Cast Iron Pipe Failure: Elements of a Forensic Investigation

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ABSTRACT

Cast iron pipe (CIP) failures are not uncommon among residential homes; however, many sanitary sewer investigations are improperly considered or performed. CIP was the primary material for sanitary plumbing systems. Over time they deteriorate leading to leaks, blockages, and potential backups that may result in damage within a home. The paper examines a comprehensive list of tasks that are key to an effective investigation. The investigation includes the site inspection, evidence documentation, sampling and testing, corrosion analysis, hydrostatic testing, environmental factors, sanitary drain maintenance and materials quality and installation. Damage from CIP releases in the living space range from subtle to catastrophic depending on the volume and duration. Visible damage is expressed as tile staining, thickness swelling, plumbing and electrical component corrosion. These observations can reveal whether a loss occurred or reveal the absence of damage. This perspective provides a basis for a sound analysis and proper evaluation.

INTRODUCTION

CIP obstructions and failures challenge insurance representatives, plumbers, and engineering experts because concealed pipe damage cannot be easily documented and circumstances that engineers and other experts contribute to pipe failure are not widely understood. When sanitary CIP backups, blockages, and stoppages occur among pre-1970's homes, they are often attributed to defects that diminish waste transport. When these types of events occur, a physical/video pipe evaluation is required. Pipe corrosion is complex and involves biological, chemical, and physical factors that change the exterior and interior pipe surfaces. Environmental factors that contribute to stoppages are often not considered. Developing a supportive or defensible pipe failure argument requires documentation of field observations, measurements, and details about the physical layout of the plumbing, the plumbing fixtures affected, pipe materials, construction, previous repairs and estimates of the time required for a material failure.

SITE INSPECTION, DOCUMENTS, AND RECORD KEEPING

A comprehensive and defensible opinion begins with a thorough visual inspection of the cast iron pipe and plumbing components. Document the location, extent, and type of failure (*e.g.*, cracks, corrosion, joint separation). Note any potential water damage or structural issues caused by the failure. There is no substitute for gathering all available relevant documents, including construction plans, maintenance records, and permits related to the cast iron and other pipe materials pipes used for repairs in question if available. The following information will support the findings of your evaluation.

- Perform a visual and/or video examination of the sanitary drain line.
- Prepare a drain system diagram and locate all the drainage fixture units (DFUs). Mark the pipe diameters, system changes, and additions. Opine whether each linear pipe section is properly sized and pitched.
- Review records of past inspections, repairs, alterations, or section replacements.
- Identify the recommended water use characteristics for each DFU and determine if the pipe sizing and design were appropriate for the intended use.
- Estimate the drain system's age based on the home's age and materials. (Differentiation in the pipe joining method would indicate repairs, alterations, or additions.)
- Calculate whether the pipe diameter(s) are appropriate for the load characteristics.
- Opine whether solids evacuation is influenced by the design, waste management or both.
- Identify whether the flow characteristics are influenced by abrupt corners, pipe buildup, flat runs, or irregular fittings.
- Classify the failure characteristics associated with the operator's waste management (*i.e.*, grease, solids accumulation, and how these factors contributed to the backup, overflow, or failure).
- Determine whether the system meets the building code that was in place at the time of construction or alteration.

Sampling and Testing: Photograph and/or collect samples from failed and nearby pipes that appear to be in poor condition should you foresee their use in litigation. Document the pipe's internal and external coatings. Inspect the pipe for uniformity in thickness and evidence of corrosion penetration. Inspection is more easily accomplished in exposed pipes or in crawl spaces. Concealed drain lines will require sewer video inspection**.**

