Condition Assessment Technologies for Drinking Water and Wastewater Pipelines: State-of-the-Art Literature and Practice Review

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ABSTRACT

Aging and deteriorating drinking water and wastewater pipelines have become a major problem in the United States, warranting significant federal attention and regulation. Many utilities have begun or improved programs to manage the renewal of their water and wastewater pipes and are proactively managing their pipeline assets rather than reactively fixing them. However, the extensive size of drinking water and wastewater systems and the severity of the deterioration problem are such that it is important to prioritize renewal, by assessing the condition of the pipelines and resolving the most severe situations first.

There is a variety of condition assessment technologies and methodologies available and in current use. This research incorporates an extensive literature review on actual cases of use of these various condition assessment technologies and techniques. This research also compiles information gathered through interviews and data mining work with utilities across the United States. The combination of case studies collected through literature review and case studies collected directly from utility sources about actual application of drinking water and wastewater pipeline condition assessment practices used have made it possible to synthesize the current practices and trends regarding pipeline condition assessment in the United States. The synthesis also allows for the identification of key lessons learned that should be considered by utilities when implementing condition assessment of pipelines. Recommendations have also been made for research priorities for filling utility needs.

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LIST OF ABBREVIATIONS

3D	Three Dimensional
AC	Asbestos Concrete
AFO	Acoustic Fiber Optic
ASCE	American Society of Civil Engineers
AWWARF	American Water Works Association Research Foundation
BEM	Broadband Electromagnetic
CCP	Concrete Cylinder Pipe
CCTV	Closed Circuit Television
CI	Cast Iron
CIPP	Cured In Place Pipe
CMOM	Capacity, Management, Operations, and Maintenance
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DI	Ductile Iron
DC	Direct Current
EPA	Environmental Protection Agency
GIS	Geographical Information System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
HAZMAT	Hazardous Materials
HDPE	High Density Polyethylene
I/I	Infiltration and Inflow
ISTT	International Society for Trenchless Technologies
K-water	Korea Water Resources Corporation
LIDAR	Light Detection and Ranging
LRGUW	Long Range Guided Ultrasonic Wave
MFL	Magnetic Flux Leakage

MGD	Million Gallons per Day
MOU	Memorandum of Understanding
NASSCO	National Association of Sewer Service Companies
NPDES	National Pollutant Discharge Elimination System
NRCC	National Research Council Canada
O&M	Operations and Maintenance
OSHA	Occupational Safety and Health Association
PACP	Pipeline Assessment and Certification Program
PCB	Polychlorinated Biphenyls
PCCP	Prestressed Concrete Cylinder Pipe
PCP	Prestressed Concrete Pipe
PPR	Pipe Penetrating Radar
psi	pounds per square inch
PVC	Polyvinyl Chloride
PWD	Philadelphia Water Department
R&D	Research and Development
RCCP	Reinforced Concrete Cylinder Pipe
RCP	Reinforced Concrete Pipe
RCRA	Resource Conservation and Recovery Act
RDII	Rainfall Derived Inflow and Infiltration
RFEC	Remote Field Eddy Current
RFT	Remote Field Technology
RTPM	Remote Transient Pressure Monitoring
SASW	Spectral Analysis of Surface Waves
SCADA	Supervisory Control and Data Acquisition
SSES	Sewer System Evaluation Survey
SSO	Sanitary Sewer Overflow

SWIM	Sustainable Water Infrastructure Management
U.K.	United Kingdom
U.S.	United States
WERF	Water Environment Research Foundation
WSSC	Washington Suburban Sanitary Commission
WSP	Welded Steel Pipe

INTRODUCTION

Today, municipal governments are facing a pipeline infrastructure crisis requiring costly repair, rehabilitation and replacement beyond their capacities. There has been a gradual decline in the state of our pipeline infrastructure over the past two decades and a growing concern is that these assets may be inadequate both for current necessities and for projected future growth (AWWA 2001, EPA 2009). Funding for carrying out repair, rehabilitation, and replacement activities is limited and therefore needs to be allocated to assets in an optimal way. Also, accidental damages to the underground pipes caused by removing materials, driving piles and posts, and more have been aggravated by the addition of utilities and new technologies in underground spaces. Such accidental damages to drinking water and wastewater pipelines cause additional burden on already strained resources. Thus utility managers need to make quick and informed decisions for implementing the technologies appropriate for their situation.

Condition assessment of pipelines is carried out through the collection of data and information through direct and/or indirect methods, followed by analysis of the data and information to make a determination of the current and/or future structural, water quality, and hydraulic condition of the pipeline (EPA 2007). Once the current condition of the pipeline is known, funds can be better allocated to the assets which need urgent attention. This proactive prioritization of pipeline renewal activities helps utilities to reduce costs. At present, the utility managers and decision makers are struggling to find easy access to comprehensive information about the pipeline condition assessment technology experiences of other utilities in handling various situations. The information about condition assessment technologies, best practices, experience with technologies (positive and negative), and relative cost of technologies that can be used as knowledge by the various utilities exists within each utility through extensive duplication of effort but is not readily shared across utilities at present. This research was done in order to create a source of information on utility usage of condition assessment techniques which will allow utility personnel to find relevant information that will help in expediting the decision making process for the selection of most appropriate condition assessment technologies and methodologies for their needs.

This research is presented in the format of two manuscripts. One manuscript contains information regarding drinking water pipelines, including raw water pipelines, and one contains information regarding wastewater pipelines, including treated discharge pipelines. Each manuscript includes a brief background on available condition assessment technologies and methodologies for drinking water or wastewater pipelines, with references to further sources of information. Additionally, each manuscript includes a comprehensive literature review of condition assessment technology experiences of utilities. This literature review provides a look at the most prevalent technologies used by utilities, as well as the ways condition assessment technologies are used, the reasons for their use, and the successes and failures involved with their use.

In addition to a literature review of utility experiences, each manuscript includes a practice review of condition assessment technology and methodology use for drinking water pipelines or wastewater pipelines. To determine the most current trends and most important concepts for utilities to understand when performing condition assessment of drinking water or wastewater pipelines, utilities were contacted directly and appropriate personnel were interviewed. Information on use of condition assessment technologies was data mined directly from those utilities. Emphasis was placed on ensuring the data mining process was not similar to surveying. To help this process, open-ended guiding questions were provided for the use of both the research team and the utilities. The guiding questions used for drinking water utilities and wastewater utilities can be found in Appendixes A and B, respectively. The process of data mining ensured the complete extraction of information, including advantages, limitations, and special considerations for use of specific pipeline condition assessment technologies, which would not be possible in performing a literature review alone. Lessons learned during utility experiences with condition assessment technologies were provided, and the information was synthesized to create a better understanding of the current state of practice of utilities performing condition assessment on drinking water and wastewater pipelines. The first manuscript, "Condition Assessment Technologies for Drinking Water Pipelines: State-of-the-Art Literature and Practice Review" will be submitted to the journal *Urban Water* for publication. The second manuscript, "Condition Assessment Technologies for Wastewater Pipelines: State-of-the-Art Literature and Practice Review" will be submitted to the American Society of Civil Engineers journal, *Infrastructure Systems*, for publication.

