# Disruptive Technology Supports Resiliency and Certifies Inflow and Infiltration Compliance

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Coastal communities worldwide are facing documented sea level rise (SLR) as a threat to their critical infrastructure. According to Lindsey (2018), the measured mean sea level in 2017 had risen 3 in. from 1993, and marks the highest level since satellite data collection began in that year. In addition, 2017 was the seventh consecutive year of documented year-over-year increases in SLR, and the 22nd year of that past 24 years where sea levels were greater than the previous year.

Hummel (2018) evaluated coastal wastewater infrastructure systems in the United States and concluded that proactive evaluation programs are an important first step in preparing for anticipated SLR conditions through the 21st century; with existing models predicting SLR to range from 0.66 to 6.6 ft by 2100 (Melillo, 2014).

With the changing climate, impacts to coastal communities will continue to challenge infrastructure operation and maintenance. Coupled with aging wastewater collection systems, the future conditions represent a significant challenge for utility owners, especially where inflow and infiltration (I/I) is reducing the available treatment capacity and unnecessarily increasing electrical demands, chemical usage, and labor costs.

Coastal communities are already being affected by the global SLR phenomena, and those in the state of Florida are especially vulnerable. The Florida counties of Miami-Dade and Broward each have greater populations that reside on land below 4 ft relative to mean sea level than any U.S. state, except Florida itself, and the state of Louisiana (Climate Central, 2018).

The latest "State of the Water Industry Report" (American Water Works Association, 2018) lists the most significant water industry concerns as aging infrastructure renewal/replacement and capital financing for the fourth straight year. This means utility owners must ensure that capital expenditures are prioritized in the most efficient manner.

The use of cured-in-place pipe (CIPP) and other trenchless lining solutions have been used for nearly 50 years. Despite the requirement to submit sample pieces of liners or coupons that contractors are often required to submit with final closed-circuit television (CCTV) videos, many CIPP lining projects are not providing anticipated I/I reductions following rehabilitation.

For over three decades, municipal utilities have relied on CCTV to inspect and certify pipeline water tightness, following rehabilitation and new installation projects, prior to acceptance and warranty expiration. Numerous recent case studies from across the U.S. have documented significant defects from CIPP and similar rehabilitation techniques that had been previously certified as watertight by CCTV inspection, resulting in excessive I/I and its negative consequences.

An innovative technology known as focused electrode leak location (FELL) has emerged that automatically locates and measures defects with precision, quantifying defects that are routinely missed by legacy CCTV inspections. There is no operator interpretation of FELL results, thus delivering an unbiased inspection to utility owners. The U.S. Environmental Protection Agency (EPA) has conducted field benchmarking studies of FELL, and since 2014 has included the technology in consent decrees across the U.S. to verify I/I compliance.

High groundwater conditions, common across much of Florida, make effective, watertight pipeline rehabilitation more challenging, and proper procedures need to be taken to mitigate quality control concerns in the groundwater conditions that adversely affect liner installations. Unfortunately, if appropriate quality control procedures are not taken, or left to a contractor's discretion, the useful service life and/or water tightness of rehabilitated pipelines can be significantly reduced.

It has been well-documented that pipeline defects occur from resin wash out, emulsification, or improper or uneven curing, and are much more prominent in CIPP installations where elevated groundwater levels exist. Recent studies have shown that most defects are nearly impossible to identify using visual technologies, like CCTV alone. Applying FELL technology offers utility owners the ability to precisely locate pipeline defects to within 3/8 in., and then quantify the defect infiltration flow rate, measured in customary units of gallons per minute (gpm).

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Other common construction defects result from poor wet-out, accelerant burn, accidental cutting, incorrect service reconnections, blistering, defective epoxy, delamination, fins and folds, pinholes, defective top-hats, and wrinkles. These common defects are often missed by even the most experienced and certified CCTV operator.

While CCTV is an important tool to document structural and operational items, visual inspection is not sufficient to document pipeline defects, particularly with difficult-to-see porosity in liner systems, often caused by external hydraulic pressure from elevated groundwater conditions. This issue led academic researchers, consulting engineers, and utility managers to seek a new way to certify the water tightness of new and rehabilitated pipes.

