Use of Low Voltage Conductivity to Conduct a 10km (30,461 LF) Inspection of Legacy Cured-In-Place Pipe (CIPP) for a Leak Assessment Project

Chuck Hansen[1]

[1] Chairman, Electro Scan Inc., United States

Abstract

In 2017, the Institute of Underground Infrastructure (IKT), Gelsenkirchen, Germany, utilized low voltage conductivity to test a variety of trenchless Cured-In-Place Pipe (CIPP) short-liners to locate and quantify leaks, several of which were utilized in a multi-million rehabilitation project in Kansas City, Missouri (USA).

While CIPP suppliers participating in the IKT government-funded research project had the opportunity to install their liners in IKT test facilities, trained & licensed contractors were responsible for installing the same liners in Kansas City, with subsequent flow monitoring indication that significantly less flow reductions had occurred. Utility management and consulting engineers determined that either (1) the wrong pipes were selected to rehabilitate, and/or (2) trenchless rehabilitation had leaks. High resolution Closed-Circuit Television (CCTV) inspection was used to both select pipes requiring rehabilitation and post-rehabilitation watertightness.

By introducing electric current inside a non-conductive pipeline (i.e. non-metallic) using a tethered probe, the defect locations found by low voltage conductivity, also referred to as focused electrode leak location (FELL), is able to locate leak location to within 1cm. By identifying where and how much electric current escapes to earth, i.e. a grounding source, algorithms estimate a liters per second (l/s) defect flow for each individual leak.

The larger the dissipation of current to earth, the larger the defect, allowing low voltage technology to detect leaks missed by conventional CCTV cameras, acoustic sensors, lasers, sonar, smoke testing, and air & water pressure testing.

Similar to *holiday testing* to assess protective coating, this paper will describe the science of low voltage, field operations, key findings, as shown in Table 1 and Table 2 (Below), and discuss the international adoption of ASTM F2550-13 (2018)[1] to assess pre- and post- rehabilitation effectiveness and defect by specific sources, Figure 1 (Below).

Table 1: Kansas City, Missouri, Total FELL Defect Flow Assessment – 30,461 LF (9,285m)

138 CIPP Liners	No. of Pipes	Total Pipe Length	Total Defects	Defect Flow GPM	Defect Flow GPD	Defect Flow GPD/IDM
Total FELL Investigation	138	30,461	521	1,464	2,108,174	5,956,801
CIPP w/Lateral Connections	96	21,919	350	627	902,779	2,381,109
Full FELL Review as a %	70%	72%	67%	43%	43%	40%

Table 2: Kansas City, Missouri, FELL Defect Flow, By Source – 21,919 LF (6,681m)

96 CIPP Liners[2]	No. of Pipes	Pipe Length	No. of Defects: Defects	No. of Defects: %	Defect Flow: GPM	Defect Flow: %
CIPP of Lateral Connections	446	NA	189	54%	480	77%
CIPP of Sewer Main Lines	96	21,919	161	46%	147	23%
Total CIPP Assessments	542	21,919	350	100%	627	100%

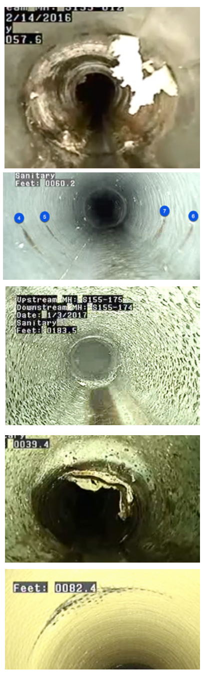
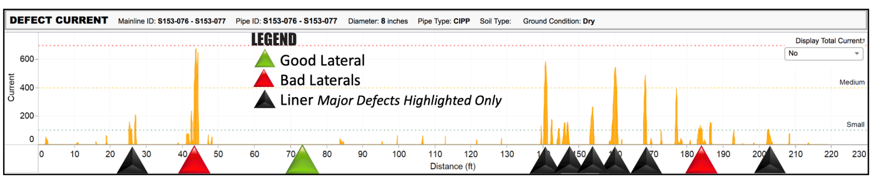


Figure 1: Example FELL Defect Identification by Source



[1] ASTM F2550, *Standard Practice for Locating Leaks in Sewer Pipes By Measuring the Variation of Electric Current Flow Through the Pipe Wall*, 2006, 2013, and Reapproved 2018.

[2] CCTV was only provided for 96 CIPP liners to allow sewer lateral identification and cross-referencing to FELL.

1.0 Kansas City, MO – Early U.S. EPA Study

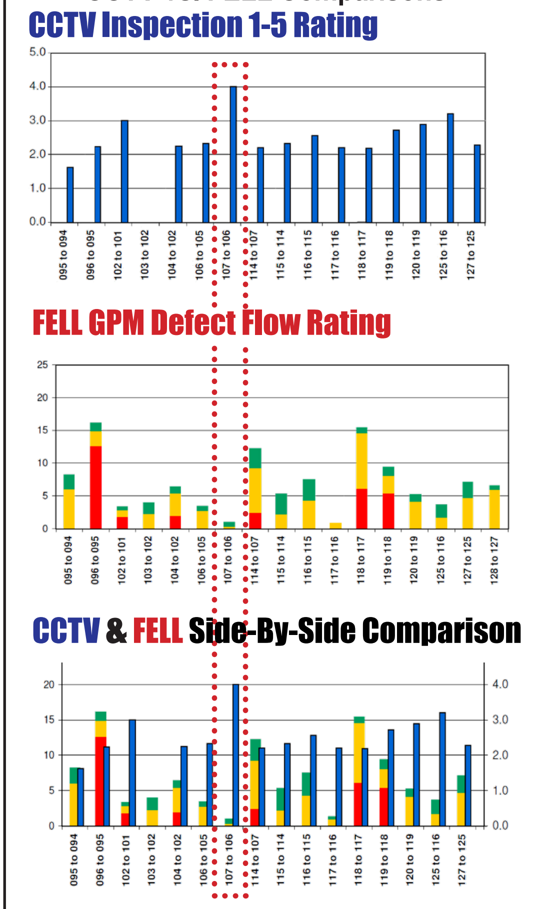
In November 2007, the U.S. Environmental Protection Agency (EPA) Office of Research and Development's (ORD's) National Risk Management Research Laboratory funded a three-year research project entitled "*Condition Assessment of Wastewater Collection Systems*" as part of the Aging Water Infrastructure (AWI) Research Program to support the USEPA Office of Water's Sustainable Infrastructure Initiative.