In addition to its use as a reference for utility decision makers struggling to better understand available pipeline condition assessment technologies and methodologies, the synthesis of the information gathered will be helpful in creation of a standard data structure for pipeline condition assessment projects. This standard data structure will be useful for utilities to share information about projects electronically and for analysis of that information to draw further conclusions about the state of condition assessment projects and practices in the United States.

CONDITION ASSESSMENT TECHNOLOGIES FOR DRINKING WATER PIPELINES: STATE-OF-THE-ART LITERATURE AND PRACTICE REVIEW

Abstract

Aging and deterioration of the United States' critical drinking water infrastructure has become a major consideration in the United States. To save costs associated with reactive renewal of drinking water pipelines, utilities have been taking a more proactive approach to effectively manage their drinking water pipeline assets. Condition assessment is a key component of this approach, providing critical information needed to assess the remaining useful life and long-term performance of a piping system and allowing utilities to prioritize renewal work. While information on the tools and techniques available for condition assessment are readily available from the vendors providing these products, more in-depth information on uses of these condition assessment tools with regard to applicability, success, and limitations for particular utility characteristics, can only be obtained from utilities that have experience with them. This paper gives a brief background on available condition assessment tools and techniques for drinking water pipelines, but also provides a synthesis of literature reviewed on utility uses of condition assessment techniques for drinking water pipelines, as well as a synthesis of information obtained directly from utilities on experiences with condition assessment techniques for drinking water pipelines.

Introduction

Aging and deteriorating wastewater pipelines have become a major problem in the United States. In 2009, the ASCE graded America's drinking water infrastructure with a *D-* (Report Card for America's Infrastructure, 2009). Pipeline break consequences include direct costs, indirect costs, and social costs. Direct costs include the cost of repair, the cost of the water lost, the cost of damage to the surrounding infrastructure and property, and any related liabilities. Indirect costs include the cost of supply interruption, the cost of the potentially increased deterioration rate of surrounding infrastructure and property, and the cost of decreased fire-fighting capacity. Social costs include the cost of water quality degradation due to contaminant intrusion, the cost of the decrease in public trust and the quality of water supply, the cost of disruption to traffic and business, and the cost of disruption of water supply to special facilities (Rizzo, 2010). Therefore, it is important to avoid the failure of drinking water pipelines. However, it would be far too costly to simply replace pipelines, as the extent of the drinking water pipeline networks mean that pipes represent the largest replacement costs in the infrastructure (Baird, 2010).

This is where condition assessment of drinking water pipelines comes in. Condition assessment is one of the core components of an asset management program, providing critical information needed to assess the remaining useful life and long-term performance of a piping system (Feeney, Thayer, Bonomo, & Martel, 2009). USEPA has defined "condition assessment" as the collection of data and information through the direct inspection, observation, and investigation and in-direct monitoring and reporting, and the analysis of the data and information to make a determination of the structural, operational and performance status of capital infrastructure assets (Innovation and Research for Water Infrastructure for the 21st Century: Research Plan, 2007).

Condition assessment is a key component of good asset management practices. Reliable information on the condition of assets is important in the process of understanding long-term performance measures, accurately estimating the remaining life of assets, and prioritizing further investigation or renewal activities. Understanding which condition assessment technologies and methodologies are available and being cognizant of the advantages and limitations of these techniques is important in choosing the appropriate condition assessment practices for a specific utility's needs. Though much information is available from technology vendors on the specifications of the technologies they provide, this information does not always represent the wholeness of a technology's interactions with various characteristics of pipeline networks, flow characteristics, environmental conditions, or utility capabilities. A more accurate understanding of the available condition assessment techniques can be gained through analysis of utility experiences. In addition to a brief background on the available technologies for condition assessment of drinking water pipelines, the below sections provide a synthesis of literature reviewed on utility uses of condition assessment techniques for drinking water pipelines, as well as a synthesis of information obtained directly from utilities on experiences with condition assessment techniques for drinking water pipelines.

Condition Assessment Technologies

In order to more effectively discuss condition assessment technologies, a classification set was created for the available technologies. The classification set divides technologies into categories based upon their primary mode of operation, and further described in Table 1.

Table 1. Description of Pipeline Condition Assessment Technology and Methodology Categorization

Category	Description
Visual and Camera Methods	These technologies primarily utilize visual images as a way to understand pipeline condition. Includes CCTV and other cameras, as well as smoke and dye testing.
Acoustic Based Methods	These technologies use sound waves to obtain data about pipeline condition. This includes sonic and ultrasonic technologies, acoustic monitoring technologies, and leak detection technologies.
Laser Based Methods	These technologies use a laser to obtain pipeline condition related data.
Electric and Electromagnetic Based Methods	These technologies use electricity or electromagnets to obtain data related to pipeline condition. Remote field technologies, ground penetrating radar, magnetic flux leakage, and sonde & receiver technologies are included in this category.
Flow Based Methods	These technologies and methodologies measure flow volume and/or velocity.
Physical Force Based Methods	This category includes technologies and methodologies that primarily use physical force to obtain data related to condition. This includes pressure related and deflection related technologies and methodologies.
Temperature Based Methods	This category includes technologies and methodologies that use a measurement of temperature to obtain pipeline condition data. Included are infrared technologies and flow temperature measurements.
Environmental Testing	Technologies and methodologies that assess the pipeline environment as part of the condition assessment process. This includes soil and water measurements and stray current analysis.
Other Methods	Analysis of existing data, destructive technologies, and any other technology that does not fit into the other categories.

Visual/Camera

Visual and camera based techniques for condition assessment are considered those that primarily utilize visual images as a way to understand pipeline condition. In addition to direct visual assessment, this category includes various types of camera inspection, as well as smoke and dye testing, which rely mainly on visual cues to be effective.

Direct Assessment

Direct assessment is the practice of visually inspecting a pipeline and drawing conclusions based upon visual clues that were observed. This is a very simple method of condition assessment, involving no tools besides the human eye and a light source, if needed. Direct assessment can be performed above ground, through excavation, or through manned entry:

- Above ground inspections typically involve an inspector walking the alignment of a pipeline, looking for clues to indicate that there are condition issues, such as depressions in the ground above a pipeline, pools of standing water, or sources of stray current.
- Excavation for direct assessment involves excavating a section of pipeline in order to look for visual signs of issues having to do with condition. This usually has to do with the condition of the exterior wall of the pipeline, but may also involve visual assessment of the conditions of the soil and/or groundwater surrounding the pipeline or the bedding conditions. Excavation for direct assessment is usually performed in conjunction with testing using other tools for condition assessment (*Condition Assessment Inspection Techniques*, 2005). This technique is usually performed opportunistically rather than being performed on a regular basis (Sunarho, 2009).
- Manned entry for direct assessment can be done with large diameter pipelines. This method involves an inspector entering a pipeline in order to look for visual signs of pipeline condition in the interior pipeline walls and joints. Man entry is one of the most common methods used for inspection of pipelines (Sunarho, 2009). Like excavation, it is also typically performed in conjunction with the use of other condition assessment tools (*Condition Assessment Inspection Techniques*, 2005).

Direct assessment may be performed on any material or diameter pipeline. The technique's primary limitations come from the fact that it is visually based and involves subjective interpretation of visual data (Sunarho, 2009).

