the exterior of the service line, either through a “pothole” excavation or where the service line enters a dwelling, valve box, or meter box. A challenge to these limited access direct methods is that the service line material may not be the same over the entire line length, so a limited external inspection could incorrectly conclude that lead is absent. An alternate direct method entails removing the meter so a camera can be inserted through the inside of the service line. This method allows direct observation of more or even all of the service lines, but scale build-up may still prohibit affirmative identification of the pipe material.

Indirect methods encompass a variety of techniques that attempt to quantify the probability that lead may exist within a service line. However, since indirect methods only assess probability, such methods do not guarantee that all LSLs have been located. The most commonly used indirect method is reviewing tap cards that the water utility may have retained since the service line was originally installed. However, reviewing tap cards can be a very labor-intensive process, and tap cards may be difficult to read due to their age, or they may not have been updated if a service line was repaired or replaced with an alternate material. Other indirect methods include water sampling to test for lead or reviewing housing records to identify homes that were constructed in a similar time frame as other homes/buildings that have been shown to have LSLs. However, both approaches still only help the utility judge the probability that a customer may be served from an LSL. A direct method must be used in conjunction with indirect methods to verify that lead is actually present.

Varying degrees of research has been undertaken on several other prospective technologies that try to positively identify if services lines contain lead without the need for excavation. Most of these non-invasive technologies attempt to utilize various forms of electromagnetic radiation or seismic waves to discern if the lead is present. Unfortunately, none of the prospective technologies that were identified in this report can reliably and cost-effectively confirm the presence or absence of LSLs at this time.

6.2 Recommendations

Identifying LSLs continues to be a significant challenge for many utilities. Because of the lack of significant promising research activities, it appears likely that drinking water utilities will have to rely on the limited number of direct and indirect LSL identification methods that are currently being used across the industry. Unfortunately, these methods can be inefficient and imperfect, so the following efforts are recommended to ensure that a utility’s LSL replacement program can proceed as effectively and efficiently as possible:

- Utilities should take the time to determine which techniques are most practical and effective for their unique circumstances.
- Utilities with good quality tap card records should invest the time and effort to digitize those records and add them to their GIS systems to help organize and manage their LSL replacement program.
- Utilities should encourage their customers to use the magnet and scratch test to report back to the utility if they suspect they have an LSL. The utility should then schedule a follow-up visit with those customers to verify that lead is present.
- Utilities should look for and share success stories in conference proceedings and journal articles so that they can identify new technologies or approaches that have been successful elsewhere.

References

Abernethy, J., A. Chojnacki, A. Farahi, E. Schwartz, and J. Webb. (2018). ActiveRemediation: The Search for Lead Pipes in Flint, Michigan. In KDD '18: The 24th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining, August 19–23, 2018, London, United Kingdom. https://doi.org/10.1145/3219819.3219896.

Ahmad, Z. (2018). “Flint Loses Focus on Finding Lead Water Service Pipes.” *Mlive.Com*. https://www.mlive.com/news/flint/2018/10/flint_loses_focus_in_finding_l.html.

American Water. (2019). *Commonwealth Water Co. Service Report*. American Water Works Company.

ANDalyze. (2019). “Products.” Accessed June 17, 2019. http://andalyze.com/products/.

Aquasana. (2019). “Health Effects of Lead in Drinking Water.” Aquasana LLC. Accessed Jan. 1, 2019. https://www.aquasana.com/info/education/health-effects-lead-in-drinking-water.

Baron-Jaimez, J., M. R. Joya, and J. Barba-Ortega. (2013). "Anodic Stripping Voltammetry - ASV for Determination of Heavy Metals." *Journal of Physics: Conference Series, 466*.

Bathla, S., and T. Jain. (2016). “Heavy Metals Toxicity.” *International Journal of Health Sciences and Research*, 6 (5): 361-368.

Bichell, R. E., and J. Pupovac. (2016). “Do You Have Lead Pipes in Your Home?” Accessed June 6, 2019. National Public Radio. https://apps.npr.org/find-lead-pipes-in-your-home.