The primary goal of this project was to help wastewater utilities better understand their wastewater collection system needs and develop and implement condition assessment programs. The overall project objectives included an evaluation of the state of condition assessment technology and compilation of cost and performance data for innovative assessment technologies, comparing legacy camera-based visual methods with newer methods and technologies adopted by other industries.

Field demonstrations were conducted in August 2010, hosted by the Kansas City, MO (KCMO) Water Services Department. Electro Scan was tested in Gracemor, a residential area with predominantly 8-in. vitrified clay pipe (VCP), with traditional CCTV inspection performed to compare findings, Figure 2 (Below).

Figure 2: Kansas City EPA Benchmark Area

Figure 3: Kansas City, Missouri CCTV vs. FELL Comparisons



Comparison of CCTV and FELL (Figure 3) by independent parties indicated that while CCTV provided visual identification of pipe features, electro scanning results provided defect severity with special focus on identifying infiltration problems, not typically detected by CCTV..

Key Findings

1. CCTV 1-5 Ratings do not provide a reliable indication of infiltration or leakages, Figure 2.

2. The Worst CCTV Rating was due to a Maintenance related observation, not Structural Defects, which compared to one of the smallest leakages found by FELL.

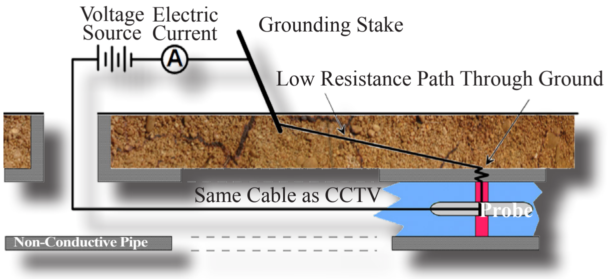
3. Pipes that were cleaned prior to CCTV Inspection resulted in more missed visual defects.

4. FELL demonstrated repeatability of results and usefulness on multiple pipe materials.

2.0 The Science of Low Voltage Conductivity Testing

After a number of Cured-In-Plae Pipe failures, during and directly after their warranty period, technical solutions were sought to create an accurate, cost-effective, and repeatable way to reliably certify the water tightness of CIPP. Complicating matters were the seemingly endless combinations of pipe materials, diameters, shapes, depths, lengths, gradients, soil types, and age profiles.

Figure 4: Principle of Low Voltage Testing



Source: ASTM F2550 (2006, 2013, and 2018).

The science of low voltage conductivity is straightforward. A similar application known as *holiday testing* had already been available and in use for nearly 40 years to evaluate protective coatings for exposed pipes, rooftops, and reservoir linings; however, the technology needed to internally assess full-length, 360-degree pipe wall integrity while allowing existing flow conditions during inspection.

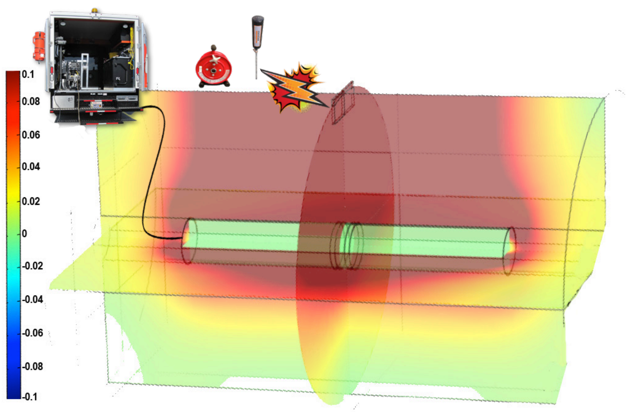
Most sewer pipe materials such as brick, clay, plastic, concrete, and resin-based liners, are poor conductors of electrical current. As a result, if a defect exists in the wall of a pipe, i.e. leakage of electrical current, third-parties cound precise location and etermine the size of leak. The measured intensity and duration of the electrical signal emanating from the pipe can be correlated to a flow rate in Gallons per Minute or Liters per Second, and determine whether water infiltration or exfiltration may occur, without bypass pumping.

An approach was developed as illustrated in Figure 4, that established a 12-volt electrical circuit with a 40 milliamp (mA) signal, using water as a conductor, which allowed two ends of the circuit to connect and close the loop. Applied to an underground pipe, one side of the circuit would remain inside a non-conductive pipe (e.g., asbestos cement, brick, epoxy-coated ductile iron, high density polyethylene, plastic, resin-based liner, vitrified clay pipe, etc.), connected to a grounding stake when any defect current traveled to the surface from an opening to confirm a corresponding pipe wall defect.

If the loop is never closed, whereby an electrical circuit is closed, the pipe would be shown to have no defects. Conversely, if the loop is closed, whereby an electrical connection is made at the surface, then an opening or defect exists in the pipe wall, allowing a pathway from inside of the pipe to ground. Since water leakage and electric current are highly correlated, the intensity and duration of measured current can provide a specific defect size and corresponding flow rate in gallons per minute.

Utilizing desktop pipe simulation tools, as shown in Figure 5, Electro Scan Inc. (sacramento, California, USA) determined how non-technical users could reliably and repeatedly find defects. Confirming probe dimensions, power settings, grounding sources, data capture, repeatability of results, and precision of leak location was then applied across various pipe materials. To determine estimated leakage rates in gpm or l/s basic assumptions related to hydraulic head conditions on a defect and surrounding pipe burial soil conditions were made to develop a calculation for a relative leakage rate.