Hand-Held Digital Cameras

Hand-held digital cameras are sometimes used to capture visual data on the external condition of above-ground wastewater lines. However, they are more commonly used for reporting purposes, or in the creation of a utility system inventory (Strauch, 2004). Man entry inspections also often involve the use of hand-held digital photographs to record various conditions (Strauch, 2011).

Like many other visual based condition assessment tools, hand-held digital cameras can be used for pipelines of any diameter or material, but the technique is limited both by the fact that it captures only visual data, and by the fact that it involves subjective interpretation of visual clues.

Traditional Closed Circuit Television (CCTV)

CCTV involves the use of a robot-mounted, forward-looking pan/tilt and zoom camera as well as a lighting system mounted on a wheeled carriage that travels between two manholes, operated by certified operators trained to control the camera and interpret video streams (Rizzo, 2010).

Pushrod Cameras

Pushrod camera inspection involves the inspection of a pipeline via a small diameter camera which produces video of the pipeline. Conventional pushrod camera systems involve a camera/probe, cable/reel, and computer/recorded/controller (Feeney, et al., 2009). These cameras are designed for use in laterals and small diameter force mains, inaccessible to crawlers due to their larger size. Their primary limitations are image quality, lighting, and ability to move past obstructions (Feeney, et al., 2009).

Digital Scanners (Optical Scanners)

Digital scanners, also called optical scanners, involve lights mounted parallel to one or two high resolution digital cameras with wide-angle lenses on a crawler. The cameras scan hemispherical images of the entire internal pipe surface during inspection, which is then transmitted to a surface station where it can be viewed in real time and recorded (Feeney, et al., 2009). Digital scanners provide the same information as CCTV, with the added benefit of being able to unwrap the pipe image and do post-processing of images (Rizzo, 2010) instead of relying on an operator to zoom into critical areas for further review. While it is still necessary to manually interpret results, much progress has been made towards automating this procedure using image processing and artificial neural networks (Costello, Chapman, Rogers, & Metje, 2007).

Acoustic Based Methods

Acoustic based methods are those condition assessment technologies and methodologies that primarily use sound waves to obtain data about pipeline condition. This category of condition assessment includes sonic and ultrasonic technologies, acoustic monitoring technologies, and leak detection technologies.

Rod Sounding

Rod sounding, or hammer sounding, is the most basic, first, and most-used method for PCCP inspection. It involves striking the pipe wall with a hammer or rod and listening to the resulting sound. Rod sounding can either be performed by dewatering a pipeline and entering the pipeline or externally, if the external wall of the pipeline is accessible. If a "hollow sound" is heard after striking the pipeline with the rod, it can be associated with the detachment of the steel cylinder from the concrete core and the delamination of the outside mortar coating (Rizzo, 2010).

Ground Microphones

The use of ground microphones is a traditional, passive approach to detect leaks in pipelines(Rizzo, 2010) which relies on the fact that when a fluid leaks from a pipeline, it generates an acoustic signal. These devices can be placed on pipe fittings, hydrants, or service connections to detect the sound produced by the leak (Fanner et al., 2007). A listening stick, which involved the use of a rod to transmit the sound of a leak up to the operator's ear, is the historical precursor to the ground microphone. Later, geophones were used to pick up on the sound and allow it to be recorded for future reference (Costello, et al., 2007). Modern electronic devices have added signal amplifiers and noise filters; however, the most important factor for success in using listening devices is that the inspector using the device has good hearing and is well trained and experienced in interpreting the sounds picked up by the device (Fanner, et al., 2007).

In order for ground microphones to be effective, one must first know the location of the pipeline and, to a lesser degree, the location of the suspected leak. It is also important to minimize background noise when using this technology. Recent research involving acoustic leak detection have focused on sound wave propagation in plastic water mains (Costello, et al., 2007).

Noise Correlators and Noise Loggers

Noise correlators typically consist of a receiver unit and two sensors equipped with a radio transmitter (Fanner, et al., 2007). These devices have been used for leak detection since the 1980s (Feeney, et al., 2009). The sensors are placed on each side of the suspected leak and pick up the leak sound from the pipe being tested. The leak noise travels at a constant velocity depending upon the pipe's material and diameter, and will arrive first at the sensor it is closest to, then at the other sensor. The correlator uses the time difference between the arrival times to calculate the leak location (Rizzo, 2010). Leak noise correlators have been found to be successful when used in distribution mains, but have had limited success when used in large diameter pipelines (Costello, et al., 2007).

Noise loggers are installed at fittings. They are turned on at night to monitor system noise and listen for acoustic signals produced by leaks. The purpose for use overnight is that, at night time, higher pressures result in increased intensity of leak noise and, at night, there is less chance of interference from ambient sound. These devices do not pin-point the location of a leak, but rather give an indication that there is a leak present within the vicinity of the logger (Fanner, et al., 2007).

Noise correlators have more recently been used by affixing two sensors to two points on a pipe, typically existing fittings on the pipe such as hydrants or line valves. An acoustic wave is then induced in the pipe, either by releasing water at fire hydrants in a controlled manner, or by tapping on a valve or other appurtenance. The propagation velocity of the induced acoustic wave is then measured based on the measured time delay between the two sensor locations, and the average wall stiffness of the pipe section between the sensors is calculated using a theoretical model. Typically, the distance between sensors is 100-300 meters, but this distance can be decreased to as low as 30 meters if a measurement is found which could represent a degraded pipe (Bracken, Johnston, & Coleman, 2011).

In-Line Acoustic Leak Detection

There are two modes of in-line acoustic leak detection: tethered and free-swimming. For both tethered and free-swimming in-line acoustic leak detection systems, a minimum pressure and flow velocity are required to successfully carry the inspection device through the pipelines, requiring extensive planning and knowledge of the pipeline system characteristics before testing. These systems are restricted to use in force mains.

Tethered In-Line Acoustic Leak Detection

The commercially available tethered in-line acoustic leak detection system consists of a sensor head with a hydrophone (used to detect sound under water) attached to a cable which carries sounds detected to processing equipment above ground (Feeney, et al., 2009). The sensor head is inserted into a pipe through any access point of appropriate diameter and is carried through the pipe, with the help of an attached parachute, by the pressure of the flow through the pipe. As the sensor head is transmitted through the pipe, acoustic signals are sent back to the processing equipment and interpreted based on their characteristics. After inspection, the sensor head is retracted through the pipe with the cable and retrieved through the original insertion point.

The commercially available tethered in-line acoustic leak detection tool can also be adapted for work in no-flow conditions by using a winch and a pull-tape to pull it through the pipeline (Webb, Mergelas, & Laven, 2009).

Free-Swimming In-Line Acoustic Leak Detection

The commercially available free-swimming in-line acoustic leak detection technology involves a foam ball equipped with an aluminum inner core that contains several sensors that measure acoustic signals, temperature, and pressure as well as a microprocessor with an ultrasonic transmitter, a data logger, and a DC battery (Feeney, et al., 2009). The ball is inserted into the pipeline and propelled by the flow within the pipeline, then retrieved at a pre-arranged retrieval location where it is captured with a net.