Black, C. J., I. T. Mcmichael, and C. V. Nelson. (2004). "Multimode Electromagnetic Target Discriminator: Preliminary Data Results." *Detection and Remediation Technologies for Mines and Minelike Targets IX*. doi:10.1117/12.565912.

Boyd, G. R., N. K. Tarbet, G. Kirmeyer, B. M. Murphy, R. F. Serpente, and M. Zammit. (2001). "SELECTING Lead Pipe Rehabilitation and Replacement Technologies." *Journal - American Water Works Association,* 93 (7): 74-87. doi:10.1002/j.1551-8833.2001.tb09245.x.

Brown, R., N. McTigue, and D. Cornwell. (2015). *Controlling Lead in Drinking Water*. Project 4409. Water Research Foundation, Denver, CO.

Cantor, A. F. (2017). *Optimization of Phosphorus-Based Corrosion Control Chemicals Using a Comprehensive Perspective of Water Quality*. Project 4586. Water Research Foundation, Denver, CO.

Casas, A., V. Pinto, and L. Rivero. (2000). “Fundamental of Ground Penetrating Radar in Environmental Engineering Applications.” *Annali Di Geofisica*, 43 (6): 1091-1103.

Cartier, C., A. Bannier, M. Pirog, S. Nour, and M. Prévost. (2012). "A Rapid Method for Lead Service Line Detection." *Journal - American Water Works Association,* 104 (11): E596-E607. doi:10.5942/jawwa.2012.104.0143.

Chin, C., R. Srinivasan, and R. E. Ball. (1999). *Discrimination of Buried Plastic and Metal Objects in Subsurface Soil published at Information Processing for Remote Sensing.* World Scientific, NJ.

City of Madison. (2019). “Information for Utilities on Lead Service Replacement.” Accessed July 3, 2019. https://www.cityofmadison.com/water/water-quality/lead-service-replacement-program/information-for-utilities-on-lead-service.

City of Tucson. (2019). “Lead and Copper.” Accessed June 6, 2019. https://www.tucsonaz.gov/water/lead-and-copper.

Conway, B. (2017). "What Pittsburgh Homeowners Need to Know About Curb Box Inspections for Lead Service Lines.” Publicsource News for a Better Pittsburgh. https://www.publicsource.org/what-pittsburgh-homeowners-should-know-about-curb-box-inspections-for-lead-service-lines/.

Cornwell. D. A., R. A. Brown, and S. H. Via. (2016). “National Survey of Lead Service Line Occurrence.” *Journal – American Water Works Association*, 108 (4): E182-E191.

Daniels, J. J. (1989). “Fundamental of Ground Penetrating Radar.” *Proceedings of the Symposium in the Application of Geophysics to Engineering and Environmental Problems*, SAGEEP’89, Golden, 62-142.

Deb, A. K., Y. J. Hasit, and F. M. Grablutz. (1995). *Innovative Techniques for Locating Lead Service Lines*. Water Research Foundation.

EARSC (European Association of Remote Sensing Companies). (2015). “Opportunities and Challenges in Emerging Applications for Millimeter, Microwave & Terahertz Remote Sensing.“ EARSC. Accessed August 23, 2016. http://earsc.org/news/opportunities-and-challenges-in-emerging-applications-for-millimetre-microwave-terahertz-remote-sensing.

EPA (U.S. Environmental Protection Agency). (1989). *The Lead Ban: Preventing the Use of Lead in Public Water Systems and Plumbing Used for Drinking Water*. EPA.

EPA (U.S. Environmental Protection Agency). (1991). “Lead and Copper Rule.” 56 FR 262460-26564. EPA.

EPA (U.S. Environmental Protection Agency). (1994). *Method 200.8 Revision 5.4: Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma-Mass Spectrometry*. EPA.

EPA (U.S. Environmental Protection Agency). (2015). “Field X-ray Fluorescence Measurement.” EPA.. https://vdocuments.site/field-xrf-measurement-pdf.html.

EPA (U.S. Environmental Protection Agency). (2016). "Very Low-Frequency (VLF) Method." EPA. Accessed July 01, 2019. https://archive.epa.gov/esd/archive-geophysics/web/html/very_low-frequency_(VLF)_method.html.