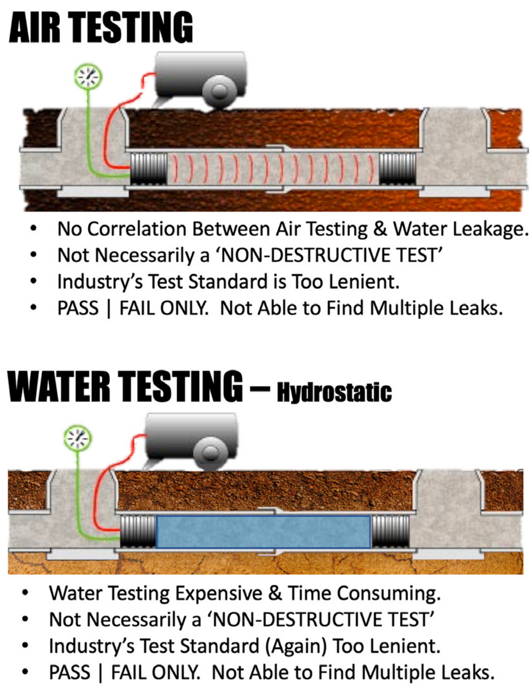
Figure 5: FELL COMSOL® Multiphysics®



Following the principle operation of AC circuits, a grounding source was needed to simulate a conductive rod driven into the earth near the operation of the device to complete its circuit. The frequency of signal sources provided direction with regards to the system physics allowing for consistenting testing of Cured-In-Place Pipe (CIPP) lining and other trenchless rehabilitation.

Now exceeding $6 billion in annual sales worldwide, Cured-In-Place Pipe (CIPP) has gained widespread acceptance as an alternative to traditional dig & replacement. First developed in 1971 in England, the CIPP process relines the interior of an existing pipe using either heated water, steam, ultra-violet (UV) lights, or light-emitting diodes (LED) to create or cure a new pipe wall inside the original host pipe, within hours.

Figure 6: Pipeline Air & Water Leak Testing



Principally guided by ASTM standard F1216, *Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube*, installation is recommended to be inspected visually if appropriate, or by CCTV if direct visual inspection cannot be accomplished.

Specifically, ASTM F1216-16 states the following:

> ***8.7 Inspection and Acceptance. The installation may be inspected visually if appropriate, or by closed-circuit television if visual inspection cannot be accomplished. Variations from true line and grade may be inherent because of the conditions of the original piping. No infiltration of groundwater should be observed. All service entrances should be accounted for and be unobstructed.***

Unfortunately, without mention of water tightness or permeabiity, popular CIPP trenchless linings products merely have to show that no visible signs of "infiltration" are evident in a post-CCTV visual inspection and show that "all service entrances [should] be accounted for and be unobstructed."

Since most Post-CIPP CCTV inspection is done by the same contractor completing the CIPP installation, reliable defect coding to protect the Owners' interest can often be problematic, and since hydrostatic testing equipment as shown in Figure 6 & 7 is only required before lateral reinstatement, little to no testing is completed prior to commissioning a new pipe, including full length sewer mains, lateral connection, or customer's service lateral, as shown in Figrue 8.

Figure 8: Key Components of Pipe

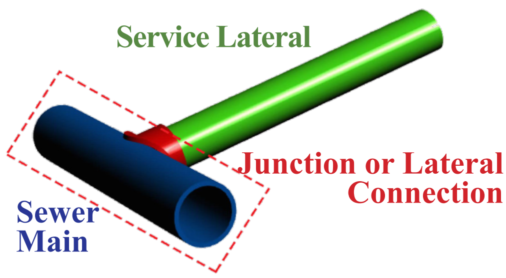
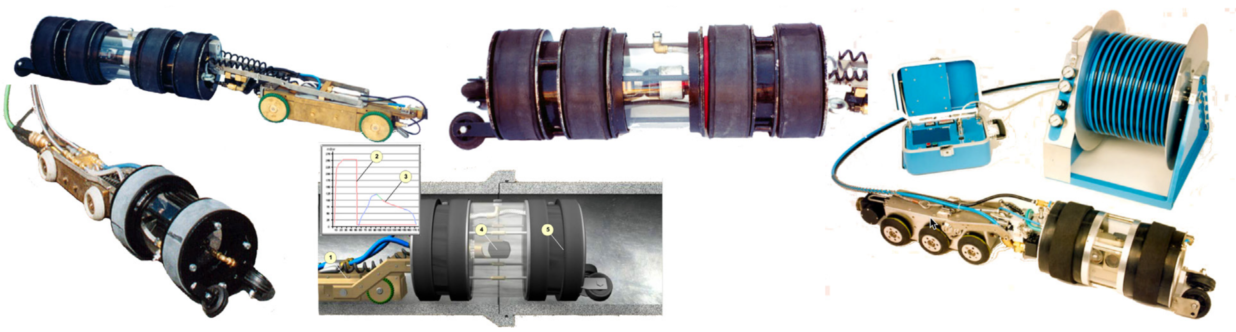


Figure 7: Standard Pressure Testing of Pre-CIPP Completed Linerrs



3.0 Using FELL to Assess CIPP Liners

First recommended in 2015 by Ken Kerri, Ph.D., P.E., in his EPA-endorsed *Operation & Maintenance of Wastewater Collection Systems*, *Volume 1* manual, Dr. Kerri recommended that "separate scans [i.e. electro scanning] should be taken before and after any pipe repair, relining, or rehabilitation activity to compare electrode current values and to determine if any visual defects were missed during initial assessment"

While CCTV cameras had been traditionally used to 'test & certify' CIPP, a multitude of defects may result in CIPP causing liner permeability (i.e. leaks) not identified by visual inspection. As shown in Table 3, a number of liner defects observed by traditional CCTV cameras are unable to be determined as water tight. In contrast, FELL's ability to precisely locate defects in CIPP liner walls, provides much needed quality control and quality assurance for local government capital improvement projects.

Table 3: CIPP Leakage Not Commonly 'Seen' By High-Resolution CCTV Cameras

- Accelerant Burns
- Accidental Cuts
- Bad Service Reconnections
- Bad Lateral Liners
- Blisters
- Delamination
- Defective Epoxy
- Equipment Damage
- Foreign Objects
- Lateral Connection Rehabilitation (LCR)
- Lowered Resin to Felt Ratios
- Mainline to House Lateral Connection (MTH)
- Pinholes
- Poor, Incomplete, or Uneven Curing
- Overcooking
- Stretching
- Top-Hat Defects
- Wet-Out Failures
- Wrinkles, including Buckling, Fins, Folds, Lifts, & Ridges

As illustrated in Figures 9 & 10, neither colored dye vacuum testing, as commonly used by the German-based Institut für Unterirdische Infrastruktur (IKT), or electric current, should be able to pass through a liner. Whether applying Torricelli's Law of fluid dynamics or Ohm's Law of resistance and voltage, CIPP liners should never be able to allow water or low voltage electric current to pass through a full-length 360-degree pipe wall.