Load Analysis: "Load" in residential plumbing refers to the number of DFUs (toilets, bathtubs, sinks, and washers). These fixtures contribute solids and liquid wastes that guide water flow and produce the load effect on the plumbing system. The drainpipe's internal diameter is selected based on the intended volume of water and solid matter it can effectively transport. A two-bath home with a kitchen, laundry, and two bathrooms is usually constructed with a 3-inch diameter drainpipe under the home while a 4-inch drainpipe outside the home is used as the building sewer before connecting to the municipal sanitary sewer line or septic tank. The smaller the load, the poorer the waste transport. A one-bedroom, one-bath home would not benefit from a 4-inch diameter drainpipe because the waste volume generated is not sufficient to create turbulent flow to sweep the waste to the termination point. Load is particularly important when garages or room additions are converted to living quarters to accommodate tenants or elderly parents. More DFUs may exceed the original design capacity and amplify the impact of pipe surface obstructions and create overloads. The relationship between the discharge volume flow and DFUs is not uniform but varies with the number and operation of fixtures. Interpretation of sanitary overflows and obstructions should consider the mechanics of waste transport as well as the occurrence of irregular interior pipe surfaces. These considerations are also applicable to homes with septic tank and drain field sanitary waste systems.

CIP Failure: Cast iron sanitary drainpipe is referred to as high carbon content gray cast-iron. When a high-carbon cast-iron pipe corrodes it forms an insoluble graphitic layer. These corrosion products are very dense and form a barrier against further corrosion. In tests of a severely corroded cast-iron pipe, the graphitic corrosion product has withstood pressures of several hundred pounds per square inch even though the corrosion had penetrated the pipe wall (**Photo 1)** (CISPI handbook).

Corrosion Analysis: The most common change inside CIP is tubercle formation. Tubercles are formed from ferrous oxide in the water not CIP corrosion (Larson and Skold, 1957). Rather than the pipe materials being "removed" as occurs with corrosion, the tubercles are biologically deposited on the pipe walls. The tubercle begins with bacteria that form a bacterial slime layer that incorporates manganese and iron in the water. The slime layer accumulates over time, and the reddish-brown products solidify and reduce the interior pipe diameter and flow capacity. Tubercle thickness inside a pipe does not reflect the extent of pitting on the pipe wall surface. The tuberculation and accumulation can be removed by proper cleaning without affecting the pipe's structural integrity. When investigating CIP failure, consider the contribution and extent of the type of corrosion present in the pipe. Galvanic, pit, microbial, erosion, graphitic, stress crack related, or corrosion may require different investigative approaches. Consider the influence of municipal water chemistry, native soil conditions, or the changes induced by stray electrical currents.

Photo 1: An example of graphitic corrosion with distinctive tubercle formation

Photo 2: Arrows point to graphitic corrosion that penetrated the pipe wall

Graphitic Corrosion: This is a form of galvanic corrosion that occurs in wet or moist environments where water acts as an electrolyte and allows a weak electrical current created by dissimilarities in the iron and graphite to remove the iron from the more cathodic graphite (Logan *et al.,* 2014). The arrows identify where the graphitic corrosion has penetrated the pipe wall **(Photo 2).** When the accumulated material on the pipe interior is removed, the exposed graphitic material has a grayish-black irregular glassy finish. As the graphitic corrosion continues over an extended period, the pipe will eventually lose its structural integrity and be subjected to erosion corrosion.

Pinhole Corrosion: This type of galvanic corrosion occurs where the corrosion cell is localized to an unprotected area of the pipe. Corrosion will progress until the pipe is penetrated and can be seen on the outside **(Photo 3).** This corrosion usually precedes other types of CIP corrosion. Water from a sanitary system that escapes the pinhole leak will contribute nutrients to the surrounding soil and encourage bacterial growth and biomat formation.