## Trenchless Technology Development

The CIPP technology was developed in 1971 in London, England, by Eric Wood. He invented this pipe rehabilitation method to repair a leaking pipe under his garage. He initially named the process *in situ* form, derived from the Latin meaning "form in place." In January 1975, Wood applied for a patent for CIPP lining that was granted in February 1977. Insituform Technologies later commercialized the patent and brought the technology to the U.S. shortly thereafter. Since its inception, CIPP has been widely adopted due to its ease of installation and low cost, compared to dig and replace.

The CIPP can be used to rehabilitate sanitary sewers, storm drains, and pressurized water and gas pipelines. Circular pipe, from 4 to 60 in., and a variety of noncircular pipes, such as egg shapes, ovoids, and box culverts, can be lined. Lining removes the pipe from service for the duration of the CIPP installation and reinstatement process, with bypass pumping sometimes necessary.

Prior to lining, the pipe must be cleaned by jetting to remove corrosion and debris. Protruding lateral connections must also be removed, with some repairs required where the existing pipe is substantially deformed, damaged, or collapsed. After lining, each service connection or lateral must be reinstated before the pipe can be returned to service, usually within the same day. Lined water mains must also be disinfected before returning to full service.

The CIPP liners of nonwoven polyester felt or fiber reinforced fabric are manufactured to fit each host pipe. Liners are typically impregnated with a polymer resin, which creates a lined pipe within the host pipe when cured or cooked. Liners are designed with sufficient thickness when cured to sustain the loads imposed by external groundwater and internal service pressure, soil, and overhead traffic.

Liners are typically saturated with polyester, vinyl ester epoxy, or silicate resin using vacuum, gravity, or other applied pressure. The resin includes a chemical catalyst or other hardener to facilitate curing. The outermost layer of the liner tube is typically coated with a polymer film to protect the liner during handling and installation, with impregnated liner typically chilled for transportation to the jobsite to maintain stability until installed.

In the mid-1990s, patents for CIPP expired, opening up competition from foreign and domestic suppliers. As the number of lining companies grew, the overall cost for CIPP declined. As municipal contracts continued to be awarded to the lowest bidder, requiring only visual inspection to accept a contractor's work, post-CIPP inspection, prior to contractor acceptance, has never been more important.

The American Society of Testing and Materials (ASTM) has established several standards pertaining to CIPP installation, summarized in Table 1.

## Initial Focused Electrode Leak Location Evaluations

Following the 2010 release of *Operation and Maintenance of Wastewater Collection Systems*, Seventh Edition, Volume 2, its primary author, Ken Kerri, Ph.D., P.E., of Sacramento State University, began documenting that pipeline rehabilitation projects using CIPP were not achieving the expected I/I reductions at utilities around the U.S. Since all postrehabilitation inspections were being performed using CCTV, and in preparation for the update to Volume 1 of his manual, Dr. Kerri sought out other technologies that may be applicable to inspect CIPP installations.

Specifically, Dr. Kerri identified and evaluated FELL technology as part of the work to update the Volume 1 manual. In 2011, EPA published "Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems" (Figure 3) where it benchmarked several new technologies, including early versions of FELL. Conducted in Kansas City, Mo., the study verified the use and advantages of FELL technology to consistently find defects missed by CCTV inspection. In 2012, EPA published "A Retrospective Evaluation of Cured-in-Place Pipe (CIPP) Used in Municipal Gravity Sewers" (Figures 2, 4, and 5). As part of the study, independent testing of CIPP was conducted in both large- and small-diameter sewers in two cities: Denver and Columbus, Ohio. The purpose of the study was to determine whether the originally expected lifespan of CIPP (typically assumed to be 50 years) was reasonable, based on the current condition of the liners. Despite the large public investment in CIPP, prior to this study, there had been little quantitative analysis to confirm if structural or operating performance was as expected.

Field samples were retrieved from CIPP linings, along with specific measurements and tests taken to measure liner thickness, annular gap, ovality, density, gravity, porosity, flexural strength, flexural modulus, tensile strength, tensile modulus, surface hardness, glass transition temperature, and Raman spectroscopy.