Figure 10: Cured-In-Place Pipe Lining Test by IKT

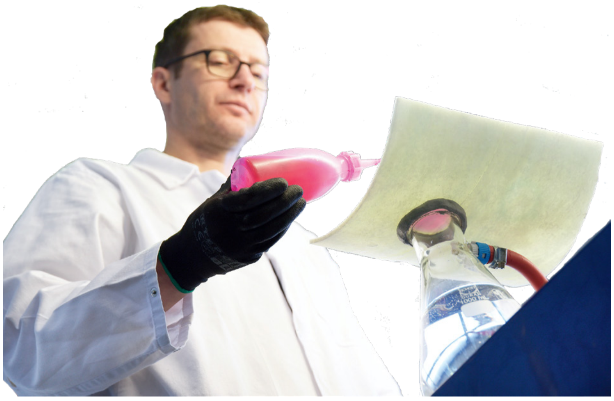


Figure 9: CIPP Lining Evaluated With Electric Current

3.1 IKT SHORT-LINER ASSESSMENT STUDY IN GERMANY

Published in 2018, Electro Scan Inc. and WRc under contract with IKT provided confidential survey services as part of IKT's Short-Liner CIPP research project. While detailed results by CIPP supplier remain confidential, IKT conducted rigorous evaluation of the top performing suppliers also using Electro Scan's FELL technology to test for permeability. As shown in Figure 39, repeatability tests were also conducted for each liner.

Key takeaways from work was confirmation of Electro Scan's ability to test silicate-based liner materials and the recommendation that Electro Scan expand its leak identification algorithm to include leaks below 100 amplitude. Some CIPP manufacturers had previously claimed electrical conductivity might unduly influence Electro Scan readings, which was not found to be the case. In addition, small pinhole leaks that can be identified by Electro Scan, but previously not counted to benefit lining suppliers, can now be included in overall l/s and gpm to four decimal rates of leakage, as shown in Figure 40.


IKT - Institut für Unterirdische Infrastruktur, Gelsenkirchen
www.ikt.de
IKT
IKT-Warentest
„Kurzliner für Hausanschlüsse"
- Auszug aus dem Forschungsbericht -
Gelsenkirchen, Oktober 2018

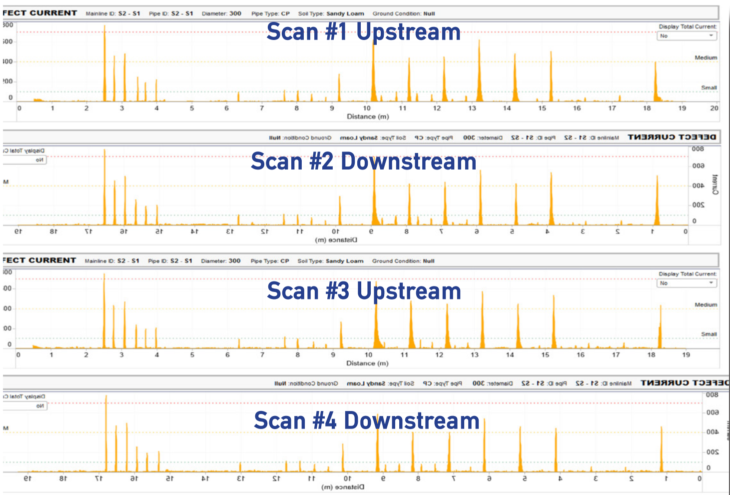
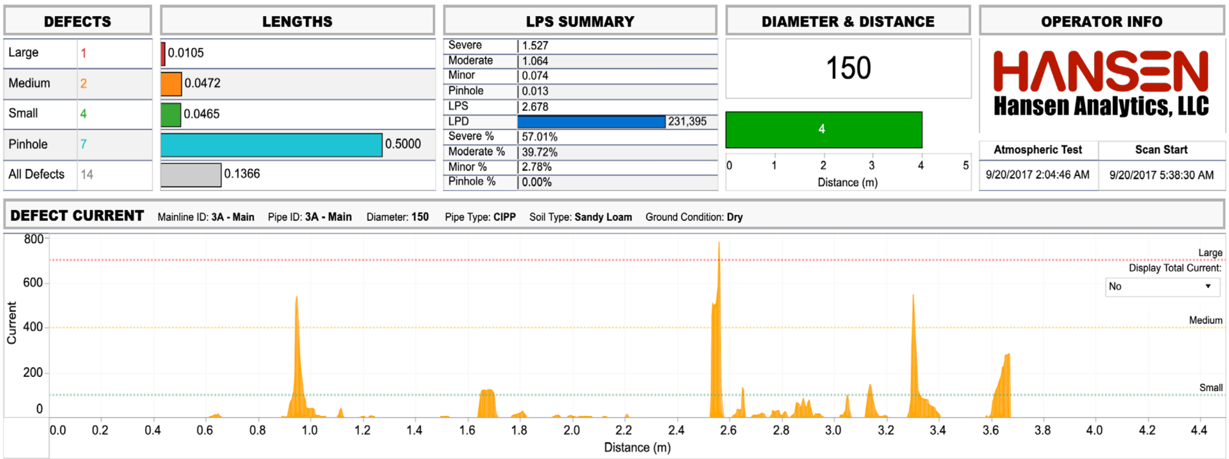


Figure 39. IKT Repeatability Testing in Germany

Figure 40. New Release of Cloud-Based CIPP Leak Assessment Application



4.0 Kansas City, Missouri's, 30,461LF (10km) CIPP ASSESSMENT

Since 2015, the City of Kansas City, Missouri (KCMO) has implemented an aggressive program to reduce infiltration and increase capacity of its wastewater collection systems, spending over $70 million in capital improvement projects utilizing trenchless technologies, including Cured-In-Place Pipe (CIPP).

As shown in Table 4 (Below) KCMO assessed 138 previously lined CIPP sewer mainlines representing 30,461 LF of rehabilitated pipes.

Representing a cross-section of interrnational, national and regional providers of CIPP suppliers, a key feature of the project was the additional relining of lateral connections.