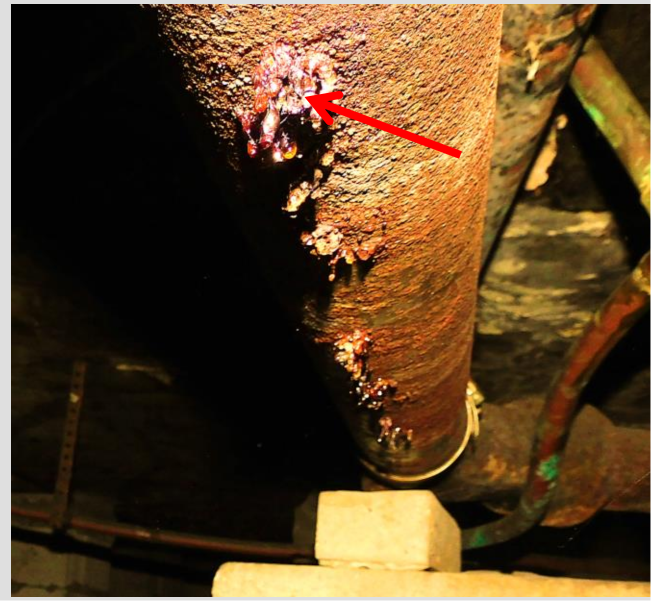


Photo 3: Pinhole corrosion is localized to a particular unprotected area of the pipe

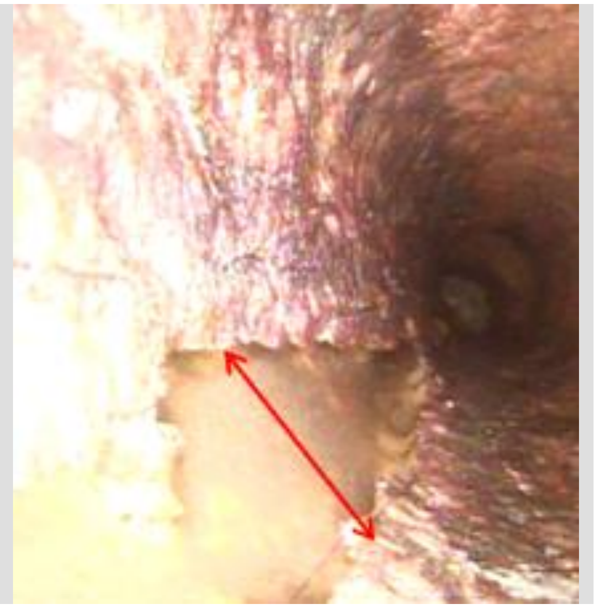


Photo 4: Erosion corrosion occurs when turbulent flow erodes the pipe bottom

Erosion Corrosion (EC): This is a consequence of turbulent water flow that erodes the bottom of the pipe at a greater rate than the sides **(Photo 4).** Erosion corrosion also exacerbates graphitic corrosion as the graphite that's left after the leaching of the ferrous material has progressed to the point where the softer graphite is more impacted by the turbulent flow. This is a very long-term event and is not representative of a sudden catastrophic failure of the cast-iron pipe. The EC rate is accelerated by turbulent flow. EC creates thinning along a narrow area along the bottom of the pipe **(Photo 5).** Thinning creates local areas of increased turbulence that increases the corrosion rate. The EC process leads to "channel rot" which causes holes and breaches on the bottom of the pipe as EC progresses.

Stress Crack Corrosion: This corrosion can occur due to several different factors including latent manufacturing defects, material handling, and installation errors as well as from a slow progression of environmentally induced corrosion over time combined with mechanical stress and corrosion reactions **(Photo 6).**

