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# Report on Condition Assessment of Wastewater Collection Systems

Office of Research and Development
National Risk Management Research Laboratory - Water Supply and Water Resources Division

# Report on Condition Assessment Technology of Wastewater Collection Systems

by

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## Disclaimer

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# Acronyms and Abbreviations

| | |
|---|---|
| 2D | Two-dimensional |
| 3D | Three-dimensional |
| AWI | Aging water infrastructure |
| B | Brick and clay pipe |
| C | Concrete pipe |
| CAD | Computer-aided design |
| CCTV | Closed-circuit television |
| CSO | Combined sewer overflow |
| DOT | Department of Transportation |
| ECT | Eddy current testing |
| EMAT | Electromagnetic acoustic transducer |
| F | Ferrous pipe |
| GGL | Gamma-gamma logging |
| GHz | Gigahertz |
| GIS | Geographic information system |
| GPIR | Ground-penetrating imaging radar |
| GPR | Ground-penetrating radar |
| GWUT | Guided wave ultrasonic testing |
| HDPE | High-density polyethylene |
| HID | High-intensity discharge |
| I/I | Inflow and infiltration |
| IE | Impact echo |
| IRT | Infrared thermography |
| JPT | Joint pressure testing |
| KARO | Kanalroboter |
| kHz | Kilohertz |
| KURT | Kanal-Untersuchungs-Roboter-Testplattform |
| LED | Light-emitting diode |
| MAD | mobile acoustic device |
| NASSCO | National Association of Sewer Service Companies |
| O&M | Operation and maintenance |
| OPS | Office of Pipeline Safety |

| | |
|---|---|
| ORD | Office of Research and Development |
| PA | Phased array |
| PACP | Pipeline Assessment and Certification Program |
| PAIRT | Pulsed active infrared thermography |
| PCCP | Pre-stressed concrete cylinder pipe |
| PIRAT | Pipeline inspection real-time assessment technique |
| PVC | Polyvinyl chloride |
| RCP | Reinforced concrete pipe |
| RFEC | Remote field eddy current |
| SAM | Sewer assessment with multi-sensors |
| SAR | Synthetic-aperture radar |
| SASW | Spectral analysis of surface waves |
| SSET | Sewer scanning and evaluation technology |
| SSO | Sanitary sewer overflow |
| UPV | Ultrasonic pulse velocity |
| USEPA | United States Environmental Protection Agency |
| UWB | Ultra wideband |
| VCP | Vitrified clay pipe |
| WERF | Water Environment Research Foundation |
| WRc | Water Research Centre |

# Executive Summary

The wastewater collection system infrastructure in the United States is recognized as being in poor condition and in urgent need of condition assessment and rehabilitation. As part of an effort to address aging infrastructure needs, the U.S. Environmental Protection Agency (USEPA) has initiated research under the Aging Water Infrastructure program, part of the USEPA Office of Water's Sustainable Infrastructure initiative. This report presents the results of a three-year research project titled *Condition Assessment of Wastewater Collection Systems*. The goal of this report is to provide utilities with information on current innovative and emerging technologies for conducting sanitary sewer condition assessments. This information, which includes performance data and, where available, cost information, can be used as a resource when selecting the most appropriate technology given a system's characteristics, history, and condition assessment goals.

Closed-circuit television (CCTV) provides a detailed view of the interior surface of pipes and permits characterization of pipe defects through a systemized coding process. It has long been the mainstay of sewer condition assessment and will likely remain a vital part of condition assessment programs. However, a number of other technologies are available and can be used to identify different types of defects as well as to assess pipe wall integrity and soil envelope quality. Data from these technologies can complement CCTV data and help target CCTV inspections in problem areas. When considering various technologies for application, utilities need to match the pipe types, materials, defects of concern, and program goals for their systems with the capabilities of different technologies. Also, a number of technologies from other industries are being evaluated for potential applications to sewer condition assessment; utilities should watch for further developments.

***Screening Technologies***

As utilities become increasingly sophisticated in structuring their condition assessment programs, screening technologies will assume greater importance. Use of zoom camera provides a rapid and cost-effective option for visual assessment, remaining stationary at a manhole and zooming optically down a pipe. It is a useful visual screening technique that is likely to detect a large portion of the defects found by CCTV. Acoustic monitoring technology detects wire breakage in pre-stressed concrete cylinder pipe (PCCP) and can be used to screen the overall condition of force mains without taking the pipe out of service. In addition, scattergraph analyses of flow data can reveal pipe conditions in the vicinity of flow monitoring locations, including obstructions, bottlenecks, surcharged conditions, sanitary sewer overflows [SSOs], or combined sewer overflows [CSOs]). The analysis can be used to select areas for more thorough evaluation.

***Detailed Evaluation of Interior Pipe Surfaces***

If a detailed, high-quality evaluation of the interior surface of the pipe is required, CCTV remains a primary option. Utilities may also consider digital scanning, which is used in Europe and has begun to be used in the U.S. Digital scanning produces high-quality images and unfolded views of the pipe and allows defect coding to be done in the office after field deployment. Its performance depends upon factors such as resolution, pipe size, and lighting. Response to the results of digital scanning inspections has been favorable, and as the technology evolves and prices shift, it may become a competitive option for condition assessment.

***Evaluation of Pipe Wall Integrity***

Evaluation of pipe wall integrity involves measuring such features as wall thickness, deviations from circularity, and leakage pathways. Sonar and laser profiling provide measurements of pipe wall geometry, giving insight into wall thickness (and therefore corrosion), sediment buildup, and deflection. These methods complement camera-based information. They may confirm or rule out potential defects seen on CCTV, and vice versa. Electro-scanning may be especially helpful in locating sources of infiltration and inflow and determining faulty joints and service connections. These defects are not always observable by camera unless water is flowing through them. The technology can also detect longitudinal and radial cracks, including fine cracks caused by corrosion. When compared to joint pressure testing, electro-scanning agreed very well in the number of defects detected. Leak detection systems "listen" for the noise made by leaks, and although performance information is limited, the method shows promise and merits systematic evaluation.

Innovative methods that are still in the research stage for pipe wall integrity include impact echo and spectral analysis of surface waves (SASW), ultrasonic pulse velocity (UPV) testing, guided wave ultrasonic testing (GWUT), micro-deflection, and fiber optics. The impact echo, SASW, and UPV methods, though widely used for the integrity testing of engineered structures (e.g., dams and roadways), have limited but promising application in the testing of pipe wall integrity. The GWUT method has been used primarily as a screening technology; however, recent research indicates that GWUT can be improved to detect critical defects and locate circumferential cracks in piping. GWUT has been used for above-ground piping at industrial facilities, and has also been used on underground piping that can be accessed at some point from an excavation or aboveground portion. The micro-deflection method, though applied to assess the general condition of brick sanitary sewers, requires more research to demonstrate its effectiveness. Fiber optic systems have been used to monitor strain and temperature changes in many structures including dams, bridges, and pipelines. These systems show the potential to measure deflections and the thickness of a pipe wall, but have limited applications on water mains and have not been applied to wastewater collection systems.

***Evaluation of Pipe Bedding***

If the evaluation of pipe bedding and void conditions is needed, ground-penetrating radar (GPR) is the most readily available option. Traditionally operated from the ground surface, GPR has a demonstrated ability to locate subsurface features, including pipelines and soil voids. However, clayey or saturated soils may attenuate the signal and limit the depth to which this technology is effective. Some studies have also been done on the potential for deploying GPR within the pipeline. Gamma-gamma logging and infrared thermography are two technologies still in the research stage for adaptation from other engineering fields to the evaluation of pipe bedding. As studies progress, the performance capabilities of these methods are expected to be confirmed.

After a utility has developed a short list of technologies to meet its condition assessment program objectives, the implementation issues should be reviewed to confirm that each technology is still a viable option. The cost effectiveness or affordability of a technology is a key factor in the selection process. Furthermore, it is useful to complete a cost-benefit analysis to check that the costs of performing the condition assessment (i.e., direct inspection costs, staff training costs, and planning and data analysis costs) do not outweigh the program benefits (i.e., avoided costs of pipe failure). When considering a new technology, a utility needs to decide whether to invest in the inspection equipment or use a contractor. It is important to understand the complexity of the technology and the staff training needed for equipment operation and data analysis. Other practical concerns include the equipment's deployment method, its requirements for access to the collection system (e.g., deployed at each manhole), and the allowable pipe conditions (e.g., minimum flow, pipe cleanliness).

In gathering the information for this report, research needs became apparent. There is an ongoing need for evaluations of technology performance. Because most available information on sewer condition assessment comes from technology vendors and operators, the success of the methods tend to be highlighted. A comprehensive third-party survey is needed to compile and analyze utility experiences with sewer inspection technologies, including their performance and cost. Municipalities will benefit from continued research on the performance of the various commercially available quantitative technologies (e.g., electro-scanning, laser, sonar, and acoustic methods) and innovative technologies (e.g., gamma-gamma logging, infrared thermography, impact echo – spectral analysis of surface waves, and micro-deflection) that provide information on pipe wall integrity or pipe bedding. When these innovative technologies become commercially available and cost-effective for sewer condition assessment, utilities will benefit from having additional options for characterizing wastewater collection system conditions.

# 1. Introduction

## 1.1 Background

Across the U.S., wastewater collection system infrastructure is generally in very poor condition. The American Society of Civil Engineers Infrastructure Report Card gave wastewater infrastructure a D− in 2005 and again in 2009 (ASCE, 2005, 2009). Aging pipes have not been inspected, replaced, or rehabilitated rapidly enough to prevent deterioration and failure of wastewater systems. The frequent occurrence of SSOs and sewer pipe failures is an additional indication that the infrastructure is in a deteriorated state and needs immediate attention.

In fiscal year 2007, the USEPA Office of Research and Development's (ORD's) National Risk Management Research Laboratory initiated the Aging Water Infrastructure (AWI) Research Program to support the USEPA Office of Water's Sustainable Infrastructure initiative. Specific objectives of the AWI research are (1) to evaluate promising innovative technologies and (2) to improve the cost-effectiveness of operation, maintenance, and replacement of aging drinking water and wastewater treatment and conveyance systems. Condition assessment of infrastructure assets is a critical topic within the infrastructure research area. The essential components of condition assessment include the collection of data through direct inspection, followed by data analysis to determine the assets' physical condition, operational status, and estimated remaining service life.

In November 2007, USEPA-ORD's National Risk Management Research Laboratory funded a three-year research project titled *Condition Assessment of Wastewater Collection Systems* in support of the Aging Water Infrastructure Research Program. This project is intended to help wastewater utilities better understand their wastewater collection system needs and develop and implement condition assessment programs. The overall project objectives include an evaluation of the state of condition assessment technology and compilation of the cost and performance data of innovative assessment technologies. The technologies include innovative camera-based methods, newer non-camera-based methods, and technologies under consideration for adoption from other industries. A field-based component of this project will be conducted in Kansas City, Missouri, in the summer of 2010 to collect cost and performance data on several promising technologies (digital scanning, zoom camera, laser, and electro-scanning). The results will be published by USEPA to help wastewater utilities select appropriate condition assessment technologies that meet their technical objectives and available operations/maintenance budgets.

This report documents research conducted under this project. It includes a summary of two published companion reports: (1) *Condition Assessment of Wastewater Collection Systems – State of Technology Review Report,* USEPA Report, EPA/600/R-09/049, May 2009, http://www.epa.gov/nrmrl/pubs/600r09049/600r09049.pdf, and (2) *Innovative Internal Camera Inspection and Data Management for Effective Condition Assessment of Collection Systems,* USEPA Report, EPA/600/R-09/082, July 2010 (to be available on EPA/ORD/NRMRL website). The first report is a white paper that summarizes the current state of technology for condition assessment of wastewater collection systems. It includes detailed information on a number of technologies, including current equipment models and vendors. The second report is a technology transfer document that addresses innovative camera-based technologies and data management practices currently used by more advanced wastewater utilities with the goal of making this information available to utilities at large. Seven utility case studies are used to illustrate key points. The report includes an example CCTV inspection report, examples of defect code methods, and technology vendor contact information.

## 1.2 Report Overview

This report provides information on the capabilities and technical performance of a variety of sewer condition assessment technologies and is intended to help utilities select those most applicable to their needs. Chapter 2 outlines the primary factors that influence technology selection, such as project objectives (e.g., system-wide screening, comprehensive inspection of high priority pipes), system characteristics (e.g., pipe material, pipe diameter, and anticipated pipe defects), cost, and implementation issues. Later chapters (Chapters 3 – 6) discuss the performance of specific technologies, organized according to function:

- Chapter 3: Screening Technologies.
- Chapter 4: Technologies for In-Depth Inspection of Internal Pipe Surface.
- Chapter 5: Technologies to Evaluate Pipe Wall Integrity.
- Chapter 6: Technologies to Evaluate Pipe Bedding and Void Conditions.

Cost information is provided where available (Chapter 7). The report includes information on technologies being considered for adaptation from other industries to give readers an indication of additional assessment capabilities that may be available in the future. Although some of these technologies may be used to inspect service laterals (i.e., pipes carrying wastewater from houses or buildings to sewer mains under the street), this report does not address the use of these technologies in laterals because accurate and reliable data are lacking. The software and decision-support systems related to these technologies are not addressed in the report.

Cost and technical performance information for the various technologies were collected from published and unpublished reports. Researchers, technology vendors, and other industry experts (including representatives of Water Environment Research Foundation (WERF), National Association of Sewer Service Companies [NASSCO], National Research Council of Canada Institute for Research in Construction [NRC-IRC], and Water Environment Foundation [WEF] contributed to this report, in part by providing survey reports, case studies, and additional contacts.

The various technologies were compared using several performance criteria. The minimum criteria are: (1) whether the technology can inspect the pipe material of concern and (2) whether it can detect the defects of concern. Other performance criteria include equipment durability, mobility/portability, cost, the status of technology applications (e.g., bench-scale testing, pilot-scale testing, or full-scale implementation), productivity (e.g., inspection rate), and the training requirements for equipment operation and maintenance. Although the successful application of these technologies/methods will depend upon a number of factors, some of them subjective, it is believed that this assessment approach would provide a basic understanding of the capabilities and potential utility of innovative condition assessment methods.

# 2. Technology Selection Considerations

Current sewer inspection technologies are applicable to a range of pipe materials and sizes, sewer conditions, and observable defects. In addition, technologies developed for other applications are the subject of on-going research for use in sewer condition assessment, as discussed in Chapters 3 through 6 of this report, and may be viable options in the future. This chapter provides an overview of the main factors and types of information that influence the selection of sewer inspection technologies. It sets the stage for Chapters 3 through 6, in which the capabilities and performance of individual technologies are described in greater detail.

## 2.1 Inventory of Pipes and Operating Conditions

The inventory information of a sewer system should be reviewed and updated as one of the initial steps in developing a condition assessment program. The information in such an inventory (e.g., pipe material, size, and condition) is useful in selecting an appropriate assessment technology. For example, extensive debris may hinder the movement of deployment devices such as pushcams, or a system that has a large number of pipe bends may be limited in the use of a zoom camera. The size of manhole required for deploying equipment in pipes should also be considered.

Table 2-1 summarizes the condition assessment technologies and their typical applications based on system characteristics (e.g., pipe type, material, and diameter) and types of defects that may be detected by various condition assessment technologies. The table presents information for commercially available methods and innovative technologies for use in wastewater collection systems. Pipe inventory and condition characteristics critical to technology selection are described below.

### 2.1.1 Types of Pipes

The three most common types of pipe in wastewater collection systems are gravity lines, force mains, and service laterals. A gravity line is a sewer pipe that is sloped to convey flow via gravitational forces. A force main is a pressure line used to convey pumped sewage. Service laterals are the lines that convey wastewater from a building's foundation to the sanitary line, or main, in the street.

### 2.1.2 Pipe Size and Material

Wastewater collection sewers may be constructed of any of the following materials:

- Ferrous pipe, including ductile iron, cast iron, and steel.
- Concrete pipe, including reinforced concrete pipe (RCP) and PCCP.
- Ceramic-based pipe, including brick and vitrified clay pipe (VCP).
- Plastic pipe, including polyvinyl chloride (PVC) and high-density polyethylene (HDPE).

**Table 2-1. Summary of Condition Assessment Technologies and Typical Applications**

| | Camera | | | | Acoustic | | | Electrical & Electro-magnetic | | | Laser | Innovative Technologies | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CCTV | Zoom camera | Digital scanning | Push-camera inspection | In-line leak detectors | Acoustic monitoring systems | Sonar | Electrical leak location | Remote field eddy current | Magnetic flux leakage | Laser profiling | Gamma-gamma logging | Ground penetrating radar | Infrared thermography | Micro-deflection | Impact echo/SASW | Ultrasonic pulse velocity | Guided Wave Ultrasonic |
| **Application** | | | | | | | | | | | | | | | | | | |
| Pipe type | G | G | G | S | G, F | F | G, F | G, F, S | G,F,S | G,F,S | G, F | G,F,S | G,F,S | G,F,S | G | G | G | F |
| Pipe material | Any | Any | Any | Any | Any | PCCP | Any | NF | F | F, PCCP | Any | C | Any | Any | B | B, C | C | F |
| Pipe diameter (in.) | >6 | >6 | 6-60 | 1-12 | ≥4 | ≥18 | ≥12 | 3-60 | ≥2 | 2-56 | > 4 | TBD | 18-30 | TBD | N/A | >6 | TBD | >2 |
| **Defects Detected** | | | | | | | | | | | | | | | | | | |
| Sediment, debris, roots | • | • | • | • | | | • | | | | • | | | | | | | |
| Pipe sags & deflections | • | • | Partial | • | | | • | | | | • | | | | | | | |
| External pits & voids | | | | | | | | | | | | • | | | Partial | • | | • |
| Corrosion & metal loss | | | Partial | | | | • | | • | • | • | | | | | | | • |
| Off-set joints | • | • | Partial | • | | | | | | | | | | | | | | |
| Pipe cracks | • | • | • | • | | | • | • | • | • | | | | | | • | • | • |
| Leaks | • | • | • | • | • | | | • | • | | | | • | • | | | | |
| Broken pre-stressed | | | | | | • | | | • | | | | | | | | | |
| Wall thickness | | | | | | | | | • | | | | | | | • | • | • |
| Service connections | • | • | | • | | | | | | | | • | | | | | | |
| Bedding condition | | | | | | | | | | | | • | • | | | | | |
| Bedding voids | | | | | | | | | | | | • | • | • | Partial | | | |
| Deteriorated insulation | | | | | | | | | | | | | | • | | | | |
| Overall condition | | | | | | | | | | | | | | | • | | | |

Pipe type: G – Gravity line F – Force main S – Service lateral TBD – To be decided N/A – Not applicable

Pipe material: NF – Nonferrous F – Ferrous B – Brick C – Concrete PCCP – Pre-stressed concrete cylinder pipe

Adapted from USEPA (2009a).

The components of a collection system are often constructed of different materials depending upon their purpose and time of installation. Older gravity sewer lines are constructed primarily of vitrified clay, brick, and concrete, while newer pipelines are constructed of plastic, ductile iron, steel, and reinforced concrete. Most force mains are constructed of ferrous materials (e.g., welded steel, ductile iron, or cast iron) or plastic (PVC, HDPE) while large-diameter force mains have also been constructed of PCCP. Service laterals are typically constructed of plastic pipe (PVC, HDPE).

Due to differences in sizes and capabilities of inspection equipment, sizes of sewer pipes must be considered when selecting the appropriate technology. For example, large diameter pipes can pose a challenge for CCTV cameras due to lighting and camera resolution issues. In contrast, zoom cameras are known to perform better in larger diameter pipes. Some vendors have claimed a sight distance of up to 700 ft in a 60-in. pipe, but the zoom camera can only "see" 100 ft down an 8-in pipe. The minimum diameter of a gravity line (excluding service laterals) is typically 8 in. while older systems may contain 6-in. A recent survey of 31 U.S. utilities found the following distribution of gravity sewer pipe diameters: 77% of pipes were from 4 in. to 12 in.; 15% from 14 in. to 33 in.; and 8% $\geq$36 in. (Thomson et al., 2004).

### 2.1.3 Inspection Data and Reports

Historical information such as inspection reports and records of pipe failure can be reviewed to identify the types of pipe defects typically found in a system, as well as each pipe's comparative ranking for future inspections and repair/rehabilitation work. The most common defects in sewer pipes are cracks and broken pipe; root intrusion; buildup of grease, grit, and debris; offset joints; corrosion; leakage (e.g., at joints, laterals, or in general); and pipe sags. This information can be used to guide technology selection for condition assessment.

Inspection and testing records may include in-line camera, sonar or laser inspections, infiltration and inflow (I/I) studies, smoke testing, flow isolation studies, and dye tracer studies. CCTV camera inspections are the most common type of inspection record and provide a visual indication of pipe condition, including evidence and location of a number of structural and operation and maintenance (O&M) defects. The defects include cracks, debris, roots, pipe sag and deflection, offset joints, and exposed rebar and aggregate. Sonar inspection can provide information on internal pipe conditions below the water line, such as pipe radius, sediment depth, and the presence of air pockets. The sonar unit indirectly indicates sediment depth by calculating the difference between nominal pipe diameter and the measured free space. Estimates of sediment depth can be used to estimate sewer cleaning costs and the sewer's hydraulic capacity. The pipe radius/diameter measurements from laser and sonar inspections can also be used to assess the pipe's structural integrity (e.g., pipe wall loss, pipe deformation, and ovality) and to plan for rehabilitation work such as slip lining.

If the inspection reports and records of pipe failures are not available or easily accessible, a pipe material inventory can be used as an indicator of possible defect types. For example, gravity pipes constructed of VCP or PVC are prone to grease buildup and joint misalignment or leakage. Force mains constructed of ferrous materials are susceptible to corrosion. Table 2-2 summarizes the most common defects for various pipe construction materials.

**Table 2-2. Pipe Defects Common to Each Pipe Material**

| Defect | Concrete | | | Ferrous | | Ceramic | | Plastic | |
|---|---|---|---|---|---|---|---|---|---|
| | Concrete pipe | Asbestos cement | PCCP/CCP | Cast iron/ ductile iron | Steel | VCP | Brick | PVC | HDPE |
| **Internal pipe surface** | | | | | | | | | |
| Root intrusion | • | • | • | • | • | • | • | | • |
| Grease build-up | • | • | • | • | | • | • | • | • |
| **Pipe wall condition** | | | | | | | | | |
| Cracks/ broken pipe | • | • | | | | • | | | |
| Internal corrosion | | • | • | • | • | | | | |
| External corrosion | | | • | • | • | | | | |
| **Leakage** | | | | | | | | | |
| General | • | • | | • | | • | | • | |
| Joint leakage | | | • | | • | | | | |
| Leaking laterals | | | | • | | | | | • |
| **Alignment/grade** | | | | | | | | | |
| Alignment | | | | • | | | | • | • |
| Joint misalignment | • | • | | • | | • | | | |
| Excessive deflection | | | | | • | | | • | • |
| Grade | | | | | | | | • | • |
| **Other** | 1 | | | | | | 2 | 3 | 4 |

1 – Liner separation, weld failure
2 – Missing bricks, soft mortar, vertical deflection, collapse
3 – Lateral connections
4 – Pressure capacity (force mains only)
Data from Thomson et al. (2004). Reprinted with permission.

### 2.1.4 Flow Conditions

Some technologies, such as the camera-based methods (CCTV, digital scanning, zoom camera) can only view pipe surfaces above the waterline. Sonar, on the other hand, requires a minimum water level for equipment deployment, and electro-scanning requires a full pipe. Historical flow monitoring data can be reviewed to determine typical and seasonal flow conditions and help utilities deploy the appropriate technology at the optimal time.

## 2.2 Data Needs for Condition Assessment Based on Program Objectives

Technology selection can be further refined by determining the type of condition assessment information needed to meet the utility's objectives. For example, the following objectives may lead to the selection of a screening tool:

- Rapidly assess the entire system.
- Establish a prioritization scheme for a sewer-cleaning program, CCTV inspection program, or maintenance program.
- Improve budget forecasting through expanded knowledge of pipe condition and maintenance needs.
- Evaluate the effectiveness of a sewer-cleaning program.
- Establish baseline conditions in low-priority pipes.

In contrast, the following objectives may lead to the selection of a condition assessment technology that can provide more detailed condition information:

- Examine internal surface conditions in problematic or high-priority pipes (cracks, pitting, grease, roots).
- Critically assess pipe wall integrity in problematic or high-priority pipes (thickness, geometry, corrosion).
- Establish baseline pipe condition following pipe rehabilitation, new pipe installation, or liner installation.
- Track specific defects over time.
- Investigate areas of the system where performance problems are known or pipe failure occurs.
- Investigate and eliminate I/I sources to increase available system capacity.
- Highlight a potential problem while the crew remains on site (and has access to the sewer for a closer inspection).

Table 2-3 summarizes the technologies that can meet different types of program objectives. It is advantageous to combine methods that provide complementary information. Multi-sensor systems (e.g., robotic platforms that include laser, sonar, and CCTV) offer the possibility of collecting different types of data during a single deployment.

**Table 2-3. Technology Selection Based on Program Objective**

| | | Camera | | | Acoustic | | | Electrical & Electromagnetic | | | Laser | Innovative Technologies | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Program Objective** | Flow data analysis | CCTV | Zoom camera | Digital scanning | In-line leak detectors | Acoustic monitoring systems | Sonar | Electro-scanning | Remote field eddy current | Magnetic flux leakage | Laser profiling | Gamma-gamma logging | Ground penetrating radar | Infrared thermography | Micro-deflection | Impact echo/SASW | Ultrasonic pulse velocity | Guided Wave Ultrasonic |
| Screening/Prioritization | • | | • | | | • | • | | | | | | | | | | | • |
| Detailed inspection of internal surface conditions | | • | | • | | | • | | | | • | | | | | • | | |
| Detailed inspection of pipe wall integrity | | | | | • | • | • | • | • | • | • | | | • | • | • | • | • |
| Detailed inspection of pipe bedding and void conditions | | | | | | | | | | | | • | • | • | | | | |

The technologies discussed in this report constitute a mix of methods that are well established, commercially available but still relatively new, and innovative methods that are in the research stage. In particular, information on innovative and emerging technologies is included to provide readers with future technology options. Utilities are encouraged to monitor the technological development for future deployment. Table 2-4 summarizes the status of the various applicable and potentially applicable technologies.