In some cases laterals were relined only for the first 1-2 feet (1m) up a customer's sewer lateral connection from the mainline, while for others contractors were to reline nearly the entire distance from sewer main connection to private residencial clean-out, in close proximity to a house or building footprint.

Already adopting the use of FELL's machine intelligent probes to assess sewer main defects in close proximity to environmentally-sensitive rivers and streams, KCMO was interested in assessing CIPP liners for watertightness that had been installed for just 24-36 months.

As part of its study, FELL intelligent probes surveyed 138 sewer mains and 446 sewer lateral connections, i.e. not customer laterals, that were rehabilitated using CIPP.

Field inspections were completed in 20 working days and performed in accordance with ASTM F2550-13 (2018) standards with field data uploaded each day to a priopri-etary cloud application provided by California-based Hansen Analytics LLC's and their Amazon Web Services (AWS)' Critical Sewers® cloud application.

While the utility found a significant number of defects in legacy CIPP liners, flow monitoring results indicated that the utility may not have selected the correct sewer mains to rehabilitate. Since CCTV was exclusively used for KCMO's rehabiitation selection, additional hydrogeoloical modeling found that no sewers were rehabiliated in areas having the lowest elevation terrain, i.e. highest groundwater areas, of the utility's basin as shown in Figure 11.

Ninety-six (96) of 138 liners or seventy percent (70%) of all sewer mains surveyed by FELL had CCTV videos made available.

A key objective of senior management of KCMO was to determine the rehabilitation effectiveness of CIPP, but more importantly, to quantify potential Post-CIPP leakage rates by sewer main and customer lateral connection. As illustrated in Figure 12, a key use of CCTV was the ability to identify lateral connection locations. Often found inaccurate,

Table 4: Kansas City, Missouri, CIPP FELL Assessment By Diameter

Diameter	8"	10"	15"	TOTAL
Number of Pipes	119	12	7	138
Linear Feet	26,212	2,922	1,327	30,461
Total Defects	456	56	9	521
Gallons per Minute (GPM)	1,339	115	10	1,464
Gallons per Day (GPD)	1,928,045	165,341	52,100	2,145,485
GPD Flow per LF	74	57	39	70
Percent of LF	86%	10%	4%	100%
Percent of GPM	91%	8%	1%	100%

even on some of the most sophisticated Geographic Information Systems (GIS), CCTV was found to be the #1 way to accurate locate customer lateral locations; however the absense of rating laterals for leakage, makes it difficult to utilize visual inspections to judge rehabilitation effectiveness.

While FELL has a 99.6% accuracy rating for identifying defective lateral and joint locations, a key objective was to identify Post-CIPP Lateral Reinstatements with LEAKS (i.e. Bad Laterals) and NO LEAKS (i.e. Good Laterals), in addition to Liner Defects.

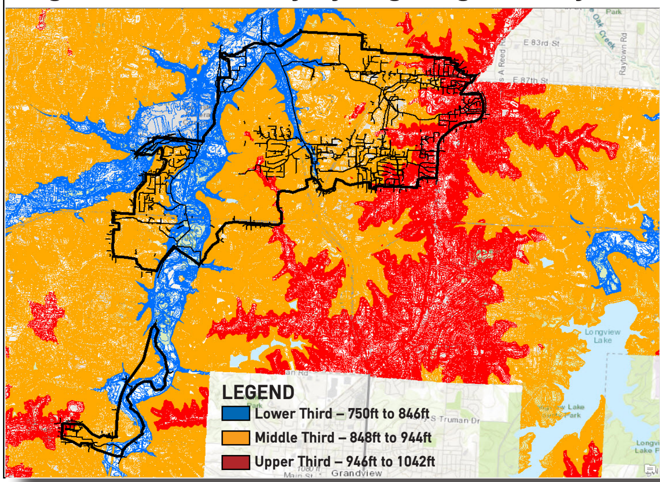
The FELL intelligent probe system was thereforce selected to assess and measure watertightness in full-length 360-degree pipe walls, without requiring third-party data interpretation.

The legacy inspection program located over 500 individual pipe defects contributing to infiltration. Data obtained identified the pipe defects to within 3/8 of an inch (1cm), and each pipe defect was quantified in gpm or l/s.

Finally, customer service lateral rehabilitation was a key element to the utility's rehabilitation program, including the use of (1) Mainline to House (MTH), (2) Lateral Connection Rehabilitation (LCR) representing a short T-liner solution, (3) Polyvinyl Chloride (PVC) tee connections, and (4) Open Cut Lateral Reinstatements..

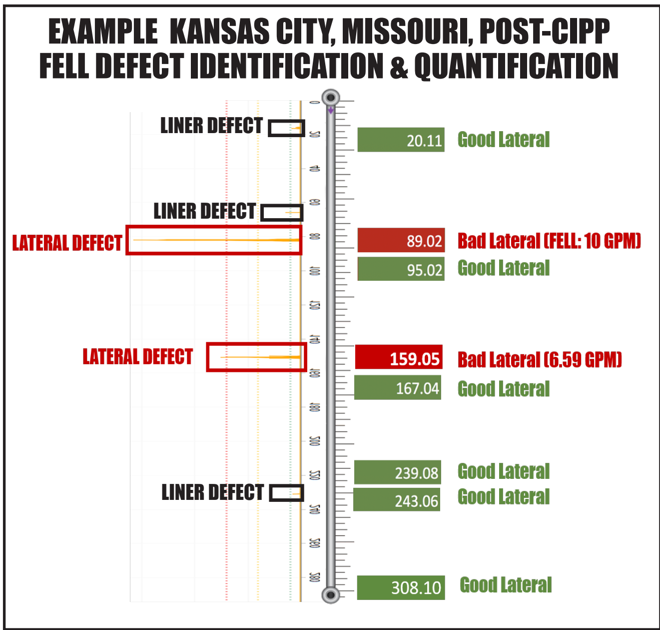
In addition to finding multiple defects at lateral re-connections, a number of liner defects were located and measured in liner walls as a single sewer main is illustrated in Figure 13.

