Using COMSOL® Multiphysics® To Quantify Leakage Rates In New & Rehabilitated Water & Sewer Pipes

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Introduction

COMSOL® Multiphysics® has been a key factor in improving the way critical water and sewer infrastructure is inspected and certified as watertight. More importantly, it has been instrumental in developing the governing equations and modeling quality assurance best practices to certify real-world pipeline construction, repairs, trenchless rehabilitation, and renewals, as watertight (Figure 1).

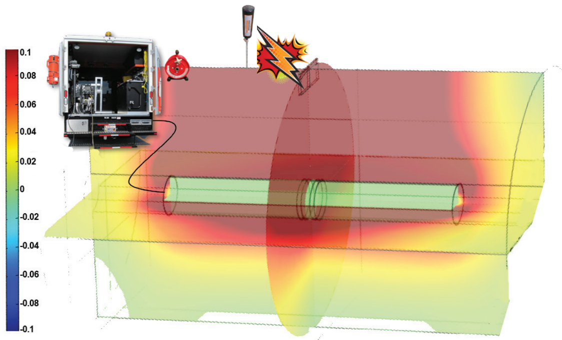

Figure 1. Electro Scan Inc.'s Focused Electrode Leak Location (FELL) pipeline assessment technology.

Industry Dynamics

According to the US Environmental Protection Agency (USEPA), each year more than 2.2 billion gallons of treated drinking water are lost and 860 billion gallons of raw wastewater reach surface water bodies from leaking sewer pipelines, resulting from pipeline cracks, bad service connections, contractor damage, poor construction, and structural failures. These pipeline defects result in both environmental impairment and lost revenue to municipal utilities, adversely affecting a community's quality of life and causing higher costs for ratepayers.

The American Society of Civil Engineers (ASCE) has estimated that $1 trillion in investment will be needed to replace and upgrade our aging and deteriorating infrastructure. Current practices used by cities, consulting engineers, and contractors have relied on legacy pipeline inspection devices (Figure 2) to make subjective, often incomplete, and inaccurate, condition-based assessments. As a result, replacement needs and rehabilitation are often incorrectly prioritized or approved.

Leak Detection Technology Timeline

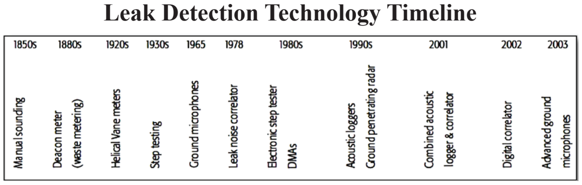

Figure 2. Leak Detection Technology Timeline, 1850-2003.

Water distribution conveyance & wastewater collection systems have traditionally relied on a variety of listening devices to *hear* leaks and closed-circuit television (CCTV) cameras to *see* leaks in pipes. While tethered and untethered acoustic hydrophones work best in high pressure water lines, CCTV cameras tend to be used when pipes are at low flow conditions or dry, after complicated and expensive dewatering, plugging, or bypass pumping is set-up.

Despite producing progressively better listening devices and higher resolution cameras, robotic sensors are still unable to accurately detect over 80% of pipeline defects, and unable to certify new or rehabilitated pipes as watertight.

Moreover, legacy acoustic and CCTV technologies have been unable to automatically quantify defect leakage rates. Without a complete data set that includes precise locations, size, and magnitude of defects in a given pipeline – before and after repairs or replacement – utility executives & managers are not equipped to make effective capital decisions for their ratepayers.

Barriers to Fixing Our Leaking Water System

Most water & sewer pipes were installed in the early-to-mid 20th Century, with anticipated useful service lives of 75-to-100 years. Given the importance of water in our daily lives, the economics of supply and demand, combined with efficient market behavior, would lead many to believe that renewal of our valuable infrastructure would be fairly straightforward to prioritize & fix. Yet, barriers prevent the efficient allocation of capital for finding & fixing pipeline assets, including, but not limited to:

- Difficult to access underground locations.
- Long government budget cycles and reluctance to increase service rates.
- Slow acceptance of new technologies.
- Emphasis on 'building' not 'repairing' assets.
- Contractors and engineers satisfied with the status quo.
- Lack of independent pipeline acceptance standards.