**Table 2-4. Status of Condition Assessment Technologies**

| Technology | Status of Application to Condition Assessment of Sewers |
|---|---|
| CCTV inspection | Commercially available |
| Zoom camera | |
| Digital scanning | Commercially available, new applications under development |
| In-line leak detectors | Commercially available |
| Acoustic monitoring systems | |
| Electro-scanning | |
| Eddy current testing (ECT)/Remote field eddy current (RFEC) [1] | |
| Magnetic flux leakage | Commercially available, but limited applications for wastewater pipes |
| Laser profiling | Commercially available |
| Ground penetrating radar | |
| Gamma-gamma logging | Under development at pilot scale |
| Infrared thermography | |
| Micro-deflection | Under development at bench scale |
| Impact Echo/SASW | |
| Ultrasonic Pulse Velocity Ultrasonic Testing | |
| Guided Wave Ultrasonic Testing | Commercially available but not yet applied to wastewater pipe |
| Sonar (ultrasonic profiling) | Commercially available as part of multi-sensor robotic platforms for use in wastewater collection systems |

[1] Method discussed in USEPA (2009a).

## 2.3 Cost

A technology's cost effectiveness or affordability is a key factor in the selection process. Research indicates that in many situations, it is the utility's budget in combination with an external requirement (e.g., regulatory or due diligence) that determines whether a condition assessment technology is affordable (Marlow et al., 2007). Ideally, a cost-benefit analysis will be performed to determine whether it is a worthwhile investment.

A cost-benefit analysis evaluates both the costs and benefits of the condition assessment program to confirm that its costs do not outweigh its benefits. The costs may include:

- Direct inspection costs (e.g., equipment rental, labor, traffic control, sewer cleaning, bypass pumping).
- Indirect costs to the utility and other parties of carrying out the inspection:
    - Costs of service interruption.
    - Customer relations.
    - Laboratory expenses (e.g., bench-scale experiments, non-destructive testing of pipe samples).
- Indirect costs to the utility and other parties for data collection, analysis, and reporting:
    - Computer hardware and software expenses.
    - Staff training on computer software, data collection, and analytical procedures.
- Labor costs before and after fieldwork for planning.

The anticipated benefits of a condition assessment program are more difficult to quantify and derive mainly from the reduction in the risk of failure (likelihood and consequences of failure) and the information that allows maintenance, rehabilitation, and replacement to be carried out on the most cost-effective schedule. Specific benefits may include:

- Reduced sources of I/I.
- Avoided emergency repair costs.
- Avoided costs of extended service disruptions due to catastrophic failure.
- Avoided restoration costs due to environmental and property damage from catastrophic failure.
- Avoided public health costs (i.e., injury, death, disease transmission) from catastrophic failure.
- Improved planning and prioritization of rehabilitation and replacement projects due to condition assessment information and improved estimates of service life.
- Avoided costs of premature pipe replacement or rehabilitation.
- Customer satisfaction and reduced numbers of complaints.
- Improved service reliability.

Thomson (2008) conducted cost-benefit analyses for inspection of gravity sewers and force mains. He reported that the cost of gravity sewer inspection is typically low with respect to the value of the asset. For example, the cost of inspecting a 12-in. diameter sewer at a depth of 13 ft is less than 1% of the asset value, and the proportion decreases with increasing depth and diameter of the sewer. Thus, the benefits from inspection of gravity sewers are likely to exceed costs for all but small-diameter sewers at shallow depths.

For force mains, on the other hand, the cost of inspection is high, with indirect costs (e.g., temporary flow bypass, accessing the line) often exceeding the costs of physical inspection. For smaller lines in less populated areas, the monetary benefits of inspection may be less than the cost of inspection. In such settings, a “fail and fix” approach may be appropriate. However, the cost-benefit ratio may change in environmentally sensitive areas. The benefits increase greatly for larger diameter force mains and urban areas due to the increased risk of major consequences.

## 2.4 Implementation Issues

In addition to selecting a technology appropriate for the pipe size, material, and potential defects of a system, logistical considerations for implementation can be important. Some of the implementation issues are described below and again in Chapter 7.

### *Purchasing vs. Contracting*

When considering a new technology, a utility may need to decide whether to invest in the inspection equipment or to use a contractor. This decision involves considering whether the long-term need for the technology justifies the expense of purchasing the equipment and software and of training staff. If several technologies are selected for a comprehensive inspection and prioritization process, subcontracting at least some of the work may be more economical. The inspection conducted by contractors may cost more (in the near term) than that by in-house staff (with extra capacity). In other cases, providing steady work to a contractor could reduce the cost of inspection in the long run.

### *Productivity*

Inspection rate or measurement speed is a significant driver for cost economy and feasibility of a technology, particularly if traffic control or bypass pumping is needed. Inspection rate varies considerably among different inspection technologies. For example, utilities that have adopted zoom camera technology as part of their sewer inspection strategy have reported inspection rates of 5,000 to 6,000 ft per day, which are roughly three to four times faster than inspections using traditional in-line CCTV (USEPA, 2010). Manufacturers of two digital scanning devices (DigiSewer and Panoramo) claim their devices can inspect pipes at a rate of 69 to 70 ft per minute (http://www.envirosight.com; http://www.rapidview.com/ ), whereas some of the newer technologies (e.g., sonar) have inspection rates <20 ft per minute (Thomson et al., 2004). Electro-scanning proceeds at a rate of 30 ft per minute. More production rates of specific technologies are provided in Chapters 3 through 6.

### *Complexity*

The relative complexity of operating a condition-assessment device and data analysis is an important factor in its selection. If advanced training is required to calibrate and operate the equipment, it may discourage its deployment. Similarly, if the labor or materials associated with maintaining the equipment are prohibitively expensive, the technology may not be suitable for wastewater collection systems. Highly specialized data analysis, if required, will add another level of complexity. Utilities may need to decide whether a technology's level of complexity is acceptable for the benefits received. If the data output is especially detailed with high quality and helps achieve the inspection objectives, a utility may be willing to use a more complex technology.

### *Durability*

The conditions under which sewer assessments are typically performed can be challenging. Devices must be durable enough to withstand the potentially harsh conditions inside a gravity sewer or force main (e.g., no lighting, water/air interface, and circular configuration).

Equipment must also be sufficiently waterproof to operate in rain or wind. Established technologies have been engineered for use in the sanitary sewer environment. However, technologies that are in the research stage will need to be evaluated for their ability to withstand conditions inside a sanitary sewer.

***Equipment Deployment and Pipe Access***

Equipment that will be deployed inside a sewer must be portable and sufficiently flexible or modular to enter through a manhole or similar point of access. It will also require autonomous traction or a tether and winch system. Equipment to be used for assessment of the pipe exterior must be portable enough to be installed inside an excavation or similarly confined space.

System-specific or project-specific constraints may cause difficulty in deploying inspection equipment by conventional methods, hence influencing technology selection. For example, a landowner may be sensitive to the presence of equipment and field crews and hence it is important to select the least obtrusive technology possible. Flood zones may restrict access. A long distance between manholes may exceed the equipment's inspection length capability, or a curved section of pipeline may be difficult to navigate. Equipment deployment is discussed in Chapters 3 through 7.

# 3. Screening Technologies

As condition assessment strategies and technologies evolve, the value of rapid screening methods becomes more apparent. For a utility with limited funds, the ability to conduct a rapid assessment and pinpoint problems for further investigation provides an advantage in asset management. Time and funds saved can be devoted to more detailed assessments in problem areas and to rehabilitation. This chapter provides technical performance information and case study examples for flow data analysis, zoom camera, and acoustic monitoring systems.

## 3.1 Flow Data Analysis

Flow data analysis can be used to locate problem areas in a collection system in support of planning for further assessment or rehabilitation. It is particularly useful in systems where there are I/I concerns. For example, data from an upstream meter can be subtracted from data taken from a downstream meter to calculate the net flow contribution from that portion of the system; unexpected values may signal I/I or leakage. Another option is to measure typical dry weather flow and compare it to wet weather flow to determine I/I (Mitchell and Stevens, 2005).

The traditional method of viewing flow data is through the use of hydrographs, which reveal information on pipe conditions upstream of a flow meter. Alternatively, flow data can be viewed as scattergraphs. A scattergraph is created by plotting flow velocity vs. depth. Manning's equation can be used to calculate a pipe curve, which represents what the data would look like under ideal, open-channel flow conditions (Figure 3-1). If a pipe is operating as designed, the scattergraph will approximate the pipe curve. However, this is often not the case. Deviations from the pipe curve can be valuable in identifying such hydraulic restrictions as silt or obstacles, bottlenecks, and negative-grade pipe. The data may also indicate surcharged conditions, SSOs, and CSOs (e.g., Mitchell and Stevens, 2005; Enfinger and Stevens, 2007). There are different approaches and assumptions in calculating the pipe curve (e.g., roughness coefficient), some of which are explored in Enfinger and Schutzbach (2005).

Examples of scattergraphs are provided below. Figure 3-1 shows a normal, unobstructed open-channel flow in which the flow data match the pipe curve calculated using Manning's equation. In this example, the pipe is not experiencing obstructions or SSOs and is functioning as designed.

In Figure 3-2, the data conform to the pipe curve until the pipe becomes surcharged, at which point the velocity levels off as flow depth increases. In Figure 3-3, the plot of velocity data (referred to as VFINAL on the y-axis) vs. flow depth (DFINAL on the x-axis) illustrates the case of a downstream flow blockage. Because water is retained behind the blockage, there are 8 in. of standing water. The scattergraph, therefore, shows a depth of 8 in. at a flow velocity of zero.

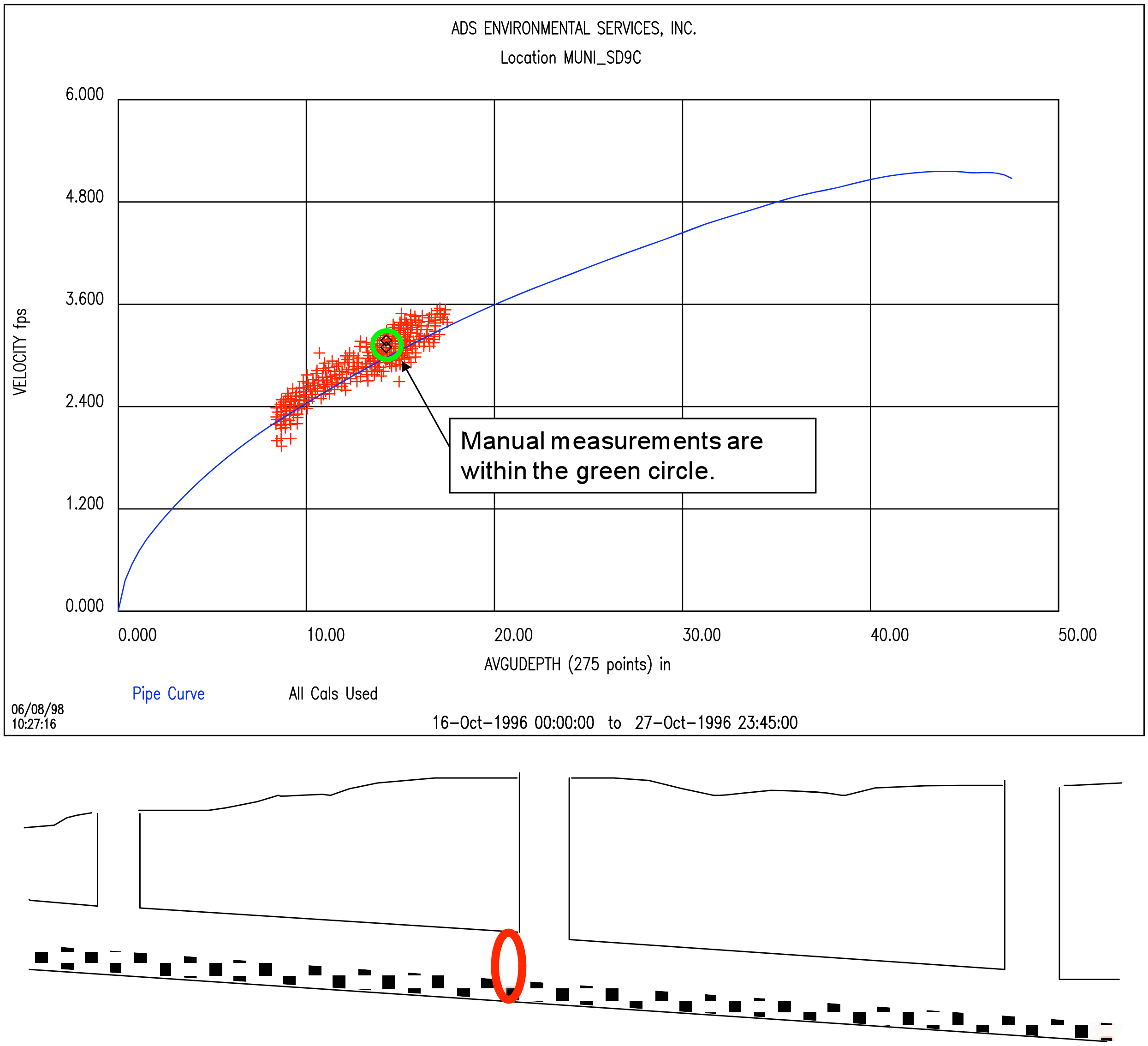


**Figure 3-1. Scattergraph representing open channel flow.**
**Image from Mitchell and Stevens (2005). Reprinted with permission.**

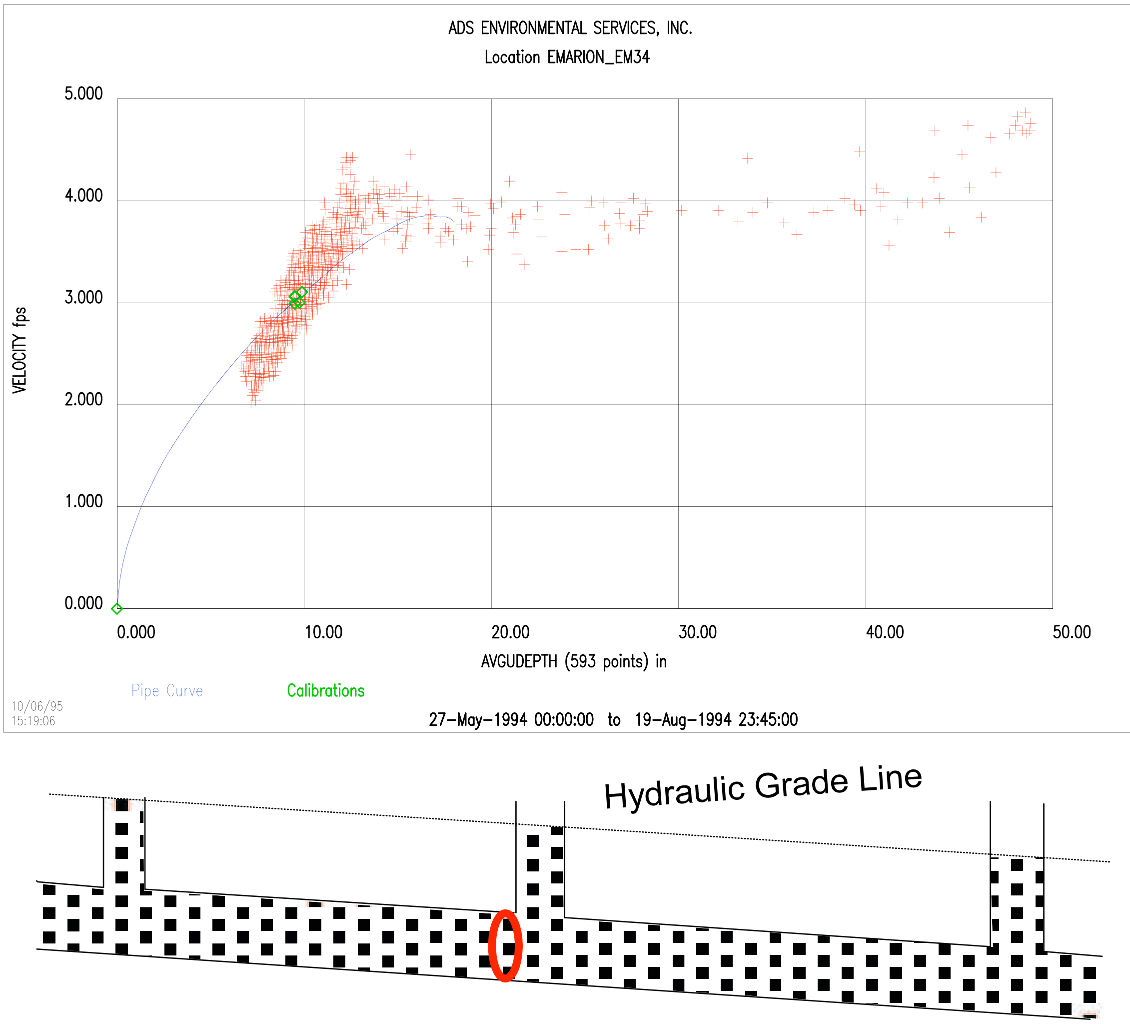


**Figure 3-2. Scattergraph showing surcharged conditions.**
**Image from Mitchell and Stevens (2005). Reprinted with permission.**

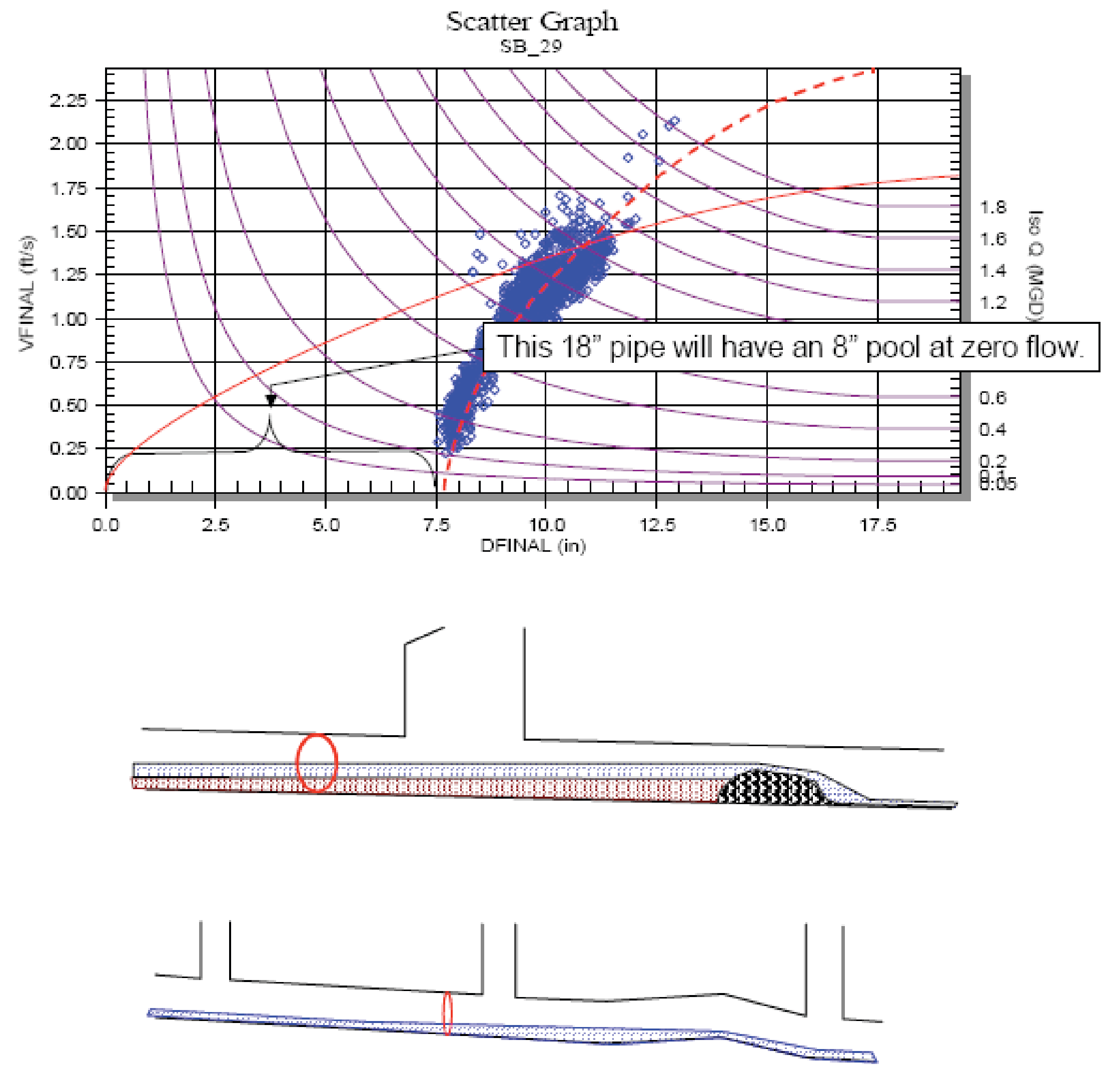


**Figure 3-3. Scattergraph depicting downstream flow blockage.**
**Image from Mitchell and Stevens (2005). Reprinted with permission.**

The use of flow data analysis with the scattergraph method has resulted in cost savings for utilities. For example, Mitchell and Stevens (2005) cite the case of a utility in the Pacific Northwest that had a large basin with poor I/I performance. By subdividing the basin into smaller basins and employing strategically placed flow meters, the utility was able to eliminate areas with low I/I, saving $300,000 over what otherwise would have been spent on condition assessment. Although the utility in this example deployed new meters for the study, valuable information can be gained from existing data. Most systems conduct flow monitoring, but much of the flow data information is not used. Analysis of historical flow data using scattergraphs can be useful for evaluating both asset condition and long-term system performance. If scattergraphs indicate obstructions or other problems, those areas can be given high priority for condition assessment.

## 3.2 Zoom camera

### *Description*

Zoom cameras can perform a visual inspection more quickly than conventional CCTV. Like traditional CCTV inspection, zoom camera inspection involves the generation of still imagery and/or recorded video imagery of a pipe (e.g., Figures 3-4 and 3-5). However, instead of passing through the pipe, the camera remains stationary. It is mounted on a truck, crane, pole, or tripod, and is lowered into a manhole to perform the inspection. Newer zoom cameras can pan 360 degrees, and any pipe entering or exiting the manhole can be inspected. Because the camera remains stationary, imaging the pipe proceeds quickly. Furthermore, the pipe need not be cleaned prior to inspection, further reducing inspection time as well as cost. Zoom camera inspection is not designed to replace conventional CCTV inspection, but rather to screen and prioritize pipes for further conventional CCTV inspection or cleaning. An inspection crew can move quickly through a service area and highlight segments requiring more detailed inspection.


**Figure 3-4. Zoom camera images of pipes showing structural defects.**
**Image from Rinner and Pryputniewicz (undated). Reprinted with permission.**

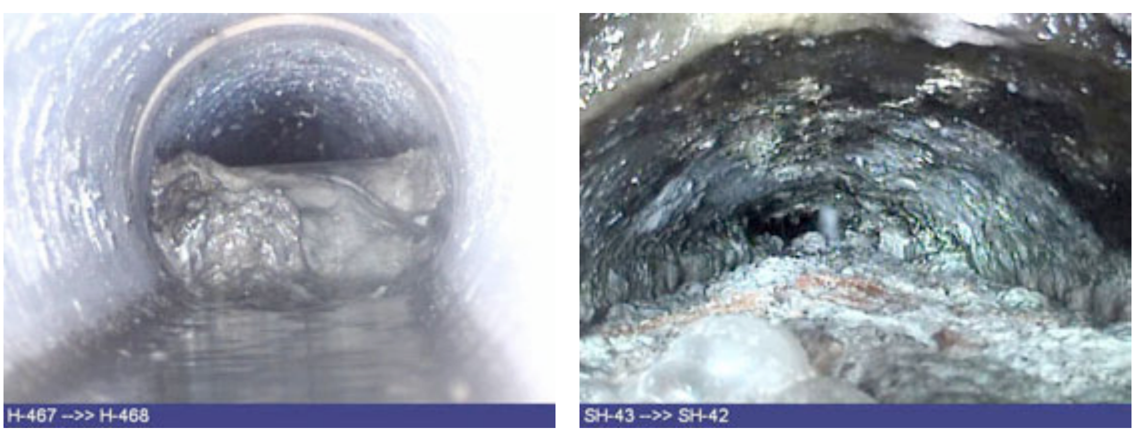


**Figure 3-5. Zoom camera images showing pipes with O&M defects.**
**Image from Rinner and Pryputniewicz (undated). Reprinted with permission.**

Although zoom camera inspection is a very efficient, cost-effective method of manhole inspection, there are some drawbacks. Like all camera technologies, zoom cameras are only useful for inspecting gravity sewers because force mains and service laterals do not have the required access points (manholes). Also, like CCTV, zoom cameras cannot inspect beneath the fluid in the pipe. Limitations in image resolution, lighting, and optical zoom also pose challenges. Further details on zoom cameras, including descriptions of some commercially available cameras, can be found in USEPA (2009a). The following sections discuss zoom camera performance.

***Sight Distance and Mainline Defect Capture***

Because a zoom camera remains at a manhole and does not travel through a pipe, a key element of camera performance is the sight distance (i.e., how far down the pipe the camera can capture an image). Bainbridge and Krinas (2008) note that the sight distance of zoom cameras is limited by conditions in the pipe such as bends, major blockages, and protruding services (where a building lateral extends into a main sewer line). Sight distance also varies with pipe diameter. Joseph and DiTullio (2003) noted that additional light is needed in larger pipes for proper illumination. Table 3-1 summarizes the range of reported sight distances.

**Table 3-1. Reported Sight Distances for Zoom Cameras**

| Pipe Diameter mm (in.) | Sight Distance m (ft) | Zoom Camera Make and Model | Reference |
|---|---|---|---|
| 152 (6) | 15 (50) | CUES-IMX | Batman et al. (2008) |
| 203 (8) | 12 to 18 (39 to 59) | CUES-IMX | Rinner and Pryputniewicz (undated) |
| 300 (12) | 45 (147) | AquaZoom | Joseph and DiTullio (2003) |
| 2,400 (96) | 100 (328) | AquaZoom | Joseph and DiTullio (2003) |
| Not specified | 30 (98)[1] | Not specified | Bainbridge and Krinas (2008) |

[1] Average sight distance for 23,566 manhole inspections.