Figure 11: Kansas City Hydrogeological Analysis



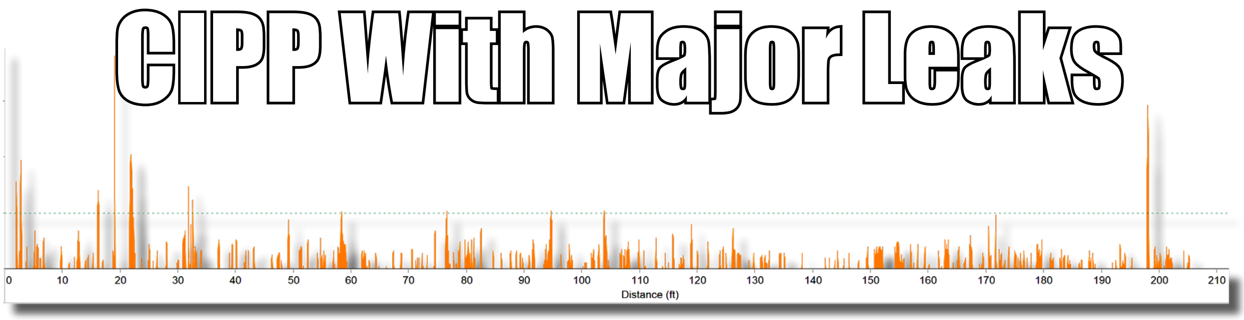
Completed using Innovyze® InfoAsset® Planner.

Figure 12: CIPP Liner vs. Lateral Connection Defects



(***Above***) Certified CCTV operator identified all 'Lateral Connections' as Tap Factory Active (TFA), i.e. no defects or leakage.

Figure 13: Example FELL Survey of a Severely Defective CIPP Liner



4.1 CIPP Pinhole Leaks

Pinhole leaks were a key goal of assessing for KCMO and may be caused by a number of factors including, but not limited to, lower resin-to-felt mixtures, low quality resin material, uneven heating or curing, accidental cuts, liner stretching, use of inapproprate tire treads on mobile CCTV camera, contractor mechanical equipment entering, and/or improperly applied cleaning equipment.

Contrary to CIPP suppliers and installation contractors, pinholes *are not* self-healing, will get worse not better over time, and may severely reduce the useful life and structural integrity of CIPP. While pinholes may not be visually seen by initial Post-CIPP televising, infiltration stains, i.e. where water has seeped through the liner, may show defect locations. Regardless, FELL is able to locate pinholes immediately following CIPP curing, which tends to register as small defects in the liner wall.

Figure 14: Example KCMO CIPP Pinholes

As shown in Figures 14, 15, and 16, a number of pinhole defects were identified by FELL, with many confirmed by visual inspection. While large holes are included in gpm calculations, smaller defects, i.e. below 0.1 GPM can be cluded in defect flow calculations.

Figure 15: FELL Defects Associated with Selected KCMO CIPP Liner Pinholes

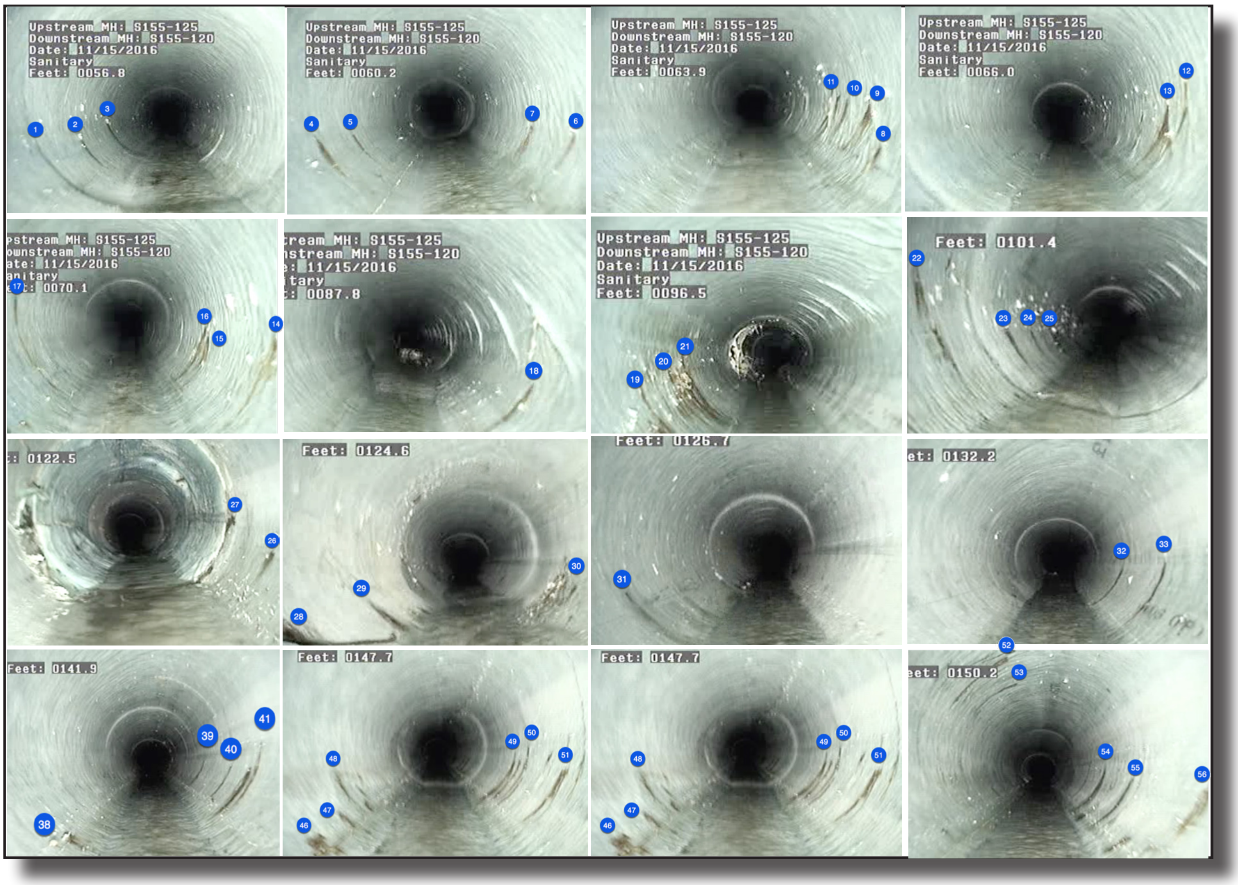


Figure 16: FELL Defects Associated with Selected CIPP Liner Pinholes

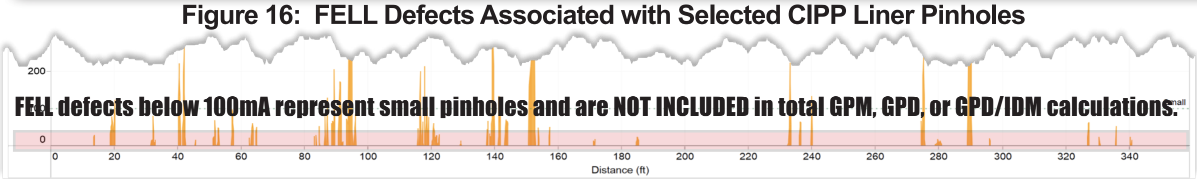


Table 5: KCMO FELL Assessment of Lateral Connections By CIPP Rehabilitation Method