Photo 5: Erosion corrosion and channel rot

Photo 6: Stress crack corrosion

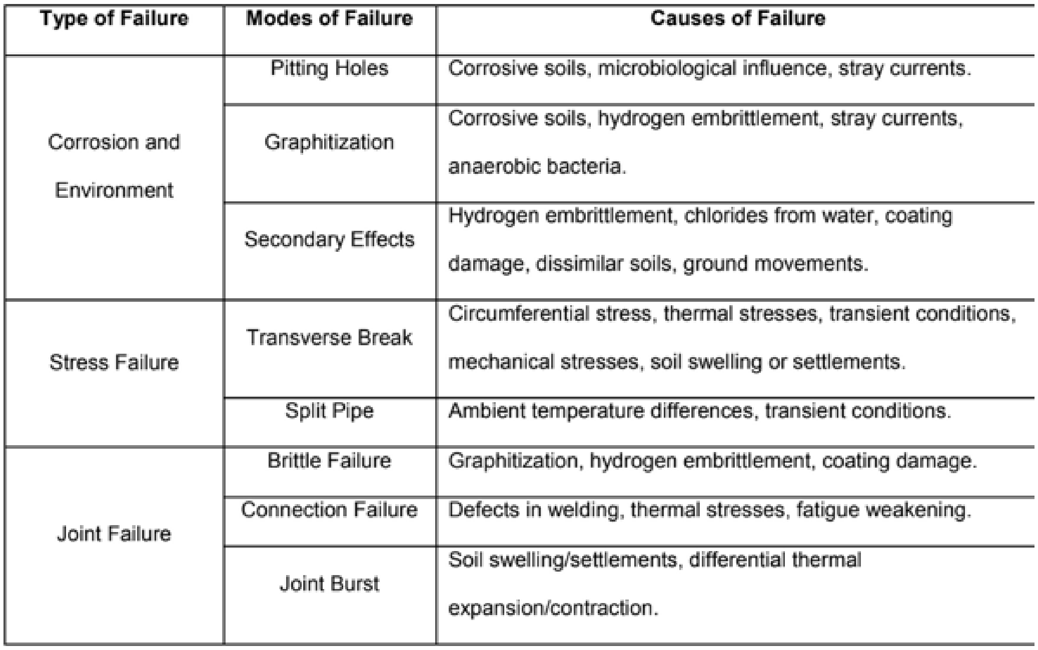
Hydrostatic Testing: CIP failures often support claims that the discharged effluent penetrated surrounding soils and caused structural damage to the fill beneath the slab. CIP hydrostatic testing is conducted to determine if the claim is valid or not. Hydrostatic testing involves purging, and then filling the pipe system with water to create a static head pressure. After the pressure and liquid levels reach equilibrium in site tubes, the liquid levels are examined for evidence of leakage over a 20-to-30-minute period. The accuracy and reliability of the test method lies in the details.

Proper implementation of a hydrostatic test requires that plugs be inserted through test tees or fixture inlets to isolate each pipe section under evaluation. All other openings are tapped with test plugs to ensure a competent seal before water is added to the desired hydraulic head. The addition of water to the system should be performed slowly to ensure that all air escapes from the system and to prevent air capture during filling. This technique will avoid the potential for air compression that causes inaccurate test results.

The ability to distinguish a valid and invalid hydrostatic test is critical to interpreting the water level measurements and providing an accurate interpretation of the system. After the water levels have reached equilibrium in at least two locations, the test is considered valid to begin. If the water level drops after full equalization, then the test is also considered valid with the identification of a leak. The crucial element in performing a competent hydrostatic test is patience. During the initial stage of testing before the water has reached equilibrium, it may be concluded that the pipe system leaks. This conclusion may be premature if the observer renders a conclusion before the water is fully equalized. A successful hydrostatic test requires proper care in the test preparation procedures and conducting the test protocol.

Environmental Factors: Many conditions can affect CIP integrity after installation. Structures built over formerly contaminated commercial, industrial, or mined areas may contain aggressive subsurface conditions (Doyle *et al.*, 2003). Soil composition, temperature fluctuations, and chemical exposure are candidates that affect pipe integrity. Resource Conservation and Recovery Act (RCRA) files at your local or state environmental agency will identify waste disposal sites, pipe spills, and waste cleanup activities that affect CIP.

The depth of soil overburden can create compressive forces that affect the structural integrity of the pipe and its connections **(Table 1).** Soil overburden depth is often modified after construction during landscaping, piping installations for new construction (swimming pools), and modifications in surface drainage to retain or discharge rainwater.



