Electrical Resistance Testing & Swab Testing of Insertion Probes Brings Next-Level Lead Pipe Risk Profiling

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Abstract

Historically, water systems have relied on hydro-excavation (potholing), visual inspection, record review, and predictive modeling to classify service line materials. While widely adopted due to regulatory familiarity, scalability, and cost considerations, these methods exhibit inherent limitations, including point-location verification, probabilistic uncertainty, high mobilization costs, and the inability to assess internal surface lead deposition independent of host material composition.

This paper presents findings from nearly 20,000 residential service line inspections conducted by Electro Scan Inc. using a dual-method protocol that integrates Electrical Resistance Testing (ERT) via its SWORDFISH platform and post-insertion surface lead Swab Testing (ST). ERT provides continuous, full-length material characterization without excavation, while Swab Testing evaluates the presence of accessible lead particulates on the pipe surface.

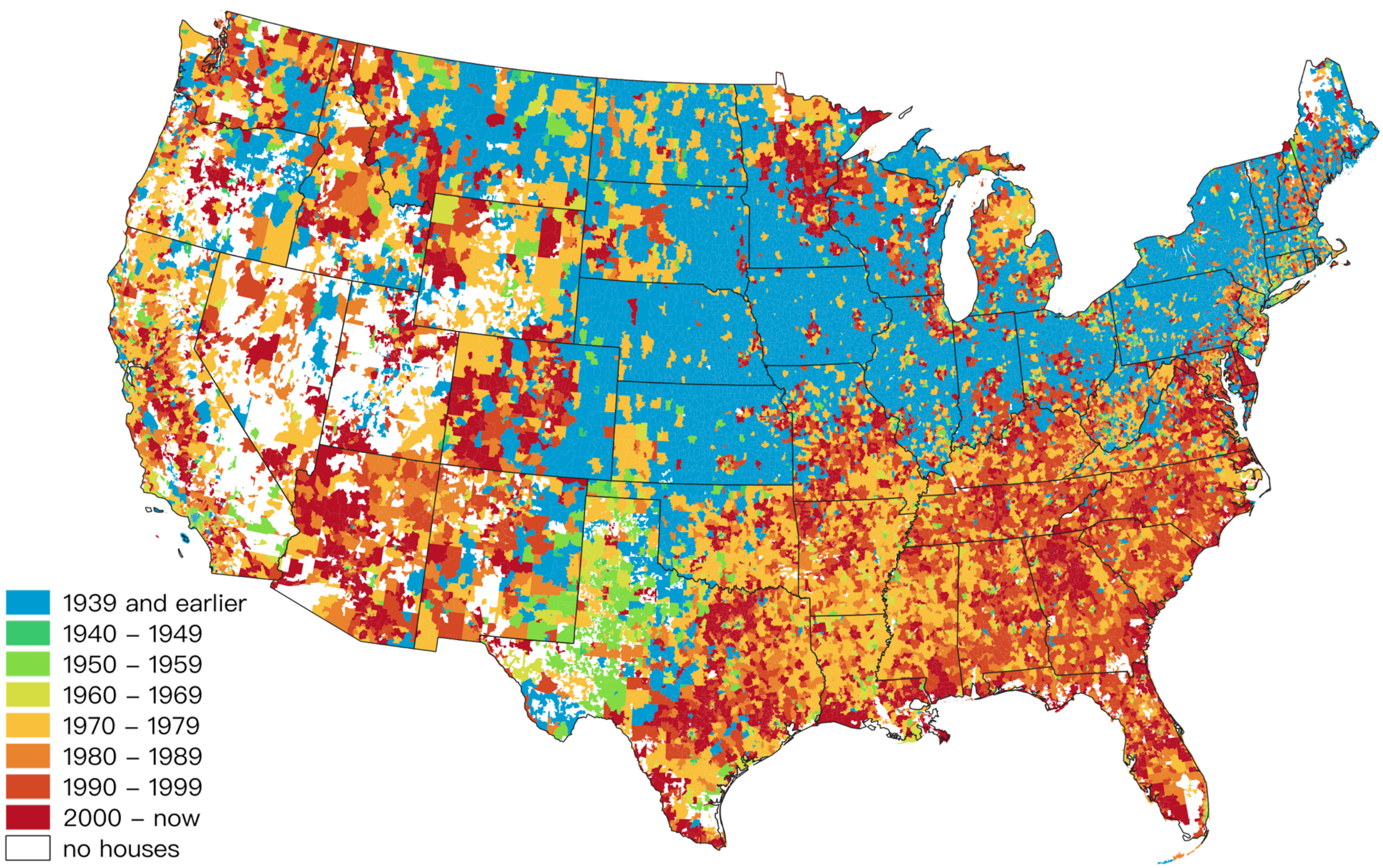
Correlation analysis demonstrates strong alignment between electrical resistance signatures and confirmed lead materials, while also identifying cases in which non-lead service lines exhibit surface-bound lead particulates due to upstream legacy infrastructure, corrosion scale accumulation, or particulate migration into bio-films or calcium build-up.

The results support four (4) conclusions:

1. Electrical resistance scanning is a robust and defensible method for full-length service line material classification.
2. Surface lead presence can occur independently of the original pipe material, indicating that material identification alone may not fully characterize exposure risk to lead.
3. ERT + Surface Swab testing provides a more comprehensive, scalable, and regulatory-aligned risk profiling framework than visual inspection, excavation or predictive modeling.
4. Copper and plastic pipes are just as likely to retain lead particulates as galvanized pipes affecting new & old homes, Figure 1.

This white paper presents the methodology, scientific rationale, and key outcomes supporting the correlation between electrical resistance signatures and surface lead presence—advancing a defensible risk-profiling paradigm that extends beyond conventional visual inventories and multiple spot excavations.

Figure 1. Plurality of houses built by decadem by U.S. Zip Code. Lead was banned in drinking water pipes by the US EPA in 1986.



Data: American Fact Finder, 2010-2015 | Map design: Szymon Pifczyk (spifczyk.tumblr.com)

1. Introduction

As of the fourth quarter of 2025, the U.S. Environmental Protection Agency (EPA) Lead Service Line Inventory Dashboard reports 66,409 public water systems and more than 100.8 million service lines nationwide. Of these, approximately 1.99 million are confirmed lead service lines, 986,542 are galvanized lines requiring replacement, and 23.8 million homes remain classified as “lead status unknown,” Table 1.

Table 1. US EPA Lead & Copper Reporting, 4Q 2025.

Category	Count
Galvanized Requiring Replacement (GRR)	986,542
Lead Service Lines (LSL)	1,994,074
Lead Status Unknown	23,828,011
Non-Lead Service Lines	73,977,225
Total Service Lines Reported	**100,785,852**

The persistence of this large unknown category—nearly one-quarter of all reported service lines—presents a significant regulatory, financial, and public health challenge as utilities transition from inventory development under the Lead and Copper Rule Revisions (LCRR) to mandatory replacement planning under the forthcoming Lead and Copper Rule Improvements (LCRI).

In the context of more than 23 million unknown service lines nationwide, integrated in-pipe diagnostics paired with surface contamination assessment offers utilities a cost-effective pathway to accelerate inventory accuracy, prioritize replacements, and strengthen defensible compliance under evolving federal lead regulations.

Electro Scan Inc. has conducted nearly 20,000 field inspections of residential water service lines in utility service territories across the United States. Each inspection employs a dual-method approach: Electrical Resistance Testing (ERT) via the SWORDFISH field platform and surface lead swab analysis collected immediately following probe extraction.

As of 4Q 2025, the US EPA’s Lead Service Line Inventory Dashboard reports 66,409 community and non-transient non-community water systems submitting service line inventory data. Collectively, these systems report the scale of national inventory obligations under the Lead and Copper Rule Revisions (LCRR) and Lead and Copper Rule Improvements (LCRI).

Notably:

- Nearly 2 million confirmed lead service lines remain in service.
- Almost 1 million galvanized lines requiring replacement are classified as lead-risk infrastructure.
- Most critically, 23.8 million service lines remain “lead status unknown”, representing approximately 24% of all reported lines.

The persistence of this large unknown category underscores the need for scalable, defensible, and non-destructive technologies capable of accelerating material identification and risk assessment.

Galvanized iron and steel pipes have long been recognized as a secondary source of lead in drinking water because their corrosion layers readily adsorb and later release lead when upstream lead sources are present.

Under the Lead and Copper Rule Revisions (LCRR) and Lead and Copper Rule Improvements (LCRI), this understanding led to the creation of the category “Galvanized Requiring Replacement (GRR)”, acknowledging that galvanized service lines can accumulate and subsequently release lead even if they were not originally constructed of lead. **However, emerging and peer-reviewed research confirms that galvanized pipes are not unique in this behavior. Copper and plastic pipe materials can also accumulate and later mobilize lead particulates when lead has historically existed upstream in the distribution system, Figure 2**.

Laboratory and field studies have demonstrated that lead released from upstream sources—such as lead service lines, lead goosenecks, lead solder, or legacy lead components—can deposit onto interior pipe walls composed of copper or polymeric materials. Salehi et al. (Journal of Hazardous Materials, 2020) showed that lead particulates can be entrapped within corrosion scale matrices and biofilms and later released during hydraulic disturbance events.

Similarly, Ghoochani et al. (Environmental Pollution, 2023) documented the role of scale formation and biofilm adsorption in promoting heavy metal retention on non-lead pipe substrates. These findings align with earlier EPA and AWWA research indicating that particulate lead release is strongly influenced by water chemistry, corrosion scale instability, and physical disturbance, rather than pipe composition alone.