Acoustic Monitoring Systems

Research done in the late 1980's and early 1990's by the United States Department of the Interior, Bureau of Reclamation, first investigated the use of continuous acoustic monitoring to track the deterioration of PCCP (Fitamant, Lewis, Tanzi, & Wheatley, 2004). Acoustic monitoring systems are installed along PCCP to provide continuous monitoring of the general condition of the pipe by detecting the acoustic signal that is produced when prestressing wires break within pipes (Feeney, et al., 2009). When a wire breaks, the redistribution of stress in the material causes the release of transient elastic waves (an acoustic emission), which are then detected by sensors like piezoelectric transducers, hydrophones, or accelerometers (Rizzo, 2010).

There are arrays of sensors available commercially for use in pipe monitoring (Rizzo, 2010). The location of each acoustic event can be determined by correlating the arrival time of the sound to the sensors that were involved in detection. Fiber optic cable monitoring systems are also commercially available. Because the entirety of the fiber optic cable acts as a sensor, very lengthy sections of pipeline can be monitored with these systems from a single access point and the distance of the sensor from an acoustic event is never greater than a single pipeline diameter (Agarwal & Sinha, 2010). Because the sensor does not contain electronics, there is little or no background noise created by the monitoring system (Feeney, et al., 2009).

Impact-Echo and Spectral Analysis of Surface Waves (SASW)

Impact-echo and spectral analysis of surface waves (SASW) methods are widely used in assessment of concrete structures, and can detect delamination as well as determining thickness (Tuccillo, Jolley, Martel, & Boyd, 2010). The method involves mechanically impacting the surface of the pipe to propagate sound waves into the material, then a simple signal processing technique is used to provide the thickness, depth of delamination, and sound velocity inside the concrete (which indicates the concrete quality) (Rizzo, 2010).

The impact-echo technique can be used on PCCP, RCP, and clay pipe, and can detect delamination and cracks in various interfaces between concrete and mortar and steel. It either requires dewatering and human access into the pipe, or external access to the pipe wall (Rizzo, 2010).

Ultrasonic Testing Methods

Ultrasonic testing methods are based on the propagation of ultrasonic stress waves through one or more probes to send broad-band or narrowband mechanical waves through a medium (Rizzo, 2010). Ultrasonic methods require pipe cleaning prior to inspection to remove debris (Costello, et al., 2007).

Ultrasonic Wall Thickness Measurement

Ultrasonic wall thickness testing uses bulk waves to test a small region within the ultrasonic probe (Rizzo, 2010). Ultrasonic wall thickness measurement equipment can be used to measure the remaining wall thickness of metallic, ceramic, plastic, and composite pipelines but performs best on steel and ductile iron pipelines (Tuccillo, et al., 2010). When using this technique with cast iron pipes, false internal reflections can skew test results due to the in homogeneity of the material (*Condition Assessment Inspection Techniques*, 2005).

Ultrasonic wall thickness measurement requires point-by-point measurements, so can be slow. These tools also require exposure of a clean area to allow direct contact of the transducer to the material surface, and also require relatively clean and dry test conditions (Tuccillo, et al., 2010).

Long Range Guided Ultrasonic Wave (LRGUW)

When ultrasound waves propagate into a bounded media, a guided ultrasonic wave, or a wave that travels along the medium guided by the medium's geometric boundaries, is generated, and may travel along a pipeline, exciting the whole longitudinal direction and cross section of the pipeline (Rizzo, 2010). This method of ultrasonic testing can detect cracks and measure the wall thickness of a metal pipeline across a long distance (Tuccillo, et al., 2010).

This method has been used on industrial piping in manufacturing as well as in the oil and gas sector, and has been successfully field tested on water mains, but has not yet been used on wastewater pipelines (Tuccillo, et al., 2010).

Laser Based Methods

Laser-based condition assessment technologies are those that primarily involve the use of a laser to obtain pipeline condition related data.

Laser Profiling

Laser profiling is the most commonly used laser technology at this point. The technology is used to determine the shape of a pipeline and any ovality or vertical deflection caused by the interaction of pipeline defects and external loads (*Condition Assessment Inspection Techniques*, 2005). This gives information about the sewers structural integrity, information that affects the design of liner systems, and, when compared to the expected pipe shape, information about the extent of corrosion of and/or build-up on the internal wall of pipes.

Light Detection and Ranging (LIDAR)

Light detection and ranging, or LIDAR, works by bouncing photons of light off an object and measuring the time it takes for that light to return to the LIDAR scanner. This measured time can be converted to a distance measurement. The photons of light are sent out by the scanner at many angles and directions, and the individual measurements can be assembled into a full 3D model of the pipe interior. This 3D model is called a "point cloud", and can be analyzed to highlight areas where the pipe contains defects (Lipkin, 2012).

Electric and Electromagnetic Based Methods

Electric and electromagnetic based condition assessment techniques are those that primarily use electricity or electromagnets to obtain data related to pipeline condition.

Eddy Current Testing

Eddy current testing can be used in pipelines that are made of electrically conductive materials or in reinforced concrete and PCCP, to qualitatively assess the steel reinforcement. Eddy current testing involves the use of a magnetic coil with an alternating current, which induces a time-varying magnetic field in the pipe that causes an electric current to be generated in the material. The currents that are generated in the pipe produce magnetic fields in the pipe material that oppose the original magnetic field and change the impedance of the magnetic coil. As the eddy current traverses the pipe, the change in impedance is measured, which has the potential to produce data that can measure wall thickness and find discontinuities that lie in the planes transverse to the currents. The main disadvantage of eddy current testing is the limitation in depth of penetration of the alternating current, which limits the depth to which defects can be found in a pipe wall at a given frequency (Rizzo, 2010).

Remote Field Technologies

The remote field eddy current (RFEC) method was proposed to overcome the disadvantage of eddy current testing, in which the depth of penetration of the alternating current at a given frequency limits the depth to which defects can be found in a pipe wall (Rizzo, 2010). RFEC involves the deployment of a probe consisting of multiple magnetic coils, an exciter coil and one or more detector coils, through the pipeline. Eddy currents are induced in the pipe wall with the exciter coil, and these currents attenuate quickly as they flow along the pipe wall towards the detector coil, which is located approximately two to three pipe diameters away from the exciter coil. A second magnetic field passes from the exciter to the outside of the pipe and flows along the outer pipe wall, then back into the interior of the pipe to reach the detector (Feeney, et al., 2009). At a distance of about three pipe diameters, the field in the pipe wall is stronger than the field within the pipe, and sensors positioned in this “remote field region” can detect minor variations in the field strength (*Condition Assessment Inspection Techniques*, 2005).

Remote field technologies are used primarily for assessment of ferrous pipe walls, and can detect pitting, corrosion, leaks, and cracks. These technologies can be used in any flow conditions and over a large range of diameters. However, certain commercially available tools using remote field eddy currents have been developed specifically to detect and quantify broken prestressing wires in PCCP. In these tools, the electromagnetic field generated by the exciter coil is amplified by the wires in the pipeline (Feeney, et al., 2009). During this type of inspection, the magnetic field of interest is very small. Interferences such as motion caused by impacts or uneven pipe floor, variations in pipe joints, the presence of steel sheeting or other steel structures adjacent to the pipeline, and changing wire diameter or pitch can distort measurements (Fitamant, et al., 2004).