Given the absence of significant innovation, little has changed (Figures 3 & 4) in how pipeline condition assessments have been conducted. And, municipal utility decision makers have not had access to the best and most informative data regarding pipeline conditions in order to prioritize their capital spending programs.

Figure 3. Nearly 100 years ago, night crews listen for water leaks using stethoscopes and aquaphones.

Figure 4. Nearly 100 days ago, listening for water leaks with acoustic hydrophones and data correlators.

Pipeline Failures Begin to Threaten the Status Quo
Lessons learned, whether or not positive, are essential in the utility industry, to promote overall improved problem solving to critical infrastructure management considerations. But, while municipal utilities frequently share success stories at conferences and seminars, problems that may reflect poorly on organizations or their appointed and elected officials, typically are shared less often.

In 2010, the renowned civil engineer & educator, Ken Kerri, Ph.D., P.E., sought ways to improve pipeline water tightness evaluations after hearing about real-world challenges faced by his former students. Surprisingly, newly renovated pipelines that used long-accepted trenchless construction practices, begun in the 1970s, were already showing deficiencies requiring replacement.

Now exceeding $5 billion in annual sales in the US, Cured-In-Place Pipe (CIPP) lining has gained widespread acceptance as an alternative to traditional *dig & replace* methods of pipe replacement. First developed in 1971 in England, the CIPP process relines the interior of an existing pipe using heated water, steam, ultra-violet, or light-emitting diodes, to create or cure a new pipe wall inside the original host pipe, within hours.

Principally guided by the currently published American Society of Testing and Materials (ASTM) standard number 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.

Traditionally, CCTV operators have inspected underground pipes before and after rehabilitation, with installation contractors being allowed to check their work utilizing a self-administered visual coding system developed and adopted by CCTV manufacturers and contractors.

According to a 2002 Congressional Study, leakage and breaks in water and wastewater pipeline systems cost more than $50 billion annually. These widespread pipeline failures threatened the status quo with respect to condition assessment and verification testing. While CIPP suppliers often claim 50-to-75 year useful lives of rehabilitated trenchless pipes, and CIPP pinhole damage that is *self-healing*, observed pipe failures following rehabilitation often result from poor curing, contractor construction damage, bad lateral reconnections, overheating, and use of sub-standard or improperly mixed resins.

In some cases, newly rehabilitated pipes were found to leak more after rehabilitation than before rehabilitation (Figures 5 & 6).

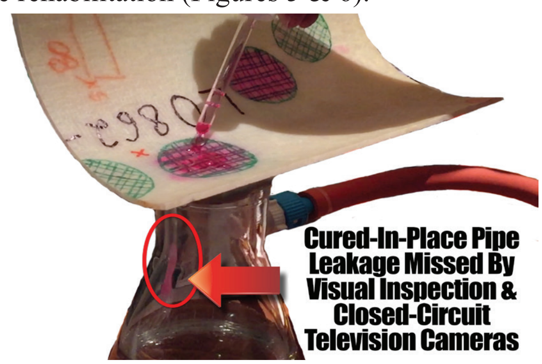

Figure 5. Testing of a Cured-In-Place Pipe (CIPP) sample finds defects missed by visual inspection.