Copper piping systems are particularly susceptible to surface deposition because corrosion scales—composed of copper oxides, carbonates, and orthophosphate precipitates—provide sorptive sites where lead can accumulate. When orthophosphate is used for corrosion control, lead-phosphate compounds may deposit within scale layers on copper interiors, effectively masking but not eliminating contamination potential. Hydraulic changes, construction disturbance, meter replacement, or partial lead service line replacement can destabilize these deposits and release particulates lead downstream.

Figure 2. Scaling in Copper, Galvanized, and Plastic pipes.

This phenomenon has been documented in multiple post-disturbance studies, including work by Del Toral et al. (EPA, 2013) and subsequent distribution system research examining particulate lead mobilization following infrastructure disruption.

Plastic pipe materials (e.g., HDPE, PEX, PVC) were historically assumed inert with respect to metal adsorption. However, research indicates that biofilms readily form on polymeric pipe interiors, and these biofilms can adsorb and concentrate metals including lead. Salehi et al. demonstrated that biofilm-associated particulate accumulation can occur regardless of pipe substrate. In systems with a history of upstream lead, plastic pipes may therefore serve as temporary reservoirs for deposited lead particles. Although plastics do not corrode in the traditional electrochemical sense, they can harbor scale fragments or biofilm-bound particulates transported from upstream legacy lead sources.

The implication for both older and newer homes is significant.

Historical records indicating copper or plastic service lines do not guarantee the absence of lead exposure risk. In older neighborhoods where partial lead replacements may have occurred, or where upstream lead mains or connectors once existed, non-lead services may still contain deposited lead particulates.

Even in newer homes, if the upstream distribution system historically contained lead components, transient particulate transport could result in surface deposition within otherwise non-lead service lines. As a result, reliance solely on installation-era records or pipe material designation can fail to capture actual contamination pathways.

From a compliance and public health standpoint, this research underscores the importance of verification strategies that assess not only pipe material composition but also internal surface condition and particulate presence.

Visual inspection, predictive modeling, and record review cannot detect surface-bound lead deposits. Even hydro-excavation confirms only spot material at the exposed point. Therefore, verification protocols that include in-pipe diagnostics and surface testing provide a more complete assessment of whether a service line truly presents a non-lead condition that typically has gone unreported, prior to the introduction of ERT technology by Electro Scan Inc.

As utilities move from *inventory development* to *replacement prioritization* under LCRI legislation, understanding that copper and plastic pipes can retain legacy lead deposits reinforces the need for defensible, science-based verification methods. The distinction between material identity and exposure risk is now well established in the literature: **a pipe may be composed of non-lead material yet still pose a lead particulate release risk if upstream lead has ever been present.** This evolving understanding supports more comprehensive field assessment protocols when confirming "non-lead" classifications in both legacy and recently constructed homes.

Electro Scan's dual-method field protocol singularly and directly addresses this national challenge.

Accurate identification and risk profiling of water service line materials first became central to public health protection and regulatory compliance under the US EPA's Lead and Copper Rule Revisions (LCRR). The October 2024 inventory deadline marked the first nationwide reporting milestone, yet data quality and completeness vary significantly across jurisdictions and state oversight.

Traditional identification approaches include:
- Historical tap cards and installation records
- Visual inspection at meter boxes and hose faucets
- Scratch tests
- Selective potholing and excavation

While useful, these approaches are inherently limited in scope and often fail to evaluate the full-length of the service line. More importantly, they do not systematically address the presence of deposited lead particulates within pipes classified as copper, plastic, or galvanized.

To address these limitations, Electro Scan Inc. developed a field protocol pairing electrical resistance diagnostics with post-insertion & extraction probe surface swab testing.

This combined approach captures:
1. Material identity along the entire service line, and
2. Evidence of accessible surface lead particulates at the point of inspection.

The result is a materially and chemically informed risk profile.

2. National Regulatory and Data Context

States and individual water utilities are now updating their service line inventories up to and beyond the EPA reporting deadline of November 1, 2027, Figure 3. With over 66,000 water systems available on the EPA's website, Figure 4 (next page), regulators and similar-sized water agencies can easily compare and contrast results of individual entitites.

2.1 EPA Dashboard Overview (4Q 2025)

As December 31, 2025, the EPA's national inventory dashboard reflected reporting from 66,409 water systems covering an aggregate total of 100.8 million service lines demonstrating the scale of the infrastructure challenge.

Figure 3. LCRI reporting deadline.

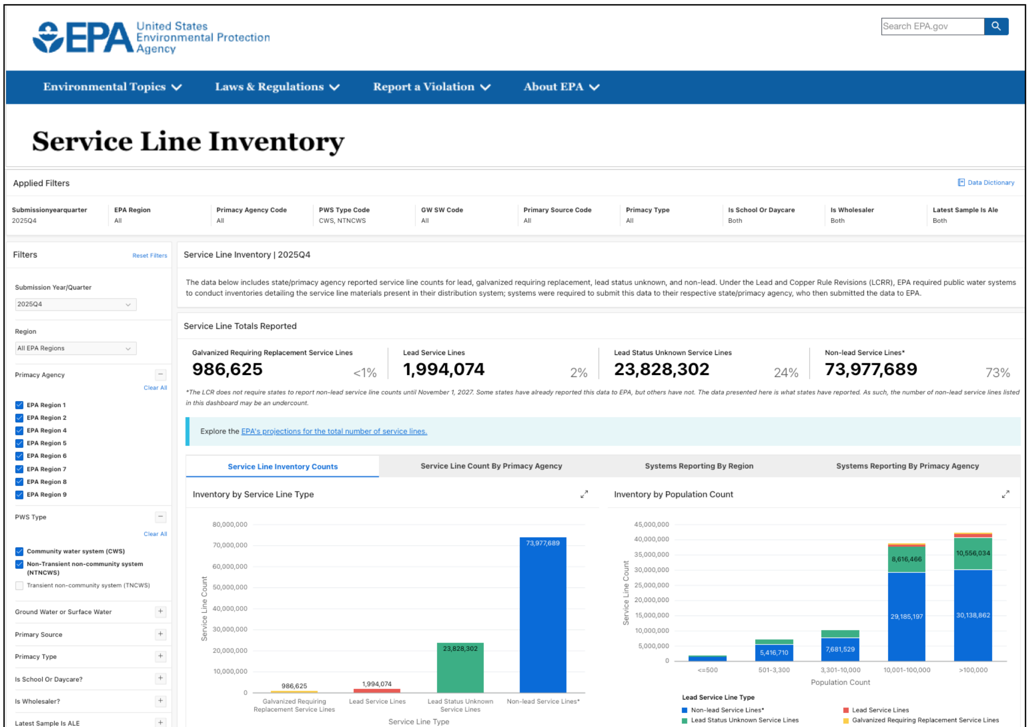
Key national observations include:
- Confirmed lead and galvanized requiring replacement lines total nearly 3 million lines.
- Unknown classifications exceed

the number of confirmed lead lines by more than 10:1.
- Many systems continue to rely on incomplete historical records rather than direct field verification.
- Smaller systems disproportionately report higher percentages of "unknown" classifications.

As utilities transition from inventory development to mandatory replacement planning under LCRI, improving classification accuracy will be critical for:
- Replacement prioritization
- Capital budgeting
- Federal & state funding allocation
- Public risk communication

Technologies capable of reducing unknowns without mass excavation are therefore strategically important to ensure public health.

Figure 4. EPA Service Line Inventory dashboard.



https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/sdwis_fed_reports_public/service-line-inventory

3. Background

Accurate service line identification has evolved significantly over the past decade, particularly following the Flint Water Crisis and subsequent federal regulatory reform.

Utilities faced urgent mandates to inventory millions of service lines—often with incomplete records and limited capital budgets. In response, three primary approaches emerged nationwide:
1. Visual Inspection
2. Hydro-Excavation (Potholing)
3. Predictive Modeling
4. Electrical Resistance Testing (ERT)
5. Swab Surface Pipe Material Testing

Each approach offers strengths, but also distinct limitations.

3.1 Visual Inspection

A number of water utilities and state environmental agencies have permitted visual inspection to satisfy portions of the Lead and Copper Rule Revisions (LCRR) inventory requirements, and in some cases to support ongoing compliance under the Lead and Copper Rule Improvements (LCRI). In practice, visual inspection is typically limited to opening meter boxes to observe pipes entering and exiting the meter setting, followed by inspection of exposed piping at hose bibs, crawl spaces, basements, or wall penetrations adjacent to homes. While this approach offers speed and low cost, it presents significant technical limitations when used as the primary method for classifying service line materials.

The most fundamental limitation is that visual inspection evaluates only exposed and accessible segments of a pipe. In most residential settings, more than 90 percent of the service line is buried below ground between the water main and the structure. Material transitions—such as short lead goosenecks, legacy lead connectors, or partial lead replacements—often occur underground and are not visible at the meter box or building entry point. A copper pipe observed at the home does not confirm that the entire service line is copper. Similarly, plastic piping at the structure does not preclude the presence of upstream lead segments. Without below-ground assessment, visual inspection provides only a partial snapshot rather than full-length verification.

Visual inspection is also inherently vulnerable to misidentification errors. Corrosion, paint coatings, mineral scale, and dirt accumulation can obscure pipe characteristics. Galvanized steel may resemble lead when heavily corroded; copper that has been oxidized or coated can be misclassified; plastic may conceal metallic connectors. Scratch tests, when used, may damage pipes and still fail to reveal short or upstream lead segments. Field variability in training and interpretation further increases inconsistency across jurisdictions.

Another significant weakness is that visual inspection does not assess internal pipe condition or surface contamination. Even if the exposed portion of a pipe is confirmed as copper or plastic, visual methods cannot determine whether lead particulates have accumulated inside the pipe from historical upstream lead sources. As documented in peer-reviewed research, lead released from upstream infrastructure can deposit within corrosion scales and biofilms on non-lead substrates. Visual confirmation of exterior material composition therefore does not equate to confirmation of a "non-lead" risk condition.