Another version of an RFEC inspection tool uses broadband electromagnetic (BEM) induction techniques to record data over a broad range of frequencies (*Condition Assessment Inspection Techniques*, 2005). BEM’s frequency independence allows operation of the device to be modified based upon the material being investigated and the site conditions, which in turn reduces the likelihood that the device will be affected by electromagnetic noise. BEM can be used through thick coatings and linings to detect cracks and anomalies in the pipe wall, as well as to measure wall thickness, quantify graphitization, and locate broken wires in PCCP. BEM can be used externally or inside a dewatered pipeline (Feeney, et al., 2009).

Pipeline condition assessment tools utilizing remote field technology are available commercially in the form of manned and unmanned internal inspection tools for full and dewatered pipes, in the form of pigs for inspection in pressurized pipes, and as tools that move along the outside of a pipeline (Biggar, 2010).

Electrical Leak Location (Electro-scanning)

The electrical leak location method was first developed in 1981 for the inspection of geomembrane liners, but was developed specifically for detecting leaks in pipelines in 1999. This method is also known as electro-scanning, and can be used for finding leaks in pipelines with materials that are electrical insulators, i.e., non-ferrous pipes (Feeney, et al., 2009).

Ground Penetrating Radar (GPR) and Pipe Penetrating Radar

Ground penetrating radar, or GPR, is a technique that uses electromagnetic radiation in the microwave band. The microwave signals are pulsed from the ground surface, propagate into the ground at a velocity related to the electrical properties of the subsurface materials (Ratliff & Russo, 2010), and are then reflected from subsurface structures. Transducers or antenna are used as transmitters and receivers (Rizzo, 2010).

GPR can detect soil voids. The technology can be used to identify leaks by detecting cavities or disturbed ground created by a leak or by detecting the presence of water from the leak (Fanner, et al., 2007). GPR is good for assessing rebar in reinforced concrete (Rizzo, 2010). Current technology allows GPR to sit directly on top of concrete structures to characterize the condition of the structure through the wall (Ratliff & Russo, 2010). Highly trained and experienced individuals are required to interpret the data resulting from a GPR inspection (Koo & Ariaratnam, 2006).

An in-pipe GPR tool, referred to as pipe penetrating radar, has been developed and used successfully, though to a limited extent, for pipeline condition assessment (Koo & Ariaratnam, 2006).

Magnetic Flux Leakage (MFL)

Now a technique widely used for gas and oil pipelines, magnetic flux leakage (MFL) detection was first developed in the 1920's and 1930's for materials testing (Feeney, et al., 2009). The first MFL in-line inspection tool for pipelines was introduced in 1965 (Rizzo, 2010).

Magnetic flux leakage is done by magnetizing a pipe wall and scanning its surface with a flux-sensitive sensor. Magnetic lines of force, or flux lines, are contained within the pipe wall; however, if there is a defect or anomaly in the pipe wall, the magnetic surface is disrupted and the flux "leaks" out of the discontinuity, which can then be detected through measurements of change in the pipe's magnetic permeability (Rizzo, 2010).

MFL pigs can be used in buried or surface cast iron and steel pipes to detect metal loss from corrosion and find circumferential and longitudinal cracks (Rizzo, 2010). Magnetic flux leakage is best used for smaller diameter, unlined cast iron and steel pipes. It has no problem finding small defects, but has difficulties regarding short and shallow defects, which lends the data obtained a degree of uncertainty (Costello, et al., 2007).

Electrical Continuity Testing

Electrically continuous ferrous pipelines are safer from risk of corrosion than those that are not electrically continuous. To test for electrical continuity, test sites along a pipeline may be set up. When a current is applied to the first site, the other sites are checked to make sure that current is detectable. This indicates electrical continuity (Ratliff & Russo, 2010).

Some work has also been done involving testing PCCP wires for electrical continuity to confirm the presence of wire breaks (Derr, 2010).

Flow Based Methods

Flow based technologies and methodologies are those that measure flow depth, volume, and/or velocity as a primary way to determine information about the condition of a pipeline. These techniques include various uses of flow meters and precipitation measurement.

Flow Meters

Flow meters typically operate by direct measurement of depth and velocity, from which flow is calculated based upon the continuity equation (Feeney, et al., 2009). The data obtained is then analyzed, many times in conjunction with rainfall data. In collection systems, this method is typically used to screen for problem areas in order to support planning for further assessment or rehabilitation, and is particularly useful in systems where there are concerns about infiltration and inflow (I/I). Flow meters can be installed in a collection system to learn flow rates at different points in the system and find unexpected surpluses or deficits of flow. Flow meters can also be used to measure dry weather and wet weather flow rates in a system and compare the rates to find the quantity of I/I (Tuccillo, et al., 2010).

Physical Force Based Methods

Condition assessment techniques that are primarily carried out with the use of physical force are included in this category. This includes condition assessment techniques that are pressure related or involve impact or hardness testing.

Gas or Liquid Pressure Testing

Pressure testing is a widely used method in new pipe installations, and is also often used to evaluate the leak-tightness of existing sewers. In this process, a section of the line is plugged on both sides of a joint, and a fluid (air or water) is inserted into it under a pressure. If the pressure stays above a certain level for a specific period of time, the pipeline "passes the test" (Sterling et al., 2006).

This process has some shortcomings. Namely, joints immediately adjacent to service connections cannot be sealed or tested; the results of the testing does not provide a quantifiable measurement of a defect, so rehabilitation work may be done to seal joints that are not cost-effective to seal; and the process is very time consuming (Harris & Tasello, 2004).

Transient Pressure Monitoring

Pressure monitoring is done on pressure lines to examine the stresses that are occurring on a pipeline. These stresses are compared to the design stresses for the pipeline to help determine if changes should be made to the line or the operational practices. Transient pressure monitoring systems typically sample pressure data once per minute and also continuously monitor for pressure transients or negative pressures. When these events occur, sampling rates go up to once every 0.01 seconds (Weare, 2007).

Micro-Deflection

Micro-deflection involves the application of a load onto a brick, concrete, or clay structure to create a slight deformation, which is then measured and displayed graphically as a plot of load versus deflection. A structurally sound material would be expected to have a consistent micro-deflection profile for various loads, while deteriorated or defective structures would not (Tuccillo, et al., 2010).

Probing

Probing simply involves putting pressure on the lining or wall of a pipeline to determine its condition through resistance to the pressure. This is an informal method of condition assessment.

Rod Sounding

See section on Acoustic Based Methods for more information.

Impact Echo and Spectral Analysis of Surface Waves (SASW)

See section on Acoustic Based Methods for more information.

Temperature Based Methods

Temperature based methods of condition assessment involve temperature measurement as a primary way to obtain pipeline condition data. This category of tools and techniques includes infrared technologies and flow temperature measurements.

Infrared Thermography

Infrared thermography works on the principle that when a material is heated, infrared radiation flows from warmer to cooler areas at a rate dependent upon the material's insulating properties. An infrared camera is used to measure the infrared radiation across the surface of an object. Uneven heating or cooling can indicate variations in pipe wall thickness, variations of the bonding of a liner to the pipe wall, or the presence of soil voids outside the pipe (Tuccillo, et al., 2010).

Environmental Testing

This category of condition assessment involves methodologies that assess the pipeline environment to obtain indirect information about the pipeline's condition as well as to make predictions about its future condition. These techniques include testing samples from the pipeline's external or internal environment as well as field analyses.