Federici, J. F., B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, and D. Zimdars. (2005). “THz Imaging and Sensing for Security Applications – Explosives, Weapons, and Drugs.” *Semicond. Sci. Technol.*, 20 (2005): S266-S280

Goldkamp, M. J., M. N. Underwood, J. L. Cloud, S. Harshman, and K. Ashley. (2008). "An Environmentally Friendly, Cost-Effective Determination of Lead in Environmental Samples Using Anodic Stripping Voltammetry." *Journal of Chemical Education,* 85 (7): 976-979. doi:10.1021/ed085p976.

Goovaerts, P. (2017). "How Geostatistics Can Help You Find Lead and Galvanized Water Service Lines: The Case of Flint, MI." *Science of the Total Environment,* 599-600: 1552-1563. doi:10.1016/j.scitotenv.2017.05.094.

H20 Connection. (2018). "Lead Service Line Replacements Are Now Underway!" https://www.cincinnati-oh.gov/water/assets/File/Lead/H2OConnection_Summer2018.pdf.

Hamelink, S. (2018). "Lansing Lead Service Line Replacement Program." Accessed May 2020. http://gettheleadoutpgh.org/lead/wp-content/uploads/2018/05/Hamelink-presentation-PDF.pdf.

Harewood, J., and A. M. Azevedo. (2019). “Alpha Thalassemi (Hemoglobin H Disease).” Treasure Island, FL: StatPearls Publishing. https://www.ncbi.nlm.nih.gov/books/NBK441826/

Hashim, M., S. W. Jaw, and M. Marghany. (2011). Ground Penetrating Radar Data Processing for Retrieval of Utility Material Types and Radius Estimation. 2011 IEEE International RF & Microwave Conference. doi:10.1109/rfm.2011.6168727.

Hiltner, S., R. Romero-Canyas, L. McCormick, and T. Neltner. (2019). "Using Online Tools to Publicize Lead Service Line Locations and Promote Replacement." *AWWA Water Science,* 1 (1): 1-15. doi:10.1002/aws2.1124.

International Plumbing Code. (2018). “Chapter 3, Section 305.4.” In *International Plumbing Code.* International Code council. Accessed July 1, 2019. https://codes.iccsafe.org/content/IPC2018/chapter-3-general-regulations.

Jaw, S. W., and M. Hashim. (2011). Accuracy of Data Acquisition Approaches with Ground Penetrating Radar for Subsurface Utility Mapping. 2011 IEEE International RF & Microwave Conference. doi:10.1109/rfm.2011.6168691.

Jaw, S. W., and M. Hashim. (2014). "Urban Underground Pipelines Mapping Using Ground Penetrating Radar." *IOP Conference Series: Earth and Environmental Science,* 18: 012167. doi:10.1088/1755-1315/18/1/012167.

Jazayeri, S., A. Klotzsche, and S. Kruse. (2018). "Improving Estimates of Buried Pipe Diameter and Infilling Material from Ground-Penetrating Radar Profiles with Full-Waveform Inversion." *Geophysics,* 83 (4). doi:10.1190/geo2017-0617.1.

Liu, T., A. Klotzsche, M. Pondkule, H. Vereecken, J. Van Der Kruk, and Y. Su. (2017). Estimation of Subsurface Cylindrical Object Properties from GPR Full-Waveform Inversion. 2017 9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR). doi:10.1109/iwagpr.2017.7996064.

LSLRC (Lead Service Line Replacement Collaborative). (2019). “Preparing a Lead Service Line Inventory.” Accessed June 11, 2019. https://www.lslr-collaborative.org/preparing-an-inventory.html.

Lu, H., R. Romero-Canyas, S. Hiltner, T. Neltner, L. McCormick, and J. Niederdeppe. (2019). "Research to Move Toward Evidence-Based Recommendations for Lead Service Line Disclosure Policies in Home Buying and Home Renting Scenarios." *International Journal of Environmental Research and Public Health,* 16 (6): 963. doi:10.3390/ijerph16060963.

MARC (Mid-America Regional Council). (2003). “Potholing Practice.” Accessed June 3, 2019. https://www.marc.org/Government/Local-Government-Services/pdf/Potholing.html.