Meter box inspections also frequently fail to capture ownership-side transitions. Many service lines include separate public-side and private-side materials, with joints located below grade. Utilities that inspect only the public-side pipe entering the meter cannot reliably infer the composition of the private-side pipe exiting toward the residence, and vice versa. In mixed-material systems, this creates substantial potential for incomplete or inaccurate inventory entries. Furthermore, reliance on visual inspection may create a false sense of regulatory completeness. The LCRR and LCRI require utilities to develop accurate and defensible inventories.

While EPA guidance permits the use of "visual inspection" as one line of evidence, it does not guarantee that such inspection is sufficient to eliminate uncertainty. Given that 23.8 million service lines nationwide remain classified as "lead status unknown," overreliance on surface-level confirmation risks perpetuating uncertainty rather than resolving it.

In older neighborhoods—particularly those developed before the 1950s—lead service lines were often installed with short connectors or goosenecks that are not visible without excavation or in-pipe diagnostics. Even in communities where records indicate copper installations, undocumented repairs, emergency replacements, or contractor substitutions may have introduced mixed materials. Visual inspection cannot detect these hidden conditions without below-ground exposure.

In summary, visual inspection is fast, minimally disruptive, and inexpensive, which explains its widespread adoption. However, it is inherently limited to exposed segments, prone to misclassification, incapable of detecting internal deposition, and blind to underground transitions, Figure 5.

When used as the sole verification method, it does not provide full-length material confirmation and may not produce a complete or defensible service line inventory. Comprehensive below-ground assessment—whether through excavation, in-pipe diagnostics, or other validated technologies—is necessary to reliably confirm non-lead conditions and reduce uncertainty in regulatory reporting, Figure 6.

Figure 5. Selected Meter Settings found inside meter boxes.

3.2 Hydro-Excavation (Potholing)

Hydro-excavation—commonly referred to as potholing —involves using high-pressure water and vacuum extraction to expose a buried service line at one or more points for direct visual inspection. The method is widely accepted by regulators because it allows physical confirmation of pipe material at the exposed location.

Why Hydro-Excavation Was Widely Adopted

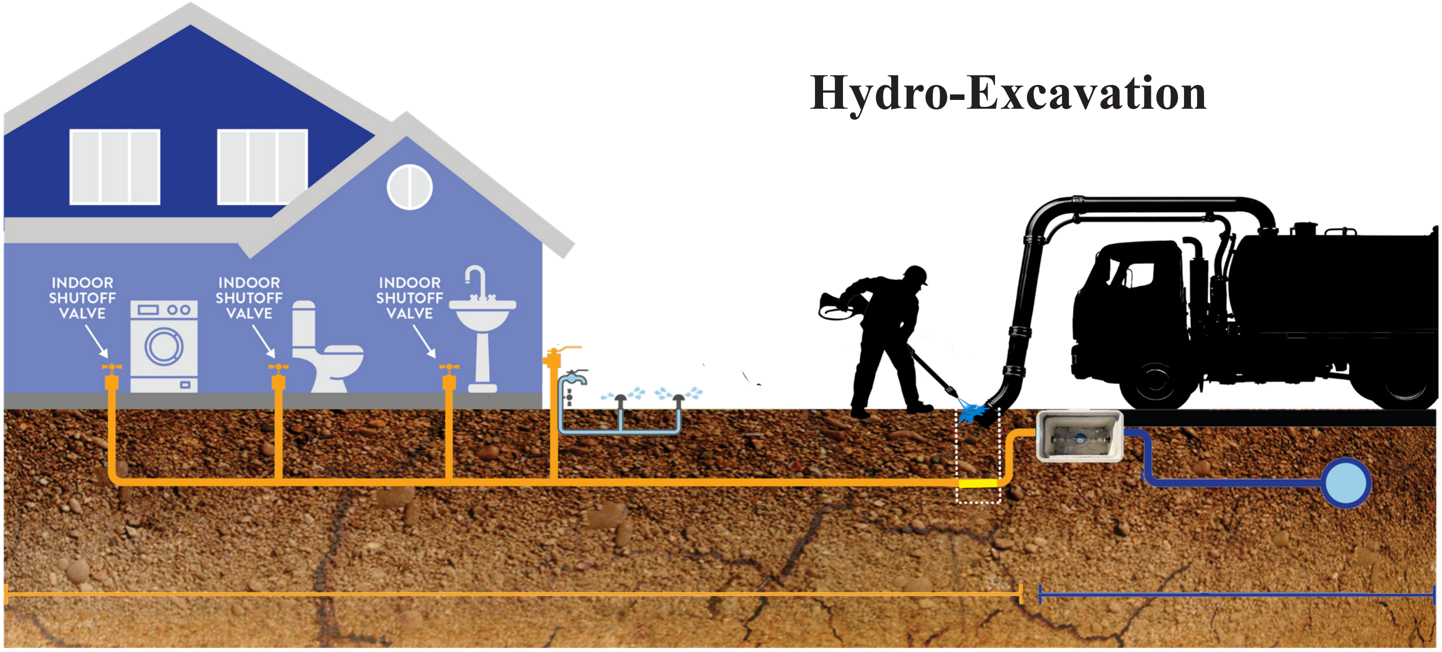
Hydro-excavation became the dominant verification method for several reasons:

- Regulatory Familiarity: Physical observation has long been considered the "gold standard" for confirming pipe material.
- Simplicity of Interpretation: Field crews can visually identify lead, copper, galvanized steel, or plastic.
- Compatibility with Existing Workflows: Utilities already performing repairs or replacements could incorporate material confirmation into ongoing excavation projects.
- Legal Defensibility: Photographic documentation of exposed pipe segments provides tangible evidence for inventory reporting.
- Damage Prevention Industry Capacity: Contractors and vacuum excavation companies were already scaled nationwide.

For many systems facing inventory deadlines under the

Figure 6. Scaling in Copper, Galvanized, and Plastic pipes.

Figure 7. Illustration of hydro-excavation, also called daylighting or potholing.



LCRR, potholing represented a straightforward and regulator-accepted approach, Figure 7 & 8.

Inherent Weaknesses of Hydro-Excavation
Despite its acceptance, hydro-excavation presents several structural limitations:

1. Point-in-Time, Point-in-Location Limitation
Potholing exposes only a small section of pipe — typically near the curb stop or meter box. Mixed-material service lines (e.g., lead goosenecks or partial replacements) may remain undetected if not excavated at multiple locations.

2. High Cost and Labor Intensity
Each excavation requires equipment mobilization, traffic control, restoration, and potential property impact. Scaling to thousands of homes is capital-intensive.

3. Surface Restoration and Liability
Excavation disturbs landscaping, pavement, sidewalks, and private property. Restoration costs and homeowner complaints can be significant.

4. Incomplete Risk Assessment
Visual inspection identifies material type but does not assess:
- Internal corrosion condition
- Scale accumulation
- Deposited lead particulates on non-lead pipes

5. Potential Water Quality Disturbance
Excavation itself can disturb service lines, potentially mobilizing scale or particulates without systematic pre- and post-disturbance monitoring.

6. Impracticality for Large Unknown Inventories
With 23.8 million service lines nationally classified as "lead status unknown," mass potholing is economically and logistically impractical for many utilities.

While hydro-excavation remains useful for replacement verification and targeted confirmation, it does not provide scalable, full-length diagnostics.

3.3 Predictive Modeling
Predictive modeling uses statistical and machine learning techniques to estimate the probability that a given service line is lead based on historical, demographic, geographic, and construction-era data.

Common model inputs include:
- Installation year
- Neighborhood construction patterns
- Property tax records
- Permit data
- Historical tap cards
- Socioeconomic and census variables
- Known nearby material classifications

Why Predictive Modeling Was Widely Adopted
Predictive modeling expanded rapidly after 2018 for several reasons:

Figure 8. Removing topsoil using hydro-excavation.

1. Scalability
Models can be applied to entire utility databases quickly, without field mobilization.

2. Cost Efficiency
Compared to excavation, modeling is inexpensive on a per-property basis.

3. Academic and Philanthropic Support
Major cities partnered with universities and nonprofit organizations to develop open-source modeling frameworks.

4. Regulatory Flexibility
EPA guidance permits probabilistic methods to inform prioritization, particularly where records are incomplete.

5. Capital Planning Utility
Models help utilities estimate the magnitude of potential replacement obligations before committing to physical verification. Predictive modeling thus became an attractive triage tool to prioritize inspections and replacements.

Inherent Weaknesses of Predictive Modeling
While powerful for prioritization, predictive models have structural limitations:

1. Probability vs. Confirmation
Models generate likelihood estimates — not definitive material identification.

2. Data Quality Dependency
Inaccurate historical records or incomplete datasets degrade model reliability.

3. Geographic Bias
Construction-era assumptions may not reflect localized contractor practices or undocumented repairs.

4. Inability to Detect Mixed Materials
Models cannot identify partial lead segments or goosenecks within otherwise non-lead service lines.

5. No Assessment of Surface Lead Deposition
Predictive modeling addresses material probability only — not internal corrosion or particulate accumulation risk.

6. Public Communication Challenges
Explaining probabilistic classifications to homeowners can undermine confidence if later contradicted by field findings.

7. Legal and Regulatory Scrutiny
As LCRI implementation advances, regulators may increasingly require physical verification to support replacement decisions.

Predictive modeling remains valuable for strategic planning but cannot substitute for physical or in-pipe diagnostic confirmation.