The report utilized a variety of approaches to evaluate the state of deterioration of previously installed CIPP liners; however, prior to this study, researchers were able to only find scattered efforts that thoroughly evaluated the long-term performance of rehabilitated sewer sections.

Typically, rehabilitated sections of collection systems were evaluated using only visual inspection or CCTV inspection before, and immediately following, the lining of a pipe. After CIPP lining, pipes were often moved to the lowest priority level for ongoing inspection, assuming that CIPP liners were near-new in quality. In general, research staff noted several advantages and disadvantages of CCTV inspection, including:

*Advantages of CCTV Inspection*

- Relatively low cost
- Familiar to agencies
- Can uncover other operating problems (potential blockages)
- Can provide broad coverage of relined sections within an agency leading to statistically meaningful results

*Disadvantages of CCTV Inspection*

- Can only identify deterioration or defects that are easily identified visually
- Liner distortion difficult to identify
- Not possible to evaluate intermediate stages of deterioration

The EPA study also tested several CIPP liners that represented a relatively new, five-year-old CIPP liner installed in an 8-in. clay pipe. Given the recent installation, consultants were able to compare test results from the quality assurance (QA) sample retained immediately following the installation five years earlier. Results were compared to current test results, both in accordance with ASTM D638 and ASTM D790.

It should be noted that many municipal-

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Table 1. Key American Society of Testing and Materials Standards Covering Cured-in-Place Pipe Installations

| | |
|---|---|
| ASTM F1216 | Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube |
| ASTM F1743 | Standard Practice for Rehabilitation of Existing Pipelines and Conduits by Pulled-in-Place Installation of Cured-in-Place Thermosetting Resin Pipe |
| ASTM F2019 | Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Pulled-in-Place Installation of Glass Reinforced Plastic (GRP) Cured-in-Place Thermosetting Resin Pipe |
| ASTM F2599 | Standard Practice for the Sectional Repair of Damaged Pipe by Means of an Inverted Cured-in-Place Liner |
| ASTM D638 | Standard Test Method for Tensile Properties of Plastics |
| ASTM D790 | Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials |

*Continued from page 23*
ities take QA samples or coupons for either laboratory testing or possible warranty claims, but no actual testing had been done on the pipes after CIPP samples had been taken five years earlier. Significant differences were found: testing of the QA coupon from the 8-in. Columbus CIPP liner performed immediately following the installation showed a finished thickness of 7.5 millimeter (mm), but, in contrast, the EPA-funded study showed an average measured liner thickness of 5.72 mm and a design value of 6 mm.

One possible explanation for the difference between the two measurements was that the original QA coupon was taken at the upstream end of the CIPP liner, while the recently exhumed coupon came from the downstream end of the lined pipe. A relatively steep slope (i.e., approximately 8 percent pipe gradient) was also found, which could have resulted in stretching the liner, causing a subsequent thinning of the pipe wall.

Another potential explanation is that QA samples are typically prepared by curing an extension of the liner within the manhole. Since this practice does not have the same installation and curing conditions within the sewer line itself, the study concluded that such samples generally will have higher test results than coupons cut from within a sewer.

## Cured-in-Place Pipe Liner Inspection Improvements

While the EPA study on CIPP concluded that there was "no reason to anticipate that tested liner samples would not last for their intended lifetime of 50 years (and perhaps beyond)," the study did not address or attempt to quantify the severe degradation in operating performance of the postrehabilitation pipe where break-ins, root intrusions, and other failures were found.

Also, shortfalls in CIPP liner wall thickness measured for most of the liners, coupled with the differences in results from QA coupons taken within a manhole, pointed to the need to develop better nondestructive tests for assessing the acceptability of newly installed CIPP liners, and then tracking their deterioration over time.

Researchers were disappointed to find that commercially available ultrasonic thickness gauges did not work adequately on field CIPP samples, even though they gave good results on laboratory-prepared samples with moderate thickness. The report went on to describe issues encountered with the use of ultrasonic thickness probes used on field samples.

The inability of commercially available tools to measure the thickness of large-diameter CIPP liners from the inner surface only (an important QA issue because large diameters are prone to thickness variation around the circumference) is a clear call for the need to develop new technologies to accomplish this task in a cost-effective and reliable manner.