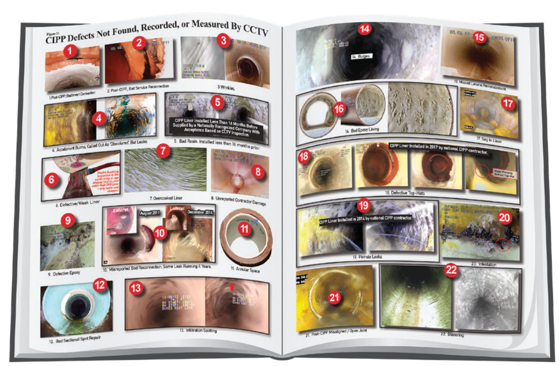

Figure 6. Example Cured-In-Place Pipe (CIPP) defects missed by Closed-Circuit Television (CCTV) camera inspection.

For pressurized water distribution networks, acoustic sensors have historically dominated the leak detection market. Almost universally accepted, experts agree that listening for leaks has long been hampered by a variety of environmental, scientific, operations, and other external influences noted in Table 1.

Table 1. Drawbacks of Using Traditional Acoustic Sensors, Data Loggers, and Correlators.

- Ambient noise interference.
- Variable water table heights affect results.
- Unable to assess innovative pipe materials, especially PE, PVC, & HDPE pipes.
- Different results for different pipe diameters.
- Leak size is difficult or unable to be determined.
- Multiple false-positive readings.
- Repair clamps on previous leaks will be bypassed by acoustic waves.
- Inability to quantify defect flow rates in GPM.
- Customer’s continuous water use similar as a leak.
- Affected by changes in backfill materials.
- Lengthy data processing & reporting times.
- Lack of repeatability, by crew, by equipment.
- Special training required for field crews.
- Need for third-party data interpretation.
- Misses silent or undetected leaks.

While acoustic leak detection equipment was considered to be satisfactory by most professionals, adoption of more sophisticated composite pipe materials offering lower installation costs, anti-corrosion, and durability features, rendered traditional acoustic sensors, data loggers, and correlators obsolete or lacking in their ability to detect leaks or anomalies. Unable to detect leaks in certain pipe materials using acoustic sensors, secondary technologies were attempted to anticipate catastrophic failures or as shown in Figure 7.

Anatomy of a Pipe Failure

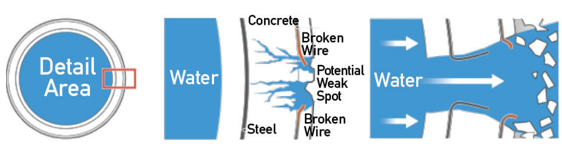

Figure 7. Progression of a Pre-stressed Concrete Cylinder Pipe (PCCP) failure.

Leaks that were normally detected using acoustic equipment became more challenged in plastic, lined, coated, and specialty-composite piping materials.

As traditional visual and listening devices have proven limited in certifying pipes as watertight, coupled with changes in advanced pipe materials and rising utility rates to finance needed repairs and capital plans, utilities have been open to new technologies that promise the ability to more accurately and dependably support complex infrastructure decision support.

COMSOL® Multiphysics® as a Change Agent

In 2016 the American Water Works Association (AWWA) sponsored the Advanced Condition Assessment & Pipe Failure Prediction (ACAP-FP) Project, where a leading water agency, industry representatives, and academicians presented their multi-year findings based on analytical validation and simulation data using COMSOL® Multiphysics® used as part of their R&D efforts. Project findings were presented at the water industry’s premier conference on infrastructure held November 2016 in Phoenix, Arizona.

Assessing numerous acoustic Pipe Wall Assessment (PWA) equipment manufacturers, COMSOL® results shared with one manufacturer identified deficiencies in the way it detected meaningful pipe wall losses/defects in large metallic cast iron and ductile iron pipes. Assistance was provided by a leading Australian university using COMSOL® Multiphysics®.

Since vendors could not capture continuous detailed geometries for pipe failure analysis, as shown in Figure 8, the lack of meaningful input questioned their claims related to assessing leaks or estimating remaining pipe wall thickness.