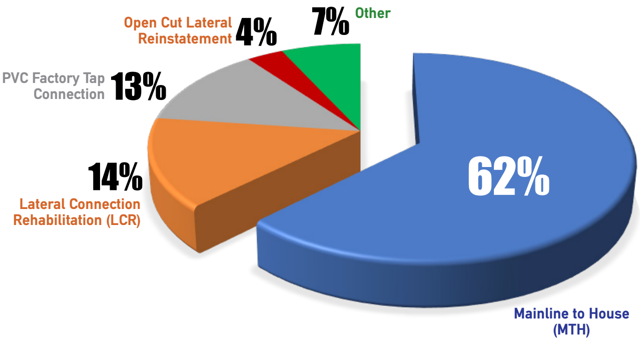
Lateral Rehabilitation By Supplier or Method	Good Laterals		Bad Laterals				Ratio Good v. Bad	Total Laterals	% of Total
			Amount		Defect Flow				
	Quantity	%	Quantity	%	GPM	%			
Mainline to House (Long T-Liner)	157	61%	118	62%	197	41%	1.33	275	62%
Lateral Connection (Short T-Liner)	14	5%	27	14%	177	37%	0.52	41	9%
PVC Factory Tee	54	21%	24	13%	54	11%	2.25	78	17%
Open Cut Reinstatement	23	9%	7	4%	11	2%	3.29	30	7%
Other	9	4%	13	7%	42	9%	0.69	22	5%
TOTAL LATERAL FELL ASSESSMENT	**257**	**100%**	**189**	**100%**	**480.2**	**100%**	**1.36**	**446**	**100%**

Total Post-CIPP Infiltration from Laterals Connections 77% v. Sewer Mains 23%

4.2 CIPP Lateral Connection Defects

Much has been written about the amount of infiltration contributed from leaking sewer mains and customer laterals. As shown in Table 5, Post-CIPP Infiltration from Lateral Connections represented 77% of Defect Flow, compared to 23% attributed to sewer mains.

Figure 17: KCMO CIPP Defects By Lateral Connection Relining Method



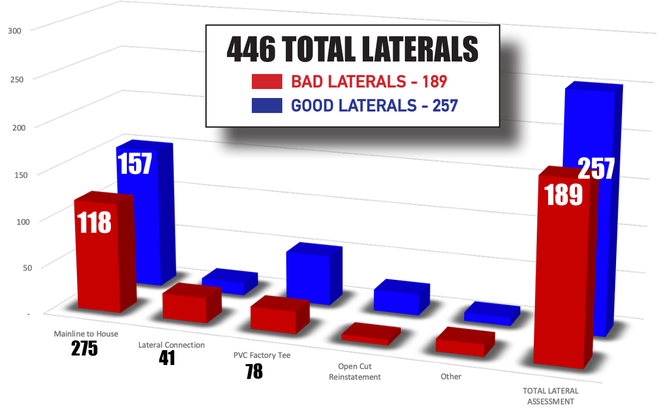
While relined sewer mains have frequently eliminated a substantial amount of infiltration caused by defective joints, cracks, and other defects, poorly reconnected laterals and defective reconnections have easily shifted infiltration from sewer main pipe wall defects to reinstated service laterals.

While CIPP suppliers and contractors have often stated elimination of infiltration as the reason to rehabilitate laterals, FELL testing found defects at both lateral connections and T-liner connections as part of the KCMO CIPP survey.

Several lateral rehabilitation methods were used as part of KCMO's overall rehabilitation efforts. Major rehabilitation methods included (1) Mainline to House (MTH), (2) Lateral Connection Rehabilitation (LCR) representing a short T-liner solution, (3) Polyvinyl Chloride (PVC) tee connections, and (4) Open Cut Lateral Reinstatements, as shown in Figures 17 & 18.

Some manufacturers have argued that FELL technology is unable to accurately detect leaks when lateral lining reconnections include silicate-based resins, for instance as used with Trelleborg epros LCR products. However, its assessment of 36 LCR short liners, showing ten (10) good laterals and twenty-six (26) bad or defective laterals, indicates that FELL can successfully be used to delineate defects in silicate-based pipe wall materials.

Figure 18: KCMO Defects By Type of Lateral Liner Rehabilitation



Based on FELL assessment, 118 of 275 or forty-three percent (43%) of MTH lateral rehabilitation were found with measurable FELL Defect Flows, indicating less than satisfactory reductions in flow. The next most popular method of rehabilitation was PVC factory tee solutions, representing eighteen percent (18%) of total lateral rehabilitation.

4.3 Defects Found at PVC Laterals

Factory tap PVC-based lateral connections or factory tees, as shown in Figures 36 and 27, resulted in 24 of 78 or 31% defective laterals found by FELL. A sample of defective PVC factory laterals with FELL leaks are shown in Figure 38.

By comparison, numerous PVC lateral connections appear to have had an epoxy-based grout component added to open cuts; however, given the amount of material component hanging from the lateral and remaining in the mainline, grouted epoxy may not have had sufficient time to set or not had a proper mixture or application to set appropriately.

PVC connection defects are not limited to laterals, but may also include defects related to end-points of their mainline T-connection. Often called out by CCTV operators, these defects should have been identfied as defective 'Material Changes' but no observations were noted as part of reviews of CCTV records.