Type of Failure	Modes of Failure	Causes of Failure
Corrosion and Environment	Pitting Holes	Corrosive soils, microbiological influence, stray currents.
	Graphitization	Corrosive soils, hydrogen embrittlement, stray currents, anaerobic bacteria.
	Secondary Effects	Hydrogen embrittlement, chlorides from water, coating damage, dissimilar soils, ground movements.
Stress Failure	Transverse Break	Circumferential stress, thermal stresses, transient conditions, mechanical stresses, soil swelling or settlements.
	Split Pipe	Ambient temperature differences, transient conditions.
Joint Failure	Brittle Failure	Graphitization, hydrogen embrittlement, coating damage.
	Connection Failure	Defects in welding, thermal stresses, fatigue weakening.
	Joint Burst	Soil swelling/settlements, differential thermal expansion/contraction.

Table 1. Summary of contributing environmental sources of CIP failure (Vipulanandan *et al.*, 2012 and Doyle, 2000)

Waste Discharge Practices: Household waste management activities can range from normal household wastes to industrial depending on occupant activities. Chemical resistance guides provide ratings of Excellent, Good, Conditional and Unsatisfactory for various pipe materials including ductile and cast iron exposed to a multitude of chemical agents (www.tylerpipe.com). Agents that could be found in a residential home and were assigned an Unsatisfactory resistance rating were as follows: apple juice, beer, bleaching water, Clorox®, citric acid, citrus juices, coffee, deionized water, photo developing solutions, gelatin, hydrogen peroxide, inks, ketchup, milk, salt brine, sauerkraut brine, sea water, and sulfuric acid. When appropriate, inquire as to the nature of household waste to determine whether discharge practices may have affected the CIP integrity.

Maintenance and Inspection Procedures: Municipalities regularly conduct maintenance and inspections that are documented in service records. Alterations made to municipal sewer lines that are reported by homeowners may lie within or outside (municipality) the property owner. All changes and alterations will be described in municipal records and may serve to understand historical changes that occurred prior to a reported loss and distinguish proper coverage. Documents that describe historical sanitary pipe blockage concerns, requests for water supply cutoffs, and maintenance to water service lines may prove helpful. Inquire as to the "call in" logs for a particular address. These records will provide a chronology of events that separate homeowner plumbing and municipal-sewage related events such as reported waste stoppages and discharge deficiencies. Inquire about the use of chemicals marketed to unclog sanitary drain lines. These generally ineffective methods pose a safety concern and provide a perspective as to how long the homeowner has experienced the problem.

Material Quality and Installation: CIP vary in quality depending on the manufacturer, material specifications and compliance with industry standards. Inquire as to the manufacturing location. Industry standards for uniformity in interior pipe diameter, pipe thickness, and connections vary by country. Imported CIP from Venezuela, for example, may contain wide variations in pipe thickness depending on where the pipe is cut. This factor introduces unexpected variability in pipe coupling.

INVESTIGATING INTERIOR WATER DAMAGE

Investigators identifying interior building and contents damage are posed three questions: 1) When did the loss occur? 2) What was damaged? and 3) Did the loss occur once or multiple times? A CIP loss prompts concern about interior contents, building material damage, and bacterial contamination. When a medical interpretation is requested, only a qualified medical professional should respond. Investigations undertaken immediately after a sanitary system overflow are self-evident with black or rust-colored discharges of liquid and solid wastes within and surrounding the commode, tubs, shower stalls, sinks, and adjacent rooms. Under these circumstances loss confirmation is unnecessary. However, most often the site investigation is scheduled months or even years after the loss, and the structure may have undergone complete remediation. Assuming that some or all the original building materials and contents are present, you will need to employ methods that document subtle changes among metal and wood materials to establish if the release occurred and the extent of its impact.

Distinguishing whether water damage has occurred depends on the presence of absorptive materials such as solid and composite wood products (*i.e.*, hardwoods, particle board, oriented strand board, medium density fiberboard), carpet tack strips, and solid and laminate flooring. Accurate measurements of swelling obtained using a micrometer are persuasive when measurements are obtained from damaged and control materials to confirm the occurrence and locations of sanitary waste contact. Floor tiles, concrete surfaces, vinyl flooring, and trim usually express little to no change other than light stain discoloration. However, physical measurements from several absorbent building materials provide quantitative evidence to support a defensible CIP release investigation.