A performance issue directly related to sight distance is the percentage of defects identified by CCTV inspection that are also documented by zoom camera inspection. It is important for utilities to know if significant information might be missed by using a zoom camera instead of CCTV. Because zoom camera inspection of a pipe segment is conducted from both the upstream and downstream manholes, the defects most likely to be missed are those in the middle section of the pipe (i.e., farther away from the entry points). To address this issue, Bainbridge and Krinas (2008) explored the statistical locations of defects in pipes. By examining CCTV data for the Canadian city of Hamilton, Ontario, the percentage of defects that occur within 20 to 30 meters (66 to 98 ft) of the manhole was calculated, which is within the sight distance noted for zoom cameras (Table 3-1). The CCTV data indicated that "on average, 59.44% of defects are found within 20 meters (66 ft) of manholes and 76.12% are found within 30 meters (98 ft) of manholes." Joseph and DiTullio (2003) also noted that "about 80% of defects . . . are usually located within the first 15 to 20 m [49 to 66 ft] from the manhole." Although the estimates differ between these two studies, both suggest that zoom cameras can detect a large percentage of defects because many defects are located within the commonly referenced zoom camera sight distances. Some possible reasons for the large percentage of defects close to manholes include vibrations from surface traffic, void areas created by infiltration around a manhole, and structural damage from vertical movement during cold weather (Joseph and DiTullio, 2003).

***Production Rate***

A primary benefit of zoom camera inspection over CCTV inspection is the speed with which major mainline defects can be assessed. A typical zoom camera inspection can cover on the order of one mile per day, compared to 1,000 to 1,500 ft per day for CCTV. Table 3-2 presents production rates for zoom cameras, ranging from 4,600 ft per day (Rinner and Pryputniewicz, undated) to 6,250 ft per day (Batman et al., 2008) when accompanied by manhole inspections. A rate of 10,000 ft per day was cited by Rinner and Pryputniewicz (undated) if manhole inspections were not performed at the same time.

**Table 3-2. Case Studies on the Use of Zoom Cameras**

| System | Description | Technical Performance and Results or Estimates | Cost | Reference |
|---|---|---|---|---|
| Dallas Water Utilities, TX | Pilot project using the AquaZoom camera. | Approximately 1 mile per day. Found that only 2% of system needed repairs and 28% needed cleaning and CCTV inspection. | Cost data not provided. | Renfro et al. (2005). |
| Fairfax, VA | 85-mile pilot program. Pipes 12 to 72 in. in diameter. | Approximately 6,250 ft per day. Found that only 66% of pipe needed CCTV inspection. | Zoom camera + in-line CCTV average \$3.33 per ft; CCTV alone average \$4.89 per ft (including cleaning) | Batman et al. (2008). |
| Auburn, MA | Zoom camera inspected 60,000 ft of sewer and connecting manholes. System has 18 mi. of gravity sewer (8 to 36 in.) and 4 mi. of force mains. | Approximately 4,600 ft per day. Identified I/I and O&M issues and structural and manhole defects. | \$1.00 per ft (with manholes). | Rinner and Pryputniewicz (undated). |
| Hamilton, Ontario, Canada | 895 mi. completed at time of report. (System has 1,632 mi. of sewer mains.) | Approximately 6,152 ft per day.[1] Level of accuracy adequate for screening program. | \$0.977 per m (\$0.29 per ft).[2] | Bainbridge and Krinas (2008). |
| Unnamed Mid-Atlantic utility (population >500,000) | Large diameter interceptors (20 to 60 in.) inspected for replacement/rehabilitation needs. Approx. 29,500 ft reinforced concrete pipe (RCP), 11,500 ft asbestos cement (AC) pipe. | 5,000 ft per day. Detected structural defects, cracked, broken, and corroded pipe. O&M findings: roots, grease, debris. | \$2.19 per ft | Lee (2005). |

[1] Estimated from average production rate of 25 manholes per day.
**[2]** Estimated funding requirement calculated for cost/benefit analysis.

***Comparison of Zoom Cameras***

The Plainfield Area Regional Sewer Authority (PARSA), which serves eight New Jersey communities, completed a series of field tests in the fall of 2006 and the winter of 2007 to evaluate the performance of three commercially available zoom cameras when inspecting 8-in. diameter sewer lines (PARSA, 2007). PARSA was looking for an inspection technology that could rapidly assess the condition of its sewer collection systems. The goal was to evaluate each camera's ability to inspect a 150-ft segment from manholes with straight or curved channels. The 8-in. pipe size was selected because it represents approximately 90 % of the 2 million linear ft of sewer pipe in PARSA's collection systems. As summarized in Table 3-3, PARSA found two major deficiencies with the zoom cameras. First, the operators had difficulty aiming the cameras down the center of the pipe and had to continually make adjustments. The PARSA investigators suggested that a guide is needed to center the camera in the pipe. Second, the cameras were unable to produce images of acceptable quality for the entire 150-ft segment inspected. Of the three models tested, the IBAK/Orion model was considered the easiest to use.

**Table 3-3. Field Test Results for Zoom Cameras by the Plainfield Area Regional Sewer Authority (PARSA) in New Jersey**

| Company/Camera | Field Observations (8-in. diameter pipe) | Ease of Use |
|---|---|---|
| CT Zoom/truck-mounted zoom camera. | Picture became fuzzy at 30 to 35 ft. | Large camera head made it difficult to position in an 8-in. manhole channel. Constant repositioning of the head was required to keep it focused down the pipe. Joystick control was too sensitive. |
| CUES-IMX truck-mounted zoom camera. | Picture became pixilated at 30 to 35 ft. | Light head arrangement made it difficult to position in an 8-in. manhole channel. Constant repositioning of the head was required to keep it focused down the pipe. |
| IBAK/ Orion camera head mounted on a hand-held pole. | Good picture for about 60 ft. | The smaller head size and the ability to keep the camera focused down the pipe made this the most user-friendly system. |

Data from PARSA (2007). Reprinted with permission.

## 3.3 Acoustic Monitoring

A camera-based technology such as a zoom camera provides a familiar and valuable type of screening information (i.e., footage) and is suitable for gravity lines. An alternate screening method is needed, however, for force mains, which are more involved and expensive to inspect via camera because they must be taken out of service and drained. Acoustic monitoring provides a screening alternative for detecting wire breakage in PCCP force mains.

***Description***

Acoustic monitoring systems may be permanently installed along PCCP force mains to provide continuous monitoring of the general condition of the pipe, or they may be temporarily installed.

Acoustic monitoring systems work by detecting the acoustic signal produced by breaking or broken pre-stressed wire within pipes. Although the systems do not identify individual defects, they are useful as screening techniques to determine whether further condition assessment should be performed. Commercially available systems and vendor contact information are provided in Appendix A.

### *Performance*

Limited data are available on the performance of acoustic monitoring systems. The case studies in Table 3-4 indicate that utilities do detect broken wires using acoustic technologies from continuous monitoring/inspection of stressed PCCP pipes. Monitoring results are used for determining where additional inspection and rehabilitation might be required.

**Table 3-4. Case Histories of Technical Performance of Acoustic Monitoring Systems**

| Device | Application (Period of Use) | Technical Performance | Reference |
|---|---|---|---|
| Soundprint® Acoustic Monitoring System by Pure Technologies (original model c. 1993 with hydrophones). | Continuous monitoring of 2,700 ft of 72-in. diameter PCCP sewage force main, built in 1975, Greater Lawrence Sanitary District, MA. (2005). | After six months of monitoring, 10 Class A[1] and 18 Class B[2] wire breaks were detected. Acoustic monitoring results were verified by electro-magnetic and visual inspections. | Higgins et al. (2006). |
| Acoustic Emission Testing (AET) System by PPIC. | Inspection of 0.5 mile of 54-in. diameter effluent force main following two catastrophic failures. Main originally constructed in 1976, North Shore Sanitary District, Ill. (Dec. 2001). | AET results indicated that pre-stressing wires in several areas were deteriorating. Based on these results, the utility conducted further inspection using PPIC's remote field eddy current transformer coupling (RFEC/TC) inspection system. Inspection results were used to identify and prioritize rehabilitation needs and to avoid pipeline replacement. | PPIC (Undated). |

[1] Class A wire breaks are defined as wire breaks that match all acoustic criteria for wire breaks.
[2] Class B wire breaks are defined as wire breaks that match most of the important acoustic criteria for wire breaks.

# 4. Technologies for In-Depth Inspection of Internal Pipe Surface

Screening data or other evidence may indicate the need for high-quality, detailed information on the internal surface condition of sewers. This can be an especially high priority for pipes where the consequence of failure is great, such as large-diameter pipes that serve a large area or those in high-traffic areas where replacement would entail major disruptions. Conventional CCTV remains a mainstay in the assessment of internal surface conditions, and digital scanning is emerging as a viable alternative.

## 4.1 Conventional CCTV

### *Description*

Used for decades, CCTV inspection is the backbone of many utilities' condition assessment programs. In a recent survey report (Thomson et al., 2004), 100% of survey respondents from large wastewater utility districts relied on CCTV as their primary method of collection system inspection. The benefits of CCTV are the ability to (1) inspect gravity sewers that are too small for human entry and as small as 6-in. diameter, (2) inspect pipe of any material, (3) locate and describe defects, and (4) create a permanent video record of sewer pipe conditions. It cannot, however, image the portions of the pipe that are underwater. CCTV also does not provide structural data on pipe wall integrity or a view of the soil envelope supporting the pipe.

Inspection by CCTV involves conveying the camera through the pipeline using various technologies such as pushrod cameras (pushcams) and remote-controlled robot crawlers. The level of optical control on the camera varies. Its ability to pan, tilt, and zoom enables the operator to gain a full circumferential view of the pipe and is why CCTV has become the industry standard for sewer inspection. Data obtained from CCTV inspection include:

- Evidence of sediment, debris, and roots.
- Evidence of pipe sags and deflections.
- Off-set joints.
- Cracks.
- Leaks (if infiltration is occurring at the time of inspection).
- Location and condition of service connections.

### *Performance*

As noted above, CCTV technology is limited to viewing the inside surface of a pipe above the waterline. However, for the portion of pipe that can be viewed, a good-quality CCTV camera provides a video record of pipe condition and allows the assignment of defect codes. Figure 4-1, for example, shows a concrete pipe in excellent condition, with no apparent cracks or corrosion. It has been assigned a NASSCO Pipeline Assessment and Certification Program (PACP) inspection code of 1 on a scale of 1 to 5, indicating that it is free of defects. The pipe in Figure 4-2 shows substantial corrosion and is in poor shape (Grade 4).

The quality of defect identification and pipe condition assessment using CCTV depends on many factors, including operator interpretation, picture quality, and water level. In terms of benefits, it is a cost-effective technology and provides the broadest base level of data for condition assessment. There are several technologies that provide data on the structural condition of the pipe wall (Chapter 5) and others that can determine the condition of the soil surrounding the pipe (see Chapter 6). However, CCTV provides valuable information on leaks, the location of service laterals, and sediment and debris accumulation; it will remain an important inspection tool in any condition assessment program for wastewater collection systems. Typical inspection rates achieved with CCTV are discussed in Section 4.2 in comparison to digital scanning rates. The complementary application of CCTV and laser inspections is discussed in Section 5.1.


**Figure 4-1. Concrete pipe – Grade 1 (excellent).**
**2 total reaches – 713 linear ft / 0.14 mi. Image from Warner and Fleury (2007). Reprinted with permission.**


**Figure 4-2. Concrete pipe – Grade 4 (poor condition).**
**Lined and Unlined Concrete Pipe. Image from Warner and Fleury (2007). Reprinted with permission.**

## 4.2 Digital Scanning

### *Description*

Digital scanning is a state-of-the-art camera inspection technology. It has been commonly used in Europe and Asia for a number of years, but has a limited history of use in North America. Like conventional CCTV, digital cameras are transported through sewer lines using self-propelled crawlers. Unlike conventional CCTV systems, digital scanning uses one or two high-resolution digital cameras with wide-angle (fisheye) lenses in the front (or both front and rear) section of the housing. This configuration allows the generation of two types of images: "unfolded" views of the sides of the pipes and circular views down the pipe (similar to CCTV). Digital scanning is primarily used for gravity lines and can be used with any pipe material. As with other camera-based technologies, it can only image above the water line. Commercially available digital scanners and vendor contact information are listed in Appendix A.

Digital scanning provides advantages over conventional CCTV. Its rate of inspection or production rate is typically 2 to 3 times greater than CCTV. Because it combines a large number of still digital images, it produces a sharper image than video (Knight et al., 2009). Also, the unfolded view of the inner pipe surface provides an excellent view of pipe conditions (Figures 4-3 and 4-4). The primary advantage, however, is the ability to access and assess the inspection data at a later time. Digital scanning does not rely on the operator panning and tilting to examine defects in the field because the entire pipe surface is imaged during the inspection and the data are stored. Inspection progresses quickly in the field, but the defect coding is done later in the office. Software is available for data reviewers to virtually pan, tilt, and zoom as needed to better identify defects. The high-quality images permit computer-aided measurement of defects and objects. Additional information on digital scanning capabilities and models can be found in USEPA (2009a).

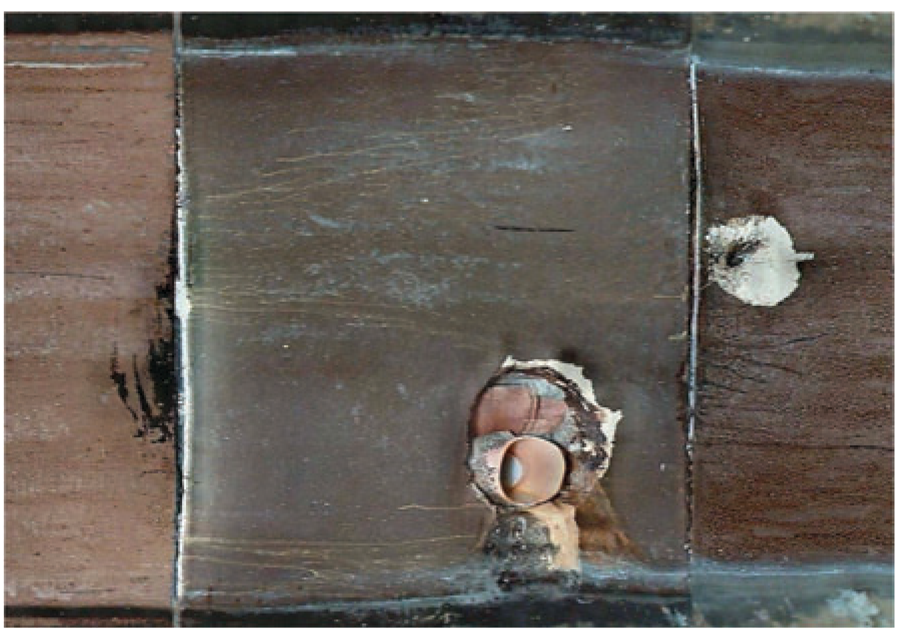

**Figure 4-3. Example of side scanning image.**
**Image from Envirosight, as cited in Livingston and Blackmun (2009). Reprinted with permission.**

**Figure 4-4. Example of side scanning results**
**Image from Hydromax, as cited in Livingston and Blackmun (2009). Reprinted with permission.**

### *Performance*

Performance issues for digital scanning are related to its ability to provide reliable images for different diameter pipes (larger pipes in particular), production rate, and comparison of image quality with that of conventional CCTV. Due to its limited use in North America, available performance information is anecdotal in nature.

Thomas Iseley of Indiana University-Purdue University Indianapolis provided background information on digital scanning development and performance (Iseley, Thomas., Phone call with author, 2009). Because the technology is relatively new, digital scanning can be expected to undergo continuing development to enhance its capabilities. As with other camera technologies, one of the limiting factors of digital scanning is camera resolution. In general, the resolution of digital scanning decreases as pipe diameter increases, although better lighting can help offset this limitation to some extent. Sewer scanning and evaluation technology (SSET) was originally designed for pipes 8 to 12 in. in diameter, but the manufacturer had worked to increase this range in response to customer needs. Apart from hardware development, current research efforts have focused on software enhancements for defect recognition and digital defect measurements.

Depending on the outcome of academic and private sector research, digital scanning may become a cost-effective option for inspecting pipes when a high level of detail is needed.

***Comparison of Digital Scanning and CCTV***

A comparison of digital scanning with CCTV can provide utilities with valuable information for deciding whether to try this new technology. A 2001 study by the Civil Engineering Research Foundation (CERF, 2001) evaluated the performance and costs of SSET at 13 North American municipalities. This study was based on the first version of SSET, which is considerably different from current products (PANORAMO and DigiSewer). The first version of SSET used a rotating mechanical scanner and a mechanical gyroscope. The second generation SSET system was fitted with a wide-angle lens, similar to the lens used in DigiSewer. Although SSET is outdated and no longer produced, an evaluation of this early digital scanning model provides some useful perspectives on digital scanning technology.

CERF tested SSET on approximately 22,000 ft of sewer pipe and compared the performance to that of CCTV. The recommended scanning speed is reported to be 1 to 3 m per min. (1,000 to 2,000 ft per day). SSET performed well in pipes constructed of PVC, concrete, and vitrified clay, but not well in HDPE and cast iron pipe. CERF (2001) extensively compared the SSET system and CCTV; a few highlights are presented here.

More defects were detected by the SSET system than by the CCTV system. The size and placement of defects were found to be accurate compared to those detected by CCTV, but the assessment of defect severity did not always correlate well with those defects identified by CCTV. In addition, the SSET system did not identify all defects equally well. It had more difficulty than CCTV with detecting infiltration, corrosion, and ovality. The SSET equipment was also unable to investigate laterals because the camera does not pan to direct the light into them. It was, however, able to identify cracks, structural defects, and joints very well.

The image quality provided by the SSET system was evaluated on the basis of a number of criteria. It was determined that SSET image sharpness was generally good, but coloring and consistency were generally poor. The presentation of data was considered to be excellent. The factors that negatively affected quality and accuracy of the SSET system included fog in the pipe and the dirtiness and depth of the sewage. In other words, cleaner pipes generally resulted in better imaging, which is true for all camera systems.

The results reported in CERF (2001) were consistent with the experience of the city of Tuscaloosa, AL. SSET was used to inspect 3,200 ft of pipe per day, as compared to 1,000 to 1,500 ft per day by CCTV. The image quality of the SSET system was better than that of CCTV (Rowe, Reggie. Phone call with author, 2009).

Stein and Brauer (2004) performed a detailed comparison of the PANORAMO system with the ARGUS 4 CCTV camera (on behalf of IBAK, the manufacturer of PANORAMO). This comparative study was performed in Wuppertal, Germany. The 46 pipe sections (totaling approximately 7,870 ft) that were inspected included concrete pipe, RCP, VCP, and brick-lined collection systems. The pipes and systems investigated ranged from 10 in. to 40 in. in diameter. From the inspection results, an average inspection speed of 10.43 ft per min. was calculated for the PANORAMO system and 5.22 ft per min. for the ARGUS 4 CCTV system. Inspection speed was affected by pipe material, diameter, and length; number of stops for photographing defects (for CCTV); and the number of connections and cleanliness of the sewer pipes.

Setup and takedown times were approximately the same for both systems. However, time spent in the field differed significantly. The ARGUS 4 CCTV was in operation inside the sewer for 70.9% of the inspection time, compared to 23.2% for PANORAMO. The PANORAMO equipment has a shorter operation time because the data it collects are not processed in the field. Forty-seven percent of the inspection time for PANORAMO was spent on data post-processing in the office. The perspective views from PANORAMO were generally of equal quality to those obtained by the ARGUS 4 CCTV. Stein and Brauer (2004) found that the ARGUS 4 CCTV system did a better job of illuminating and capturing 3-D objects such as connections and manholes because the system's pan and tilt features allow the light source to be better directed. The optical zoom on the ARGUS 4 CCTV system was considered to be better than the digital zoom on the PANORAMO because the resolution decreases with increased digital zooming. The PANORAMO picture quality was poorer in pipes with diameters greater than 20 in. However, describing the condition of the collection system was easier with PANORAMO because of its abilities to unfold a view and change the viewing direction and angle (using imaging software during data post-processing).

These studies indicate that digital scanning provides an alternative to CCTV that saves time in the field, provides a good image, and is relatively easy to work with in terms of data presentation and description of defects. As the technology progresses, utilities are encouraged to monitor for pricing reduction and determine whether the digital scanning technology is a cost-effective option for detailed defect evaluation.

***Example of Utility Experience***

Hamilton, Ontario, Canada's ninth largest city (population: 520,000), is one North American utility that has begun to use digital scanning. The City's collection system handles an average of 420 million liters per day (111 MGD) of wastewater and has a total of 2,700 km (1,680 mi.) of sanitary, combined, and storm sewers. In 2006, Hamilton was involved in a pilot test using Blackhawk's SSET system for its sewer pipes. City personnel were pleased with the high level of detail provided by this technology (Bainbridge, Kevin. Phone call with author, 2009). They noted that digital scanning had identified more details of pipe defects than CCTV. However, city personnel commented that the primary drawback with the SSET system was the limit in pipe sizes for effective detection of defects. The SSET system worked best in smaller pipes and was not as effective for pipes with diameters greater than about 36 in., although the city's contractor has since reported to Hamilton that they have successfully used SSET in pipes up to nearly 60 in. in diameter. With the dissolution of Blackhawk, SSET is no longer manufactured or supported.

## 4.3 Multi-Sensor Technology

Several researchers (Eiswirth et al., 2001; Kuntze and Haffner, 1998) have proposed combining two or more condition assessment technologies to detect different types of defects in wastewater collection systems. This strategy offsets the limitations of using a single inspection technology and augments the information obtained by camera-based technologies. These multi-sensor inspection robots have been commercialized in various forms in Europe, North America, Japan, and Australia. Commercially available multi-sensor inspection robots include critical sensors (e.g., CCTV, sonar, and laser scanners). The more innovative sensors (e.g., infrared sensors, radioactive sensors, and impact-echo hammers) have not been deployed on commercial robots. Some of the multi-sensor robotic platforms available to assess wastewater collection systems are:

- KARO (Kanalroboter).
- PIRAT (Pipeline inspection real-time assessment technique).
- SAM (Sewer Assessment with Multi-Sensors).
- KURT (Kanal-Untersuchungs-Roboter-Testplattform).
- KANTARO.

The number and type of sensors mounted on these robotic platforms have varied depending on the potential needs. The initial semi-autonomous prototypes (e.g., KARO and PIRAT), developed by German and Australian researchers, were equipped with CCTV, 3-D optical (infrared), ultrasonic (i.e., sonar), laser, and microwave sensors (Kuntze and Haffner, 1998). The PIRAT system could automatically interpret and categorize the defects found during the inspection. Both the PIRAT and KARO systems were so-called “two-pass” systems, where the device would make a first pass to detect candidate defects and then complete a more detailed second pass inspection to confirm the defects (Ahrary, 2008).

Subsequent versions of sewer inspection robots (e.g., SAM, KURT, and KANTARO) were autonomous. The prototype SAM system, also developed by German and Australian researchers, was equipped with numerous sensors including sensors used in KARO as well as an impact-echo hammer, radioactive sensors (based on gamma-gamma logging), a geo-electrical sensor for leak detection, and a hydro-chemical sensor to detect groundwater infiltration (Eiswirth et al., 2001). However, this research team has since changed direction to focus on digital CCTV applications for sewer condition assessment (Burn, Stewart. Email with author, 2009).

These multi-sensor inspection robots have been commercialized in various forms in Europe, North America, Japan, and Australia. The commercial versions include critical sensors (e.g., CCTV, sonar, and laser scanners); however, some of the more innovative sensors (e.g., infrared sensors, radioactive sensors and impact-echo hammer) have, for the most part, not been deployed on commercial robots.

# 5. Technologies to Evaluate Pipe Wall Integrity

Structural pipe failure may occur due to defects in the pipe wall, such as cracks, misaligned or offset joints, deflection, and corrosion. Because camera-based technologies are limited to examining the interior surface of a pipe, they cannot indicate pipe thickness, quantify pipe geometry, or demonstrate the potential for leakage when there is no visible infiltration at the time of inspection. Other methods such as laser, sonar, and electrical scanning are used to evaluate such features. Also, emerging technologies, such as impact echo, spectral wave analysis, and ultrasonic testing, are being explored for application to sewer condition assessment.

This section provides a description of the performance and application of these technologies. For the established methods (i.e., laser and sonar), the reader can refer to previous documents for additional descriptions and information about currently available vendors (USEPA, 2009a; USEPA, 2010). For the emerging technologies, this chapter provides descriptions, along with information about their use in other industries and any exploratory research underway for their use in wastewater collection systems.

## 5.1 Laser Profiling

***Description***

Laser-based pipe inspection allows the detection of changes in pipe shape that may be caused by deformation, deflection, corrosion, or siltation. Laser profiling generates a profile of the pipe's interior wall. This technique involves using a laser to create a line of light around the pipe wall. It can only be used to inspect dry portions of a pipe. To assess the entire internal surface of a pipeline, the pipe must be taken out of service, drained, and cleaned. Lasers are often used in combination with other inspection methods, most commonly CCTV or sonar. A listing of commercially available laser scanners and vendor contact information are provided in Appendix A.

Laser profiles can be generated in either two or three dimensions. The 2-D lasers, also known as profiling lasers, are the most common laser technology used in pipe inspection. A 2-D laser projects a pattern of beams (usually a circle) onto the pipe walls. The light is then detected by a camera to create the 2-D laser image. The 2-D image can provide information on pipe geometry (e.g., diameter, perimeter, and cross-sectional area), but it cannot provide information to further characterize defects in the pipe wall. The accuracy of 2-D images depends upon the proper calibration of the camera and the alignment of the laser with the cross section of the pipe. Dettmer et al. (2005) reported that the relative positioning of the laser scanner may lead to difficulties in image interpretation. For example, under certain circumstances, it is not possible to tell whether a robot has changed position or the pipe has changed position or shape. If the robot strays from the longitudinal axis and is at an angle, the cross-section of the pipe may erroneously appear to be oval. Dettmer et al. (2005) presented suggestions for correcting inaccurate laser profiles.