Soil and Groundwater Testing

The soil and groundwater conditions have a great bearing on the likelihood of external corrosion of a ferrous pipeline, even to the point of being recognized in numerous codes and guides as being a key factor when screening for likelihood of failure due to external corrosion (Thomson, Morrison, Sangster, & Hayward, 2007).

Relevant parameters to test soil for include soil resistivity, in-situ hydrogen ion content (pH), chloride ion content, soluble sulphate ion content, presence of sulfides, and oxygen reduction (redox) potential of soils (Clothier, Oram, & Kubek, 2011). Groundwater levels are important because wetted soils have different properties than dry soils (Thomson, et al., 2007).

In-Pipe Flow Testing

In-pipe flow testing refers to sampling and testing parameters of the fluid conveyed within a pipeline. Changes to the nature of the effluent being conveyed through pipes may create a more aggressive internal environment that would contribute to the likelihood of increased risk of internal conditions (Thomson, et al., 2007).

Pipe to Soil Potential/Stray Current Mapping

Cell-to-cell potential surveys measure voltage gradients in the soil surrounding the pipe and are conducted on electrically discontinuous pipelines. They provide a snapshot of areas where active corrosion processes are taking place at the time of survey. They can also be used to detect whether stray current corrosion is occurring. When used in conjunction with resistivity and other data, cell-to-cell potential measurements can be used to pinpoint locations of greatest exposure with the highest likelihood of exhibiting observable corrosion damage. Similar to resistivity measurements, cell-to-cell potentials cannot provide a direct assessment of pipeline condition; however, high electrical potentials indicate locations of potentially significant deterioration that can be used to target at-risk infrastructure for focused condition assessment inspections (Clothier, et al., 2011).

Other Methods

This category of condition assessment techniques include coupon sampling and other types of material sampling as well as other technologies that do not fit into the other condition assessment categories previously described.

Coupon and Other Sampling

Coupon sampling typically involves the use of under pressure tapping equipment to remove a 50mm diameter coupon from a pipe wall while the pipe is still operational (*Condition Assessment Inspection Techniques*, 2005), then measuring pit depths, testing, or examining the coupon in various ways to determine the extent of corrosion of the pipeline or other parameters. Larger samples of pipe wall can also be taken; however, this involves closing down the section of pipe and so is more expensive and disruptive than coupon sampling. Samples of pipe wall for lab analysis can also be taken from failed pipelines as a part of forensic investigation. Linings of pipelines can also be scraped and sampled for further testing, as can PCCP wires.

Conveyance Systems

Conveyance systems refer to those systems used to move condition assessment equipment through pipelines. These include a wide variety of mobile robots called tractors or crawlers, float rigs, and segmented robots that move like inchworms (Feeney, et al., 2009) and allow condition assessment tools to be adaptable to flow or other pipeline conditions.

Gamma-Gamma Logging

Gamma-gamma logging is an innovative technique primarily used to evaluate cast-in-place concrete pilings, as well as for investigation of vertical boreholes in the mining, oil, and gas industries (Feeney, et al., 2009). This technology is based upon the principle that emitted radioactive gamma rays are backscattered and detected in proportion to the density of the surrounding material. For most materials, the natural log of backscattered gamma ray particles has a linear relationship with the density of the material (Tuccillo, et al., 2010).

This equipment consists of a probe containing a small amount of radioactive material and two or more scintillation detector to detect the gamma rays. This technology has been used to identify and locate pipe bedding cavities, and has been proposed as a tool to be mounted on a robotic crawler for pipeline condition assessment (Tuccillo, et al., 2010).

State-of-the-Art Literature Review for Technology Use

Literature about drinking water pipeline condition assessment technologies and practices was reviewed to establish the current state-of-the-art. A web search was done, which provided publicly available articles and major reports, such as those published by the EPA. In addition to a web search, database search engines available through the Virginia Tech library were used to access literature. The most prevalently used database search engines were the ASCE Civil Engineering Database, Compendex, and Web of Science. Access to the WERF publication database was also provided for two weeks, during which time all relevant and available WERF publications were accessed. The library of the SWIM Laboratory was also searched for relevant reports and other publications.

Definition of Scope

The literature review focused on the use of pipeline condition assessment technologies by drinking water utilities. Literature reviewed was pragmatic from the viewpoint of drinking water utility personnel, involving information on actual use of the technologies and methodologies, as well as surrounding management practices and costs directly related to the use of the technologies and methodologies. The review focused less on in-depth information on modeling and data analysis practices, asset management from a larger perspective, and research related to development of new technologies and methodologies.

Major reports meant for use as reference documents by utilities were reviewed for inclusion in this literature review, as were journal articles and conference papers.

Reports Reviewed

Ten reports were found that were specifically useful and applicable to the practice of using condition assessment technologies and methodologies for gathering information on the condition of drinking water pipelines. These reports are illustrated in Figure 1.