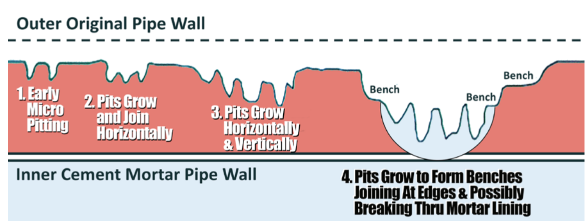

Figure 8. Unable to find leaks in cement mortar lined metallic pipes, vendor’s claims to reliably measure wall thicknesses were disproved using COMSOL®.

Unfortunately, visually *seeing* and acoustically *listening* for defects has been problematic. Often representing highly subjective results, not easily repeated even when the same inspector assesses the same pipe multiple times. Different inspectors who may have been trained by the same instructor, also failed consistency tests. Over-reliance on third-party data interpretation and long reporting cycles, showed a game-changing solution was badly needed.

Legacy technologies also indicated the need for an unbiased, unambiguous machine-intelligent technology capable of overcoming obvious drawbacks of defect detection tools. A key requirement also included the ability to provide results automatically, whereby defects could be accurately & immediately identified to support repair or replacement decisions in a timely manner, especially while crews were still mobilized on the jobsite.

The Challenge: To create an accurate, cost-effective, and repeatable solution that could certify the water tightness of pipelines, i.e. not just find a random leak. More importantly, overcome long-held inspection practices in an industry known for its glacial speed in adopting new technologies. Complicating matters would be the seemingly endless combinations of pipe materials, diameters, shapes, depths, lengths, gradients, soil types, and age profiles.

New Entrant: Low Voltage Conductivity
The science of using low voltage conductivity is straightforward. A similar application known as *holiday testing*, was already in use to evaluate protective coatings for exposed pipes, rooftops, and reservoir linings. The technology need was for a low voltage equivalent to internally assess full-length, 360-degree pipe wall integrity while allowing existing flow conditions during inspection.

An approach was developed by establishing a low, 12-volt electrical circuit with a 40 milliamps (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, any defect current would need to travel to the surface to confirm a corresponding pipe wall defect, or leak.

If the loop is never closed, whereby an electrical connection is never made, the pipe would be shown to have *no defects*. Conversely, if the loop is closed, whereby an electrical connection is made, 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 that could reliably model variable impedance of the electric circuit would be the first step. Confirming probe dimensions, power settings, grounding sources, data capture, repeatability of results, and precision of leak location would offer precise locational accuracy. Similarly important to defect location is quantifying a leakage rate. 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 that is not made by other existing leak location products.

Real-world field trials having the same conditions would be expected to confirm & calibrate the product for design, production, commercial roll-out, customer validation, and market acceptance.

Moving From Theory to Experimentation
A key first step was to translate theoretical assumptions into mathematic formulas. If successfully modeled, then selection of the right simulation tool was expected to drastically reduce a commercial product's *time-to-market*.

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. In other words, modelling and thinking of electric fields, current and charge sources were done under the assumption of steady state or "static" conditions. Analyzing electric fields and current densities were performed under several static conditions including, but not limited to, pipe size, pipe material, defect size, voltage levels, and defect location along the pipe, relative to the probe.

Electrostatic operational properties and parameters were modeled, analyzed, and plotted using COMSOL® Multiphysics® and MATLAB, a multi-paradigm numerical computing environment and proprietary programming language developed by MathWorks. Summing static condition values over different parameter sweeps enabled accurate generation of results.

While COMSOL® has multiple choices on meshing approaches, it was found that more coarse mesh reduced simulation time and memory resources, while a user-defined mesh could affect data accuracy. To verify results, different meshed geometries were needed during testing, noting that a normal mesh created a more accurate response, as shown in Figure 9.

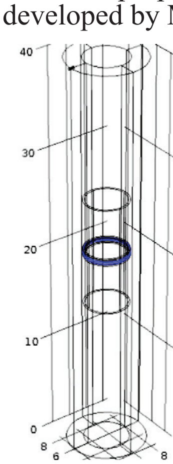

Figure 9. COMSOL Electro Scan ES-38.