A new generation of laser-based pipe inspection technologies, 3-D lasers are based on the principles of laser detection and ranging (LADAR). LADAR-based systems use point laser-beams and have a built-in receiver and a two-way transmitter. Unlike 2-D systems, which produce pipe profiles or cross-sectional views, these systems produce 3-D views of entire pipe segments. The 3-D LADAR system can also develop accurate cross sections of a pipe even when the scanner is not directly aligned with the pipe's longitudinal axis. RedZone (undated) recommends using 2-D laser profiling for pipes with diameters less than 36 in. because the 2-D profile is sufficiently accurate for pipe this size and is less expensive than 3-D technology. For larger pipe, 3-D LADAR scanners are recommended. Figures 5-1 (a) and (b) show 2-D and 3-D laser images, respectively.

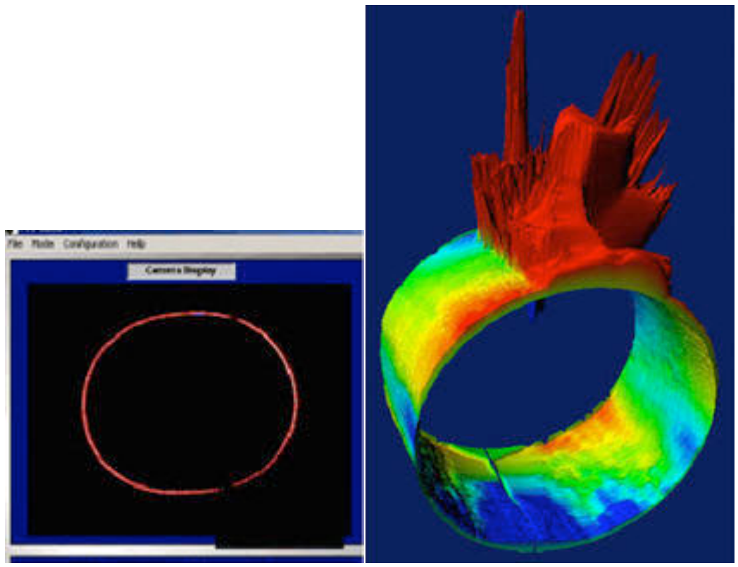

**Figure 5-1. (a) Two-dimensional (2D) laser profile and (b) Three-dimensional (3D) laser profile. Image from RedZone (undated). Reprinted with permission.**

### *Performance and Use with CCTV*

The case studies presented below reflect the experiences of two organizations, RedZone Robotics, Inc. and CUES, Inc. Although these case studies provide a limited perspective, useful information is provided on how this technology can be used and where performance information can be found given that independent studies by third parties have yet to be done.

Thayer et al. (2009) reported on the technical performance of 3-D LADAR technology instead of a mandrel to verify the proper installation of flexible pipelines. (A mandrel is a circular device that is pulled through a pipe to test its shape. It is physically stopped by any deviation from circularity.) The 3-D LADAR technology was used in Georgetown, Texas, to better understand the geometry of a newly installed interceptor and to establish a baseline for future inspections. The project included the inspection of 24,554 linear ft of 30-, 36-, and 42-in. centrifugally cast glass fiber pipe (CC-GFP). An initial inspection to test a line and verify baseline performance was conducted using a mandrel and a 3-D LADAR system. The 3-D LADAR measurements were found to be accurate to within 1/16 in. The inspection identified five pipe segments that exceeded the 5% deflection limitation for CC-GFP requiring repairs. City personnel noted that the “three-dimensional LADAR proved to be a valuable and viable method for installation verification of flexible pipelines subject to acceptance criterion based on internal geometric deflection."

Laser profiling is often used with other inspection methods, most commonly CCTV or sonar. RedZone (2008a) recommended the use of lasers and CCTV when inspecting large pipes because together these technologies produce complementary data that provide more accurate and comprehensive information on pipe condition. For example, laser profiling can detect small changes in pipe geometry (e.g., ovality) that are difficult to detect in a CCTV video image. Laser-based images can also be used to verify defects observed by CCTV and provide details on the size and shape of those defects. On the other hand, CCTV can be used to detect fine cracks and other non-geometric defects that do not appear in the laser images. The additional inspection costs incurred when using both technologies are offset by the cost savings associated with better defined rehabilitation projects.

To illustrate the benefits of a combined laser/CCTV inspection, RedZone (2008a) examined the results of inspections at four locations in which CCTV and lasers were used. Based on 10,000 ft of inspection data, the laser detected about three defects per 100 ft and CCTV detected about two defects per 100 ft; however, the two technologies usually identified different defects. In other words, the net result was that the combined CCTV and laser inspections nearly doubled the available pipe defect information.

Several other case studies further illustrate how CCTV and laser inspections together can provide complementary and comprehensive pipe condition information (RedZone, 2008a). In one case, laser data were used to discount pipe defects originally identified by CCTV inspection. A well-qualified CCTV operator observed a number of structural problems in a pipe, including multiple fractures and a single hole. The corresponding laser data did not confirm the presence of these defects. It was determined that lighting was responsible for the apparent pipe wall fractures and the hole was really a mirage created by shadows. The additional condition assessment information provided by the laser data helped the owner save hundreds of thousands of dollars by avoiding costly and unnecessary rehabilitation work.

In another case, a municipality performed an inspection to assess the quality of a cured-in-place pipe (CIPP) liner. A CCTV inspection revealed a number of blisters, a known installation defect with these liners. The corresponding laser inspection was able to provide the exact height, width and length of each blister, information needed to analyze the severity of the situation and facilitate repairs.

In a third example, laser scans showed inches of material loss along the walls of the pipe near the flow line. The laser scans showed a distinct pattern that clearly resembled the rebar present in RCP. However, closer analysis of corresponding CCTV images determined that the grid pattern was caused by an exposed layer of brickwork. Ultimately, the "reinforced" concrete pipe was determined to actually be a brick pipe with a layer of mortar applied later. The CCTV information helped the asset owner formulate a more appropriate and intelligent rehabilitation program.

Bennett and Logan (2005) presented three additional case studies in which the ClearLine Profiler (CUES, Inc.) was used to evaluate pipes with diameters of 6 to 88 in. Moving at the recommended speed of 30 ft per min., the ClearLine Profiler captures a laser image every 0.2 in. Using the requisite software, a utility can determine the pipes' ovality, capacity (cross-sectional area), and diameter. Highlights from the three case studies are presented below.

The city of Portland, Ore., needed to determine the degree to which a CIPP liner became distorted after imploding during installation. Bennett and Logan (2005) used graphs of minimum and maximum diameters of the pipe to evaluate the liner's condition. The results showed that the liner deviated substantially from the expected internal diameter and was considered to have "serious deformation." Figure 5-2 shows a ring of light with clear deviation from circularity. The ClearLine Profiler was able to measure the deformation to a tenth of an inch. City personnel were able to determine where the liner needed to be replaced, thus avoiding the need to replace the entire length of liner.

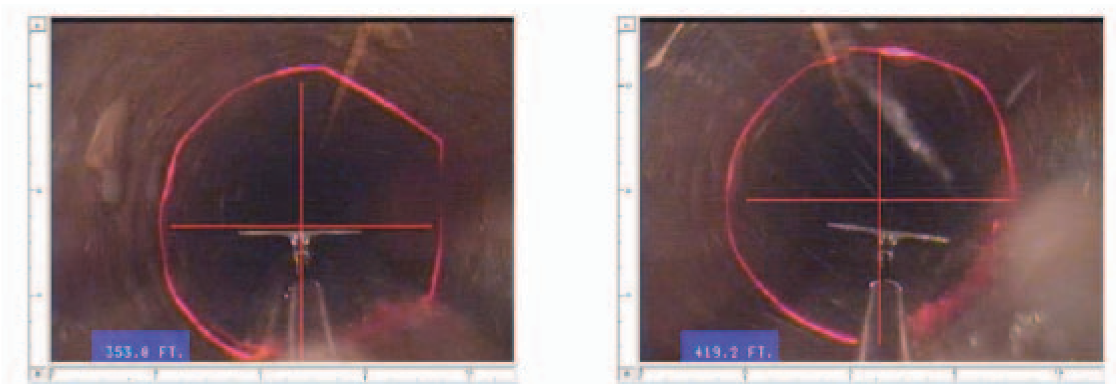


**Figure 5-2. Examples of laser profiling for Portland, Oregon.**
**Image from Bennett and Logan (2005). Reprinted with permission.**

The New Zealand city of Tauranga used laser profiling to determine the degree of corrosion caused by hydrogen sulfide attack in a 24-in. gravity main (Bennett and Logan, 2005). Software was used to map the laser scan data to a flat graph, similar in concept to the unfolded view used in digital scanning. The graph used colors to indicate topography, showing where the radius had a different value than expected. In addition, a capacity graph was used to display cross-sectional area as a function of distance. The graphic results could pinpoint the locations of corrosion damage (e.g., a 6.3-in. hole that had been missed by CCTV). Laser scanning was also used in Auckland, New Zealand, to find corrosion as part of a pipe characterization project conducted in anticipation of pipe rehabilitation (Bennett and Logan, 2005). Ten mi. of 88-in. sewer main were scanned. The flat graph and capacity graph showed areas where corrosion had changed the pipe circumference. The utility used this information to better evaluate rehabilitation needs and saved more than $10 million in rehabilitation costs over 10 years.

## 5.2 Sonar

### *Description*

Sonar is used to inspect pipe surfaces below the water line and to map the accumulation of debris and sediment in sewers $\geq$ 12 in. in diameter. Sonar can also provide information on pipe geometry, pipe wall deflections, pits, voids, and cracks. This technology can be applied to gravity sewers and sewage force mains made of any material. One benefit is that it can be deployed in pressurized force mains without taking them out of service. A number of units are commercially available for wastewater applications. Several case studies, summarized in Table 5-1, highlight sonar's ability to evaluate a pipeline's sediment buildup, physical shape, and structural condition and corrosion levels. Information on commercially available sonar models can be found in USEPA (2009a). Figures 5-3 and 5-4 show examples of sonar output. In Figure 5-3, pipe wall thickness and deviations from ideal diameter can be seen. Data are shown in cross section and longitudinal views. In Figure 5-4, 9 in. of silt can be seen at the bottom of the pipe where the image deviates from circularity. Figure 5-5 shows the results of a combined sonar and CCTV scan. The horizontal bar shows deviations in wall thickness indicative of corrosion; red and orange areas show greater corrosion. The cross sectional view shows sediment at the bottom of the pipe.

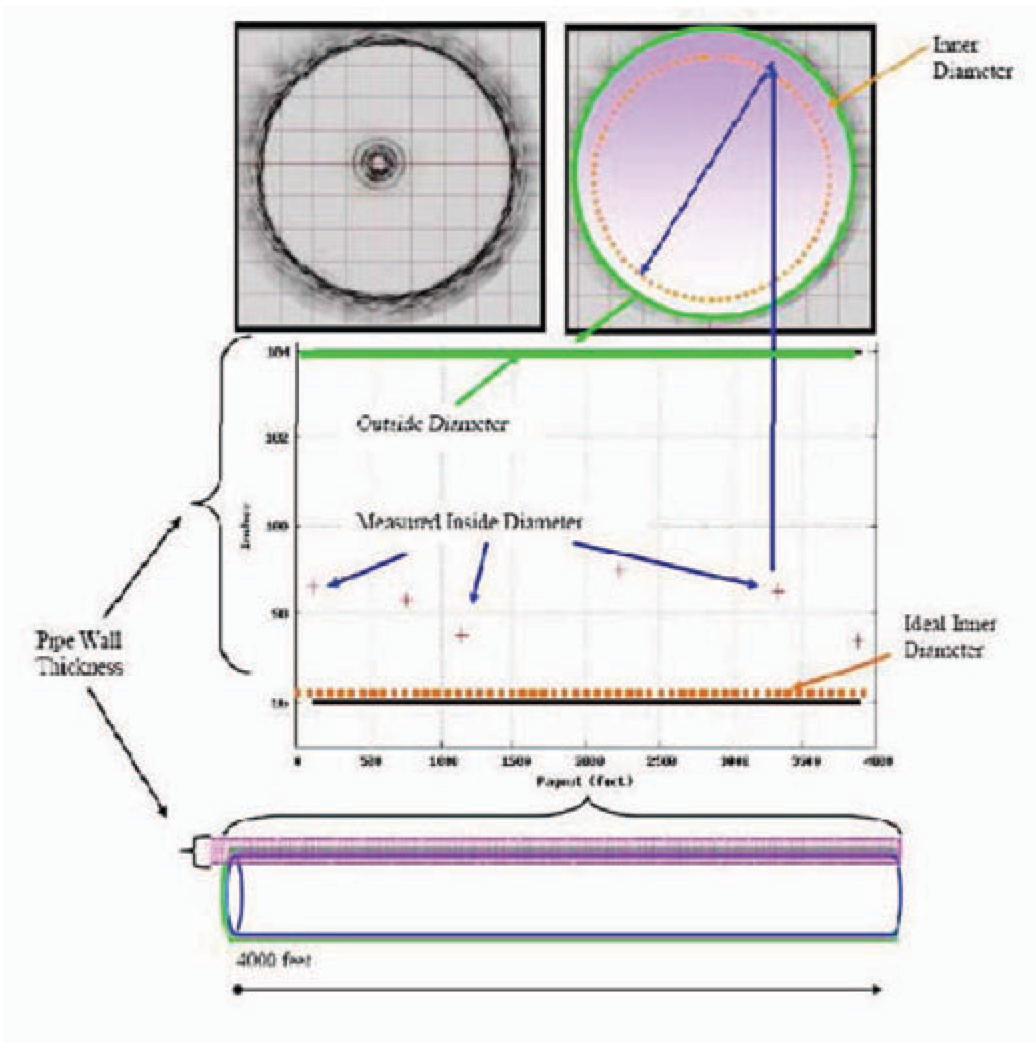


**Figure 5-3. Typical sonar results.**
**Image from Hydromax, as cited in Livingston and Blackmun (2009). Reprinted with permission.**

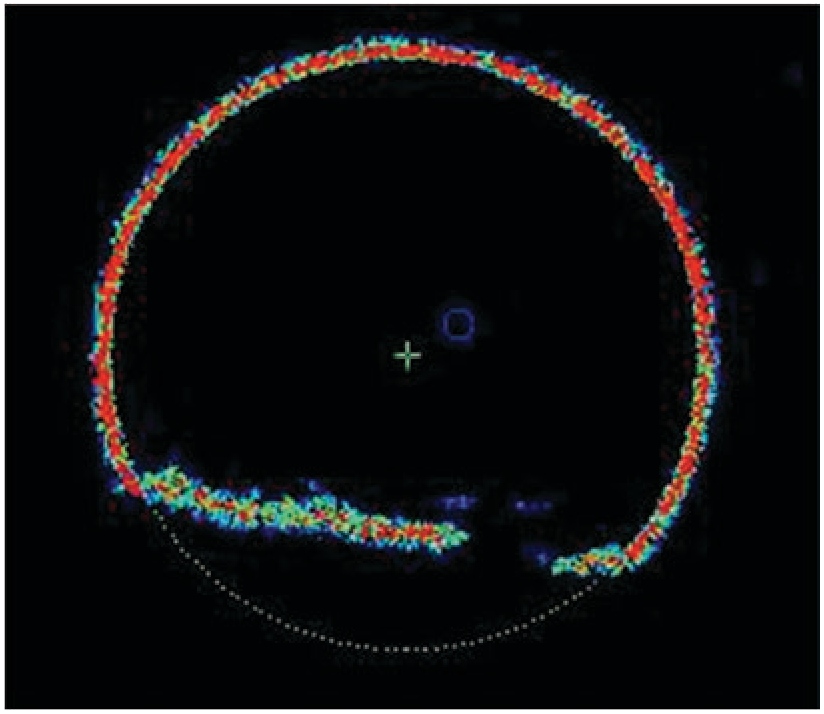

**Figure 5-4. Sonar results of a 30-inch line.**
**Image from Hydromax, as cited in Livingston and Blackmun (2009). Reprinted with permission.**

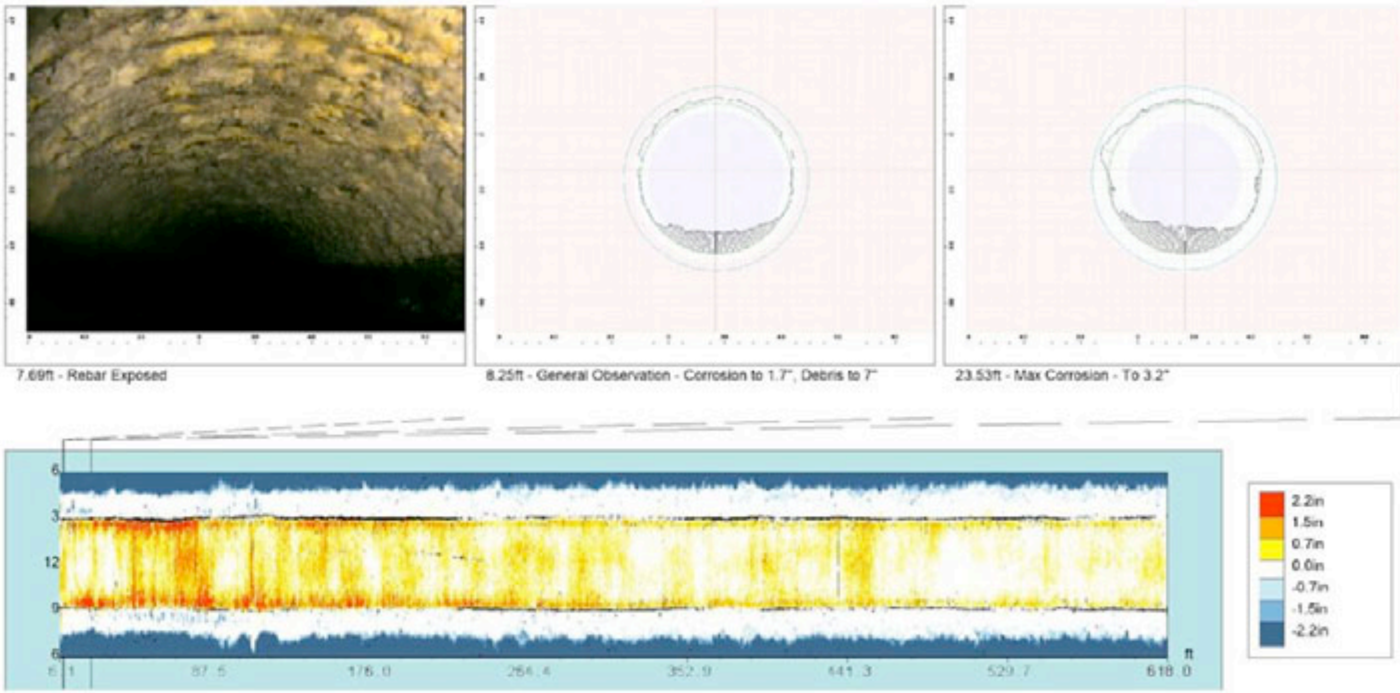


**Figure 5-5. Combined sonar and CCTV results of a 42-in. RCP pipe.**
**Image courtesy of Hydromax. Reprinted with permission.**

### *Performance*

Acoustic frequency is an important criterion in selecting a sonar device because it affects image sensitivity and power requirements (Andrews, 1998). As the acoustic frequency and resolution increase, the background "noise" tends to decrease; however, signal loss also tends to increase with increases in acoustic frequency, resulting in less penetrating power. Andrews (1998) (Table 5-1) found that a frequency of 2 MHz was suitably accurate to provide information on a sewer's interior shape; however, the same device provided limited information on structural condition and wall thickness because the higher frequency pulse was unable to penetrate the pipe surface. Typically, lower frequency units are used to obtain structural information because they have greater penetrating power. For most pipe inspections, single frequency sonar units are used.

**Table 5-1. Case Histories of Technical Performance of Sonar Devices**

| Device | Application (Inspection Period) | Technical Performance/Results | Reference |
|---|---|---|---|
| Multi-frequency sonar scanner mounted on RedZone track-mounted robotic platform along with other sensors. Frequency range 650 KHz to 2 MHz. | Inspection of 17,300 ft of 96-in. diameter RCP, built in 1984. Trinity River Authority, Texas (Fall 2008). | Sonar data were used to estimate pipe cross-sectional area and sediment volume. | Hines et al., 2009. |
| High frequency (2 MHz) rotating sonar transducer (make and model not specified) mounted to a pipe crawler or floating platform. | Inspection of 10,000 m (6.2 mi.) of 1.8 to 2.6 m (6 to 8.5 ft) diameter brick-lined interceptor, built in 1908, Toronto, Canada (1995). | The brick lining was found to be in good to very good condition except in several isolated areas. Brick-to-concrete interface was found to be in good condition. | Andrews, 1998. |
| High frequency (2 MHz) rotating sonar transducer (make and model not specified). | Inspection of 15 km (9.3 mi.) of 2.1 and 2.4 m diameter (6.9 and 7.9 ft), 35 m (114.8 ft) deep, fully surcharged concrete lined tunnel, built in 1959 in Ottawa, Canada (1996). | Sonar images showed pipe invert well scoured but no significant sediment buildup. The sewer cross section was found to be 7% to 9% larger than the theoretical design value. | |
| High frequency (2 MHz) rotating sonar transducer (specific make/model not specified). | Inspection of 9 km (5.6 mi.) of 1.5 m (60 in.) to 2.6 m (102 in.) diameter concrete-lined tunnel built in late 1950s and located in an area of heavy industry in Hamilton, Ontario (1995). | Sonar images showed no significant chemical corrosion as expected from heavy industry in the area. Some structural distortion was observed. CCTV inspection confirmed sonar findings. | |

RedZone (2008b) emphasizes the importance of a sonar device that can adjust to changing conditions (a common occurrence in a live sewer) and still provide good-quality data. A multi-frequency sonar unit can be used to meet a utility's specific information needs despite varying pipe conditions.  For example, different frequencies may be required to accurately evaluate extra large pipes, multiple pipe materials, and pipes carrying highly turbulent water or large amounts of suspended solids.  In addition, a utility can use a multi-frequency sonar unit to scan a pipe segment at multiple frequencies to better characterize features and objects such as debris, blockages, and pipe wall deformation.

Andrews (1998) found that a sonar device’s travel rate through the sewer affects the precision of the results.  A “practical” speed of advancement, such as 100 mm per second (4 in. per second), allows for the optimal identification of critical defects but prevents the detection of very small defects.  The precision of sonar results and image quality are also affected by the quantity of suspended solids and debris, air entrainment from incoming flow, and the degree of turbulence in the pipe.

## 5.3 Leak Detection Systems

### *Description*

Leak detectors are devices used to detect the sound or vibration produced by leaks in pressurized waterlines or in sewers.  The different types include 1) hand-held listening devices such as listening rods, underwater microphones (also known as aqua phones, sonoscopes, water phones, or hydrophones), and geophones (ground microphones);  2) leak noise correlators; and 3) in-line devices, which collect information on leaks remotely.  Listening devices and leak noise correlators are widely available and have been used for leak detection for decades.  In-line leak detectors are a more recent advancement.

The most complex leak detectors are in-line systems, which are deployed in a pipeline and continuously monitor leakage.  There are several commercially available models.  Regional and national providers of leak detection systems and services can evaluate wastewater systems, although the technology is far more often used for condition assessment of water distribution systems.  Commercially available systems are described in USEPA (2009a).

### *Performance*

The technical performance of leak detection systems in wastewater pipelines was documented in several case studies (Table 5-2).  These investigations were conducted on sewer force mains (12 to 66 in. in diameter) and inverted siphons (12 to 54 in. in diameter).  In wastewater force mains, the leak detectors are not only used to detect leaks, but also to identify air or gas pockets where hydrogen sulfide gas can collect and corrode the pipe.

Based on simulated leakage tests, Derr et al. (2009) found that the Sahara® leak detection system could detect active leaks and air pockets in sewage force mains.  The study also showed that water velocity is a critical factor in deploying acoustic systems.  Although the Sahara® leak detection system has been used at lower velocities, Derr et al. (2009) recommended a minimum of 1.0 fps for straight pipe segments and a velocity of 1.5 fps to provide sufficient energy for sensor operation in complex sewer systems with vertical bends.  In general, an average velocity greater than 2.0 fps is suitable for deployment in all types of piping systems (Pure Technologies, 2007).

Knight et al. (2007) presented findings from two case studies of the Sahara® leak detection system in North America. The studies demonstrated the ease of deployment while sewers remained in service; however, no leaks were identified, so the system's sensitivity could not be evaluated. Laven et al. (2008) used the Sahara® leak detection system to inspect a 66-in. diameter force main after its partial failure and found no other leaks in the 8.5-mile pipeline. They also conducted two leak simulation exercises to verify that the Sahara® system could detect leaks in force mains operating at pressures between 10 and 30 psi (Table 5-2).

Pure Technologies (2009a; 2009b) documented the use of the SmartBall™ Leak Detector for detecting gas pockets in sewage force mains; in both cases, leak detection could not be confirmed because the line pressure of 15 psi was below the equipment's threshold. In Grand Forks, N.D., sensors were deployed at 15 different sites to help pinpoint the location of gas pockets and other detected anomalies. Equipment was extracted using two techniques: by the standard under-pressure net extraction and by removal at the trash rakes inside the treatment plant. The system detected gas pockets, but leak detection could not be confirmed because of low pressure in the line. In San Jose, California, the SmartBall™ equipment was inserted into the pipeline using pigging facilities at a sewage lift station and removed at the trash rakes inside the treatment plant (Pure Technologies, 2009b). Fourteen gas pockets were detected, ranging from 5 to 500 ft in length; no leaks were detected. This technology shows promise, but information from case studies is limited; systematic study by third-party organizations is needed to further verify its performance in detecting leaks.