3.4 Electrical Resistance Testing (ERT)
Electrical Resistance Testing (ERT), as deployed through the SWORDFISH platform, was developed in response to a structural challenge facing water utilities nationwide: how to achieve the material certainty associated with excavation while maintaining the scalability and cost-efficiency of predictive modeling. Excavation provides physical confirmation but is disruptive, slow, and expensive when applied systemwide. Predictive modeling can prioritize inspections efficiently but produces probability-based classifications rather than direct verification, Figure 9.

ERT was engineered to bridge this gap by delivering continuous, full-length material characterization through a minimally invasive, non-destructive field procedure.

At its core, ERT measures the conductivity profile of a service line by introducing a conductive probe into the pipe and electronically scanning from the meter toward the main. Because different pipe materials possess distinct electrical properties, each produces a measurable and repeatable resistance signature. Lead typically exhibits

Figure 9. Illustration of electrical resistance testing.

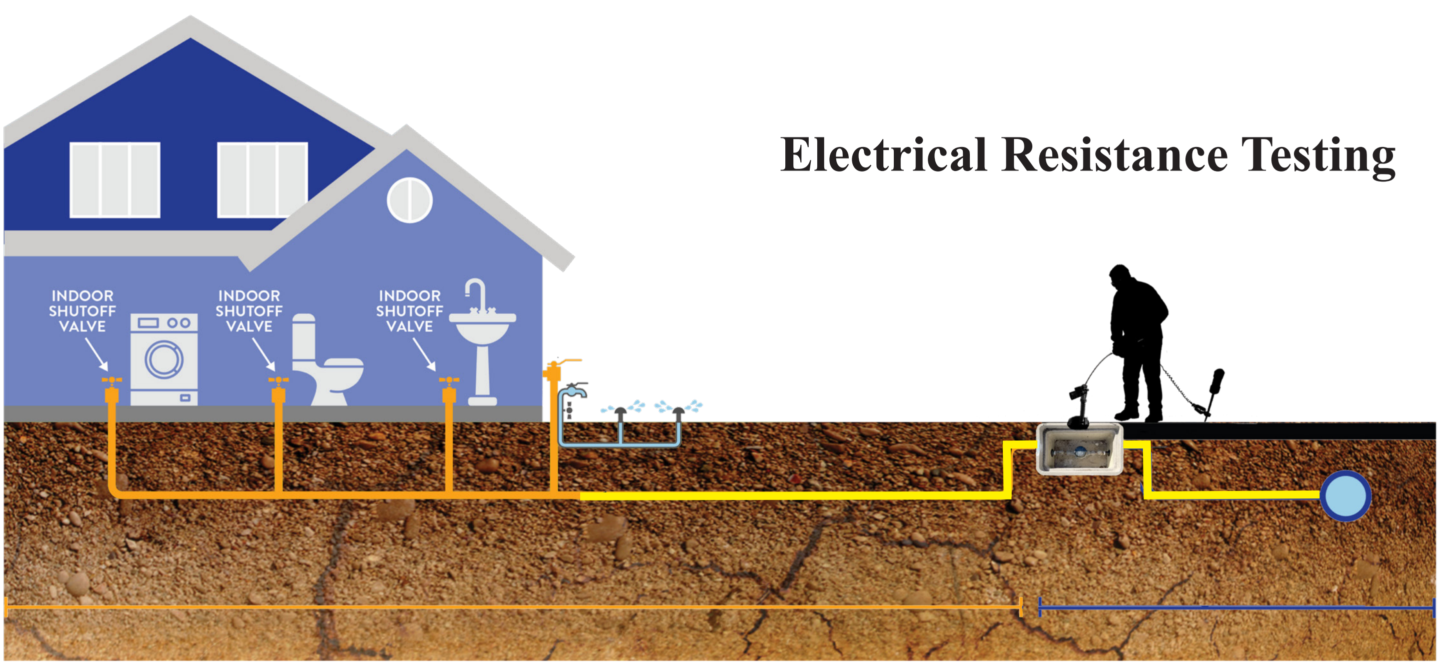
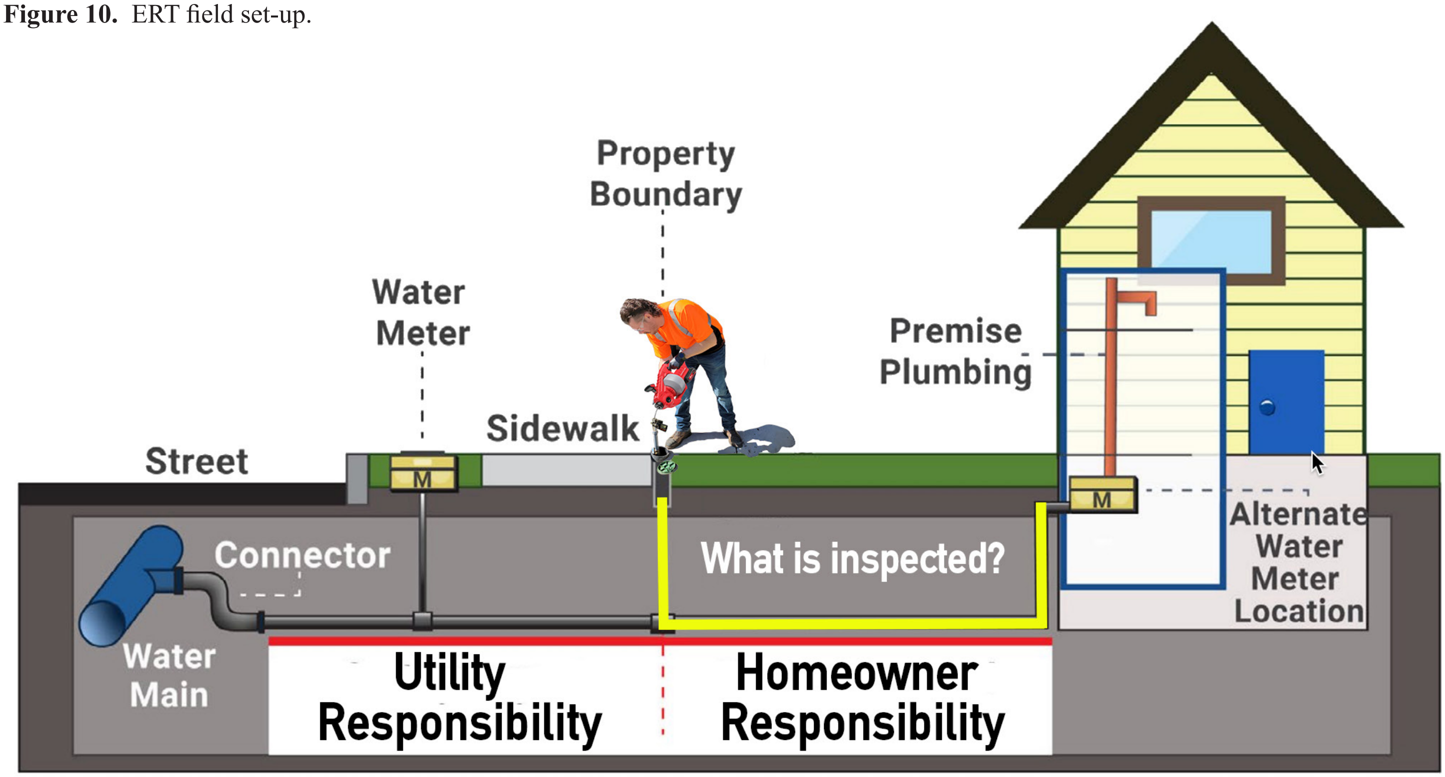


Figure 10. ERT field set-up.



medium-to-high conductivity with characteristic waveform patterns influenced by its metallurgical composition and surface condition, Figure 10.

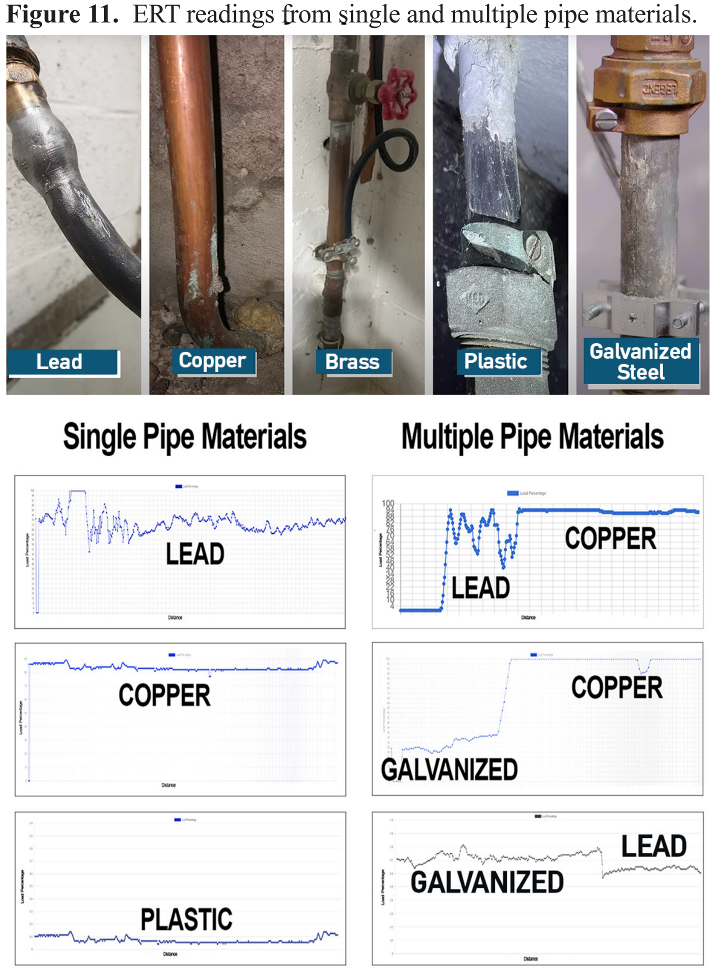
Copper and brass display high conductivity with stable signal characteristics. Galvanized steel produces conductivity profiles altered by corrosion layers and mineral scale, often distinguishable from both copper and lead. Plastic materials such as HDPE and PEX, by contrast, exhibit minimal conductivity, generating low or near-zero signal responses. These material-dependent signatures allow trained analysts to interpret not only pipe type but also transitions along the service line, Figure 11.