A New Standard for Leak Locational Accuracy
A major drawback of commercially available leak location products is their inability to reliably & repeatedly locate leaks. With solutions ranging from using satellite technologies to locate individual leaks to within 100 ft accuracy to acoustic wave analysis finding leaks to within 6 ft accuracy in metallic pipes, COMSOL® applications were used to determine if significantly greater location accuracy was possible.

The focused electrode leak location (FELL) technology developed by Electro Scan Inc. was evaluated using COMSOL® tools. As shown in Figure 10, COMSOL® simulation results and data, along with the 3D image processing of Electro Scan data and verification plots, confirmed consistently repeatable leak location results to withing three-eighths (3/8th) of an inch, or one (1) centimeter (cm), accuracy across all non-conductive (i.e., non-metallic) pipes. These results are an industry breakthrough for leak location.

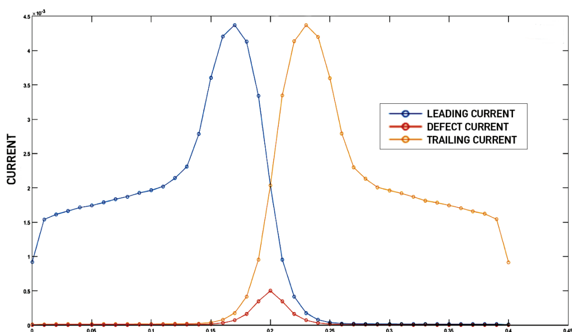

Figure 10. Triangulation of electric current confirms positional accuracy of leak location to 3/8th inch.

Quantifying Leaks in Gallons Per Minute (GPM)
When generating a high frequency electrode signal, one important aspect of the AC signal is that current levels of the defect electrode are able to be measured, demonstrating the breakthrough use of low voltage conductivity to locate leaks.

When the probe approaches a pipe defect, AC current levels on the electrodes increase with spatial dependence inside a pipe, comprising the

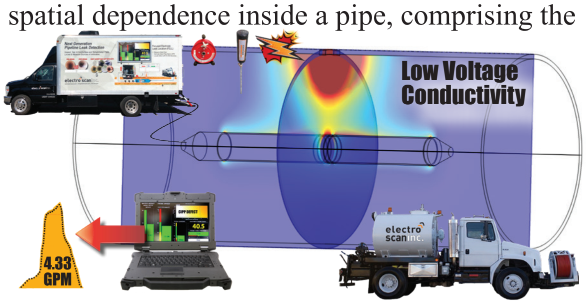

Figure 11. Use of COMSOL to confirm quantification of defect electric current of low voltage conductivity.

most important conduction characteristics that make the device perform, as shown in Figure 11. In other words, pipe defects are identified by the probe measured current levels. The measured area beneath the current spike curve can be used to compute the flow rate of the defect. Flow rates can be provided in any customary unit of measure, such as gallons per minute (GPM), liters per second (LPS), and so on.

Finding All (i.e. Multiple) Leaks In The Same Pipe
Following the confirmation of successfully identifying defect locations & quantifications, benchmark testing was required to determine that all defects could be consistently and sustainably identified, when subjected to repetitive testing.

The Electro Scan FELL technology found all pipe defects, as depicted in Figures 12 and 13. More importantly, its was able to support the systematic selection of the best approach for pipe rehabilitation.

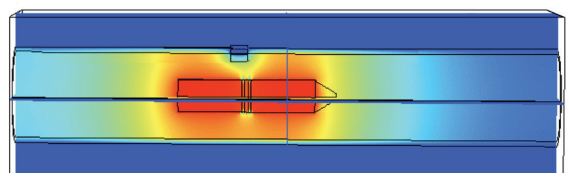

Figure 12. Electro Scan Inc. COMSOL model of defect current patterns.