Figure 36: PVC Factory Tee

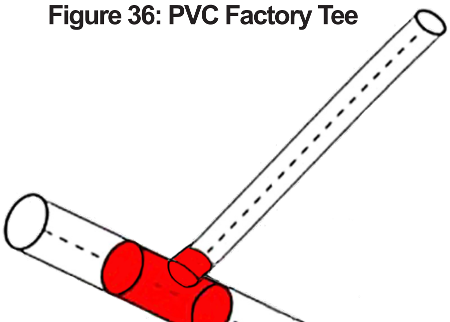
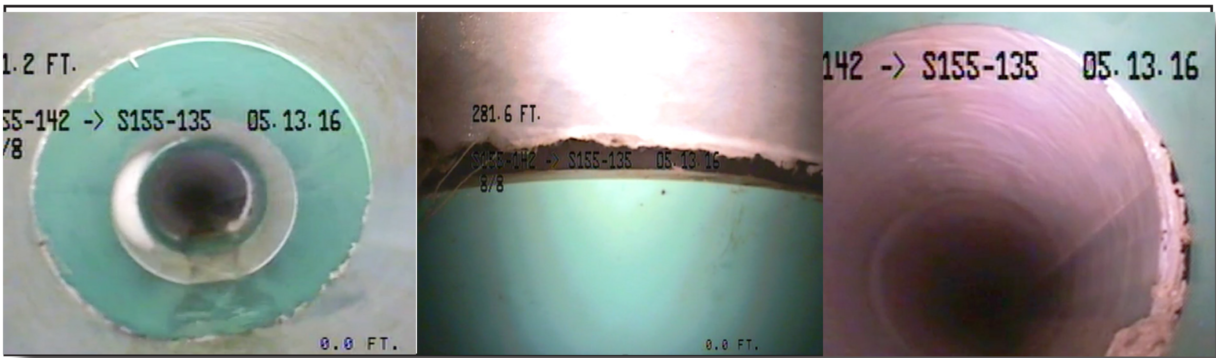


Figure 38: KCMO FELL Defects at PVC Connections

As illustrated in Figure 38 (Above), while CIPP may eliminate a significant amount of infiltration from sewer mains, poor lateral reinstatements may risk defect flows being greater *after* CIPP rehabilitation, than *before* rehabilitation.

Figure 37: KCMO PVC Tee Mainline Defects

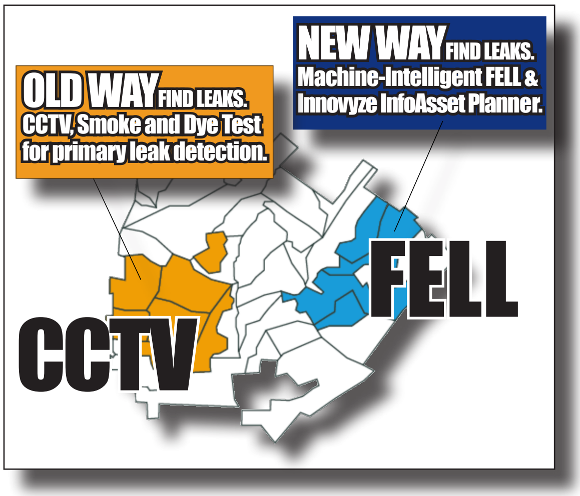


5.0 SUMMARY

CIPP technologies have improved since first introduced in the 1970s, with CCTV cameras used as the principal means to judge acceptance; however, the ability of contractors to obtain more consistent quality installations has not yet been demonstrated, requiring additional safeguards, environmental stewardship, and acceptance standards to ensure pipeline sustainability and resiliency.

Figure 41: Utility Expections vs. Market Delivery

Figure 42: Comparison of Leak Detection Methods and Selection for Rehabilitation



FELL testing of CIPP in Kansas City, Missouri, reveals that even with rigorous quality control regimes, a significant percentage of CIPP liners will fail to meet specification, requiring subsequent repair, relining, or replacement to achieve expected performance levels. As shown in Figures 41 and 42, if proper testing is not conducted after curing and lateral reinstatement, a gap will exist between a utility's expection of CAPEX performance and a supplier's delivery of CAPEX, risking incorrect targeting of repairs and insufficient testing & certification.

REFERENCES

Addressing the Shortcomings of a Sampling Strategy in CIPP Quality Assurance Programs, Tony Araujo and Po-Szu (Bruce) Yao, P.Eng., Paragon Systems Testing, Concord, Ontario, CANADA, NASTT 2019 No-Dig, Chicago, IL, March 2019.

ASTM F1216-09 and F1216-16, Standard Practice for Rehabilitation of Existing Pipelines and Conduits by the Inversion and Curing of a Resin-Impregnated Tube.

ASTM F2550-06 and F2550-13 (2018), Standard Practice for Locating Leaks in Sewer Pipes By Measuring the Variation of Electric Current Flow Through the Pipe Wall.

Generational Thinking In Water Management, Water Online, By Kevin Westerling, @Kevin OnWater, July 26, 2017.

Guide for Evaluating Capacity, Management, Operation, and Maintenance (CMOM) Programs at Sanitary Sewer Collection Systems, United States Environmental Protection Agency, Office of Enforcement and Compliance Assurance (2224A), EPA 305-B-05-002, www.epa.gov, January 2005.

IKT-Liner Report 2018, Dipl.-Ök. Roland W. Waniek, Dipl.-Ing. Dieter Homann, Barbara Grunewald, M.Sc. IKT - Institute for Underground Infrastructure GmbH, Exterbruch 1,45886 Gelsenkirchen , Germany,

Retrospective Evaluation of Cured-in-Place Pipe Technology for Municipal Gravity Sewer Rehabilitation, Allouche, E., L. Wang, R. Sterling, And A. Selvakumar. EPA/600/R-12/004|January 2012.

Operation and Maintenance of Wastewater Collection Systems, Volume I, Seventh Edition, ISBN 978-1-59371-066-8.

USEPA Sewer Electro Scan Field Demonstration Revisited, 2013, Terry Moy, Manager, Program Management and Engineering, Clayton County Water Authority, 1600 Battle Creek Road, Marrow, GA 30260, USA, Charles G. Wilmut, Vice President, Burgess and Niple, 11117 Shady Trail, Dallas, TX 75229, USA, and Robert J. Harris, President, Leak Busters Inc, 3157 Bentley Drive Rescue, CA 95672, USA.