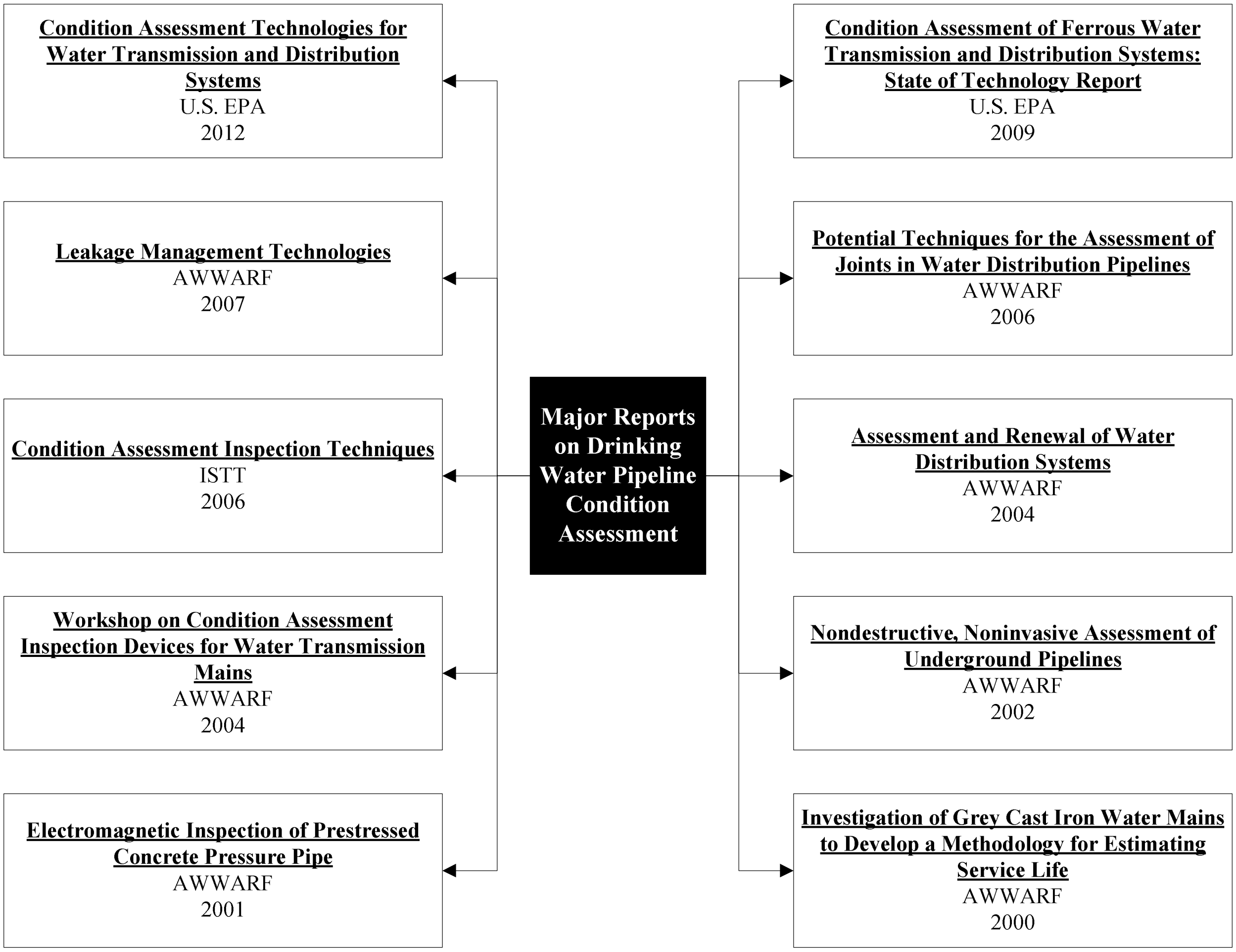

Figure 1. Major Reports Useful for Practicing Drinking Water Pipeline Condition Assessment Technologies and Methodologies

Technology Use in Literature Sources Reviewed

Information was gathered from reports, journal articles, conference papers, and other literature sources on the use of various condition assessment techniques by specific utilities for drinking water pipelines. Information on specific work as well as information on trends in use found in the literature is described in this section, classified by type of condition assessment technology.

Visual and Camera Methods

Though visual and camera based methods were not the most prevalently mentioned technologies as used by drinking water utilities for pipeline condition assessment, there were a large quantity of examples of utility use of direct visual assessment.

Direct Assessment

Direct visual assessment can involve an above-ground inspection during which look for indirect signs of pipeline condition, an excavation of a pipeline to visually assess the condition of the exterior pipe wall, or a manned entry into a large diameter pipeline to visually assess the condition of the interior pipe wall. Above ground inspection was not mentioned at all. Manned entry direct visual inspection was the most frequently mentioned method of direct assessment in the literature reviewed:

- The Washington Suburban Sanitary Commission has experienced several premature, catastrophic failures of PCCP installed during the 1960's and 1970's and thus implemented a PCCP management program, including the use of internal direct visual assessment in conjunction with rod sounding as part of inspection of 77 miles of pipeline 48 inches and above in diameter. A visual and sounding inspection may not be able to identify pipe sections that have small to moderate levels of wire break damage, since the pipe may not have deteriorated to the point of showing internal signs of distress or delamination of the concrete core (Fick & Wagner, 2010).
- The Metropolitan Water District of Southern California, implemented a PCCP condition assessment program in 1996 which included internal inspections that uses direct visual assessment in conjunction with rod sounding and impact echo. Since that time, additional technologies have been added to the PCCP inspection process (Harren & McReynolds, 2010).
- In 2005, Providence Water implemented an inspection program of a 102-inch PCCP aqueduct that had catastrophically failed in 1996. The program included direct visual assessment in addition to rod sounding, electromagnetic inspection, resistivity testing and the installation of an acoustic monitoring system (Stroebele, Bell, & Paulson, 2010).
- After finding a leaking PCCP, Elizabethtown Water Company in New Jersey decided to perform an internal visual and sounding inspection of 1,700 feet of the pipeline isolated between valves for leakage repairs. A half-inch diameter steel pipe with capped ends was used for the sounding, striking the surface every two feet in a spiral manner. No hollows were found with the sounding, but longitudinal cracks and many un-mortared joints were found with the direct assessment (Lewis & Schaefer, 2004).
- The City of Houston uses direct visual assessment with manned entry as part of a much larger condition assessment program for its large diameter water transmission mains. The inspections involve identification of cracks or delaminations in the mortar lining, inspection of grout quality at joints, changes from design lay schedule, and other similar issues (Henry & Long, 2009).
- In order to avoid catastrophic failure, protect structural integrity of pipelines, determine condition and extend service life, and develop strategies for maintenance and renewal, the San Diego County Water Authority uses internal visual inspection as one of many techniques for inspecting PCCP lines (Grigg, 2006).
- To verify the results of RFTC inspection of PCCP water mains, Miami-Dade Water and Sewer Department in Florida has used manned entry visual inspections in addition to other techniques (Terrero, Coates, & Garaci, 2011).
- Providence Water, Rhode Island, implemented a condition assessment project for inspection of a 102" PCCP aqueduct in 2005 and 2006 including an internal, manned RFTC inspection in conjunction with visual and sounding inspections, resistivity testing of PCCP wires (requiring excavation to the crown of the pipe, chipping hammer to expose the prestressing wire, and a resistance meter used to measure the resistance of a

prestressing wire loop, which if high, indicates that it is broken), and acoustic fiber optic monitoring system (Higgins et al., 2007).

- After reports of large mortar lining failures, the Metropolitan Water District of Southern California conducted an internal, manned, direct visual inspection of 5.3 miles of a 144 inch diameter welded steel pipeline in 2008 to evaluate the condition of the lining. Approximately a third of the total length of the pipeline had either missing or delaminated mortar. After determining the extent of the problem and researching to understand the reasons behind the lining failure, the utility concluded that the stresses in the pipe should be limited as should fluctuations in stress (McReynolds, Peng, & Romer, 2010).

Several cases of use of excavation for direct visual assessment were also found, though the circumstances for that excavation varied:

- After a 66-inch diameter steel water main in the City of Houston was damaged during unassociated concrete pile driving construction activities, the line was excavated for condition assessment and deformations in the line were visually observed and measured (Saenz & Card, 2011).
- The City of Salem, Oregon implemented a condition assessment program for a 36-inch diameter steel and RCCP water supply main following high water losses. Several test pits were excavated in 2009 and the external surface of the concrete and steel pipe was visually inspected and determined to be in good condition). While tracking the location of the alignment above-ground for the purpose of carrying out leak detection work with a ground microphone, water was also observed flowing out of the ground. A field test helped to determine that the water was chlorinated and therefore was likely to be flowing from a leak in the pipeline that was to be assessed (Bowers, Jones, & Connolly, 2011).
- In 2008, an unexpected catastrophic failure of a 48” diameter PCCP line in Houston, Texas, caused flooding and closure of a major state highway. Service was maintained due to multiple groundwater wells operating in the area. After quick restoration of the pipeline with installation of a section of steel line, condition assessment of the failed pipeline included visual observations of the pipeline interior and limited observations of the exterior, in addition to electromagnetic testing (resulting in identification of four segments with minor distress in the range of 5-10 broken wires). Visual observations provided the most useful information, including evidence of corrosion, longitudinal and circumferential cracks, and deterioration of grout (Crook & Henry, 2010).
- The Southern Nevada Water Authority initiated a program to assess water transmission laterals constructed before 2000, focusing on the assessment of conditions likely to affect the structural degradation and mechanical strength of the pipeline. Indirect and direct inspection techniques were used to evaluate both soil geochemistry and physical and operational pipeline parameters. Direct assessment through excavation was used to

inspect AC, PCCP, tar epoxy or tape coating, and reinforced concrete pipe (Ratliff & Russo, 2010).