A key advantage of ERT is that it captures data along the entire accessible length of the service line rather than at a single exposed point. This continuous profile enables detection of mixed-material configurations, short lead segments, lead goosenecks, partial replacements, or undocumented repairs that would otherwise remain hidden without multiple excavations. In contrast to visual inspection or single-point potholing, which provide localized confirmation, ERT offers longitudinal verification. The ability to detect material transitions is particularly important in older neighborhoods where historical installation practices included short lead connectors attached to otherwise non-lead piping.

ERT's non-destructive deployment is another defining characteristic. The probe is inserted through existing meter infrastructure without excavation, eliminating surface disturbance, restoration costs, and property impact. This significantly reduces mobilization time, traffic control requirements, and homeowner disruption. When applied at scale, these operational efficiencies translate into lower per-service-line inspection costs compared to hydro-excavation. For utilities confronting thousands—or tens of thousands—of "unknown" classifications, the economic implications are substantial.

Importantly, ERT provides direct material confirmation

Figure 11. ERT readings from single and multiple pipe materials.



rather than probabilistic inference. Unlike predictive modeling, which relies on historical records and statistical associations, ERT produces a physical measurement tied to the electrical properties of the pipe itself. This distinction strengthens regulatory defensibility and reduces uncertainty in inventory reporting.

While predictive models remain useful for prioritization, they cannot independently confirm material composition or identify undocumented field variations. ERT converts uncertainty into measurable field evidence.

When paired with surface lead swab testing, ERT addresses a further limitation shared by both excavation and modeling: neither method evaluates internal surface contamination independent of bulk pipe material. Excavation confirms composition but does not reveal whether lead particulates have accumulated inside a non-lead pipe. Predictive modeling cannot assess surface condition at all.

By combining ERT's full-length material characterization with targeted swab testing at the probe interface, utilities gain insight into whether surface-bound lead particulates are present—even on copper or plastic services. This dual assessment recognizes the now well-documented distinction between material identity and exposure risk.

In effect, the integrated ERT + swab protocol creates a three-dimensional understanding of a service line: longitudinal material composition, potential mixed-material transitions, and surface contamination status. This approach aligns with the evolving regulatory environment under LCRI, where inventory accuracy, replacement prioritization, and public health protection increasingly demand methods that are both scalable and scientifically grounded.

As utilities continue working to reduce the national total of 23.8 million unknown service lines, technologies that combine excavation-level certainty with modeling-level scalability will be critical. ERT was designed to occupy this middle ground—providing defensible, high-resolution, full-length diagnostics without the cost and disruption of systematic excavation.

ERT offers:
- Continuous, full-length pipe characterization
- Non-destructive deployment
- Lower cost per inspection compared to excavation
- Direct material confirmation rather than probability
- Compatibility with large-scale unknown inventory reduction

ERT measures the conductivity profile along the interior of a water service line by electronically scanning the pipe using a conductive probe. Different pipe materials exhibit distinct electrical resistance characteristics:
- Lead—medium-to-high conductivity w/distinctive signatures
- Copper/Brass—high conductivity
- Galvanized Steel—conductivity altered by corrosion products
- Plastic (HDPE, PEX) — low conductivity

ERT provides high-resolution data along the entire length of the service line without excavation.
When paired with surface swab testing, ERT further addresses a gap left by both potholing and modeling: the ability to assess surface lead presence independent of host material.

3.5 Surface Lead Swab Testing
Field swab tests use chemically treated wipes applied directly to the interior pipe surface at the ERT probe contact point. The swab reacts with exposed lead particulates and indicates the presence or absence of surface-accessible lead. Unlike bulk material identification, swab testing evaluates whether lead is physically present at the pipe surface at the time of inspection—whether originating from the pipe itself or from upstream deposition, Figure 12.

Swab testing alone, however, cannot distinguish:
- Whether the lead originates from the pipe substrate or from deposited scale;
- Whether a negative result reflects absence of lead or masking due to corrosion control chemistry;
- Whether a positive result reflects host material or migrated particulates.

When combined with Electrical Resistance Testing (ERT), interpretation becomes materially grounded. ERT determines pipe composition along the full service line. The swab then characterizes surface condition at the inspection interface. Together, these tools allow differentiation between material identity and contamination state — a distinction not possible with swab testing alone.

Below is a detailed analysis of each combined outcome category.

I. LEAD SERVICE LINES

ERT Positive LEAD + Swab Positive LEAD
The Highest Risk Combination
This is the most concerning and highest-confidence finding.
- ERT confirms the pipe substrate is lead.
- Swab confirms exposed lead particulates are present at the interior surface.

Figure 12. Commercial lead testing swab testing.

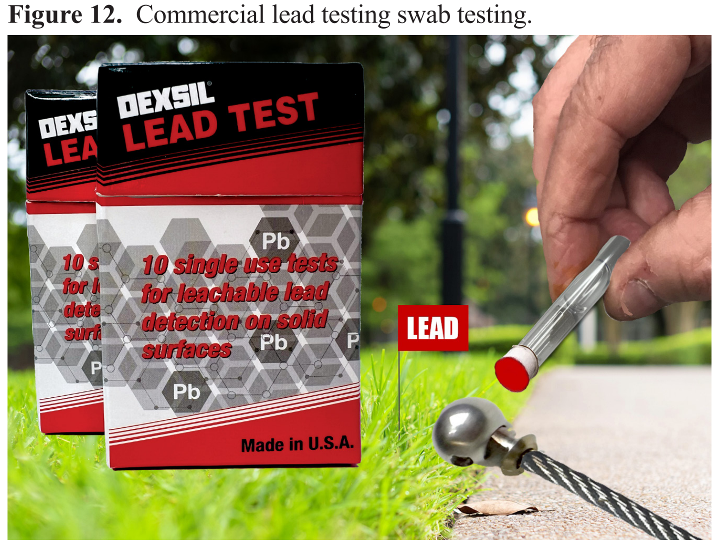
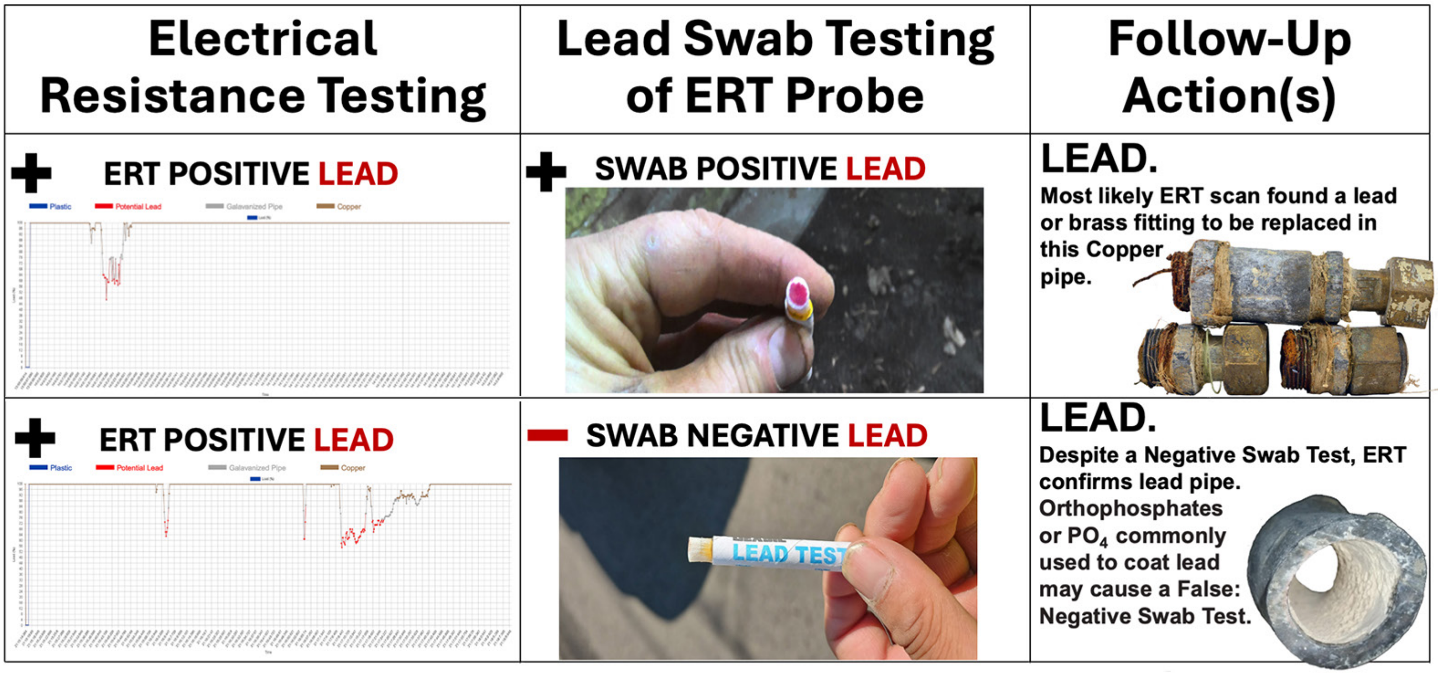


Figure 13. Lead ERT + Swab Test Results



Implications:
- Active or accessible lead is present.
- Particulate mobilization risk is elevated.
- Replacement prioritization is strongly indicated.
- Corrosion control may be insufficient, unstable, or recently disturbed.