Health and Safety: Sanitary waste investigations require personal protection equipment (PPE) because the investigation may require intimate proximity to building materials and biological wastes. Discretionary use of a Tyvek® suit, gloved hands, booties, and knee pads will prevent hand-to-mouth transfers and minimize the transport of bacteria and organic debris onto clothing, vehicles, and homes. Immunizations for tetanus, Hepatitis A&B, polio, typhoid fever should be considered. Where opposing experts did not use PPE, inform counsel, and leverage your use of PPE should the opposing expert emphasize the serious health threat posed by the CIP overflow.

Prepare a Floor Plan: A floor plan can document the loss extent and identify the findings. Should the loss proceed to litigation, floor plans guide the mediator or jury to envision the loss and locate your findings within the structure.

Carpet Tack Strips: Carpet tack strips provide a sensitive indicator of moisture exposure. Depending on the degree of discoloration and deterioration, estimates of the exposure duration can be made (Nehrig and Moon, 2018). Using pliers, pull back the carpet in affected (test) and unaffected rooms (control) and compare the degree of discoloration. Carpet tack strip discoloration can confirm the extent of wastewater migration and identify historical releases that may be unrelated to the reported loss.

Wood Flooring: Flooring materials (*i.e.,* laminate, engineered, solid hardwood, and bamboo) express varying degrees of damage depending on the promptness of waste removal and the drying efforts conducted. Laminate flooring is a high-density fiberboard (HDF) "wood like" appearing laminate that is manufactured in four layers pressed together. The inner core is wood pulp and prone to moisture absorption. Sanitary overflows and remediation efforts cause laminate flooring to swell though the surface may appear unblemished (Wells *et al*., 2022). Engineered wood flooring is manufactured using three to five ply layers and appears like plywood in cross section. Engineered flooring is stable and will neither cup nor express visible changes after days and weeks of exposure. Bamboo flooring is constructed in a horizontal or vertical orientation that are glued together to form floor planks. Bamboo expresses surface splitting between seams following moisture exposure**.** Hardwood flooring tends to "cup" within a few days of moisture exposure and express a slightly darker surface appearance**.** Where appropriate, document flooring materials from both affected and unaffected areas of loss for thickness measurements and appearance comparisons.

Vinyl Flooring: Vinyl and "luxury vinyl" flooring serve as competent vapor barriers. With the exception of surface staining or pink discoloration (mold growth) there may be no expression of water exposure. Vapor drive (water vapor migration from high to low concentration) causes vinyl flooring to capture moisture between the concrete foundation and the flooring whether a release occurred or not. Floor moisture surveys can deceive an investigator by indicating excessive moisture accumulation beneath the flooring when it is often a normal consequence. When water losses occur on vinyl, excess moisture is exhibited through the butted joints because they offer no impedance to the upwards moisture movement.

Floor Tiles: A sanitary overflow should express no changes to a tiled floor. Evidence of tile separation from the underlying thin set *via* tile tapping is associated with installation errors or conditions that preceded the CIP loss. Among seven floor tiles (*i.e.*, ceramic, travertine, marble, porcelain, limestone, sandstone, and slate) tested for movement following immersion using strain gauges, only marble and sandstone exhibited movement (± 75 microstrain [με]) above ambient control conditions (Wells *et al.*, 2019). A CIP sanitary release is not expected to cause any changes in tile bonding near the release. Evidence of tile unbonding (thin set separation) is a condition attributed to improper installation practices. Surface discoloration of the tiles and grout lines and tile trim separation can be caused by repeated CIP overflows; however, grout coloration in proximity to a CIP release should be compared to conditions in unaffected areas.