**Table 5-2. Case Histories of Technical Performance of Leak Detection Systems**

| Device | Application (Inspection Period) | Technical Performance | Reference |
|---|---|---|---|
| SmartBall™ Leak Detector by Pure Technologies. | Inspection of 8.7 mi. of 24-in. and 36-in. PCCP and PVC sewage force mains, Grand Forks, N.D. (Oct. 2008). | Survey was completed in two days in 10.5 hours run time and a line pressure <15 psi. The average flow velocity was 1.0 fps with a maximum velocity >10 fps. The system detected six gas pockets ranging from 2 to 18 ft in length. Leak detection could not be confirmed because line pressure was less than the threshold (15 psi). | Pure Technologies (2009a). |
| SmartBall™ Leak Detector by Pure Technologies. | Inspection of 8,533 ft of 24-in. ductile iron (DI) sewage force main, San Jose, CA. (Nov. 2008). | Survey was performed in 61 minutes at a line pressure of 15 psi. The system detected 14 gas pockets ranging from 5 to 500 ft long. No leaks were detected. | Pure Technologies (2009b). |

| Device | Application (Inspection Period) | Technical Performance | Reference |
|---|---|---|---|
| Sahara® Leak Location System by Pressure Pipe Inspection Company (PPIC). | Pilot-scale investigation including leak simulation tests of 3 mi. of sewage force mains (30-in., 42-in., 48-in. PCCP; 16 in. AC pipe; 24-in. DI pipe; 20-in. PVC pipe; and 20-in. CI pipe) for Hampton Roads Sanitation District, Va. (Sept. 2008). Sewage pipe age ranges from 1 to 85 years with average age of 43 years. | Equipment deployment and retrieval were successful in pipelines with velocities >1.5 fps for pipelines with numerous bends; velocities as low as 1.0 fps were sufficient for relatively straight pipe segments. The system was found to detect active leaks and air pockets. First round pilot testing costs were $6.25 per ft including mobilization, field set up, inspection, data analysis, and final report. Second round pilot test included retesting of problem areas and a simulated leak test so costs are not considered to be typical. Based on pilot program, the cost of a full-scale leak testing program would be an estimated $6 to $8 per ft. | Derr et al. (2009). |
| Sahara® Leak Location System by PPIC. | Two leak simulation exercises (April 2007) and inspection (March 2007) of 8.5 mi. of 66-in. diameter PCCP sewage force main, built in 1972, following pipeline failure at leaking joint, Muskegon County, Mich. | Leak simulation exercises confirmed accuracy of leak location system: all simulated leaks identified (1.6 and 14 gallon per hour). The pipeline inspection revealed no further leaks in the pipeline following its partial failure. | Laven et al. (2008). |
| Sahara® Leak Location System by PPIC. | Case Study 1: Inspections on 1,995 ft of 12-in. AC force main, 3,914 ft and 446 ft of two 12-in. steel inverted siphons, and 256 ft of 28-in. diameter inverted siphon in Calgary, Alberta (August 2006). Pipe age not provided. | Surveys were completed without major complications and exceeded anticipated survey distance and number of siphons inspected within project budget. Significant electrical noise observed in one survey was eliminated by repeating the survey with a new acoustic sensor. This system located one air pocket. | Knight et al. (2007). |
| | Case Study 2: Inspections on 30 to 54-in. DI inverted siphons, utility location not named (2006), pipe age not provided. | Surveys were completed in 4 of 5 siphons without complications. In the 54-in. diameter siphon, the instrument could not be deployed more than 31 ft due to a blockage of debris in the line and inadequate hydraulic conditions. No leaks were identified in the surveys. | |

## 5.4 Electro-Scanning

### *Description*

Electro-scanning is based on the conduction of electric current through the material of interest. In the case of sewer inspection, electro-scanning (i.e., Focused Electrode Leak Location; FELL-41 for mains and FELL-21 for laterals) measures the current flowing between an electrode on the ground and a sonde (source of current) that moves through the pipe. Non-ferrous pipe materials (e.g., clay, concrete, and PVC) act as electrical insulators, and voltage only flows through defects. Therefore, an area with defects has a high current density, which can be detected by the electrode on the surface. Because water is needed to conduct the current, the pipe must be filled; a sliding plug is often used to hold water in the pipe as the sonde progresses. The electro-scan data are displayed graphically as a plot of electric current (amps) vs. distance along the pipe (ft), as illustrated in Figures 5-6 and 5-7. The electric current level indicates the severity of the defect. For example, a 1 – 4 amp rating is considered equivalent to a small defect; a 4 – 7 amp rating signifies a medium defect, and >7 amps indicates large defects (Wilmut and D'souza, 2010). Best practices are outlined in ASTM Standard F2550 – 06, *Standard Practice for Locating Leaks in Sewer Pipes Using Electro-Scan--the Variation of Electric Current Flow Through the Pipe Wall* (ASTM International, 2006).

Electro-scanning can discern sites of rainfall-dependent I/I such as joints and service connections, which are not readily identified through CCTV inspection. It can also identify exfiltration defects and structural anomalies such as corrosion and cracks. CCTV can generally detect defects at joints or service connections if there are roots protruding into the defect or water flowing through it. However, CCTV cannot be deployed during periods of high flow, when water would be most likely to flow through joint and service connection defects (Harris and Tasello, 2004). Thus, electro-scanning is potentially valuable for collection systems with known I/I problems. Based on inspection of more than 150,000 linear ft of pipe, electro-scanning has produced repeatable results when inspecting the same pipeline under both wet and dry weather conditions (Wilmut and D'souza, 2010). Additional description of this technology can be found in USEPA (2009a). Figure 5-6 shows a hypothetical example of a pipe with defects and the patterns in current that the different defects would produce. For example, a longitudinal crack would produce a longer anomaly along the chart than a radial crack. An anomaly that lines up with the location of a joint indicates that the joint is faulty. Figure 5-7 shows processed electro-scanning data; corrosion results in numerous sharp peaks. Figure 5-8 shows the change in electric current due to a change of pipe material and illustrates several joint anomalies. Figure 5-9 shows the increase in current due to a manhole.

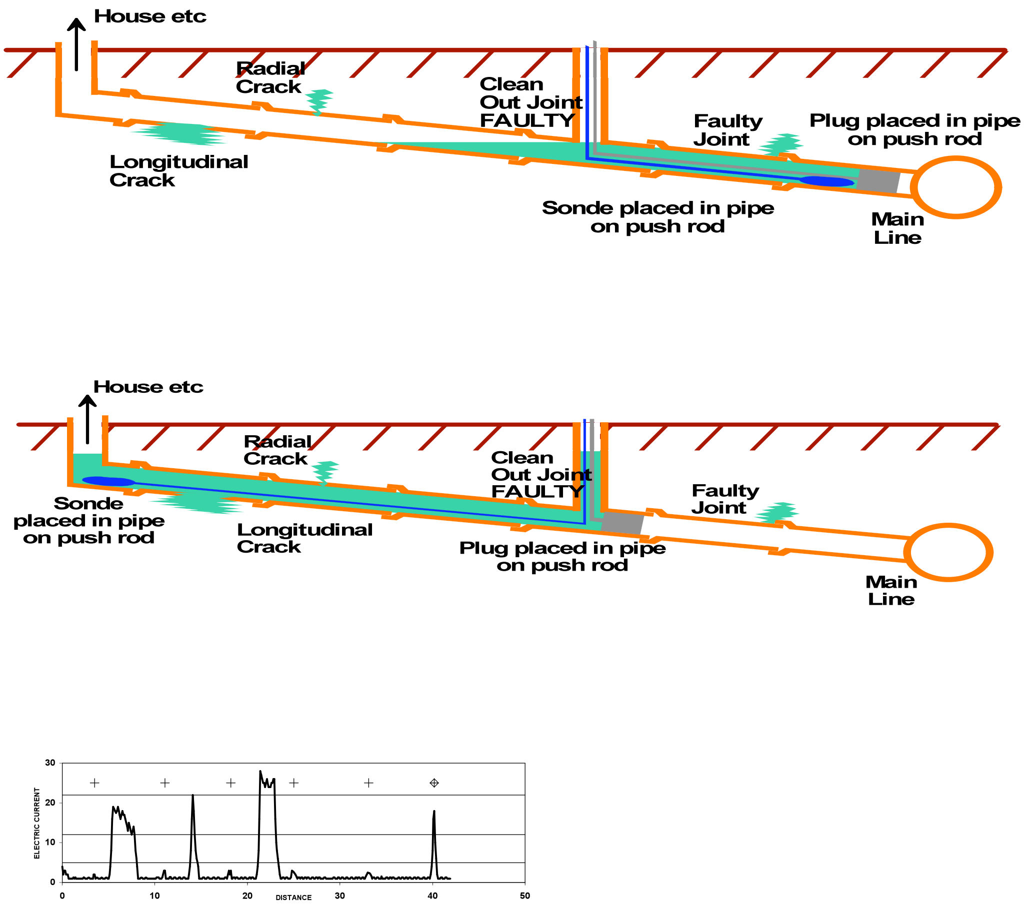


**Figure 5-6. Hypothetical FELL-21 testing and resulting data showing locations of defects.**
**Image from Dayananda et al. (2007). Reprinted with permission.**

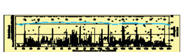

**Figure 5-7. Example of electro-scanning results showing corrosion/cracks in a RCP pipe.**
**Image courtesy of Burgess & Niple. Reprinted with permission.**

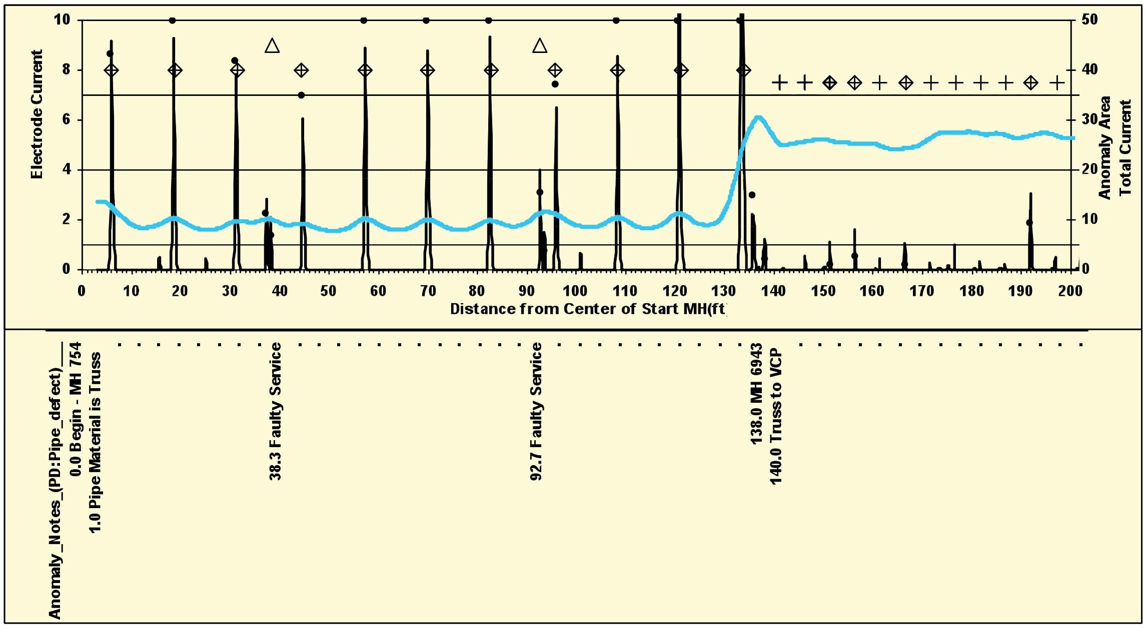


**Figure 5-8. Current plot showing change in pipe material from truss to clay, faulty services and joint anomalies.**
**Image courtesy of Burgess & Niple. Reprinted with permission.**

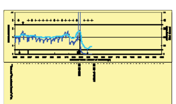

**Figure 5-9. Surge of electro-scan current due to a manhole.**
**Image courtesy of Burgess & Niple. Reprinted with permission.**

*Performance*

Case studies that demonstrate electro-scanning performance are presented in Table 5-3 and briefly summarized in this section.

**Table 5-3. Electro-scanning Case Studies**

| System | Application | Technical Performance/Results | Cost | Reference |
|---|---|---|---|---|
| Athens/Clarke County, GA. | Inspection of eight segments of 36-in. RCP interceptors with total length of 9,200 ft. | Numerous anomalies at joints. Small defects not at joints may represent hairline cracks. | Estimated at $15,000. | Moy et al. (2006). |
| Louisville, KY, and County of Sacramento, CA. | Field testing to compare relative effectiveness of joint pressure testing (JPT), CCTV, and electro-scanning in gravity sewers. | Electro-scanning agreed well with JPT, but predicted 3 times as many joint defects and 4 times as many defective service connections as CCTV. | Electro-scanning less costly than CCTV. | Harris and Dobson (2006). |
| Redding, CA. | Pilot study of main line sewers to locate sources of infiltration on 25,000 ft of 6-in. and 8-in. pipe. | Electro-scanning found to be useful in locating important sources of I/I. Resulting repairs reduced I/I from 0.45 MGD to 0.24 MGD. Inspection rates of 3,000 to 4,000 ft per day. | Cost information not provided. | Harris and Tasello (2004). |
| Louisville, KY. | Pilot testing program for gravity sewers: (7.9 – 9.8-in. VCP; 7.9 – 11.8-in. PVC pipe; 7.9-in. cured in place pipe (CIPP); 7.9-in. HDPE pipe). Compared with air testing and CCTV. | Advantages in identifying leaks in dry weather, prioritization by leak intensity, alternative to air testing, and good reproducibility. | Cost information not provided. | Gokhale and Graham (2004). |

A number of case studies illustrate how electro-scanning has been used to locate various types of leaks.  For example, Moy et al. (2006) used electro-scanning to help in planning CIPP rehabilitation in a section of 36-in. reinforced concrete pipe in Athens-Clarke County, GA.  Their scans revealed many anomalies at joints, as well as anomalies caused by structural defects such as cracks.  Small anomalies were interpreted to represent hairline cracks, possibly from corrosion.  The authors found this information useful in designing rehabilitation.

Harris and Tasello (2004) described a case study of electro-scanning in sewers with known infiltration problems in Redding, California.  Previous attempts to locate and remedy sources of infiltration in Redding's system using flow monitoring, CCTV inspection, joint air pressure testing, and smoke testing had proven to be inadequate. Therefore, a pilot study using electro-scanning was conducted. The electro-scanning results were verified through direct inspection and spot repairs, and the leak locations obtained via electro-scanning were found to be accurate. The study demonstrated that electro-scanning can form the basis of a cost-effective program to rehabilitate sewers and reduce infiltration.

It is valuable to compare electro-scanning to joint pressure testing (JPT) to verify electro-scanning results. JPT involves isolating the joint with a device such as a packer and introducing water or air into the void. Failure to reach a specified water or air pressure indicates pipe leakage. In a study of eight pipe segments in Kentucky and California, Harris and Dobson (2006) found that the number of joint defects identified by JPT and electro-scanning agreed within 4%; out of a total of 419 joints tested, 270 failed the JPT, and 286 joint anomalies were found by electro-scanning. When JPT was combined with CCTV, the results agreed within 1% of those obtained by electro-scanning. Based on this study, electro-scanning may be a viable alternative for JPT, and it was reported to cost only 20% to 25% as much as JPT.

Gokhale and Graham (2004) suggest that electro-scanning may actually be superior to JPT in finding defects. They participated in a pilot study in which the FELL-41 system showed many more joint anomalies than JPT. Gokhale and Graham (2004) noted that this discrepancy reveals a potential problem with air testing. During an air test, packers used to isolate sections of pipe for testing may force deformed pipes to become rounder and provide a better seal with the connecting pipes compared to normal field conditions. Therefore, it was concluded that the results from electro-scanning might be more representative of true pipe condition.

Harris and Dobson (2006) found that electro-scanning detected three to four times as many pipe defects as did CCTV. For example, based on testing of 59 service connections, CCTV identified 12 defective service connections, whereas electro-scanning found 48 defective service connections. Defects at joints and service connections are not readily apparent on CCTV unless water is flowing through them; electro-scanning can locate such "invisible" defects. Although it is not a replacement for CCTV, electro-scanning may be valuable if deployed in addition to or before CCTV.

In terms of production speed, Harris and Dobson (2006) reported that the speed of electro-scanning depends on pipe diameter. The scanning rate for large-diameter pipes is slower than that for small-diameter pipes. The rates for electro-scanning were similar to those for CCTV (excluding the time needed to clean the pipe prior to CCTV deployment). Pipe preparation for electro-scanning includes debris removal, but not complete sewer cleaning. The total time to inspect 300 ft of 8-in.VCP was estimated to be 45 minutes for CCTV, 190 minutes for JPT, and 35 minutes for electro-scanning.

## 5.5 Impact Echo and Spectral Analysis of Surface Waves

The impact echo (IE) and spectral analysis of surface waves (SASW) methods measure sound waves that are generated by a mechanical impact. Both were originally developed for conventional testing of concrete structures to measure the thickness of cracks and to locate voids. Although not yet commercially available in the U.S., the IE method, as demonstrated by researchers in Japan, can locate and measure longitudinal and circumferential cracking in wastewater collection systems. Prototypes have seen limited use in wastewater sewers in Japan by Sekisui Corporation and in large water supply tunnels in the U.S. by Olson Engineering (Kamada and Okubo, 2005, Dingus et al., 2002).

According to the Japanese manufacturer, IE can be used in reinforced concrete and clay pipe with diameters from 8 to 28 in. (200 to 700 mm) (Asano, Masanori. Email with author, 2009). Research has shown that the technology can only be used in clean pipes with flow depth less than 20% of the inside pipe diameter. Kamada and Okubo (2005) first tested the IE system, mounted on a robotic platform along with a CCTV camera, in buried 10-in. (250 mm) diameter concrete pipes under controlled conditions. The results from the controlled condition study were used as a reference for field tests of 14-in. (350 mm) diameter concrete sewer pipe. The field tests showed that the IE technique could identify longitudinal and circumferential cracking in a pipe.

### *Impact Echo*

The IE technique consists of striking the material of interest with a hammer or similar tool (the impact) and recording the vibrations of the resulting acoustic response (the echo). The underlying principle of IE is that the sound waves (the compression waves in particular) generated by the mechanical impact reflect off cracks, discontinuities, and the outside edges of the subject material. The reflected sound waves are detected by a receiver and translated into output, which is interpreted by the operator. Figure 5-10 graphically describes the IE method.

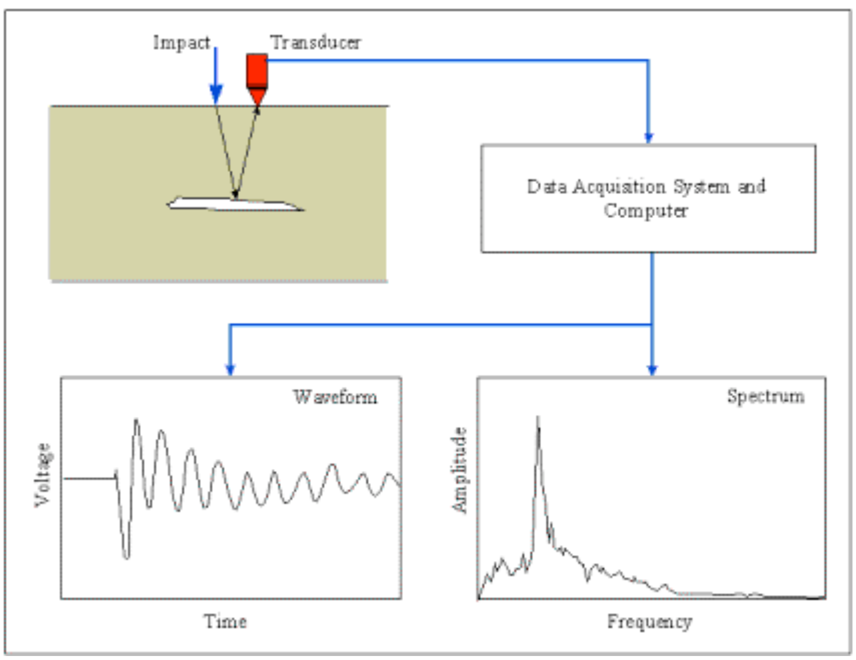


**Figure 5-10. Illustration of Impact-Echo method.**
**Image from Sansalone and Streett (1998). Reprinted with permission.**

### *Spectral Analysis of Surface Waves (SASW)*

Like the IE technique, the SASW technique measures sound waves that are generated by a mechanical impact. But unlike the IE technique, which measures compression waves, the SASW method measures surface waves. (Surface waves travel the surface of a material to a depth of one wavelength.) This method allows testing over a range of depths (from the surface of material being tested) corresponding to different wavelengths. The SASW technique provides information on wave velocity variations over the depth of a material, which helps define individual layers and transitions between layers in the material being tested. Both IE and SASW are analogous in many ways to seismic profiling techniques used by geophysicists to detect subsurface structures.

### *Equipment*

The equipment requirements for IE and SASW are similar. Both methods require a mechanical impact tool, a displacement transducer (or accelerometer), and a computer for data acquisition and signal analysis. Equipment for both conventional and innovative testing is described in the sections below.

### *Conventional Equipment*

Steel balls or an electrically driven solenoid hammer are typically used to generate the mechanical impact for the IE method. The steel balls, which are mounted on spring rods, are selected based on diameter. The duration of the impact (or contact time) of the steel balls varies with their diameter (Carino, 2001). The impact of the solenoid-activated hammer is moderated by the voltage in the solenoid (Carino, 2009). The contact time for the steel balls or the solenoid hammer ranges from 30 to 60 microseconds.

The transducer is in direct contact with the material being tested to detect the reflected sound waves. A standard transducer measures the displacement (i.e., vibration) at the material surface and converts the displacement reading into voltage. Many of the commercially available portable IE testing kits combine the solenoid hammer and transducer into one handheld device.

The conventional equipment for the IE technique has several disadvantages:

1. It is relatively slow for inspecting large surfaces.
2. It requires exposure of a clean surface to allow direct contact of the transducer with the material surface.
3. It requires relatively clean and dry test conditions.

### *Innovative Equipment*

To overcome the disadvantages of conventional IE and SASW systems, innovative equipment has been developed, including laser scanners, air-coupled transducers, and robotic scanners. In particular, transducers have been improved to address problems stemming from the need for direct contact with test materials.

Laser scanners have been used to detect sound waves, with a laser beam projected onto the material to record vibrations. Because the operation of the laser scanner relies on the smoothness of the material, the inherent roughness of concrete has limited its application (Zhu and Popovics, 2007). Sometimes paint is applied to the surface to enhance reflection. Laser scanners have been widely used in the restoration of artwork and historic buildings.

Air-coupled transducers have been proposed by researchers (Zhu and Popovics, 2007) to replace the conventional IE direct contact sensors. These transducers are composed of small, highly directional microphones located relatively close to the material to be tested; hence, there is no need for a fluid or gelatinous substance to couple the transducers to the test material. Air-coupled sensors used with the IE technique have proved to be effective in locating delaminations and voids in concrete (Zhu and Popovics, 2007).

Scanners or robots may be used to address the relatively slow production and difficult handling of the conventional IE point-by-point technique (Grosse et al., 2005). For pavement and wall testing, scanners have been developed to increase the testing speed. It has also been found that the data generated using scanners are easier to interpret and less prone to operator error than data from the point-by-point technique (Colla et al., 1999). Scanners are mounted on the wall or pavement over the area to be tested and are moved manually and reattached at the next area to be tested. German and French researchers have developed and extensively tested these scanners on concrete walls and pavement (Wiggenhauser, 2009).

A recent innovation in SASW techniques is the mobile acoustic device (MAD) prototype system in which the impact hammer and the air-coupled transducer are mounted on a wheeled cart (Marzani et al., 2007). Experimental testing on the MAD system was suspended due to lack of funding (Marzani, Alessandro. Email with author, 2009). Researchers have shown that prototype mobile devices similar to the MAD system can detect defects in pavement and road sub grade (Ryden et al., 2009).

### *Application and Performance in Other Industries*

The IE and SASW methods have been used extensively to test engineered structures. When used on concrete structures, IE has been found to be effective in locating surface delaminations and voids. These are formed during construction when the mortar does not fill the spaces among the coarse aggregate particles. The IE method has also been used to measure the depth of surface-opening cracks and the thickness of structural supports. In Germany, where there are regulatory requirements for tunnel linings, the IE method has been used extensively for quality control (Grosse et al., 2005).

In the U.S., researchers have applied IE technology to the condition assessment of large water mains for the Bureau of Reclamation (Sack and Olson, 2007).

The SASW method has been used to monitor dams and bridges to measure the depth of surface-opening cracks and freeze-thaw damage and to measure relative concrete quality. SASW has also been used to profile the thickness of pavement, including asphalt and layer systems for highways and roads (Olson Engineering, 2007). It has been used to assess the condition of concrete liners in tunnels and large-diameter concrete and brick water lines. But it has not been applied to wastewater collection systems (Olson Engineering, 2007; Makar, 1999).

## 5.6 Ultrasonic Testing

### *Description*

Two emerging ultrasonic testing technologies, the ultrasonic pulse velocity method and guided wave ultrasonic testing, are potentially suitable for the condition assessment of wastewater collection systems. The ultrasonic pulse velocity method is based on the speed with which an ultrasonic pulse passes through the test material. Guided wave ultrasonic testing (discussed in Section 5.7) induces plate or "guided" waves in the material, permitting detection of cracks and measurement of pipe wall thickness.

Ultrasonic testing assesses the surface as well as the internal features (e.g., thickness and material properties) of the object being tested. For wastewater sewers, ultrasonic testing can measure pipe thickness, detect corrosion, and detect and measure cracks. In its simplest form, ultrasonic inspection uses the pulse-echo method to measure the thickness of materials. The short burst or pulse is induced in the material using a transducer. The pulse passes through the material until it reaches the other side, where its echo is reflected to the surface. The duration and velocity of the pulse are measured and used to determine the distance from the surface to the outer side. The pulse can also be directed into the material at an angle using an angle beam transducer. The angle allows for more accurate detection of cracks or flaws in the material. The conventional ultrasonic testing method typically involves point-by-point measurements along the surface of the material being tested. To ensure sufficient transmission of sound waves, a couplant, either water or a gel, must be applied between the sensor and the test material.

Like the IE and SASW methods, the conventional transducers used for ultrasonic testing have several potential drawbacks:

1. They are relatively slow for inspecting large surfaces due to the required point-by-point measurements (including the movement of angle beam transducers).
2. They require exposure of a clean surface to allow direct contact of the transducer with the material surface.
3. They require relatively clean and dry test conditions.