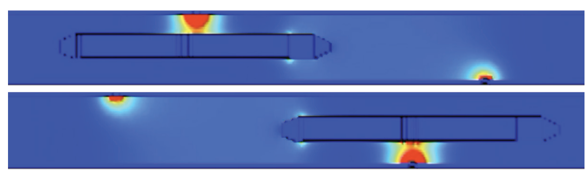

Figure 13. Electro Scan Inc. COMSOL model of multiple defects, including display of defect current.

FELL leak locations were able to quantify key performane metrics for each defect, including:

- Starting Point, Ending Point, and Maximum Defect Current.
- Defect Classification as Large, Medium, or Small.
- Flow Classification as Sever, Moderate, or Minor Defect Readings.
- Total Estimated Defect Flow in units of volume over time.
- Total Pipe Segment Defect Flow in units of volume over time per unit pipe diameter and segment length.

One of the benefits of utilizing COMSOL® Multiphysics® was the ability to model, test, and confirm single and multiple pipe defects, in minutes across multiple pipe materials, as listed in Table 2.

Table 2. Selected benchmark tested pipe materials.

ABS	Acrylonitrile-Butadiene-Styrene Pipe
ACP	Asbestos Cement Pipe
BRK	Brick Pipe
CMLSP	Cement Mortar Lined Steel Pipe
CON	Concrete Pipe
CIPP	Cured-In-Place Pipe
DIP	Ductile Iron, with coating
FRP	Fiberglass Reinforced Pipe
FRPM	Fiberglass Reinforced Polymer Mortar
GRP	Glass Reinforced Pipe
GROUT	Grouted Joints and Laterals
HDPE	High Density Polyethylene Pipe
ORP	Orangeburg Pipe
PB	Polybutylene Pipe
PCCP	Pre-stressed Concrete Cylinder Pipe
PE	Polyethylene Pipe
PFP	Pitch Fiber Pipe
PP	Plastic Pipe
PVC	Polyvinyl Chloride Pipe
RCP	Reinforced Concrete Pipe
RPM	Reinforced Plastic Mortar Pipe
RTR	Reinforced Thermosetting Resin Pipe
SIPP	Spray-in-Place Pipe
SPR	Spiral Wound Pipe
VCP	Vitrified Clay Pipe

While COMSOL® easily accommodates multiple pipe materials, internal pipe pressures, gradients, and water conductivity, desktop results needed to be field validated to account for environmental constraints and demands of working in residential, commercial, and open area locations to internally access actual pipe networks.

Moving from a computer simulation to actual pipes was the next step. By assessing various pipe materials, altering defect size, dimension, and severity, calibration was needed to ensure repeatability of results, including defect flow totals, as illustrated in Figure 14.

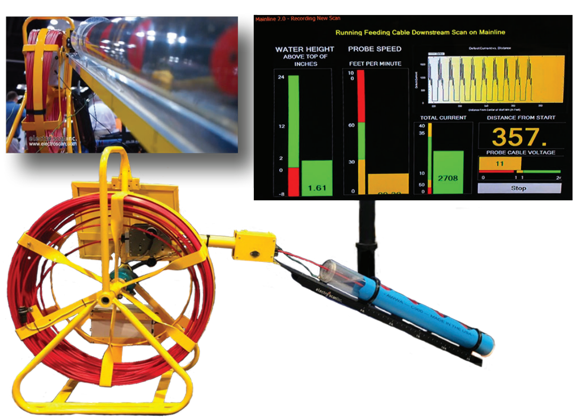

Figure 14. Electro Scan Inc. table top prototypes used to finetune repeatability of results of multiple defects.

Moving From the Desktop to Blacktop

Desktop testing is a terrific way to fine-tune new technologies, and potentially test commercial products that require documented field verification to demonstrate superior benefit-cost ratios, safety, and operating feasibilities.