It was also noted that significant differences existed in data reported from QA and quality control (QC) testing at the time of installation when compared with data from tests conducted by different laboratories. This suggested that more attention needed to be done on documenting and reducing the variability of test results derived from coupon recovery procedures and comparing test results from different laboratories.

Finally, the report stated that "while liner cross sections should continue to be laboratory-certified, long-term operating performance of CIPP may not be assured, especially if proper installation and inspection protocols are not satisfied."

## New Nondestructive Testing Methods

The FELL technology was first offered as a commercial service in 2012 for gravity pipes up to 8 in. in diameter. In 2013 the technology was further developed to retrofit existing CCTV trucks, with the ability to inspect pipes up to 66 in. in diameter. The FELL technology provides an automatic and unbiased identification of pipeline defects where water can pass through the wall of a nonmetallic or coated metallic pipe. The technology principle is that if pipe wall defects exist that allow an electric current to pass through, then the pipe will leak water. Using a focused alternate current (AC) band, each pipe wall defect is located, quantified, and tabulated in real time and presented in a summary report for each individual defect in a pipe segment.

The FELL technology can be used in five important ways:

1. Establish baseline defect flow conditions to prioritize a rehabilitation program.
2. Overcome shortcomings of visual observations and cataloging defects using CCTV cameras.
3. Quantify specific flow reductions from repairs, relining, and renewal projects by testing lines before and after rehabilitation.
4. Establish minimum allowable standards for defect flows.
5. Certify that postrehabilitated repairs, relining, and renewal of pipes conform to the owner's contract specifications.

Figure 1 depicts a schematic cross section of the FELL process.

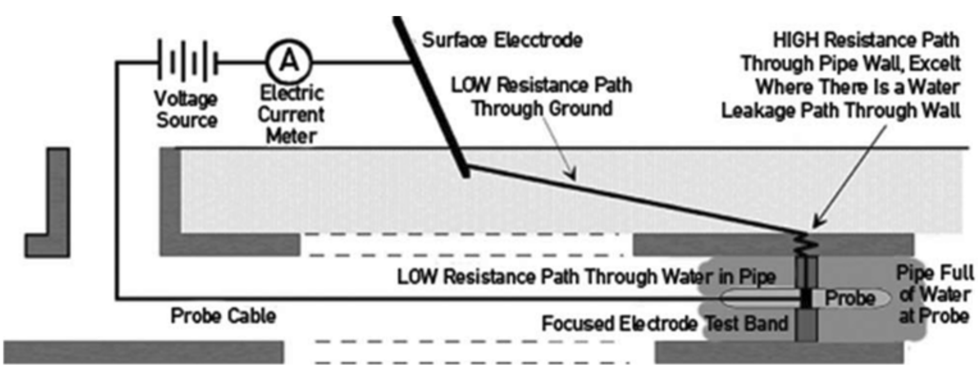


Figure 1. Schematic of a Simplified Electrical Scanning Circuit in a Nonconductive Pipe

## Publication of ASTM F2550-13 and ASTM F2550-18

In 2013, ASTM International ratified and published ASTM F2550-13, *Standard Practice for Locating Leaks in Sewer Pipes by Measuring the Variation of Electric Current Flow Through the Pipe Wall* (Figures 8, 9, and 10). Managed by ASTM Committee F36, ASTM F2550-13 had been previously issued in 2006 as ASTM F2550-06. Building on its earlier scope, terminology, significance, use, principle of operation, apparatus, field procedures, and reporting, the 2013 version was modified to state the following:

"It is recommended that separate scanning tests be taken before and after any pipe repair, relining, or renewal activity to compare electrode current values, and for closed-circuit television (CCTV) video to re-examine pipes to determine if any visual defects were missed or not recorded during initial examination."

The 2013 version of ASTM F2550 was again ratified with no other modifications in 2018 for its application as the standard for FELL pipeline inspection through 2026.

## Florida Case Studies Summary

During 2018 and 2019, several FELL field demonstration inspections were performed for large and small Florida utilities in the gravity collection systems. Table 2 lists relevant data collected during 10, one-day field pilot demonstrations.