This combination confirms both material hazard and surface exposure condition, Figure 13.

ERT Positive LEAD + Swab Negative LEAD
Lead Pipe with Surface Suppression

This combination does not invalidate the ERT result.

ERT confirms the pipe is lead. A negative swab most commonly indicates:
- Effective orthophosphate corrosion control forming a protective coating;
- Stable mineral scale encapsulating the lead substrate;
- Limited accessible particulate at the specific contact point;
- Sampling location variability.

Orthophosphate and PO-based, i.e. phosphate ion (PO_4^{3-}), corrosion inhibitors are specifically designed to create insoluble lead-phosphate layers that reduce surface solubility and particulate release. These coatings can produce a negative swab result even though the pipe itself is lead.

Implications:
- Pipe remains a lead service line.
- Corrosion control appears effective at the time of testing.
- Replacement classification should remain "Lead."
- Negative swab does not reclassify the pipe as non-lead.

This combination illustrates a critical limitation of swab-only testing: without ERT, a negative swab could falsely suggest absence of lead.

II. GALVANIZED SERVICE LINES

ERT Positive GALVANIZED + Swab Positive LEAD
Galvanized Requiring Replacement (GRR). This finding is consistent with EPA's GRR classification.

Galvanized steel, when historically connected to upstream lead components, can accumulate lead within corrosion scale. Over time, scale can release particulate lead, oftentimes by change in pressure, water hammer events, valve exercising activities, and water shut-offs and turn-ons.

Implications:
- Lead deposition is present within galvanized corrosion layers.
- Replacement is generally recommended.
- Re-testing typically unnecessary.
- Classified as Galvanized Requiring Replacement.

This combination confirms both material type and active lead contamination, Figure 14.

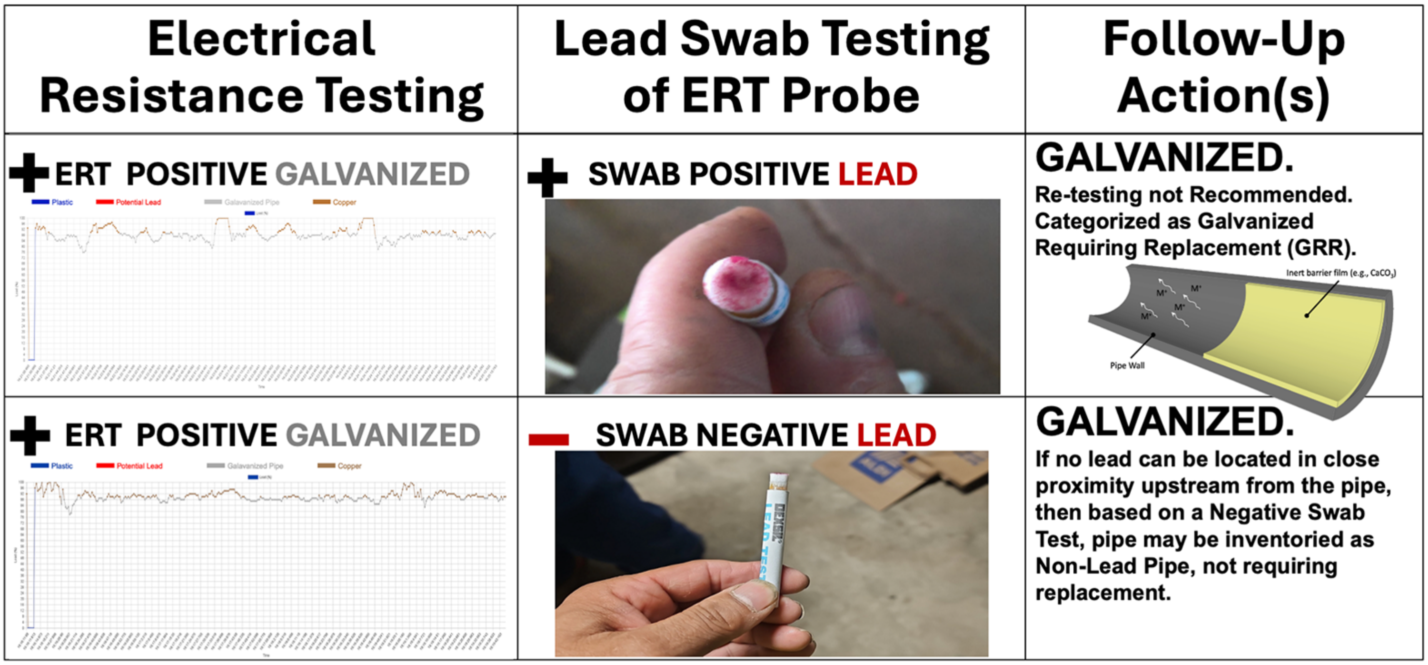
ERT Positive GALVANIZED + Swab Negative LEAD
Galvanized Without Detectable Surface Deposition

This outcome suggests:
- No detectable surface lead at the sampling location; and/or
- No historical upstream lead exposure; and/or
- Stable scale without active particulate release.

If upstream investigation confirms no historical lead source in close proximity, the pipe may be inventoried as non-lead galvanized not requiring replacement. However, because galvanized steel can accumulate legacy lead, historical context is essential in interpretation.

Swab-only testing would not distinguish between galvanized and copper/plastic materials; ERT provides the necessary substrate identification.

Figure 14. Galvanized ERT + Swab Test Results



CASE STUDY: 411 Main Street, USA

ERT testing for 411 Main Street, Figure 15, confirmed a copper pipe from the meter to the house, but suspicously swab-tested positive for lead. A known highly corrosive area, before and after water test results, both at stagnation and post-ERT survey and flushing, confirmed lead (according to independent water test results using TapScore water quality tests by SimpleLab, Inc.), Figure 15.

While digital maps showed galvanized piping as the upstream segment from the meter to the main, maintenance field workers confirmed that every house on the street had a lead gooseneck section of pipe connecting the galvanized pipe to the main. Immediately cataloged as a GRR, ERT + Swab Testing provided greater risk scoring for these pipes.

No prior home or utility field inspection had taken place, prior to Electro Scan's survey and testing.

III. COPPER SERVICE LINES

Copper has historically been assumed to represent a "safe" classification in inventory reporting. However, field data and peer-reviewed research demonstrate that copper pipes can accumulate lead particulates from upstream legacy sources.

ERT Positive COPPER + Swab Positive LEAD
Copper with Surface Lead Deposition

This combination is highly instructive.