Innovative ultrasonic transducers have been developed to overcome the drawbacks of deploying conventional transducers in the field. These sensors include phased array (PA) transducers, electromagnetic acoustic transducers (EMAT), and air-coupled transducers (including lasers). The PA transducer eliminates the need to move an angle beam transducer across the surface of the material. The EMAT and air-coupled transducers eliminate the need for direct contact. As a result, they can increase the speed of ultrasonic inspections and allow testing of some otherwise difficult surfaces (e.g., coated pipes). Both the PA and EMAT transducers control the "noise" associated with surface waves so that guided wave inspections can occur (Section 5.7).

### *Application and Performance in Other Industries*

Ultrasonic testing of the exterior of pipe walls (on aboveground or excavated portions) has been common practice in many industrial sectors, including water and wastewater utilities. Ultrasonic testing equipment is commercially available and has been implemented on ferrous water mains and wastewater force mains (Thomson et al., 2004; USEPA, 2009b). It has been used under controlled laboratory and field conditions. It can test most pipe materials including metals, ceramics, plastics, and composites but performs best on steel and ductile iron pipe (Iowa State University, 2008). Because the conventional ultrasonic testing method is typically operated from the outside of the pipe, it can be used on pipes of all sizes.

Ultrasonic testing can also be used to inspect the interior of petroleum liquid pipelines. The natural gas industry has developed various devices (e.g., liquid-filled transducer wheels and EMATs) to deploy ultrasonic testing equipment in gas mains. These devices have not been adapted for wastewater collection systems and water transmission systems due to their high cost and potential operational difficulties (Marlow et al., 2007).

Though ultrasonic testing has seen widespread use on pipes constructed of homogeneous materials (i.e., steel pipe), researchers at the University of Waterloo are researching its use on pipes constructed of heterogeneous materials (i.e., concrete pipe) (Jiang et al., 2006; Lopez et al., 2001). Ultrasonic testing has also been used to measure the depth of cracks in concrete pipe (Yang et al., 2009).

## 5.7 Guided Wave Ultrasonic Testing

### *Description*

Guided Wave Ultrasonic Testing (GWUT), also known as long-range ultrasonic testing, uses ultrasonic waves to inspect metal pipes (Cawley and Alleyne, 2004). It uses ultrasonic waves at the lower end of the ultrasonic frequency spectrum (normally below 100 kHz)). GWUT can detect cracks and measure the wall thickness of a metal pipeline across a large distance. GWUT is commercially available and has been used on industrial piping in manufacturing and in the oil and gas sector. It has not been used on wastewater force mains but has been successfully field tested on water mains in the U.K. (Reed et al., 2004).

Unlike other forms of ultrasonic testing, GWUT testing induces plate-type waves rather than compression waves in the material being inspected. These plate-type waves are called “guided waves” because they travel by interacting with the upper and lower surfaces of the plate or pipe wall. Plate waves can travel long distances (up to 100 meters under some conditions) and can detect the loss of plate or pipe wall thickness (i.e., erosion or corrosion) and cracks (Edwards, 2006). However, these waves need to be controlled in order to generate a high-quality signal (Cawley and Alleyne, 2004). GWUT can be used to inspect large surfaces from a single probe, thereby eliminating the manual movement of the transducer used for conventional ultrasonic testing.

Like other ultrasonic techniques, GWUT testing requires transducers, a pulser-receiver (processor), and display equipment. On pipelines, the transducer can be in the form of a wrap-around collar or a thin ferromagnetic strip sensor mounted on the pipe’s exterior (Figure 5-11).

**Figure 5-11. Example wrap-around collar with piezoelectric shear motion sensor (Teletest sensor collar).**
**Image courtesy of TWI Ltd (http://www.twi.co.uk/). Reprinted with permission.**

### *Application and Performance in Other Industries*

GWUT has been used most often to scan metal pipe in the process, oil, and gas industries for erosion or corrosion. However, more recent studies using EMAT or PA transducer technology have used GWUT for defect sizing (Mudge et al., 2007; Rose et al., 2009).

The GWUT technique can be used on a wide range of geometric structures, from the simple (e.g., pipes and plates) to the more complex (e.g., wire cable, rails in railroads, and sheet piling) (Edwards, 2006). Because GWUT does not require direct contact with the entire material surface, it has been widely used to inspect insulated industrial pipe for corrosion. Similarly, GWUT testing can be used on piping that is inaccessible or located in short sleeves (e.g., road crossings). Though GWUT has been used for above-ground piping at industrial facilities, it has also been used for underground piping that can be accessed at some point from an excavation or aboveground portion (Marlow et al., 2007). This method is used to inspect steel pipe, but it has not been proven for gray cast iron and ductile iron pipe (USEPA, 2009b). It has been shown to work best on continuous butt-welded steel pipe (USEPA, 2009b; Lillie et al., 2004).

GWUT reportedly can inspect up to 300 ft of pipe (USEPA, 2009b). On pipe with flanged, socket-welded, and socket-and-spigot fittings, the length of inspection is limited to the length of a single spool (Reed et al., 2004). In general, pipes with diameters from 2 to 48 in. and with walls less than 1.6 in. thick can be inspected with GWUT (USEPA, 2009b; Marlow et al., 2007; Lillie et al., 2004).

Although it is an effective screening technology, GWUT may miss critical defects and cannot measure the depth of a defect (Thomson et al., 2004; USEPA, 2009b). GWUT technology can be improved using PA transducer technology to better detect critical defects and locate circumferential cracks in pipelines (Mudge et al., 2007; Rose et al., 2009). In research conducted for the U.S. Department of Transportation, Mudge et al. (2007) confirmed that a proposed wave focusing technique enhances GWUT so that it can detect corrosion or coating faults on coated or encased gas pipelines. In a series of laboratory tests and field investigations, PA transducers were used to focus the ultrasonic waves on piping with diameters ranging from 6 to 20 in. The study results indicate that wave focusing enhances GWUT to: (1) increase the detection of small defects; (2) decrease the number of false positives; (3) locate a defect at any part of the pipe circumference; and (4) estimate the defect size.

## 5.8 Micro-deflection

### *Description*

According to USEPA (2009a), micro-deflection is a non-destructive technology used to evaluate brick, concrete, and clay structures. The method involves the application of a load onto the structure to create a slight deformation, called a "micro-deflection." The structure's micro-deflection is measured and displayed graphically (as a plot of load vs. deflection). Structurally sound test materials would be expected to have a consistent micro-deflection profile for various loads, while deteriorated or defective structures would deviate from expected values.

Micro-deflection was used to perform condition assessments of brick sanitary sewers in Montreal in the mid-1990s (Makar, 1999), but has not been widely used since (USEPA, 2009a). The usefulness of micro-deflection is limited because it can give only a general understanding of pipe condition, such as the integrity of joints, rather than identification of individual defects. In addition, plastics such as PVC and HDPE cannot be inspected using this method. The technology is still under development (Eldada, M. Victor. Email with author, 2009).

## 5.9 Fiber Optic

### *Description*

In fiber optic systems, light pulses generated by a laser or light-emitting diode (LED) are transmitted through thin glass fiber optic lines the diameter of a human hair. Fiber optic sensors measure the backscattering of the light pulses. Typically, many fiber optic lines are assembled into a fiber optic cable that is used to monitor strain and temperature changes in structures such as dams, bridges, and pipelines. Temperature changes are used to detect and locate pipeline leaks. Changes in strain indicate deflections in the structure, potentially from geologic or human-induced movements. Wall thickness can be measured by strain sensors on the outside of the pipe wall (USEPA, 2009b). Fiber optic technology is not currently applied to wastewater collection systems, but merits investigation due to its success in monitoring oil and gas pipelines and water mains.

The equipment required for the fiber optic system typically includes a transmitter (either a laser or LED), the optical fiber itself (usually hardened cable), regenerators (for distances beyond 12 – 15 mi.), and an optical receiver (LxSix, 2007). One optical fiber and data acquisition system can monitor up to 15 mi. of pipe without regenerators (Higgins and Paulson, 2006). The cost of fiber optic monitoring of pipelines can be as low as \$1 to \$2 per meter (\$0.30 to \$0.60 per ft) for long-distance pipelines (OzOptics, 2008).

### *Application and Performance in Other Industries*

For structural monitoring of oil and gas pipelines, the fiber optic cable is installed permanently within a few yards of the pipeline. Various companies, including LxSix, Omnisens, and Ozoptics, provide proprietary pipeline monitoring systems that use fiber optic distribution strain and temperature sensors.  The systems can distinguish between pipeline leaks, tampering, intrusions, and machinery and vehicles operating in the vicinity of the pipeline.

The use of fiber optic cable sensors on water mains has been limited (Higgins and Paulson, 2006).  Researchers from Pure Technologies compared the results of acoustic testing (for wire breaks) of pre-stressed concrete cylinder pipe (PCCP) using fiber optic sensors and more conventional hydrophone arrays.  The fiber optic lines (4 to 8 lines used) measured the strain energy released from the wire breaks in the PCCP mains.  The sensors were tested on 4,700 ft of a 48-in. PCCP main in Baltimore County, Maryland during the winter of 2005 – 2006.  The fiber optic sensors were found to be accurate to within ± 5 ft of the break.

According to USEPA (2009b), there are limitations to using a fiber optic system for corrosion monitoring in ferrous pipe.  These authors assert that "only a small number of locations can be monitored, and the rate of deterioration is slow and would require years of data collection to yield any useful data."

# 6. Technologies to Evaluate Pipe Bedding and Void Conditions

Pipes may undergo structural failure due to defects in the soil envelope (soil bedding and cover soil) that supports the pipe. The soil bedding acts as a foundation for the pipe and distributes the vertical load around the exterior of the pipe wall. Loss of bedding can result in the pipe bridging areas of reduced bedding or increased voids. This can lead to pipe deflection, pipe deformation, and longitudinal cracking. There are established and emerging methods to help evaluate the condition of the pipe bedding and locate voids. Ground-penetrating radar (GPR) is a well-developed option. Other techniques, such as gamma-gamma logging and infrared thermography, have been used in other applications and are being studied for their potential use in sewer condition assessment.

## 6.1 Ground Penetrating Radar

### *Description*

GPR operates on the same principle as radar by transmitting high-frequency radio waves from an antenna into the ground (USEPA, 2009a). The waves travel through the ground until they reach a material with a different conductivity and dielectric constant than the earth. In general, an object that is harder than the surrounding soil will reflect a stronger signal. Utilities, tunnels, and other buried objects can therefore be located by transmitting a GPR signal, which is reflected and recorded by a separate receiving antenna. The amount of time it takes for the electromagnetic radio waves to be reflected by subsurface features can be analyzed to determine their position and depth.

GPR is generally used in reflection/scattering mode, as depicted in Figure 6-1 (left side). Alternatively, GPR can transmit and receive signals between two boreholes, as depicted in Figure 6-1 (right side).

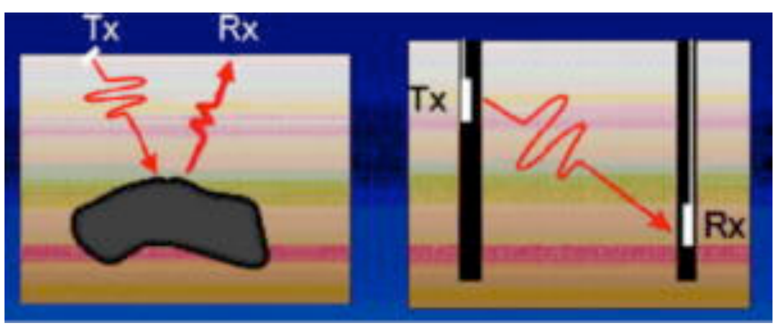


**Figure 6-1. GPR applications in (left) reflection/scattering or (right) trans-illumination mode. Image from Annan (2003). Reprinted with permission.**

### *Inspection from the Ground Surface*

GPR can provide information on the condition of the soil surrounding the pipe, including voids. Hyun et al. (2007) conducted controlled laboratory experiments to evaluate the potential use of GPR as a ground-radar-transmitting tool to detect leaks in water pipes. The laboratory scaled-down model consisted of a dry sand tank, a pipe, and a simulated zone of leakage adjacent to the pipe. The size and depth of the pipe, impulse generator, and antennas were scaled to approximately 1/6 of real world conditions. Results showed that the buried pipe and the effects of leakage in the soil were clearly identified in the 2-D data plots.

In a review of condition-assessment tools based on new developments and field trials in the U.S. and UK, Costello et al. (2007) summarized the applications and limitations of GPR. As a ground surface pipe-locating technique, GPR is independent of the pipe material. As a result, GPR can locate non-metallic pipes (unlike other pipe location methods that can only detect metallic pipes). The GPR transmitting unit is most effective when passed perpendicular to the line of the pipe (Costello et al., 2007). When the pipe's orientation is not known, a grid is laid out on the surface to ensure complete coverage. The maximum depth of detection is typically about 9.8 ft (3 m) under favorable conditions.

The use of GPR is limited in several ways (Costello et al., 2007). The pulses lose strength in conductive materials such as clays and saturated soils, affecting the depth of penetration and the GPR response. Because GPR does not identify specific utilities (e.g., water or gas pipelines, electrical or telephone cables), other methods must be used for verification. Finally, interpretation of GPR data requires highly skilled operators. Research into GPR technologies has focused on overcoming these drawbacks through antenna design, connections to Computer-aided Design (CAD) and Geographic Information System (GIS) mapping systems, and the interpretation of GPR images. For imaging, there are new technologies such as ground penetrating imaging radar (GPIR) and synthetic-aperture radar (SAR) imaging to present output in 3-D images.

Makar (1999) described a field test conducted by the National Research Council of Canada at the Waterline Test Facility in Ottawa to examine the effectiveness of GPR when emitting a signal from the ground surface. Several test voids were created in the Leda clay soil that occurs naturally at the test site. Before the beginning of the test, the radar operator was informed of the number of voids and their approximate locations and the depths of various water lines. The results showed high levels of false positive and false negative results, which were attributed to likely interference with the GPR signal by clay soils at the site. Makar (1999) concluded that the ground surface GPR used at the time of testing would yield unacceptable results in any city with clayey soils. In another study conducted around the same time, Hunaidi et al. (2000) used a commercial radar system to collect GPR images of a simulated water leak and concluded that the method showed promise for initial leak surveys in subsurface environments other than soft, clayey soil.

***Inspection from within the Pipeline***

Recently, GPR has been used for in-pipe inspection in conjunction with other inspection technologies (e.g., digital scanning, CCTV, and ultra-bandwidth). These in-line assessment methods are generally limited to non-conductive pipe, which allows the signal to propagate through the pipe wall into the surrounding soil (Sterling et al., 2009). GPR can be operated remotely as part of a CCTV inspection system using two or three antennas capable of detecting different frequencies to investigate the structure of the surrounding soil, the interface between the soil and the pipe, and the structure of the pipe itself. For example, a new remotely operated in-line GPR robot, released in May 2010, identifies pipe wall thickness, rebar cover, the composition of defects, the condition and thickness of pipe liners, and location of cracks for 18 in. to 30 in. non-ferrous pipes (SewerVUE Technology Corp. 2010). "Data collection is continuous, allowing capturing several miles of data in a few hours. High frequency GPR can locate targets to a distance of 36-inches…"

GPR was used in combination with sewer scanning and evaluation technology (SSET) to assess large-diameter PVC-lined concrete pipe in Phoenix, Arizona (Koo and Ariaratnam, 2006; Ariaratnam and Guercio, 2006). This hybrid technology could "see" through the liner and evaluate possible voids in the reinforced concrete sewer pipe.

Jaganathan et al. (2009) described a method that uses ultra wideband (UWB) technology to detect voids in the soil bedding surrounding a pipe. It is expected that this new technology, when fully developed, will be able to accurately assess the condition of predominantly non-ferrous buried pipes, including external corrosion, pipe wall thickness, and the presence, location, orientation, and dimensions of soil voids. Unlike commercially available GPR systems, the new UWB system uses ultra-short electromagnetic pulses to provide higher resolution and greater accuracy. The signal produced by the impulse generator is transmitted and received using two types of UWB antennas. The radar operates in the bandwidth between 3.1 and 10.6 gigahertz (GHz).

***Application and Performance in Other Industries***

GPR has been widely used for concrete inspection by emitting a signal from the ground surface to locate underground infrastructure (USEPA, 2009b). It has also been used in military, mining, archeology, and law-enforcement applications (Makar, 1999). Surface-based surveys using GPR can provide information about the relative size of a pipe, depending on depth and surrounding conditions. Determination of material type and other characteristics is generally not possible with surface-based GPR surveys (Sterling et al., 2009).

## 6.2 Gamma-Gamma Logging

***Description***

The gamma-gamma logging (GGL) technique is based on the principle that radioactive gamma rays, emitted either naturally from the environment or artificially from a shielded industrial source, are backscattered (and therefore detected) in proportion to the density of the surrounding material. For most materials, the natural log of the gamma count rate has an approximately linear relationship to the density of the material (Leibich, 2001; Federal Highway Administration, 2009a).

The equipment required for GGL consists of a probe containing a small amount of radioactive material (e.g., cesium-137) that is used as the gamma ray source, and a scintillation detector to detect the gamma rays. A crystal inside the scintillation detector sends out light pulses when it receives radiation. The light pulses are converted into an electronic signal that is proportional to the number of pulses (Ohmart/Vega Corporation, 2010). The probe usually contains two or more scintillation detectors, which are shielded from direct radiation by a heavy metal such as lead (USEPA, 2009a).

GGL has been used to identify and locate cavities in pipe bedding (Eiswirth et al., 2001). Based on testing in Germany and Australia, researchers have proposed using the GGL technique to assess the condition of sewers and water lines (Eiswirth et al., 2001). The proposed radiation probes (i.e., gamma and neutron) would be mounted on a multi-sensor robotic crawler for sewer condition assessment. Initial laboratory-scale tests have been completed in Germany for the Sewer Assessment with Multi-Sensors (SAM) system, but this research team has since changed direction to focus on digital CCTV applications for sewer condition assessment (Burn, Stewart. Email with author, 2009).

Figure 6-2 illustrates the construction and functional principle of the gamma ray probe and shows a graph of typical results. The graph shows the counting rate of gamma radiation over pipe distance (meters). When the probe passes a pipe joint, an orifice, or a cavity in the pipe bedding, the counting rate changes. The relative sensitivity of the measurement can be increased by using a lead shield around a portion of the detector (dotted and dashed lines in Figure 6-2). The solid line in the Figure 6-2 graph represents a more accurate position of pipe anomalies.

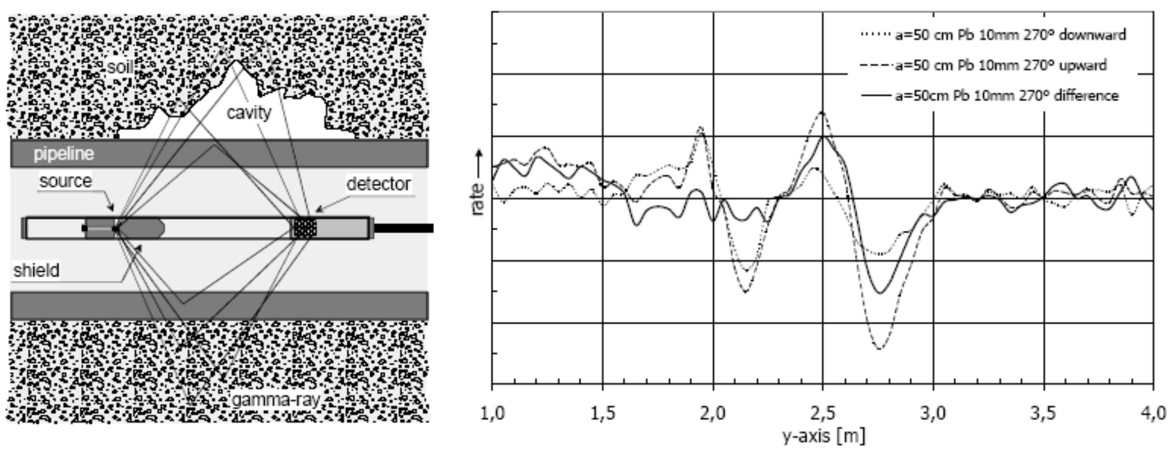


**Figure 6-2. Gamma-Gamma Logging.**
**Image from Eiswirth et al. (2001). Reprinted with permission.**

### *Application and Performance in Other Industries*

GGL is typically used to measure densities in concrete and other pipe construction materials. The California Department of Transportation (DOT) has been using GGL probes for quality control of concrete in structural pilings for decades (Leibich, 2001). A GGL probe is inserted in small-diameter PVC ducts placed in the concrete during curing. The relative average density measurement obtained with the GGL probe is used to confirm that the concrete is homogeneous. If repeated measurements show statistically significant differences, then there is sufficient evidence of voids in the concrete. Because the size and strength of the gamma ray source can vary with the brand of probe, the California DOT requires a specified density precision and radius of detection.

GGL has been thoroughly researched as a geophysical technique and is well established in mining and petroleum exploration. GGL is used to determine the porosity of the surrounding material, converted from the measured bulk density (Federal Highway Administration, 2009a, 2009b).

Researchers have tested gamma ray scattering techniques in the characterization of process pipelines at steel mills (Song et al., 2008). The study used a prototype inspection device containing cesium-137 to externally inspect the tar deposits in gas pipelines (diameter is 3.5 to 8.5 in. or 90 to 216 mm). The prototype quantified the volume of the tarry deposits to an accuracy of ±10%. In contrast, ultrasonic and magnetic inspection methods were not able to penetrate the dense tarry deposits.

## 6.3 Infrared Thermography

***Description***

When a material is heated, infrared radiation flows from warmer to cooler areas. Because various construction materials have different insulating properties, they retain heat differently and, therefore, emit different amounts of infrared radiation. Infrared thermography (IRT) uses an infrared camera to measure infrared radiation across the surface of an object. It produces images that show areas of differing temperatures in gray tones or colors. Uneven heating or cooling of a pipe wall or liner can indicate the presence of pipe defects (i.e., variations in pipe wall thickness, bonding of a liner to the pipe wall, or the presence of soil voids outside the pipe) (Sterling et al., 2009). Because IRT cannot measure the depth to the pipe, it has limited value for locating pipes (Costello et al., 2007).

The IRT imaging and analysis system typically includes an infrared sensor and optics head (similar in appearance to a portable video camera), a real-time microprocessor and display monitor, data acquisition and analysis equipment, and image recording and retrieving devices. Equipment is available from several manufacturers. Most non-destructive infrared testing takes place in the near-infrared region and slightly beyond it in the electromagnetic spectrum, up to ~15 μm (Dingus et al., 2002).

There are two basic IRT methods: passive IRT, which requires no external heat source, and active IRT, which requires a heat source such as an infrared tube light (USEPA, 2009a). With passive IRT, the sun serves as the energy source by warming the ground. Conversely, if the test is performed at night, the ground becomes the heat source and the sky acts as the heat sink. Active IRT can be used for pipeline assessment when the temperature of the pipes can be adjusted using a heat source.

When used from the ground surface, IRT has proved to be an accurate and efficient method of locating subsurface pipeline leaks and voids caused by erosion, deteriorated pipeline insulation, and poor backfill (Wirahadikusumah et al., 1998). Researchers have found that IRT can also be deployed inside a sewer and can detect variations in wall thickness, liner bonding, soil voids in pipe bedding, and leaks. Hunaidi et al. (2000) conducted a field trial to test the applicability of IRT for detecting leaks in water distribution systems. Thermal trends in infrared images were conflicting, but the investigators concluded that IRT could be used for leak detection, especially as an initial survey tool. Generally, the leak area was seen clearly as a warm spot in thermographic images. However, several issues were identified for further investigation, including the effects of ambient conditions (e.g., sky cover, relative humidity), thermal noise (especially in urban areas), and ground cover.

Maldague (1999) described the use of pulsed active infrared thermography (PAIRT) to detect thinning pipe walls. The PAIRT technique was demonstrated under laboratory conditions by focusing an infrared camera on a bent and corroded pipe segment and recording the changing infrared thermographic images as a function of time. A thermal transient was generated by either changing the temperature of the circulating water inside the pipe or by heating the external surface of the pipe with a heat gun. After imposing a thermal gradient, the temperature distribution and patterns on the outside surface of the pipe were observed using the infrared camera; abnormal temperature patterns were noted. Maldague (1999) concluded that the high thermal contrast on the pipe surface and the absence of reflective noise are advantages of this technique in assessing pipe condition. Sterling et al. (2009) noted that for thick-walled pipe inspection, prior heating or cooling of the pipe over a period of time may be necessary to get measurable results. For thin pipe liners in relatively small pipes, differences reportedly can be observed using a light bulb as a heat source.

***Effects of Environmental Factors***

Weil (2001) and others (Weigle, 2005; Stockton and Tache, 2006; Costello et al., 2007) described the influences of environmental factors (e.g., subsurface conditions, type of ground cover, wind speed) on IRT measurements. Ground cover with a rough surface (e.g., concrete) can release high amounts of energy, whereas smoother surfaces release less energy. A high-quality backfill material that is properly placed has the least resistance to conducting energy, while soil erosion and poor backfill surrounding buried pipelines acts like an insulator (Vavilov and Burleigh, 2001). In general, the best time for conducting IRT testing is when rapid heating or cooling of the ground cover surface occurs, and when there is little or no cloud cover. Wind has a cooling effect on surface temperature. Moisture tends to disperse the surface heat and thus mask subsurface anomalies.

***Application and Performance in Other Industries***

IRT has been used to test petroleum transmission pipelines, chemical plants, steam power plants, and natural gas pipelines (Weil, 2001; USEPA, 2009b; Costello et al., 2007). IRT has also been used for special building assessments (Tavukçuoğlu et al., 2005; Weil and Rowe, 1998) and other civil engineering applications (Stimolo, 2003; Maser, 2009).

Astronomers use infrared radiation to investigate the universe. Because it has a longer wavelength than other forms of radiation, it can pass through clouds of gas and dust and provide information on distant formations such as stars, planets, galaxies and black holes.