Marchetti, M., V. Sapia, and A. Settimi. (2013). “Magnetic Anomalies of Steel Drums: A Review of the Literature and Research Results of the INGV.” *Annals of Geophysics*, 56 (1): R0108-0120.

McCormick, L., S. Lovell, and T. Neltner. (2017). "Grading the Nation: State Disclosure Policies for Lead Pipes." *EDF Health*. https://www.edf.org/sites/default/files/content/edf_lsl_state_disclosure_report_final-031317.pdf.

Minelab. (2019). *Metal Detector Basics and Theory.* MineLab. Accessed July 1, 2019. https://www.minelab.com/__files/f/11043/KBA_METAL_DETECTOR_BASICS_&_THEORY.pdf.

Moreland, C. W. (1999). *BFO Theory*. Geotech. Accessed July 1, 2019. https://www.geotech1.com/pages/metdet/info/bfotheory/bfo.pdf.

Moreland, C. W. (2006a). *Coil Basics*. Geotech. Accessed July 1, 2019. https://www.geotech1.com/pages/metdet/info/coils.pdf.

Moreland, C. W. (2006b). *Induction Basics*. Geotech. Accessed July 1, 2019. https://www.geotech1.com/pages/metdet/info/induction.pdf.

NC (State of North Carolina). 2020. *Residential Property and Owners' Association Disclosure Statement*. State of North Carolina. https://www.ncrec.gov/Forms/Consumer/rec422.pdf.

Nelson, C. V. (2004). "Metal Detection and Classification Technologies." *Johns Hopkins APL Technical Digest*, 25 (1).

Nelson, C. V. (2005). Multi-mode Electromagnetic Target Discriminator Sensor System and Method of Operation Thereof. US Patent 6,967,574 B1. Filed December 19, 2003, and issued November 22, 2005.

Nelson, C. V., D. Mendat, and T. B. Huynh. (2003). "Three-Dimensional Steerable Magnetic Field Antenna for Metal Target Classification." In *Proceedings of Detection and Remediation Technologies for Mines and Minelike Targets VIII*. doi:10.1117/12.484900.

NJDEP (New Jersey Department of Environmental Protection). (2016). *Asset Management Technical Guidance*. NJDEP. Accessed July 3, 2019. https://www.nj.gov/dep/assetmanagement/pdf/asset-management-plan-guidance.pdf.

Nordberg, M., G. F. Nordberg, B. A. Fowler, and L. Friberg. (2007). "Ecotoxicology of Individual Metals." In *Handbook on the Toxicology of Metals*. 3rd ed. Elsevier B.V.

NPR (National Public Radio). (2019). "Do You Have Lead Pipes in Your Home." Accessed July 1, 2019. https://apps.npr.org/find-lead-pipes-in-your-home/en/#intro.

PCTE (Papsworth Construction Testing Equipment). (2019). *Pulse Induction Metal Detectors – The Principle*. Accessed July 1, 2019. http://www.pcte.com.au/images/pdf/Profometer%20Covermeter/Data-Sheet-(Pulse-Induction-Covermeters).pdf.

PA (Commonwealth of Pennsylvania). (2010). #16A-5618 Seller Property Disclosure Statement. 40 Pa.B. 6487.

Pullin, J. (2019). "Hydrovac Trucks: How Did They Become So Popular?" Summit Hydro-Vac Services Ltd. Accessed June 3, 2019. https://www.summithydrovac.ca/hydrovac-trucks-popular/.

Rabin, R. (2008). "The Lead Industry and Lead Water Pipes: A Modest Campaign." *American Journal of Public Health,* 98 (9): 1584-592. doi:10.2105/ajph.2007.113555.

Rowan, M., and W. Lahr. (2019). "How Metal Detectors Work." University of Alaska Fairbanks Geophysical Institute. Accessed July 1, 2019. http://www2.gi.alaska.edu/~jesse/treasure/misc/howdetector.html.

Ryan P. B. (2008). "The Great Lead Water Pipe Disaster." *Environmental Health Perspectives*, 116 (1): A46.