Figure 15. Case Study: 411 Main Street, USA

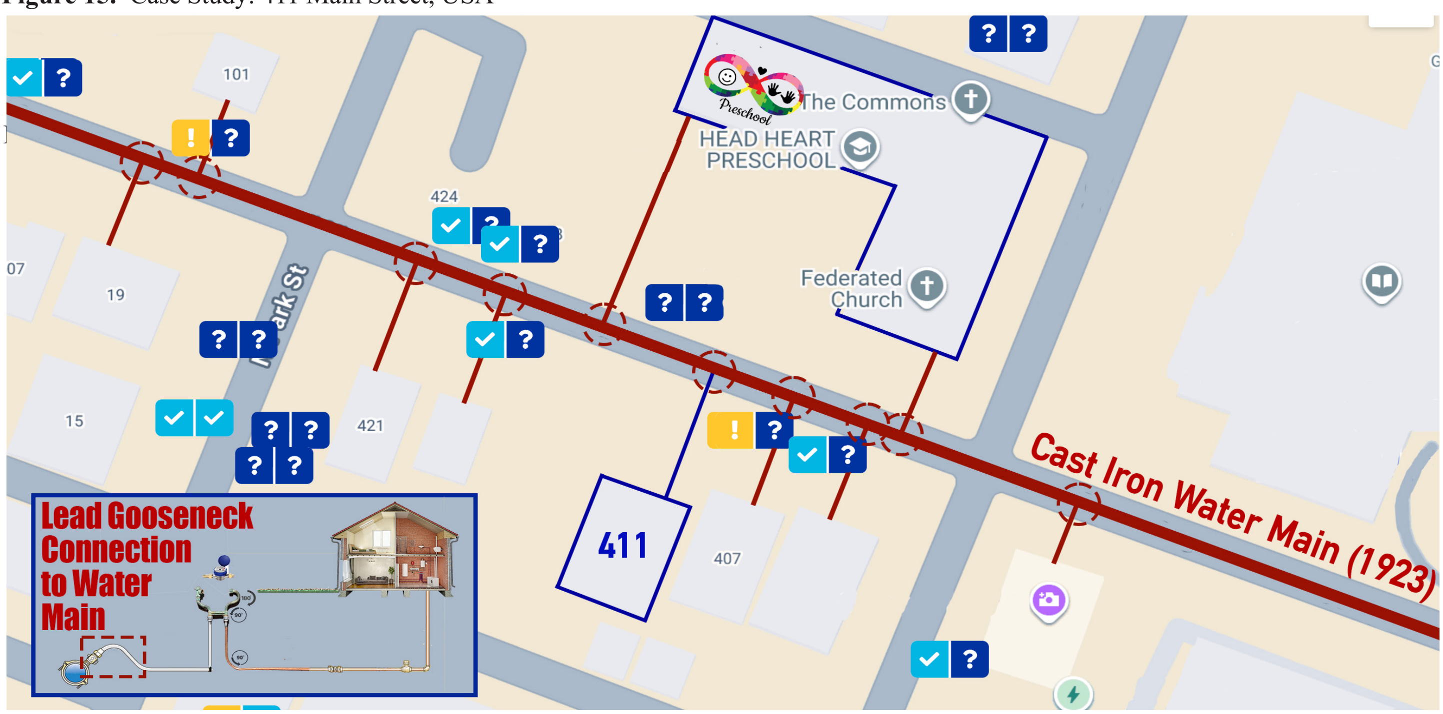
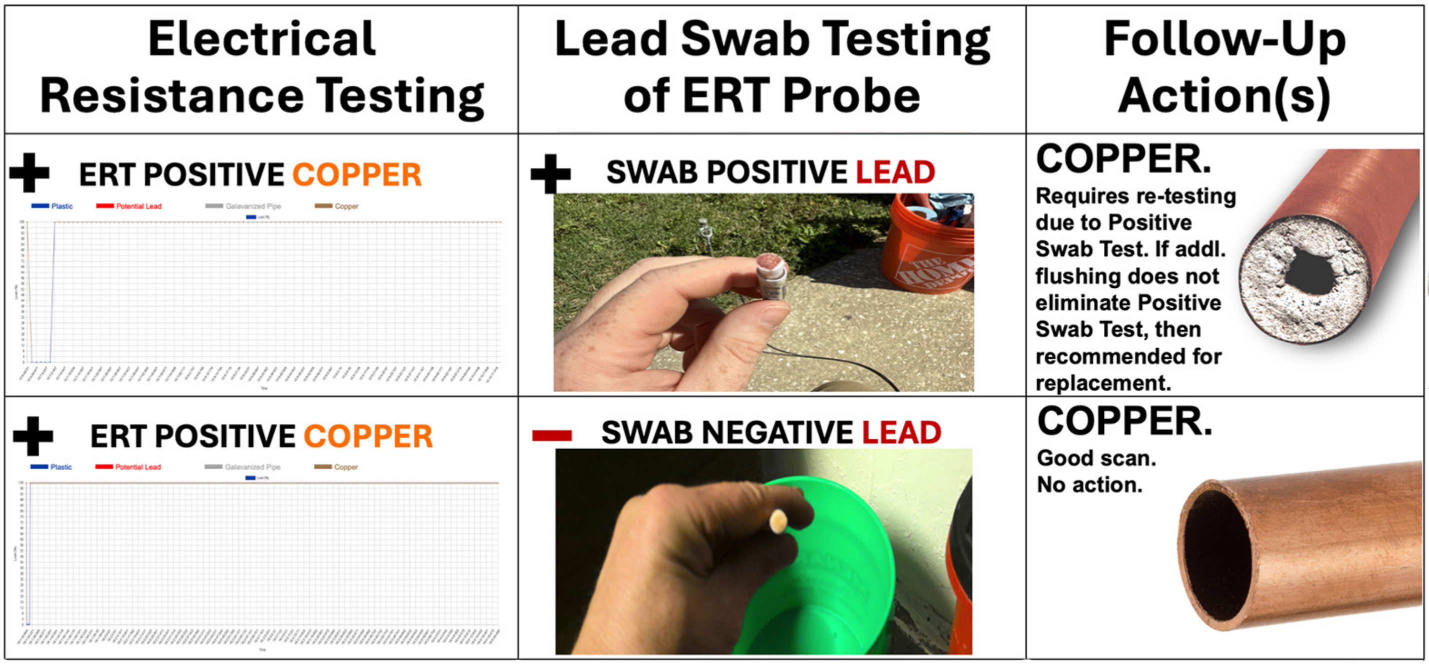


Figure 16. Copper ERT + Swab Test Results



- ERT confirms the pipe substrate is copper.
- Swab confirms accessible lead particulates at the surface.

Potential causes include:
- Upstream lead goosenecks;
- Partial lead replacements;
- Lead solder residues;
- Lead main segments;
- Disturbance-induced particulate migration;
- Scale entrapment within copper corrosion products.

Implications:
- Pipe material is not lead.
- Exposure risk exists due to surface deposition.
- Re-flushing and re-testing are appropriate.
- If persistent, replacement or upstream investigation is recommended.

This finding cannot be identified through material records or visual inspection alone. Nor can swab-only testing determine whether the positive result originates from copper substrate or migrated lead, Figure 16.

ERT Positive COPPER + Swab Negative LEAD
Copper, No Detectable Surface Contamination

This represents a stable and low-risk condition.
- Material confirmed copper.
- No accessible surface lead detected.

Implications:
- No action required.
- Inventory as non-lead copper.
- Good scan.

This is the ideal confirmation scenario for copper services.

IV. PLASTIC SERVICE LINES (HDPE, PEX, PVC)

Plastic pipes are non-conductive and inert with respect to corrosion. However, biofilm formation and particulate migration can result in surface-bound lead deposition.

ERT Positive PLASTIC + Swab Positive LEAD
Plastic with Deposited Lead Particulates

ERT confirms the pipe is plastic.

A positive swab indicates:
- Upstream legacy lead exposure;
- Biofilm adsorption of particulate lead;
- Entrapped scale fragments;
- Disturbance-induced particulate transport.

Plastic does not generate lead internally. Therefore, any positive swab reflects migrated contamination, Figure 17.

Implications:
- Re-flush and re-test recommended.
- Investigate upstream infrastructure.
- If persistent, further action warranted.

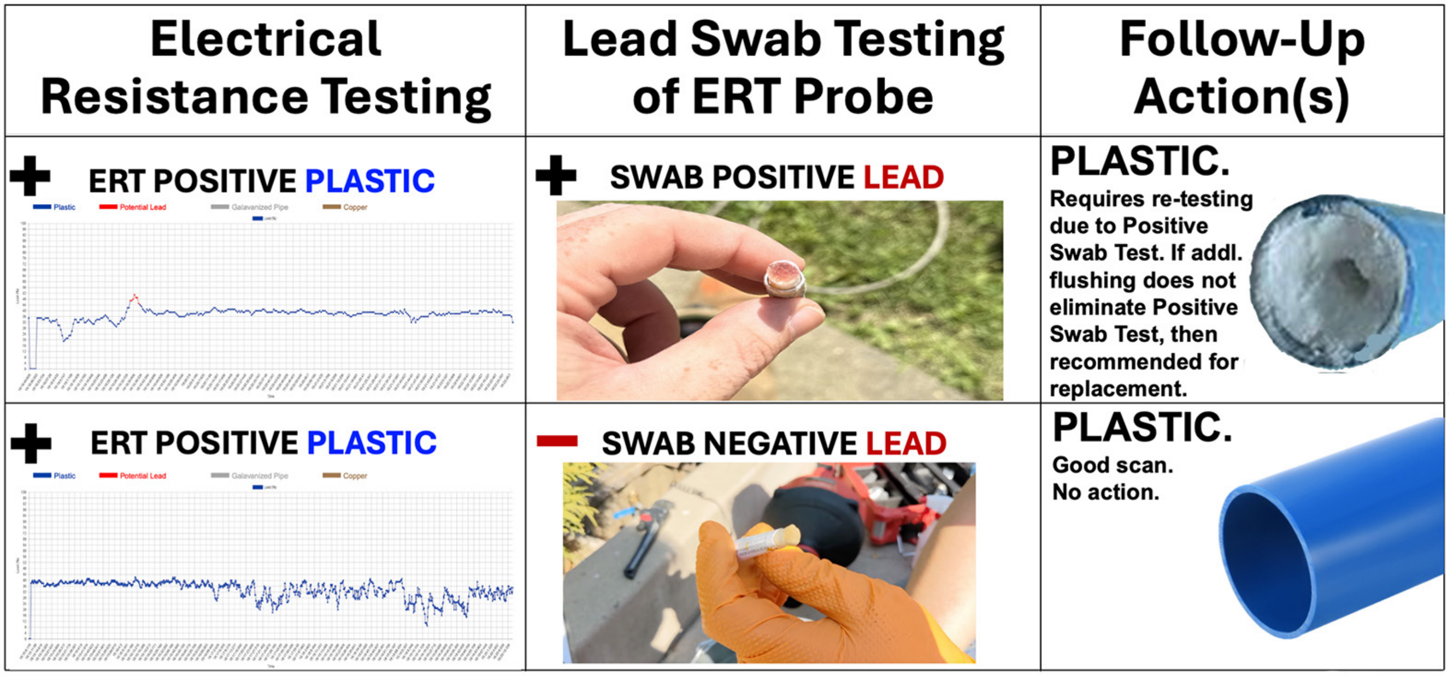
Swab-only testing would detect lead but could not determine that the substrate is plastic. ERT clarifies that the pipe itself is not a lead source.

ERT Positive PLASTIC + Swab Negative LEAD
Plastic, No Surface Contamination This is a low-risk and stable condition.
- Substrate non-metallic.
- No detectable surface lead.

Inventory classification: Non-lead plastic. No action required.
Why ERT + Swab Testing Is Superior to Swab Testing Alone? Swab-only testing lacks substrate context. It cannot:
- Differentiate lead pipe from copper pipe with deposited lead;
- Detect lead substrate masked by orthophosphate coatings;
- Identify mixed-material transitions;
- Confirm non-lead status along the full pipe length.

ERT provides full-length material confirmation. Swab

Figure 17. Plastic ERT + Swab Test Results



testing adds surface contamination insight. Together, they create a two-dimensional diagnostic:

1. Material Identity (Structural Risk)
2. Surface Condition (Exposure Risk)

This integrated framework allows utilities to:

- Distinguish between lead hazard & surface deposition;
- Prioritize replacement more intelligently;
- Evaluate corrosion control effectiveness;
- Detect disturbance-related particulate migration;
- Reduce misclassification risk.

Most importantly, it reinforces a critical principle supported by modern research were pipe material identity and lead exposure risk are related but not synonymous. The dual-testing approach makes that distinction measurable, defensible, and actionable.