# 7. Implementation and Cost Considerations

After the utility has developed a short list of technologies that can address its condition assessment program objectives, implementation issues should be reviewed to confirm that each technology is still a viable option. As noted in Chapter 3, the issues include pipe access and staff training requirements. Cost will also be a key factor in technology selection, and certain site conditions and pipe characteristics can strongly influence overall project costs. Sections below present both logistical and cost issues, including costs for various technologies where available.

## 7.1 Pipe Conditions and Site Access

The common denominator for most of the commercially available condition assessment technologies is the need for access through manholes. However, access requirements and required pipe conditions can vary. For example, zoom cameras can be used in areas where access is tight; in addition to truck mounting, they can be pole-mounted or tripod-mounted to facilitate access to a site not amenable to using a vehicle-mounted camera. This technology also has the advantage of not requiring pipe cleaning. However, to get as much coverage as possible, a zoom camera must be deployed at every manhole, which might be problematic in areas where manhole access is limited.

Like the zoom camera, electro-scanning (FELL-41, FELL-21) does not require pipe cleaning before inspection. It does, however, require the pipe to be filled. A sliding plug facilitates this by allowing small portions of the pipe to be filled at a time. The periods during which high flow occurs are best for conducting electro-scanning; otherwise supplemental water must be used. One beneficial strategy is to combine an electro-scanning inspection with pipe cleaning. The hose used for cleaning can also be used to fill the pipe. Sonar also cannot operate in a dry pipe; if the pipe is not full, it can only image the portion of the pipe that is under water. A benefit of this feature is that it can image force mains without taking them out of service. Leak detection systems also do not require pipes to be taken out of service and can travel extended distances. The Sahara method remains tethered to the surface access point, but the SmartBall™ is free swimming and can travel for up to 15 hours, requiring only two access points. This need for minimal access to the pipe is a clear benefit.

Among the emerging technologies (i.e., those still in the research phase), GGL is relatively simple to mobilize in current and proposed applications. For sewer condition assessment, it would be deployed within the pipe mounted on a robotic platform. The probe is small enough to be easily carried and manipulated by one person, but the gamma ray source may be subject to special handling requirements of local and federal regulations.

Some technologies do not operate exclusively from the pipe interior. GPR, for example, is traditionally operated from the ground surface, although it has also been deployed within pipes in conjunction with SSET. IRT in passive mode is also executed from the ground surface. In active IRT mode, pipe access is required to adjust the temperature of the pipe.

Some emerging methods pose a more difficult deployment challenge in that inspection must be executed from the exterior of the pipe. For IE, the equipment must be in direct contact with or close to the test material. GWUT also requires direct contact for its operation. As a result, one section of buried pipe must be excavated and exposed sufficiently so that the transducer can be attached or placed near the pipe. The distance over which this technology works depends on the coating, condition, and construction of the pipe as well as the soil conditions. These methods, which require external access to the pipe, may be limited to special situations where the pipe is exposed. Therefore, they may not be suitable for system-wide surveys.

## 7.2 Durability of Equipment

As assessment methods from other industries are emerging for crossover into sewer condition assessment, their ability to withstand harsh conditions needs to be taken into account. For example, the durability of the GGL technique is questionable due to the possible mishandling of the nuclear radiation source. Even though GGL uses a sealed radiation source, there is potential for the probe to become lodged within the sewer. For example, when the California DOT uses GGL for acceptance testing of concrete in drilled shafts, the probe was carefully inserted in PVC inspection tubes. The California DOT first uses a dummy probe to ensure that the probe will not become lodged in the tube. Similar precautions may be required for inspections of sewers. Impact echo may also not be robust enough for application in sewer infrastructure assessment because of its requirement for a clean and dry surface.

GPR and IRT, on the other hand, are relatively durable. GPR has been deployed under harsh conditions including landmine detection and hazardous waste site investigation. As a result, the GPR equipment would be exceptionally durable in the typical conditions of the interior of wastewater collection systems. IRT can be performed using infrared cameras that are protected from the environment. These cameras have been adapted to many hazardous applications, including fire fighting.

## 7.3 Complexity of Training and Data Analysis

Complexity is a measure of the level of training and certification required to execute an inspection program and evaluate the data. It includes both the labor hours spent in training and the costs of the training and certification programs. Complexity varies substantially among the different technologies; greater complexity may limit the ability to use existing in-house resources to implement an inspection program, which would have a direct impact on cost. Complexity also is factored into the standardization of a technology. For example, technologies for which there is an established American Society for Testing and Materials (ASTM) and/or NASSCO standard have platforms that may be transferable to utilities. Complexity may also affect the ability to generate useable/repeatable data.

The training to operate camera-based technologies is relatively simple, but training for consistent classification of defects is more involved. The experience and training of the staff reviewing the inspection footage is important for providing consistent and reliable inspection results and a quality condition assessment program. Defect coding systems such as those established by the Water Research Centre (WRc; http://www.wrcplc.co.uk), NASSCO (PACP; NASSCO, 2001), and the System Condition & Risk Enhanced Assessment Model (SCREAM™) provide options for training staff and standardizing condition assessment data. Some utilities have chosen to develop their own in-house coding system. Although these standardized coding systems require training, they would pay off in greater long-term efficiency (see case studies in USEPA, 2010).

Electro-scanning provides immediate results, and the manufacturer of FELL-41 (and FELL-21) claims that personnel can be trained to operate the unit in a few hours. The output is simply a graph of changes in current with distance and does not require elaborate processing. Sonar and laser scanning, however, require post-processing of the data. Although they do not have standardized coding systems, some skill would be needed to interpret the images produced.

Multi-sensor instruments such as the Cleanflow system, which incorporate high-definition imaging, sonar, and laser, can entail complex data analysis. Cleanflow produces detailed reports, including 3-D color-coded images. However, it takes weeks for the data to be processed by the vendor and the reports to be produced. Data analysis requires a specific skill set, which is not transferable to utilities. A system that uses standardized software, on the other hand, is more easily adopted by utilities with some training. In selecting a condition assessment technology, the utility will need to balance the quality and features of the data acquired with the training and data processing needs involved.

For GWUT, the inspection requires basic operation skills and a single technician; however, data processing requires advanced analytical skills (Marlow et al., 2007). For IRT, the greatest limitation to performing viable infrared surveys of underground fluid lines is the experience and proficiency of the camera operator (Weigle, 2005).

## 7.4 Costs of Condition Assessment

Cost is an important factor in the selection of inspection methods. Total cost for the project will depend upon cleaning required prior to the inspection, costs for field deployment, costs for data analysis, and site characteristics and access issues. Although the costs associated with location, setup, and environmental conditions are largely independent of condition assessment technologies, the amount of equipment and difficulties in moving or setting up certain equipment will affect the final project costs. The following sections cover general factors likely to influence cost for all inspection technologies, as well as available cost information for specific commercially available technologies. Cost information for emerging technologies is not available, as confirmed in communications with researchers.

## 7.5 Factors Influencing Cost for Condition Assessment

Apart from the costs associated with a specific technology, certain characteristics of a wastewater collection system or specific pipe segment influence inspection costs. Location, project setup, and environmental conditions all affect deployment costs. For example, difficult site access, high flows, large amounts of debris, and unusually large or small pipes can lead to higher costs. Equipment type and inspection requirements are also critical factors influencing the cost of a particular project. Some of the most common "general" cost factors and estimated costs are summarized in Table 7-1 (Location Cost Factors), Table 7-2 (Project Setup Cost Factors), and Table 7-3 (Environmental Cost Factors). Many of the "general" cost elements are calculated on a "per-project," "per-setup," or "hourly" basis depending on the nature of the cost factor. Identification and management of cost factors applicable to a particular project can help a utility anticipate and/or control project cost.

**Table 7-1. Site Location Cost Factors**

| Factor | Reason | Cost | Cost Basis | Recommendations To Minimize Additional Cost |
|---|---|---|---|---|
| Distance between project site and location of operator equipment. | For non-local sites, operator will incur and pass on equipment/ personnel transportation and per diem (e.g. lodging) costs. | $1 to $10 per mile from equipment location to project site (round-trip). | One time per project. | Work with qualified operators near the project site.<br>Plan projects with the same operator to minimize multiple trips. |
| Distance between a project's deployment locations. | Multiple operator trips (with or without equipment) across the project area will add set-up and transportation costs. | $100 to $500 per hour of intra-project transportation. | Project duration (hourly). | Send detailed plans to operator ahead of time so that deployment locations can be optimized. Minimize area required to complete project by identifying a particular set of locations and easy access points. |

**Table 7-2. Site Setup Cost Factors**

| Factor | Reason | Cost | Cost Basis | Recommendations To Minimize Additional Cost |
|---|---|---|---|---|
| Traffic control or other security measures. | Operator will incur and pass on traffic control and security costs. | $50 to $500 per hour on-site for each site requiring traffic control and security measures. | Project duration (hourly). | Provide traffic control or security information to operator.<br>Arrange to provide in-house traffic control/security and support. |
| Number of deployment locations. | The number of deployment setup locations affects total project cost. | Up to $5,000 per setup location, depending on the technology's set up requirements. | Project duration (per setup). | Send detailed plans and photos to operator or arrange site visit ahead of time to optimize deployment locations.<br>Minimize area required to complete project by focusing on a particular set of locations and easy access points. |

| Factor | Reason | Cost | Cost Basis | Recommendations To Minimize Additional Cost |
|---|---|---|---|---|
| Special procedures required to set up on site. | Operator will incur costs associated with special setup. This includes modifying or creating non-standard access points, river crossings, flow diversion, etc. Examples of non-standard access include a pipe without a manhole access at the required location and elevated manholes. | $500 to $25,000 per setup, depending on work required. | Project duration (per setup). | Send detailed plans and photos to operator or arrange site visit ahead of time to identify any additional setup requirements.<br>Complete site setups prior to deployment. |
| Special equipment or personnel. | Special equipment or personnel required for a project could increase its cost. | $1,000 to $100,000 per project. | One time per project or project duration (per setup), depending on requirements. | Inform operator ahead of time and provide in-house resources when available. |
| Awareness of locations and accessibility of manholes or access points. | Contingency costs may be added if a utility is known to have problems with mapping accuracy or buried manholes. | Cost estimate not currently available. | One time per project. | Resolve any uncertainties in the locations of manholes and access points and provide available information to contractor. |

**Table 7-3. Environmental Cost Factors**

| Factor | Reason | Cost | Cost Basis | Recommendations To Minimize Additional Cost |
|---|---|---|---|---|
| Impacts of weather on deployment procedures. | Operator may arrive at project site but be unable to deploy during unfavorable weather conditions, leading to additional site setup charges during re-deployment.<br>Operator may need to deploy equipment at night or may require flow control prior to deployment, incurring additional charges. | $500 to $5,000 per setup. | Project duration (per setup). | Plan projects during periods with historically favorable weather and flow conditions. For example, if low flow conditions are needed for equipment deployment, plan project for a dry weather period or nighttime when flows are typically lower. |

| Factor | Reason | Cost | Cost Basis | Recommendations To Minimize Additional Cost |
|---|---|---|---|---|
| Unusual site conditions that pose health and safety concerns. | Operator may require special equipment and procedures to work safely under atypical conditions. | $500 to $5,000 per setup or $5,000 to $20,000 per project. | Project duration (per setup or hourly). | Ensure operator is aware of these issues ahead of time. Provide in-house equipment, support, or training whenever feasible. |
| Abnormally high flows. | Use of equipment may not be possible, forcing flow control, equipment changes, or other costs. | Up to $5,000 per setup. | Project duration (per setup). | Make operator aware of flows ahead of time. Provide detailed metering or photo information whenever available.<br>Control flow and pump stations prior to deployment to minimize operator on-site time. |
| High volumes of sediment, known structural failures, or other issues that would slow progress through the pipe. | Individual deployments may take abnormally long periods of time, causing operator to incur increased costs (i.e., more labor and equipment time). | $50 to $500 per hour of additional deployment time. | Project duration (per hour). | Make operator aware of issues ahead of time. |
| Sewer cleaning disposal costs. | Material accumulated during cleaning will require disposal. | No cost estimate available. | One time per project (at the end of the project). | Make operator aware of issues ahead of time. |

***Project Economy***

Inspection costs will also vary depending on the type of work completed as part of the inspection and how the work is accomplished (contractors vs. utility-owned equipment and in-house staff). The projects conducted by contractors may cost more (in the near term) than the projects conducted by in-house staff for utilities that have human resources. In other cases, providing steady work to a contractor could reduce the project cost. The Denver suburb of Westminster, CO, for example, has achieved extremely low CCTV inspection costs by providing a private contractor with steady work (system-wide inspections on a five-year cycle). The city has also used the findings from CCTV inspections to improve scheduling and prioritization of maintenance work (Sterling, Raymond. Email with author, 2009).

Projects that have similar unit costs may not yield the same amount of information. A comparison of zoom camera inspections in Hillsborough County, FL, and Auburn, MA shows that Hillsborough County had a more cost-effective project (Pryputniewicz, Susan. Email with author, 2009). Auburn completed a zoom camera inspection of sewer pipes and did a quick manhole inspection, while Hillsborough County collected global positioning system coordinates of structures, completed a zoom camera inspection of manholes and sewers, cleaned the sewers, and then conducted a CCTV inspection for the similar inspection costs reported ($1 to $2 per ft). When comparing inspection costs for two different studies or systems, it is important to understand the work completed and the total costs for each case.

## 7.6 CCTV Costs

Although CCTV has been a mainstay of sewer condition assessment for decades, publicly available CCTV cost data are limited. Two utility surveys containing CCTV cost data were identified and reviewed. The following section summarizes findings from the surveys conducted by RedZone (2009) and the Trenchless Technology Center at Louisiana Tech (Simicevic and Sterling, 2003) independent of this project.

***Survey by RedZone***

RedZone compiled and analyzed CCTV inspection costs for small-diameter pipes (8- to 12-in.) at 21 utilities as part of a market research endeavor (RedZone, 2009). Because of the proprietary nature of the market research project, only generalizations can be drawn from the study. An obvious observation is the considerable variability in CCTV inspection costs, from \$0.28 to more than \$1.00 per ft.

Table 7-4 summarizes the average inspection costs and project size (i.e., length of pipe inspected) for small, medium, and large utilities surveyed. The average costs are generally higher for smaller utilities. The costs among the small utilities are skewed upward by one unusually high value (\$5.01 per ft). When this outlier is removed, the average cost for the small utilities is \$0.84 ± \$0.37 per ft, which still exceeds the average cost for medium and large utilities.

RedZone identifies other factors that affect inspection costs, including prevailing regional wages and the use of outside contractors rather than utility-owned equipment and in-house staff. For example, the northeastern U.S. has higher labor rates and thus higher CCTV inspection costs. Average costs are higher for utilities that outsource inspections (\$1.19 ± \$1.25 per ft) than for those that perform inspections in-house (\$0.64 ± \$0.35 per ft). Most of the small utilities in the RedZone study outsourced inspections, which may partially explain the higher costs.

**Table 7-4. CCTV Inspection Costs from Market Research Study**

| Utility Size (n=sample size) | Average Cost per ft ± Standard Deviation | Range of Cost per ft | Average Length of Sewer Pipe Inspected ± Standard Deviation (ft) |
|---|---|---|---|
| Small (n=8) | \$0.84 ± \$0.37 | \$0.35 to \$1.47 | 513,755 ± 160,293 |
| Medium (n=8) | \$0.62 ± \$0.29 | \$0.28 to \$1.21 | 1,370,572 ± 377,091 |
| Large (n=4) | \$0.76 ± \$0.44 | \$0.33 to \$1.17 | 5,586,947 ± 3,657,579 |

Data from RedZone (2009).

***Survey by Trenchless Technology Center (TTC) at Louisiana Tech***

Simicevic and Sterling (2003) compiled 310 bid tabs or bidding summaries from 67 municipalities in 39 states that sought to contract for sewer pipe rehabilitation by various trenchless technology methods. More than 100 of the bid documents – representing 19 municipalities in 17 states – received by TTC included costs for CCTV inspection of main lines.

As shown in Figure 7-1, average CCTV inspection costs on the basis of geography exhibit a fairly wide range. Average costs in two localities (Long Island City, NY, and San Antonio, TX) were particularly high; however, no explanations were provided in the report. Plotting the linear footage of pipes inspected and the average inspection cost yields a generally inverse relationship between project size and average per-unit cost. In general, bid prices for larger projects (i.e., more footage) are associated with low per-unit inspection costs (Figure 7-2). Furthermore, although the range of costs was large, over 50% of the bid prices were at $2.00 per ft or less, as shown in the histogram in Figure 7-3. The costs reported by Simicevic and Sterling (2003) are generally higher than those compiled and reported later by RedZone (2009). This may be partly due to the sizes of the projects; the linear footages in the RedZone data were much greater than the data from the Simicevic and Sterling report because the latter were associated with rehabilitation projects and were not full system inspections.

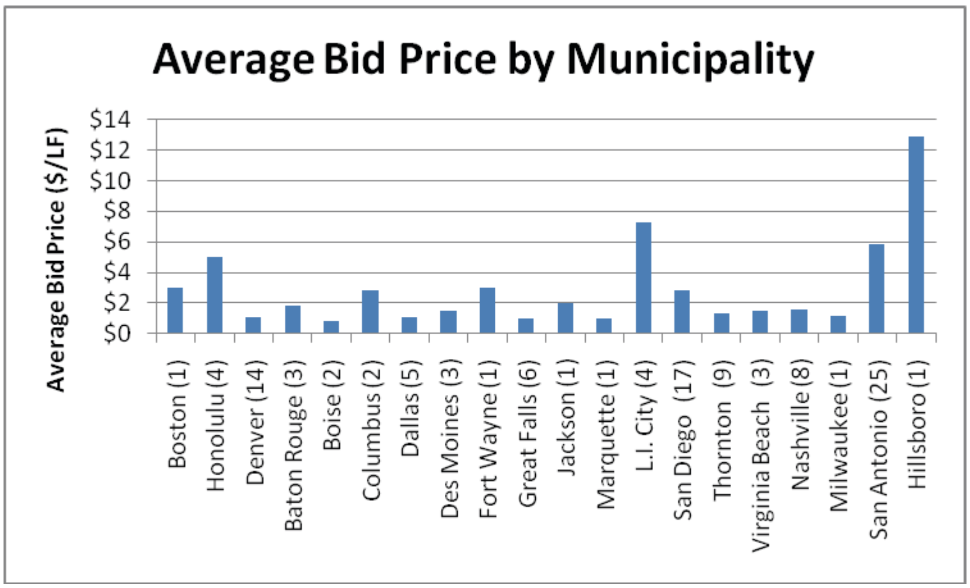


**Figure 7-1. Average bid price ($ per linear ft) for CCTV inspection of pipelines in various U.S. municipalities (number of bids).**
**Data from Simicevic and Sterling (2003).**

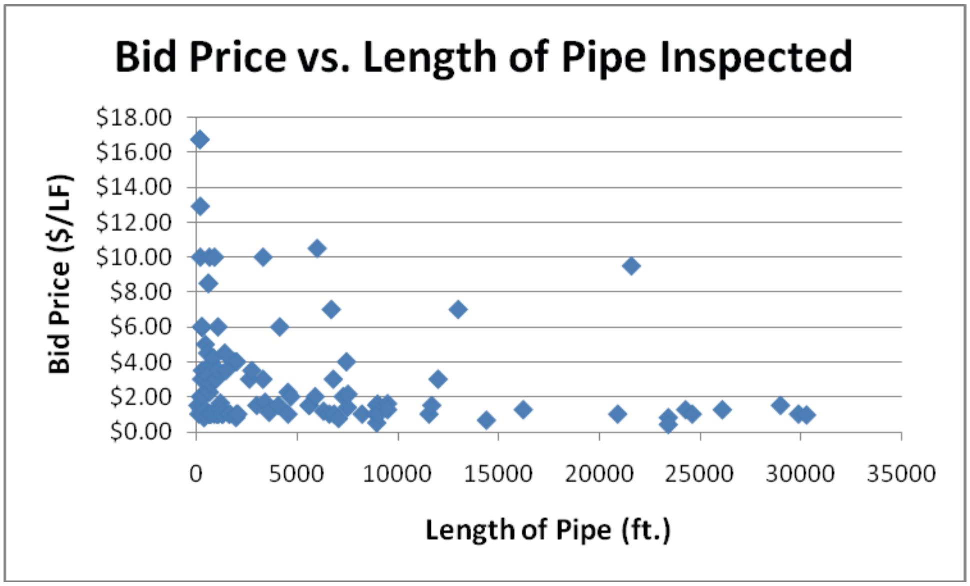


**Figure 7-2. CCTV inspection bid prices for projects of various lengths.**
**Data from Simicevic and Sterling (2003).**

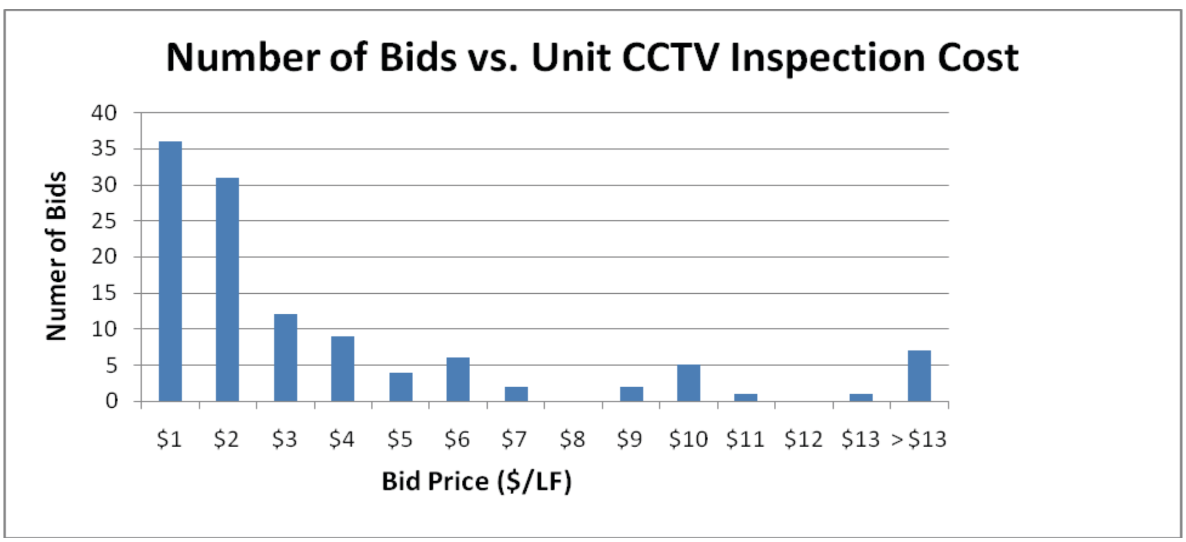


**Figure 7-3. Distribution of bid prices for CCTV inspection.**
**Data from Simicevic and Sterling (2003).**

## 7.7 Cost of Other Technologies

***Cost of Digital Scanning***

Available cost data for digital scanning are limited. In addition to evaluating the performance of the early version of the SSET system, CERF (2001) performed a comparative cost analysis of the inspection of 22,000 mi. of pipe in 13 municipalities. The cost of digital scanning with the SSET system was conservatively estimated at $3.00 per ft. This estimate is about 50% higher than the costs for CCTV inspections with sewer line cleaning and 75% higher than CCTV inspections without sewer line cleaning. The report noted that SSET might be economically attractive to utilities that have very high CCTV costs. In their comparison of CCTV and digital scanning in Wuppertal, Germany, Stein and Brauer (2004) reported that the ARGUS 4 CCTV system cost approximately $0.38 per ft, while the PANORAMO system (including data post-processing) cost approximately $0.24 per ft.

### *Zoom Camera Costs*

A number of case studies point out the benefits of using zoom cameras to achieve savings for utilities. According to Rinner and Pryputniewicz (undated) and Joseph and DiTullio (2003), zoom camera surveys are one-half to one-third of the cost of cleaning sewer lines and conducting CCTV inspections. The town of Auburn, Massachusetts, saved about $50,000 by inspecting 60,000 ft of sewer pipes with zoom cameras instead of performing CCTV inspections (Rinner and Pryputniewicz, undated). Lee (2005) reported that a mid-Atlantic utility spent $90,000 for zoom camera inspection of 41,000 ft of interceptors. In-line CCTV inspection for the same system, including cleaning and flow control, would cost about $750,000.

Zoom camera inspection has the disadvantage in not detecting problems with lateral connections (other than those that protrude into the main line). This shortcoming may render the technology inappropriate for some inspection purposes (e.g., inspection of laterals and lateral connections). However, if the primary objective is to inspect interceptors and mains, use of zoom camera for inspection is a cost-effective alternative.

### *Cost of Electro-Scanning*

Few data are available on the cost of electro-scanning. Moy et al. (2006) indicated that the estimated cost of electro-scanning is $15,000 per event, compared to an anticipated $100,000 per event to clean and inspect the pipe twice (during design and then prior to rehabilitation) using CCTV. Similarly, Harris and Dobson (2006) found that electro-scanning was 3 to 4 times less expensive than CCTV and JPT. One factor contributing to the lower electro-scanning costs is the low cost to train field crew as they are not required to analyze the captured data. Data analysis is typically performed in the office following the field operation.

# 8. Conclusions and Future Research Needs

For decades, utilities have used conventional CCTV to identify defects and obtain a record of their wastewater collection systems' conditions. A number of newer technologies, however, are now either commercially available or being researched for adaptation to sewer condition assessment. Some of these newer technologies are camera-based (zoom camera, digital scanning) like CCTV, but others are based on different principles and provide information complementary to that obtained by CCTV. This expanded list of sewer condition assessment technologies offers utilities new options for designing condition assessment programs that meet their objectives (e.g., rapid screening, in-depth assessment, evaluation of pipe wall integrity).

In gathering the information for this report, research needs have become apparent:

> ***There is an ongoing need for evaluations of technology performance.*** Because most available information on sewer condition assessment comes from technology vendors and operators, the successes of the methods tend to be highlighted. A comprehensive third-party survey is needed to compile and analyze utility experiences with sewer inspection technologies, including their performance and cost. Systematic testing of promising technologies is also needed.
>
> ***Comprehensive cost data are not available for all technologies, and where available, they can vary widely.*** For example, according to the studies cited in this report, CCTV costs vary greatly depending on such factors as local labor rates and size of project. Cost/benefit analyses performed in support of a planned sewer inspection and condition assessment program will be affected by local rates for CCTV inspections and for any newer or alternative technologies under consideration. As new technologies mature, the costs tend to decrease. Hence, cost data presented for innovative technologies represent a snapshot that may be useful for comparative purposes but may not be indicative of future costs. The information presented in this report also outlines some of the site- and project-specific factors influencing the inspection costs. Because of the variety of factors involved, "generic" costs cannot be provided for each technology. However, an understanding of the factors that influence pricing may help utilities anticipate the relative cost of a condition assessment program.