Wood Cabinetry: Sanitary drain releases can cause swelling, separation, and discoloration when they contact wood cabinetry**.** Solid wood and plywood cabinets express fewer damaging moisture effects than particleboard or medium-density fiberboard (MDF) materials (Davis and Moon, 2015). Use a micrometer to measure the material thickness of cabinet panels near the floor to provide a quantitative comparison to measurements obtained several feet above the floor or from identical cabinets positioned outside the CIP release. Comparative photographic measurements from control and test cabinets help identify the occurrence and extent of loss (Moon, 2012).

Solid Wood Furniture: Sanitary pipe releases will stain cabinet panels and furniture legs along the lower ¼ to 1-inch. Plywood paneled contents will express an irregular absorption line and elevate the depth perception of the release. Stain height on solid wood furniture legs will obtain a more precise measurement of the release depth.

Metal Components: Research conducted on a variety of metal bathroom (*i.e.,* cabinet door hinges, sink fasteners, galvanized electrical conduit, junction boxes) and plumbing components (*i.e.,* sink drain and garbage disposal assemblies, angle stop valves, and escutcheon plates) revealed corrosion when they were continuously or repeatedly exposed to liquid water for extended periods (> 200 days) (Wells *et al.*, 2018, 2022). The research revealed little to no corrosion when exposed to elevated humidity for the same period. CIP releases must contact metal elements for an extended time or during repeated events to initiate corrosion. Visible corrosion on any of these components was consistent with long-term moisture exposure (>11 to 16 months). Metal corrosion could not be attributed to a short-term, one-time sanitary release (< 30 days).

Bacterial Testing: *Escherichia coli* (E. coli) and coliform testing are used to confirm fecal contamination from a CIP release. *E. coli* and coliform bacteria are soil and waterway biota that can be introduced inside a structure by foot traffic and pets (Ishii and Sadowsky, 2008). Bacterial swab sampling should be accompanied by proper control sampling (*i.e.*, field blanks, trip blanks, lab blanks, duplicates) to avoid criticism of sample unrepresentativeness during legal examinations (Hung *et al.*, 2020). *E. coli* sampling is time-sensitive and requires analysis within 24 hours of sample collection to avoid bacterial amplification. Experts should be familiar with proper bacterial sampling and handling procedures before their testimony. A critical element is obtaining bacterial samples in unaffected (control) areas. Because the presence of *E. coli* bacteria is common on many surfaces, the sampling plan should address efforts to avoid cross-contamination.

Infra-red (IR) Thermography: IR camera surveys often accompany CIP releases to identify the extent and confirm evidence of damaged contents. IR surveys should be accompanied by instrument calibration documents and conducted by trained IR users. IR interpretations should be confirmed by a moisture survey. These practices ensure that images obtained from an IR camera are properly interpreted. IR images taken months or years after a CIP release should be viewed with caution since other water releases, exterior water sources, and diurnal temperature fluctuations could produce thermal anomalies that are misinterpreted as excessive moisture.

Floor Moisture Surveys: Floor moisture surveys establish current site conditions, locate recent and historical residual moisture releases. CIP releases prompt allegations that moisture from gravity fed drain lines migrated upwards into concrete foundations causing floor covering and contents damage. Where possible, plot the sanitary drain line locations and depths and obtain detailed floor moisture measurements above and away from the drain line locations. This task will provide a measurable relationship between the sanitary drainpipe location, the extent of the suspected sanitary release, and the foundation interface.

CONCLUSION

Forensic investigations into CIP failures can require a multidisciplinary approach involving material scientists, engineers, and plumbers to uncover the root causes of failure and ensure the appropriate corrective actions to prevent future incidents. A successful courtroom defense will be aided by the breadth of the investigation and the personal strength and passion you exhibit in your findings.

LIMITATIONS

The authors recognize that forensic investigations are limited by time and/or budget. The proposed investigation methods are intended to remind the investigator of the types of procedures that could be performed. Before undertaking a CIP investigation, review the suggested procedures and identify those efforts that you deem most relevant to your situation.

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