But, moving from a laboratory to assess actual buried pipes, below streets, was the next step. By accessing & assessing underground pipes, operating considerations, safety, and other guidelines were established, again to ensure repeatability of results, scalability, production rates, and documented benefits over legacy inspection methods.

Fortunately, early adopters often suffering key pipe failures utilizing legacy inspection devices and others looking to prevent such occurrences, were more than willing to undergo early commercial trials & benchmarking, prior to adopting new test standards. One example was in the City of Boston (Figure 15). While it might seem straightforward to test a tethered probe inside a pipe segment surrounded by water, accomplishing the task with repeatable results would be crucial to demonstrate.

Figure 15. Boston field trial.

As shown in Figures 16 & 17, alternate entry configurations were tested and documented.

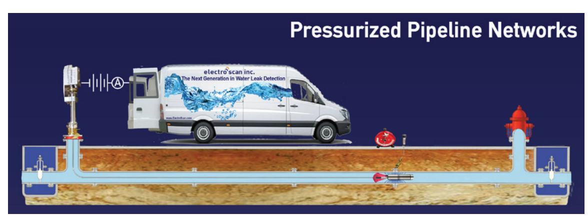

Figure 16. Electro Scan Inc. set-up in pressurized water mains.

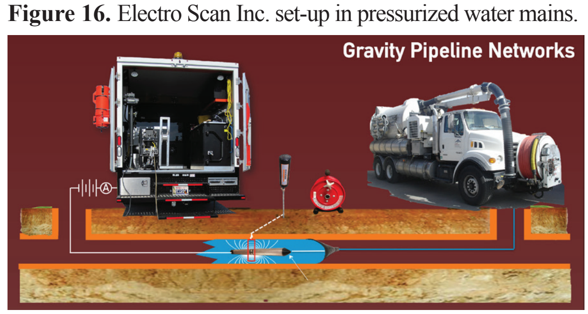

Figure 17. Electro Scan Inc. set-up in gravity sewer and stormwater pipelines.

Based on a series of field tests, curb-side data displays were required to allow field technicans to monitor the probes as they traversed through the pipes. Speed, pressures, data metrics, voltage indicators, and other monitors, were identified to help streamline full production engagements, as shown in Figure 18.

Figure 18. Electro Scan showing real-time defect identification in the field.

Once testing was completed, data needed to be instantly transferred and analyzed to determine if immediate action would be needed. Utilizing an Amazon Web Service (AWS), a separate cloud application using a commerical Software-as-a-Service (SaaS) subscription model was developed to enable office-based Owners and engineers to access field data as it is collected.

Figure 19. Electro Scan machine-intelligent field data displayed within minutes from the field to review or recommend immediate remediation.

The resulting benefits for infrastructure assessment include:

1. More accurate assessment of critical sewer and water infrastructure.
2. The ability to quantify reductions (sewer) or improvements (water) in flow, before and after rehabilitation, on a pipe-by-pipe basis.
3. The ability to QA/QC new construction and trenchless rehabilitation, within minutes of completing field work.

Sewer & Water Industry Disruption

Reaction to the introduction of new leak detection technology by pipe manufacturers, trenchless technology suppliers, construction companies, contractors, and consulting engineers, was swift.

One well-established Cured-In-Place Pipe (CIPP) trenchless technology supplier, after seeing Electro Scan's low voltage leak detection technology included in a statewide bid specification, issued a strongly worded letter stating:

> "…only visual inspection and CCTV can accurately identify observations and defects that affect installation (pre-construction) and acceptance (post-construction) of CIPP projects."
>
> "Visual inspection and CCTV are currently the only industry-accepted methods of verifying pipeline defects in ASTM F1216, the CIPP "bible", which has governed CIPP installations since the inception of the standard almost 30 years ago."

The supplier's letter went on to state, that "each of these widely accepted Standards identify visual inspection and CCTV as the only acceptable method for post-CIPP installation inspection," then threatened not to bid the project unless the more stringent inspection method to ensure pipes are watertight [FELL], was removed from the bid as a mandatory requirement.