Sewer condition assessment technologies can be loosely divided into the "visual" (i.e., camera-based) technologies (CCTV, zoom camera and digital scanning) and the "quantitative" technologies (electro-scanning, laser, sonar, acoustic, GPR, and other innovative methods). Zoom cameras offer greater production rates than CCTV and can serve as a screening and prioritization tool. Uncertainties surrounding zoom cameras' performance involve effective sight distance and the detection of defects away from the inspection manhole. Digital scanning provides detailed and high-quality images and allows post-processing of data; but from the limited available cost data, digital scanning is more expensive than zoom cameras and CCTV. Given the long history and value associated with visual inspection, it is likely that camera-based methods will remain in the forefront of inspection and assessment programs. Additional performance and cost data will help utilities decide which newer visual method is better for their needs.

Quantitative technologies provide very different types of information than camera-based technologies, allowing better elucidation of pipe geometry, sediment accumulation, thinning of pipes due to corrosion, joint defects, and I/I. It is challenging to compare condition assessment information provided by electro-scanning, laser, sonar, or acoustic methods directly with information from camera-based inspections. Comparisons that have been made (e.g., electro-scanning compared to CCTV) underscore the fact that different technologies may detect different numbers and types of defects in a pipe. The available performance information indicates that visual and quantitative technologies can be complementary and may be best used in concert to meet utilities' needs.

Municipalities will benefit from continued research on the performance of the various quantitative technologies as compared to CCTV inspection. A field demonstration program planned as part of this project is one such research effort. The purpose of the field demonstration is to collect cost and performance data that will help wastewater utilities select the most appropriate condition assessment technologies for their wastewater collection systems. The field demonstration will be conducted in Kansas City, Mo. in the summer of 2010. Four condition-assessment technologies are selected for testing in addition to a baseline CCTV inspection: digital scanning, zoom camera, electro-scanning, and 2-D laser. The field demonstration methods and findings will be presented in a separate report.

A number of technologies currently used in other fields have been identified as having a strong potential for transfer to sewer condition assessment. These "crossover" technologies (e.g., gamma-gamma logging, infrared thermography, impact echo – spectral analysis of surface waves, and micro-deflection) will be appropriate primarily for inspecting pipe wall integrity and pipe bedding. One technology - ground-penetrating radar - is already commercially available and allows evaluation of the soil envelope surrounding the pipe. When these innovative technologies become commercially available and cost-effective for sewer condition assessment, utilities will have many additional options to assess the conditions of their wastewater collection systems.

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# Appendix A: Technology Fact Sheets

## Fact Sheet on CCTV Camera Inspection Technology

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|---|---|
| **Description** | CCTV technology uses a video camera with lighting to provide a visual recording of the interior pipeline condition. Cameras are deployed using mobile robots called crawlers or tractors and can also be mounted to float rigs for inspecting larger diameter pipe. The ability to pan, tilt, and zoom allows the operator to gain a full circumferential view of the pipe that is partially filled with water. |
| **Innovative Features** | • Digital CCTV cameras produce high-resolution images.<br>• LED lighting combined with a digital CCTV camera provides image quality adequate for assessing wall condition in large-diameter pipe.<br>• Digital CCTV vehicles equipped with fiber optic cabling can inspect 10,000 ft of sewer at a time compared to 2,000 ft for analog CCTV cameras.<br>• New cameras are smaller, more robust and less expensive. |
| **Vendors** | There are numerous vendors of CCTV cameras. |
| **Research Questions** | • What is the most effective way to use historical CCTV records?<br>• How can CCTV data be integrated with other historical system data, inspection records etc. to form a baseline of system condition? |
| **Current Applications** | • Primary method for comprehensive inspection of gravity sewers and service laterals.<br>• Documents location of leaks, service laterals and sediment/debris levels.<br>• Used in combination with laser and sonar to provide full circumferential view of interior pipe conditions.<br>• Standard CCTV inspection is used as a benchmark or baseline for comparing inspection data from other condition assessment technologies. |
| **Limitations** | • CCTV can only provide a visual representation of the interior pipe surfaces above the waterline; it does not provide any quantitative data on pipe wall structure, degree of corrosion, or sediment depth.<br>• Analog CCTV cameras do not provide a high-resolution image.<br>• It does not provide quantitative data to determine variations in sewer dimensions, subtle deformations, or debris level, and does not provide a view of the soil envelope supporting the pipe.<br>• The quality of defect identification and pipe condition assessment is highly dependent on operator interpretation and skill level, on picture quality, and on flow level.<br>• CCTV inspection is hindered by varying pipe diameters, materials (including brick, concrete, ductile iron, and clay), odd shapes, sumps, and angle entries.<br>• There are needs for higher resolution cameras with better lighting; and improvements in crawler technology to better negotiate obstructions, grease, and off-set joints. |
| **Vendor Claims** | • Inspection distance, line resolution, inspection reporting software, portability.<br>• Waterproof housing designed for sewer environment.<br>• Rotating head with 360° viewing angle. |
| **Pipe Type** | Gravity sewers. Push cameras are used in service laterals. |
| **Pipe Material** | No restrictions; Applicable for any pipe material. |
| **Pipe Diameter** | >6 in. (push cameras can inspect 1 in. – 12 in.) |
| **Flow Regime** | Lower flow conditions will provide more pipe surface area for inspection. |
| **Preparation** | Sewer cleaning may be required prior to inspection. |

## Fact Sheet on Digital Scanning Technology

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|---|---|
| **Description** | Digital scanning uses one or two high-resolution digital cameras equipped with wide-angle lenses to generate two types of images: an "unfolded" view of the sides of the pipe, and a circular view down the pipe. Information from the two cameras can be combined to form 360-degree spherical images. Digital scanners are transported using self-propelled crawlers. Data are typically transmitted to a surface viewing station where they can be viewed in real-time or recorded for later evaluation. |
| **Innovative Features** | • The unfolded view enhances computer-aided measurement of defects and objects.<br>• Digital measurements of defects allow direct comparison from one inspection to the next.<br>• Post-processing software enables the analyst to identify defects and define their magnitude.<br>• Increased quality assurance and quality control of data imagery. |
| **Limitations** | • More costly and lower production rate compared to traditional CCTV.<br>• Only identifies defects above water line. |
| **Potential Vendors** | See vendor table below. |
| **Research Questions** | • Is digital scanning more cost-effective in terms of total production rate than CCTV?<br>• How does the quality of data compare to that produced by "conventional CCTV inspection" (defined as a CCTV inspection in compliance with NASSCO standards)?<br>• Does post-processing of data enhance the quality of condition assessment information?<br>• Are vendor claims regarding inspection rate and camera resolution valid? |
| **Typical Applications** | • Measure pipe grade, ovality and deflection.<br>• Detect and measure cracks, leaks, root intrusion, overall condition of pipe. |
| **Status** | Commercially available; technology enhancements under development. |
| **Vendor Claims** | **1.** Inspection Rate: According to vendors, the inspection rate for both Panoramo and DigiSewer is 70 fpm.<br>**2.** Applicable Pipe Size: The Panoramo system literature claims adequate camera resolution for inspection of up to 80-in. diameter, while DigiSewer literature states an upper diameter of 60-in.<br>**3.** Image Quality: In general, vendors report that the digital scan image quality is superior to conventional CCTV image data. |
| **Pipe Type** | Gravity sewers. Limited applicability for force mains and service laterals. |
| **Pipe Material** | No restrictions; Applicable for any pipe material. |
| **Pipe Diameter** | 6-in. to 72-in. depending on equipment model and pipe conditions. |
| **Flow Regime** | Dry pipe or during periods of low flow. |
| **Preparation** | Pipe must be cleaned prior to inspection. |

Potential Vendors:

| Product(s) | Vendor | URL |
|---|---|---|
| DigiSewer | Envirosight, LLC | http://www.envirosight.com |
| Panoramo | Rapidview-IBAK USA | http://www.rapidview.com |
| Cleanflow/Fly Eye | CUES Inc. | http://www.cuesinc.com |

## Fact Sheet on Laser Scan Technology

<table>
<tr><td>Description</td><td>Laser scanning generates a cross-sectional profile of a pipe's interior wall. The common 2-D technique uses a laser to create a line of light around the pipe wall that is typically observed via an onboard camera. The laser light highlights the shape of the sewer, allowing for the detection of changes to the pipe's shape, which may be caused by deformation, corrosion, or siltation. The 3-D technique employs multiple points measured individually to create a 3-D model of the pipe wall. A 2-D cross-section can be extracted from the 3-D model.</td></tr>
<tr><td>Innovative Features</td><td>Generates precise models of pipe surfaces that reveal minor surface abnormalities. Provides geometric information about the pipe interior that is different from and complementary to CCTV data.</td></tr>
<tr><td>Limitations</td><td>Laser inspection can only be used to inspect dry portions of a pipe. Assessment of the entire internal surface of a pipeline requires the pipe to be taken out of service.</td></tr>
<tr><td>Vendors</td><td><table>
<tr><th>Product</th><th>Vendor</th><th></th></tr>
<tr><td>Active 3-D Laser Scanning</td><td>Redzone Robotics</td><td>http://www.redzone.com</td></tr>
<tr><td>Coolvision</td><td>Sima Environmental</td><td>http://www.simaenvironmental.com</td></tr>
<tr><td>Laser Profiler</td><td>CUES IMX</td><td>http://www.cuesinc.com</td></tr>
<tr><td>Laser Profiling Tool</td><td>Envirosight</td><td>http://www.envirosight.com</td></tr>
<tr><td>Cleanflow</td><td>Hydromax</td><td>http://www.hydromaxusa.com</td></tr>
<tr><td>Laser Profiler</td><td>R&R Visual, Inc.</td><td>http://www.expipeinspection.com</td></tr>
</table></td></tr>
<tr><td>Research Questions</td><td>• In terms of technical performance and cost, what are the differences between 3-D and 2-D laser profiling?<br>• Does the added cost of the laser profile produce definable, tangible benefits in terms of enhanced condition assessment information?</td></tr>
<tr><td>Typical Applications</td><td>• Measure pipe grade, ovality and deflection.<br>• Detect and measure cracks, corrosion, sediment depth, water depth, and service locations.<br>• Verify the installation of new pipe or pipe liner and identify any necessary remedial actions.</td></tr>
<tr><td>Vendor Claims</td><td>• Can create accurate 2-D or 3D models of pipes.<br>• Can measure characteristics such as pipe ovality, capacity, grade and deflection, sediment depth and volume, water depth, and cracks.</td></tr>
<tr><td>Pipe Type</td><td>Gravity sewers, force mains.</td></tr>
<tr><td>Pipe Material</td><td>No restrictions. Applicable for any pipe material.</td></tr>
<tr><td>Pipe Diameter</td><td>24-in. to 60-in. (typical application); 4-in. to 160-in. (full range).</td></tr>
<tr><td>Flow Regime</td><td>Dry pipe or during periods of low flow.</td></tr>
<tr><td>Preparation</td><td>Pipe must be cleaned prior to inspection. Minimum 24-in. diameter for deployment in manhole. Previous CCTV inspection records should be reviewed to understand pipe condition.</td></tr>
</table>

## Fact Sheet on Sonar Technology

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|---|---|
| **Description** | Sonar/ultrasonic inspections of pipelines are accomplished by passing a sonar head through the pipe being inspected. Depending on the size and flow conditions of a pipe, the sonar head is deployed into the pipeline on a raft, skid, or robotic tractor. As the sonar head moves through the pipeline, it sends out high-frequency ultrasonic signals, which are reflected by the pipe walls and then received by the sonar head. The reflection of the signals changes when there is a change in the material reflecting the signal, allowing for the detection of defects. The time between signal transmission and receipt can be used to determine the distance between the sonar head and the pipe wall, as well as to determine the internal profile of the pipe. |
| **Innovative Features** | Sonar is capable of inspecting pipes below the water surface. The technology does not require bypass pumping or pipe cleaning. |
| **Limitations** | Sonar is currently not applicable to pipe surfaces above the water line. Current research is evaluating new sonar devices to address this issue. |
| **Potential Vendors** | There are numerous manufacturers of sonar equipment. |
| **Research Questions** | • Can sonar technology map defects (i.e. pipe wall loss, ovality) in the invert as effectively as it can quantify sediment accumulation?<br>• Does the usage of sonar in combination with laser or digital scanning provide an assessment of the full pipe circumference?<br>• Can data interpolation of sonar be standardized? |
| **Vendor Claims** | • Results in a detailed profile of the pipe wall below the water surface, in both full and partially full pipes.<br>• Detects defects greater in than 1/8-in. in size, including pits, cracks, corrosion, and debris accumulation. |
| **Pipe Type** | Gravity sewers, force mains. |
| **Pipe Material** | No restrictions. Applicable for any pipe material. |
| **Pipe Diameter** | $\geq$2-in. |
| **Flow Regime** | A minimum water depth is required to submerge the head of the sonar unit. See manufacturer's guidelines. |
| **Preparation** | Pipe cleaning is not required prior to inspection. Previous CCTV inspection records should be reviewed to understand pipe condition. |

## Fact Sheet on Zoom Camera Technology

<table>
<tr><td>Description</td><td>Zoom camera inspection involves the generation of still imagery or recorded video imagery of the pipe interior using a stationary camera mount. The camera equipment does not pass through the entire length of the pipe segment(s); instead, the camera is truck- or pole-mounted and lowered into a manhole to perform the inspection.</td></tr>
<tr><td>Innovative Features</td><td>Newer zoom cameras can pan 360 degrees and zoom farther down pipes. Some cameras have inter-changeable camera heads with different zoom capabilities.</td></tr>
<tr><td>Limitations</td><td>The effectiveness of zoom cameras is limited by sight distance, the distance from which a defect remains visible. Limitations in sight distance make it difficult to complete inspections from manhole to manhole, and may prevent identification of significant defects.</td></tr>
<tr><td>Current Applications</td><td><ul><li>Detect and measure cracks, leaks, root intrusion, overall surface condition of pipe/manholes.</li><li>Typically used as a screening tool to identify and prioritize gravity sewers for more detailed CCTV inspection, cleaning and/or maintenance.</li></ul></td></tr>
<tr><td>Status</td><td>Commercially available.</td></tr>
<tr><td>Vendors</td><td><table>
<tr><th>Product</th><th>Vendor</th><th></th></tr>
<tr><td>Aqua Zoom</td><td>AquaData, Inc.</td><td>http://www.aquadata.com</td></tr>
<tr><td>Aries HC3000 Zoom Pole Camera</td><td>Aries Industries</td><td>http://www.ariesind.com</td></tr>
<tr><td>QuickView</td><td>Envirosight, LLC</td><td>http://www.envirosight.com</td></tr>
<tr><td>Everest Ca-Zoom PTZ</td><td>GE Sensing & Inspection Technologies</td><td>http://www.geinspection technologies.com</td></tr>
<tr><td>CUES IMX Truck-Mounted Zoom Camera</td><td>CUES IMX</td><td>http://www.cuesinc.com</td></tr>
<tr><td>PortaZoom</td><td>CTZoom Technologies</td><td>http://www.ctzoom.com</td></tr>
</table></td></tr>
<tr><td>Research Questions</td><td><ul><li>How much does the limited sight distance of this technology inhibit its use in condition assessment?</li><li>How does the quality of data compare to that produced by conventional CCTV inspection?</li><li>Is zoom camera a cost-effective tool for prioritizing inspections?</li><li>Can the term “sight distance” be standardized?</li><li>How do the inspection rate and inspection distance compare to vendor claims?</li></ul></td></tr>
<tr><td>Vendor Claims</td><td><ul><li>Higher production rate than conventional CCTV inspection.</li><li>Lower inspection cost as compared to CCTV.</li><li>Sight distance for specific pipe diameters (Note: these claims should be verified with field data).</li></ul></td></tr>
<tr><td>Pipe Type</td><td>Gravity sewers.</td></tr>
<tr><td>Pipe Material</td><td>No restrictions. Applicable for any pipe material.</td></tr>
<tr><td>Pipe Diameter</td><td>>6-in.</td></tr>
<tr><td>Flow Regime</td><td>Dry pipe or during periods of low flow.</td></tr>
<tr><td>Preparation</td><td>None required.</td></tr>
</table>

## Fact Sheet on Focused Electrode Leak Location (FELL) Technology

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|---|---|
| **Description** | FELL locates pipeline leaks and identifies their magnitude using the electro-scan method in accordance with ASTM Standard F2550-06. The electro-scan test is carried out by applying an electrical potential between an electrode in the electrically non-conductive pipe and an electrode on the ground surface. A sliding pipe plug prevents the current from traveling along the pipe's interior walls and maintains hydraulic surcharge conditions. The pipe wall has a high electrical resistance, preventing the flow of current to the ground surface unless there is a pipe defect. |
| **Innovative Features** | FELL technology provides a quantitative measure of leak potential without relying on visual observation and interpretation of pipe defects and external conditions that are temporal in nature (e.g., seasonal, wet weather dependent). Pipe defects are coded automatically by the accompanying software. |
| **Limitations** | Drawbacks include the inability to determine the cause of a pipe defect (e.g., roots, misaligned joints, crown corrosion) or the defect's position along the pipe circumference. |
| **Potential Vendors** | **Product** / **Vendor**:<br>FELL-41 — Burgess & Niple — http://www.aquadata.com<br>New (pending specifications from vendor) — Leak Busters Inc. — http://www.ariesind.com<br>QuickView — Envirosight, LLC — http://www.envirosight.com |
| **Research Questions** | • Can leak potential be interpreted qualitatively for use in defect coding?<br>• Can leak potential be correlated to defect magnitude?<br>• Can the electrical current data distinguish among types of defects?<br>• How does information on pipe defects based on FELL inspection compare to information generated from conventional CCTV inspection? |
| **Current Applications** | Inspection of main lines and laterals. |
| **Vendor Claims** | The manufacturer claims that the technology locates defects within inches, detects any leak type, determines size of defects, quantifies leakage rate on active and inactive leaks, produces reliable and repeatable results, uses a production rate of 3,000 to 4,000 ft/day), and provides results independent of ground conditions. |
| **Pipe Type** | Gravity sewers, force mains, and service laterals. |
| **Pipe Material** | Non-conductive, non-ferrous pipe materials including PVC, VCP, RCP, or in ferrous pipe lined with cementitious mortar. |
| **Pipe Diameter** | 3-in. to 60-in. |
| **Flow Regime** | The pipe upstream of the sliding plug should be fully surcharged. A nearby source of water is necessary because the time required to let the pipe fill would otherwise be excessive. |
| **Preparation** | Debris must be removed to allow the sonde (i.e., probe) to traverse the pipe, but complete sewer cleaning and vehicle access are not required. |

## Fact Sheet on Leak Detection Systems

<table>
<tr><td>Description</td><td>Leak detectors are devices used to detect the sound or vibration produced by leaks in pressurized waterlines or in sewers. In-line leak detectors are a more recent advancement in the use of acoustic technology for condition assessment of pipes. They are deployed in a pipeline to continuously monitor leakage.</td></tr>
<tr><td>Innovative Features</td><td><ul><li>Can detect very small leaks.</li></ul></td></tr>
<tr><td>Vendors</td><td><table><tr><th>Product(s)</th><th>Vendor</th><th></th></tr><tr><td>Sahara® Leak Detection System</td><td>Pressure Pipe Inspection Company</td><td>http://www.ppic.com</td></tr><tr><td>Smartball® Leak Detector</td><td>Pure Technologies</td><td>http://www.puretechnologiesltd.com</td></tr></table></td></tr>
<tr><td>Research Questions</td><td><ul><li>How can equipment deployment be improved at low water velocities (<3 fps)?</li><li>How does the technical performance and cost of available technologies compare in third party investigations?</li><li>How accurate is leak measurement at line pressures >20 psi under simulated or field conditions?</li></ul></td></tr>
<tr><td>Typical Applications</td><td><ul><li>Leak detection in pressurized water lines.</li><li>Leak and gas pocket detection in wastewater force mains.</li></ul></td></tr>
<tr><td>Limitations</td><td><ul><li>The Sahara® system requires a minimum water velocity of 3 fps to ensure the device can move through the pipe and requires a system pressure between 10 and 150 psi for the system to recognize leaks.</li><li>The Smartball® sensor requires a minimum water velocity of 1.64 ft/sec.</li></ul></td></tr>
<tr><td>Vendor Claims</td><td><ul><li>The Sahara® system can detect leaks as slow as approximately 0.25 gallons/hour.</li><li>The Sahara® system can locate leaks within 2 feet.</li><li>As the Smartball® passes through the pipe, its progress can be tracked, allowing for leak location to be determined within one meter of accuracy.</li><li>The Smartball® can operate and store data for up to twelve hours before it is retrieved.</li></ul></td></tr>
<tr><td>Pipe Type</td><td>Wastewater force mains.</td></tr>
<tr><td>Pipe Material</td><td>No restrictions; applicable for any pipe material.</td></tr>
<tr><td>Pipe Diameter</td><td>≥4-in. (Sahara®); ≥10-in. (Smartball®).</td></tr>
<tr><td>Flow Regime</td><td>Requires minimum flow to be carried through the pipe.</td></tr>
<tr><td>Preparation</td><td>Sewer cleaning may be required prior to inspection.</td></tr>
</table>

## Fact Sheet on Acoustic Monitoring Systems

<table>
<tr><td>Description</td><td>Acoustic monitoring systems are installed along pre-stressed concrete cylinder pipe (PCCP) to provide continuous monitoring of the general condition of the pipe. The systems work by detecting the acoustic signal produced by breaking or broken pre-stressed wire within pipes. General distress in the pipeline is characterized by the frequency and number of wire breaks, or wire-related events, over a period of time. While the systems do not identify individual defects, they are useful as screening techniques to determine if further condition assessment should be performed.</td></tr>
<tr><td>Innovative Features</td><td><ul><li>Some systems work while pipelines are fully operational.</li><li>All systems provide advanced warning of pipe failure.</li><li>The SoundPrint® AFO system uses acoustic fiber-optic cable for detecting acoustic signals. The sensor does not contain any electronics, therefore there is little to no background noise created by the device.</li></ul></td></tr>
<tr><td>Limitations</td><td><ul><li>Only detects general distress in the pipeline, not individual defects.</li><li>SoundPrint® AFO system can only be installed when the pipeline is taken out of service and dewatered.</li></ul></td></tr>
<tr><td>Vendors</td><td><table><tr><th>Product(s)</th><th>Vendor</th><th>URL</th></tr><tr><td>Soundprint® Acoustic Monitoring System</td><td>Pure Technologies</td><td>http://www.puretechnologiesltd.com</td></tr><tr><td>Acoustic Emission Testing (AET) System</td><td>Pressure Pipe Inspection Company</td><td>http://www.ppic.com</td></tr></table></td></tr>
<tr><td>Research Questions</td><td><ul><li>How does technical performance and cost of available technologies compare in third party investigations?</li></ul></td></tr>
<tr><td>Typical Applications</td><td><ul><li>PCCP sewage force mains.</li></ul></td></tr>
<tr><td>Status</td><td>Commercially available.</td></tr>
<tr><td>Vendor Claims</td><td>The SoundPrint® acoustic fiber optic sensors can monitor up to 15 miles of pipeline from one insertion point.</td></tr>
<tr><td>Pipe Type</td><td>Wastewater force mains.</td></tr>
<tr><td>Pipe Material</td><td>PCCP.</td></tr>
<tr><td>Pipe Diameter</td><td>≥18-in.</td></tr>
<tr><td>Flow Regime</td><td>No limits.</td></tr>
<tr><td>Preparation</td><td>None.</td></tr>
</table>

**Fact Sheet on Ground Penetrating Radar (GPR)**

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| **Description** | GPR operates on the same principle as radar. A transmitting antenna emits high-frequency radio waves into the ground. The waves travel through the ground until they reach a material that has a different conductivity and dielectric constant than the earth. The signal is reflected and recorded by a separate receiving antenna. The return time can be analyzed to determine the position and depth of features below the ground surface. Since GPR can detect underground voids, it is potentially useful for examining pipe bedding; and since saturated soil slows radio waves, GPR can also potentially be used to locate leaks. Research into using GPR for sewer and bedding condition inspections is ongoing. |
| **Innovative Features** | Recently, GPR has been deployed with the digital scanning and ultra-bandwidth technologies on an inspection robot inside a pipeline to assess its condition. New technologies such as ground penetrating imaging radar and synthetic-aperture radar imaging have improved the presentation of output with 3-D images. |
| **Limitations** | GPR does not identify specific utilities (e.g., water, gas, telephone, electric), so verification is necessary. GPR is unlikely to be feasible for ferrous force mains. The pulses lose strength in conductive materials, such as clays and saturated soils, thereby affecting the depth of penetration and the GPR response. Interpretation of GPR data requires highly skilled operators. |
| **Vendors** | **Product(s)**: Surveyor; **Vendor**: SewerVUE; http://www.sewervue.com |
| **Research Questions** | • How will in-line GPR perform in assessing pipeline bedding under controlled conditions?<br>• What other defects/characteristics can GPR detect in pipeline inspections?<br>• Current research is focused on overcoming current drawbacks (e.g., pulse strength in conductive materials) through antenna design, connections to CAD and GIS mapping systems, and the interpretation of GPR images. |
| **Typical Applications** | • Location of underground tunnels, mines, concrete structures and voids.<br>• In-line assessment of non-conductive pipe.<br>• Rapid reconnaissance survey tool for leak management. |
| **Status** | • Commercial GPR systems are available for locating underground utilities but have not been used for pipeline inspections.<br>• GPR systems for internal pipe inspection are in the prototype stage. |
| **Pipe Type** | Any. |
| **Pipe Material** | Concrete, asbestos cement, plastic, brick. |
| **Pipe Diameter** | Any. |
| **Flow Regime** | No limits. |
| **Preparation** | Unknown. |