Table 2. Recent Florida Focused Electrode Leak Location Field Demonstrations

| Utility | Collection System Size (miles) | CIPP Inspected | | VCP Inspected (Segments/LF) | |
|---|---|---|---|---|---|
| | | Segments – LF | Defect Flow (gpm) | Segments – LF | Defect Flow (gpm) |
| 1 | 1,400 | 10 – 2,849 | 244 | 3 – 851 | 178 |
| 2 | 1,800 | 3 – 985 | 310 | 1 – 372 | 0.5 |
| 3 | 3,900 | 3 – 390 | 10 | 1 – 380 | 8 |
| 4 | 900 | 2 – 748 | 62 | 2 – 699 | 23 |
| 5 | 140 | 3 – 869 | 101 | 1 – 335 | 24 |
| 6 | 925 | 1 – 393 | 1 | 2 – 494 | 5 |
| 7 | 499 | 2 – 508 | 11 | 2 – 788 | 3 |
| 8 | 355 | 2 – 420 | 38 | 2 – 492 | 43 |
| 9 | 107 | 0 – NA | NA | 4 – 674 | 3 |
| 10 | 59 | 0 - NA | NA | 2 – 558 | 1 |

The pipe segments selected by the individual owners to reflect a small portion of the collection system they wished to inspect relating to how CIPP installations compared to unlined host pipe. In all cases, the unlined segments were vitrified clay pipe (VCP), and ranged from 50 to 60 years in age. The field demonstrations were performed to show utility operators and their consulting engineers how the FELL data acquisition process is conducted. Results were presented immediately following each individual pipe segment scanned. Following field work, FELL results were compared to CCTV inspection videos, where available.

In every case where FELL found defects in CIPP liners, the companion CCTV results log indicated that no defects contributing to infiltration. In one case, the CIPP inspection showed a water-tight installation. The majority of CIPP defects identified were related to poor lateral reinstatements, and less so due to liner tears, wrinkles, or fins. In most cases, CIPP liners showed numerous very small defects, though less than the ASTM level relating to "small defects." These small defects are characterized as "pinhole" leaks and are not included in the total defect flow rate reported by FELL. The follow-up scanning work with other U.S. utilities over the previous six years has shown that pinhole leaks identified in an original FELL inspection degrade over time, often resulting in measurable defect flows, as defined by ASTM F2550.

In several cases, inspections of 50- to 60-year-old VCP showed nearly water-tight conditions or very low infiltration flow rate potential. These data were used immediately by the utilities to avoid planned CIPP rehabilitation, where previous intentions were to line the pipe due to its age. In this way, capital resources can be optimized to avoid rehabilitating pipes that do not require attention at this time.

## Lessons Learned

Results of FELL pipeline inspections across the U.S. over the past six years, and shown recently in 10 field demonstrations in Florida in 2018 and 2019, provide the following lessons learned:

1. The CCTV inspection has inherent disadvantages where it cannot reliably or consistently detect lining defects, quantify openings to ground, or assess service reinstatements. Defects in CIPP often do not become visible on camera until a few seasons later, often after the warranty period has expired.
2. The CIPP lining of sewer mains does not always reduce defect flows. Post-CIPP defect flows may be higher after lining than before, as remote tap cutters may accidentally create collateral openings to the soil.
3. To better manage capital expenditures, lateral connection liners should be a post-CIPP decision, not an across-the-board pre-CIPP specification requirement.
4. Since FELL inspection provides a highly precise location and flow quantification for each defect, post-CIPP CCTV should be done after FELL, with cameras stopping at each defect location identified by FELL to pan, tilt, and zoom accordingly. Otherwise, CCTV will likely pass by or miss the defect.
5. Utilities should not just measure success on a top-down basis to see area reductions in defect flow; rather, they should assess contractor performance on a pipe-by-pipe basis.
6. Lateral connection liners should only be recommended for those services that have unacceptable levels of defect flow.
7. Future wastewater rehabilitation specifications should consider: 1) a contractor performance bonus for every service connection that registers zero defect flow, 2) a requirement to joint-grout all service connections where defect flows are found by FELL, and 3) requiring the installation of a lateral connection liner at the cost to the contractor, where all services show post-CIPP defect flows greater than pre-CIPP levels.

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