Conversely, other pipe manufacturers, CIPP suppliers, consulting engineers, cities, and investor-owned utilities have just as quickly adopted the new standard for assessing the water tightness of pipes, before and after rehabilitation, as recommended in ASTM F2550-13 (2018), *Standard Practice for Locating Leaks in Sewer Pipes By Measuring the Variation of Electric Current Flow Through the Pipe Wall*.

Today, the San Francisco Public Utilities Commission (SFPUC), California's third largest municipal utility and the City of San Francisco Department of Public Works, leaders in the adoption of cleantech technologies, green initiatives, and water reuse, have initiated some of the toughest standards for the acceptance of new and rehabilitated pipes.

In May 2016, SFPUC became the first organization to issue a green bond, certified under the Climate Bonds Water Criteria, to help fund its reconstruction and rehabilitation efforts.

Criteria-based climate bonds were created to provide investors with verifiable, science-based criteria for evaluating bonds earmarked for financing sustainable water infrastructure projects.

Issued with 7-to-30 year maturities and coupons of 4% and 5% rated by Moody's and S&P as Aa3 and AA, respectively, SFPUC's bond was designed to fund eligible sustainable storm water management and wastewater projects from Phase 1 of the Utility's Sewer System Improvement Program (SSIP).

To date, over 30 public bids valued at nearly $250 million have been published utilizing new testing and inspection standards based on ASTM F2550.

Conclusion

COMSOL® Multiphysics® has allowed Electro Scan Inc. to validate its groundbreaking leak detection technology and offer it commercially. By maintaining a relentless wave of ingenuity, expanded to small & large diameter pipes, and manhole and other access chambers, Electro Scan has been able to surpass slower and less nimble providers of legacy solutions.

Subsequent and ongoing testing has been performed by the US Environmental Protection Agency, Water Research Foundation, Water Research Centre (WRc) plc, and Institute of Underground Infrastructure (IKT) gGmbH. This has allowed global commercial rollout benefiting all water and sewer investor-owned and municipal utilities serving the potable water, wastewater effluent, and reuse markets, worldwide.

While many water & sewer agencies had long suspected problems using legacy acoustic and visual-based techniques to accept open trench and trenchless construction projects, the lack of an unbiased and unambiguous ways to dispute or challenge contractors led many projects to experience localized and catastrophic failures or reduced life spans for pipe repairs, renewals, and rehabilitation.

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About the Author

Chuck Hansen is Managing Partner, Hansen Investment Holdings LLC, a private equity firm, and Chairman, Electro Scan Inc., a leading provider of pipeline leak detection technologies and cloud-based Software-as-a-Service (SaaS) analytics.

During his career, Hansen was involved in some of the world's largest statewide and utility asset management implementations, including work with 16 of the 20 largest U.S. cities and counties, the sewer & water industry of New Zealand, and largest water utilities in Australia, Canada, and the UK.

A multi-patent holder in designing and developing advanced applications using low voltage electrical conductivity to find and measure pipeline leaks, in 2015 Hansen negotiated a strategic partnership with WRc plc (Swindon, England), developer of the National Association of Sewer Service Companies' (NASSCO) Closed-Circuit Television (CCTV) inspection coding standards, recommending Electro Scan's FELL and ASTM F2550 for pre- and post-rehabilitation assessments since 2015.

Hansen received his BS from U.C. Berkeley (1978) and MBA from UCLA (1982). An instrument-rated pilot, Hansen also plays baritone & bass saxophones, playing with several artists & bands, including Charles Kelley (Lady Antebellum), Eddy Money, Huey Lewis, and Prairie Prince (The Tubes). In 2018, Tower of Power celebrated its 50th Anniversary releasing a new studio album "Soul Side of Town" recorded at Hansen's Sacramento-based Track Shack recording studio, featuring Hansen on Bass Sax.