3.6 Scientific and Operational Context

Peer-reviewed research (e.g., Salehi et al., Journal of Hazardous Materials; Environmental Pollution) demonstrates that lead particulates can accumulate on plastic and copper plumbing surfaces through biofilm formation, scale entrapment, and water chemistry interactions, particularly in hard water systems. These findings underscore the need to assess both material identity and surface deposition risk, Table 2.

3.7 Strategic Implications Under LCRI

With 66,409 water systems reporting over 100 million service lines—and nearly 24 million still classified as unknown—utilities require approaches that are:

- Scalable
- Defensible
- Cost-effective
- Minimally disruptive
- Scientifically grounded

Hydro-excavation and predictive modeling were widely adopted because they were immediately available, regulator-accepted, and deployable at scale under time pressure. However, their inherent limitations highlight the need for

Table 2. Comparative Summary

Method	Strengths	Weakensses
Visual Inspection	Inexpensive, fast, manual labor can easily complete	Unreliable, incomplete, doesn't test underground piping
Hydro-Excavation	Visual confirmation; regulator familiarity	High cost; limited exposure area; disruptive; no surface contamination insight
Predictive Modeling	Scalable; low cost; useful for prioritization	Probabilistic; dependent on data quality; no physical confirmation. Misses multiple pipe materials
ERT + Swab Testing	Full-length material profile; non-destructive; surface lead assessment. Accurate, cost-effective	Proprietary equipment. Requires trained operators

integrated approaches that combine material confirmation with surface contamination insight.

The dual ERT + swab protocol represents an evolution in inventory methodology, designed to address both infrastructure classification and exposure risk within a single inspection workflow.

4. Methodology

4.1 Field ERT + Swab Testing Protocol

1. Water is turned off and meter removed from setting.
2. ERT Scanning: A SWORDFISH probe is inserted to the service line interface and an electrical resistance profile is captured from the meter to the main.
3. Swab Collection: Immediately after ERT, a surface contact swab is taken at the probe contact point.
4. Water service line flushing in accordance with AWWA 810 standards.
5. Complete entries into the mobile ERT app and upload all testing results and photos to the Electro Scan Amazon Web Services (AWS) cloud application.
6. Swab Analysis: Swabs are processed using EPA-approved field test kits or laboratory confirmation, depending on territory protocols.
7. Dual Classification: The service line is assessed by:
   - o ERT material signature
   - o Lead presence or absence on swab

4.2 Quality Assurance

Field crews follow a standardized Field Standards and Practices (FS&P) manual, approved by multiple state EPAs, including Maryland and Pennsylvania, including equipment calibration checks, new probe installed for each home to limit cross-contamination, and swab test verification, to maintain high data quality across jurisdictions.

5. Data Summary

Across ~20,000 inspections:

- ERT signatures consistently identified pipe material with high resolution.
- Surface swab results correlated with ERT signatures in expected patterns (i.e. lead pipes with lead swabs; non-lead with non-lead swabs).
- Non-lead materials with positive swabs were observed in multiple contexts:
  - o Copper services adjacent to legacy lead goosenecks,
  - o Plastic services downstream of known lead mains, and
  - o Scale and biofilm traps harboring lead particulates.

These data highlight that material identification alone does not capture lead exposure risk.

6. Correlation Analysis

6.1 True Positives (ERT Lead + Swab Lead)

Service lines with conductive signatures consistent with lead and confirmatory swab results. In all regions, this correlation supports the validity of ERT for identifying lead service lines.

6.2 Discordant Cases (ERT Non-Lead + Swab Lead)

A significant minority of inspected lines classified as copper or plastic by ERT yielded positive swab results. These cases often correlated with:

- Known legacy lead infrastructure upstream,
- High hard water conditions, and
- Evidence of particulate migration & scale accumulation.

This pattern aligns with literature demonstrating deposition of lead on non-lead interiors.

6.3 Discordant Cases (ERT Lead + Swab Negative)

The inverse scenario suggests potential surface masking due to water chemistry (e.g., orthophosphate treatment) or sampling limitations. In such cases, the material classification retains priority, but swab results prompt repeat testing, additional flushing or descaling, and follow-up.

7. Discussion

7.1 Why Dual Testing Matters

ERT alone provides a material classification, whereas swab testing provides surface contamination evidence. Combining both strengthens the interpretive context, enabling:

- Identification of latent lead exposure risks
- Enhanced prioritization for replacement
- Defensible documentation for compliance reporting
- Reduced uncertainty in inventories

Given widespread findings of lead deposition on apparently non-lead pipes, dual testing addresses a critical gap in current practice.

7.2 Implications for Utilities and Stakeholders

Utilities relying solely on visual inventories or limited excavations risk underestimating exposure risk and misrepresenting results with false:negative findings, when pipes may be required to be replaced.

The combined ERT + Swab approach supports:

- More accurate inventories
- Better resource allocation
- Improved public communication
- Alignment with health protection objectives

8. Conclusion

The correlation of ERT signatures with surface lead swab results across nearly 20,000 inspections demonstrates that:

- Electrical resistance scanning is a robust tool for material classification.
- Surface lead presence can occur independently of host pipes
- Dual testing provides a more complete risk profile than either method alone.

This integrated approach supports defensible, data-driven decision making in service line inventories, replacement prioritization, and exposure mitigation.

9. Next Steps

Future efforts should include:

- Statistical modeling of ERT/Swab correlation metrics
- Refinement of predictive thresholds

- Expanded laboratory confirmation protocols
- Peer-review publication of aggregated datasets
- Investigation of upstream asbestos cement pipe installed having known lead-sealed joints
- Adoption of a time-of-survey water quality test kit to validate household lead severity.
- Testing of post-1986 home construction where underground pipes may have been installed prior to 1980.

Recent testing has shown positive lead reading for tap water (both at stagnation and post-survey/flushing) where no galvanized, lead, or lead goosenecks were immediately located upstream of a service address; however, asbestos pipes with possible lead joints may have contributed to the lead readings. As a result, additional lead testing may be needed in water mains.

10. Special Recognition

The authors gratefully acknowledge the help and support of the homeowners and administration of the City of Baltimore Department of Public Works, MD; especially, Paul Sayan, Deputy Bureau Head, Bureau of Water and Wastewater, City of Baltimore Department of Public Works.

Electro Scan Inc. was awarded a $7.6 million purchase order in July 2024 to conduct a 10,000 home door-to-door inspection of buried water services for using the company's SWORDFISH solution and supporting cloud-based field applications, Figures 18 & 19. The data from Baltimore and other communities has become an invaluable reference point to fine-time field procedures and homeowner communications, to identify and remediate lead water service lines and galvanized requiring replacement pipes.

11. Final Thoughts

The purpose of this white paper is not to disparage previously accepted methods to inventory water service lines. Instead, the authors recognize that technological innovation often brings new capabilities and features that may highlight improvements from previous methods.

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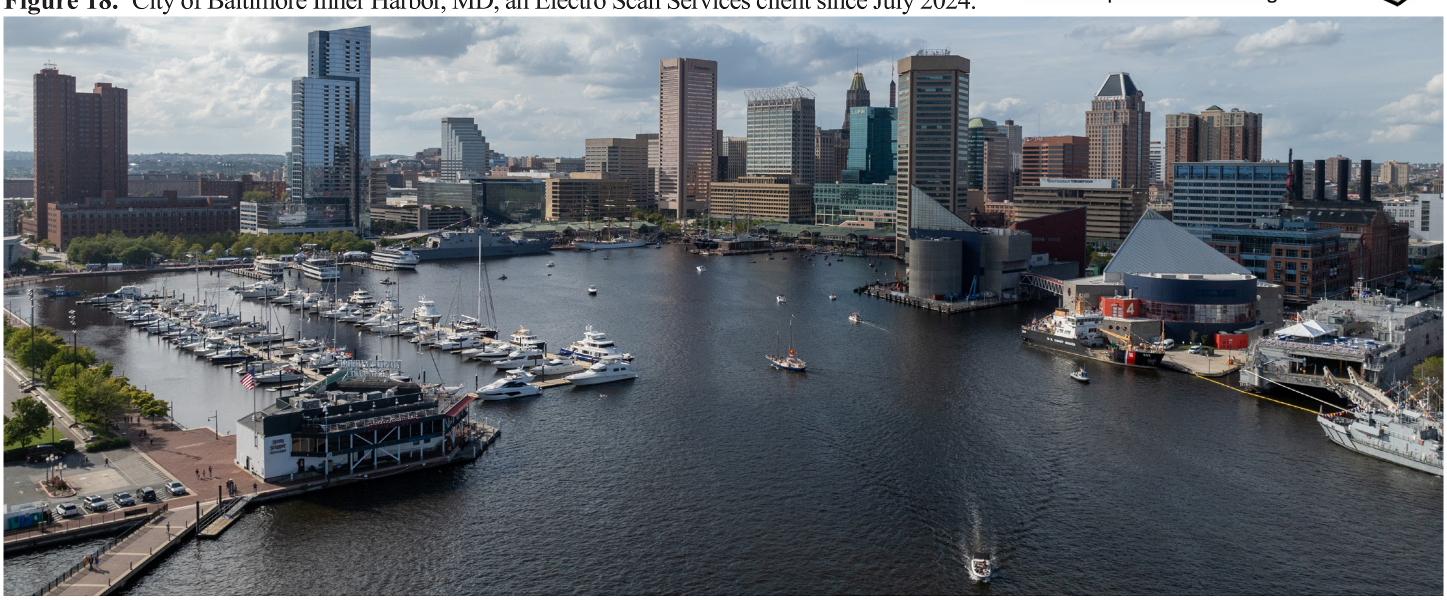
Figure 19. City of Baltimore homeowner inspection protocol.

Figure 18. City of Baltimore Inner Harbor, MD, an Electro Scan Services client since July 2024.



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