Schmidt, S. (2016). "First in the Nation: The City of Madison Replaced All Lead Pipes." WisconsinWatch.org. Accessed July 01, 2019. https://www.wisconsinwatch.org/2016/02/first-in-the-nation-city-of-madison-replaced-all-lead-pipes/.

Shefsky, S. (1997). Comparing Field Portable X-Ray Fluorescence (XFR) to Laboratory Analysis of Heavy Metals in Soil. International Symposium of Field Screening Methods for Hazardous Wastes and Toxic Chemicals.

SimpleWater. (2019). "Is There Lead Where You Live?" Accessed July 3, 2019. https://mytapscore.com/pages/the-lead-map.

Sjoblom, K., M. Mazzotti, C. N. Haas, and I. Bartoli. (2018). Identification of Water Pipe Material Based on Stress Wave Propagation. US Patent US20170254782A1. Filed March 2, 2017, and issued December 4, 2018.

Song, Y., H. Jiang, X. Shi, J. Chen, Y. Wu, and W. Wei. (2018). "Detection of Lead Using a Sensitive Anodic Stripping Voltammetric Method Based on Composite Mesoporous Silica/Bismuth Oxychloride Modified Electrode." *Chemistry Select.,* 3 (8): 2423-29.

State of California. (2005). *Department of Real Estate. Disclosures in Real Property Transactions*, Sixth Edition. http://www.dre.ca.gov/files/pdf/re6.pdf.

Super Products. (2019). "Locating and Exposing Utilities." Super Products LLC. Accessed June 3, 2019. https://www.superproductsllc.com/applications/hydro-excavation/exposing-utilities/.

Svatoš, J. (2016). "Single-Tone, and Polyharmonic Eddy Current Metal Detection and Non-Destructive Testing Education Software." *Journal of Physics: Conference Series,* 772: 012052. doi:10.1088/1742-6596/772/1/012052.

Svatoš, J., T. Pospíšil, and J. Vedral. (2018). "Application of Poly-harmonic Signals to Eddy-current Metal Detectors and to Advanced Classification of Metals." *Metrology and Measurement Systems,* 25 (2): 387–402.

Triantafyllidou, S., and M. Edwards. (2010). *Contribution of Galvanic Corrosion to Lead in Water after Partial Lead Service Line Replacements*. Project 4088b. Water Research Foundation, Denver, CO.

Tucson Water. (2018). "Get the Lead Out: Proactive Lead Service Line Removal Programs." https://cotgis.maps.arcgis.com/apps/Cascade/index.html?appid=13b3899bb7374156a031414de36007fe.

Tyson, J. (2001). “How Metal Detectors Work.” Accessed July 1, 2019. https://electronics.howstuffworks.com/gadgets/other-gadgets/metal-detector.htm.

Vac-Tron Equipment. (2019). “Vacuum Excavation.” Accessed June 3, 2019. https://www.vactron.com/applications/vacuum-excavation/.

Walsh, M. P. (2007). “The Global Experience with Lead in Gasoline and the Lessons We Should Apply to the Use of MMT.” *American Journal of Industrial Medicine*, 5: 853-860.

Wani, A. L., A. Ara, and J. A. Usmani (2015). “Lead Toxicity: A Review.” *Interdisciplinary Toxicology*, 8 (2): 55-64. doi: 10.1515/intox-2015-0009.

Welter, G., D. Giammar, Y. Wang, and A. Cantor. (2013). *Galvanic Corrosion Following Partial Lead Service Line Replacement*. Project 4349. Water Research Foundation, Denver, CO.

Weston, R. F., and Economic and Engineering Services, Inc. (1990). *Lead Service Line Replacement: A Benefit-to-Cost Analysis*. AWWA, Denver.

Windsor, C., L. Capineri, P. Falorni, S. Matucci, and G. Borgioli. (2005). “The Estimation of Buried Pipe Diameters Using Ground-Penetrating Radar.” *Insight*, 47 (7): 394-399.

THE
Water
Research
FOUNDATION

advancing the science of water®

1199 North Fairfax Street, Suite 900
Alexandria, VA 22314-1445

6666 West Quincy Avenue
Denver, CO 80235-3098

www.waterrf.org | info@waterrf.org