Traditional Closed-Circuit Television (CCTV)

Traditional CCTV is typically used in wastewater pipelines. Inspection of drinking water lines with this technology is impractical since it requires the line to be dewatered and, because of the structure of drinking water lines, it is difficult to insert the equipment into the line. Nevertheless, two examples of use of traditional CCTV in drinking water pipelines were found during the literature review:

- Video inspection of a 36" steel and RCCP water supply main in Salem, Oregon was conducted as part of a condition assessment of the line. The line was drained and four existing access ports and two newly installed core drilled access ports with manholes were used to insert the video equipment into the pipe. Biofilm encountered on the interior walls of the concrete caused the camera vehicle to lose traction in some areas, so the camera was retrofitted by adding additional weight to the vehicle and installing screws to the vehicle tires to add traction. Biofilm eventually built up on the tire studs, but the retrofitting measures were generally effective. Areas of concern identified included pipe material transition joints, locations of suspected leakage, waterway crossings, road crossing, and a railroad crossing (Bowers, et al., 2011).
- In Australia, Water Corporation's trunk main network, mostly consisting of wrapped steel pipes with cement mortar lining, has flexibility such that a significant number of trunk mains that can be taken off-line without affecting service provision. Therefore, a routine CCTV inspection program has been implemented in which trunk mains are inspected when they are taken out of service for maintenance purposes. The lining is checked for cracking or delamination and the cement mortar lining is checked for stains, which indicates corrosion of the steel (Marlow et al., 2007).

Pushrod Cameras

Numerous examples of use of small diameter, in-line cameras were found mentioned in literature. However, some of the examples given were tests done using prototypes. Examples of use of this technology are as follows:

- An in-line leak detection program commenced recently in Manila, Philippines, and in less than two months of inspections, 72 leaks had been found (frequency of 6 leaks per mile of pipeline). The leak detection efforts are employed in conjunction with in-line video to detect illegal connections (Laven & Kler, 2011).
- Philadelphia Water Department used in-line camera technology on a 48" cast iron water main in 2008. Major features were visible, such as joints between pipe segments, outlets, inline gate valves, and patches or wear and corrosion; however, small defects could not be reliably seen due to defects with the prototype camera system that was used (Jo, Laven, & Jacob, 2010).

- In June of 2009, the City of Wichita Falls inspected portions of a 20" steel pipeline using tethered in-line video technology in conjunction with tethered in-line acoustic leak detection. The camera technology used was an intermediate prototype. Due to improved video resolution, a wide variety of features were successfully detected such as joints with grout missing, longitudinal cracks, a pocket of trapped air, and debris buildup on the bottom of the pipe (Jo, et al., 2010).
- After finding chlorinated water surfacing in a shallow section of a creek, the Charlotte-Mecklenburg Utility Department in North Carolina used in-line video technology in conjunction with in-line acoustic leak detection to assess a 54" main, from which the leak was suspected, due to recent blasting in the area during tunnel construction. The leak was successfully located under a bank of the creek, and the inspection also showed that a number of joints in the pipeline were missing grout or had discoloration indicative of corrosion (Jo, et al., 2010).
- Dallas Water Utilities in Texas recently conducted a tethered inline video survey on a 24" water transmission pipeline that revealed visual confirmation of debris in the bottom of the pipe, several side outlets, and the presence of WEKO seals inside the pipeline that had been installed 14 years prior to the inspection (Jo, et al., 2010).
- The Ontario Clean Water Agency (Region of Peel) employed in-service video in a 60" pipeline in an attempt to visually verify the location of a leak previously indicated by acoustic testing. The inline video survey was not able to detect visual indications of a leak, but a tee in the line was clearly visible and clear visuals of the pipe walls were obtained (Jo, et al., 2010).
- The City of Atlanta Department of Watershed Management conducted an R&D trial of the prototype in-service video technology by inspecting three parallel cast iron raw water lines in 2008. The video data was useful in confirming that prior joint seal projects were undertaken and in what portions of the pipeline. During this inspection, the first visual detection of a pocket of trapped air inside a water pipeline was obtained. The video also provided a general sense of the condition of the internal mortar liner (Jo, et al., 2010).

Acoustic Based Methods

Acoustic based methods for drinking water pipeline condition assessment were, by far, the most prevalently mentioned types of technologies found during the literature review of examples of utility use.

Rod Sounding

Rod sounding was found frequently in literature examples of utility practices, most commonly in conjunction with other techniques of condition assessment. Though more advanced technologies for PCCP condition assessment are available, many examples of utility use of rod sounding were found in very current literature:

- The Washington Suburban Sanitary Commission has experienced several premature, catastrophic failures of PCCP installed during the 1960's and 1970's and thus implemented a PCCP management program, including the use of rod sounding in conjunction with internal direct visual assessment for inspection of 77 miles of pipeline 48 inches and above in diameter. A visual and sounding inspection may not be able to identify pipe sections that have small to moderate levels of wire break damage, since the pipe may not have deteriorated to the point of showing internal signs of distress or delamination of the concrete core (Fick & Wagner, 2010).

- The Metropolitan Water District of Southern California, which has 163 miles of PCCP varying from 42 to 201 inches in diameter within its distribution system, implemented a PCCP condition assessment program in 1996 which included internal inspections that use rod sounding in conjunction with direct visual assessment and impact echo. Since that time, additional technologies have been added to the PCCP inspection process (Harren & McReynolds, 2010).
- In 2005, Providence Water implemented an inspection program of a 102-inch PCCP aqueduct that had catastrophically failed in 1996. The program included rod sounding in addition to direct visual assessment, electromagnetic inspection, resistivity testing and the installation of an acoustic monitoring system (Stroebele, et al., 2010).
- After several major failures of the very long, above-ground PCCP water transmission line that is the Great Man Made River Project in Libya, it was determined that the cause was chloride-induced corrosion of the prestressing wires. An extensive survey was undertaken which included, at the beginning of the program, external rod sounding. Additional technologies were introduced in 2000 (Omar Essamin, El-Sahli, Hovhanessian, & Diouron, 2005).
- After finding a leaking PCCP, Elizabethtown Water Company in New Jersey decided to perform an internal visual and sounding inspection of 1,700 feet of the pipeline isolated between valves for leakage repairs. A half-inch diameter steel pipe with capped ends was used for the sounding, striking the surface every two feet in a spiral manner. No hollows were found (Lewis & Schaefer, 2004).
- The City of Houston, Texas, uses rod sounding in conjunction with manned entry and direct visual assessment as part of a large diameter water transmission main condition assessment program. Mortar delaminations are found using this technique (Henry & Long, 2009).
- In order to avoid catastrophic failure, protect structural integrity of pipelines, determine condition and extend service life, and develop strategies for maintenance and renewal, the San Diego County Water Authority, California, uses internal visual inspection in conjunction with rod sounding as one of many techniques for inspecting PCCP lines (Grigg, 2006).
- To verify the results of RFTC inspection of PCCP water mains, Miami-Dade Water and Sewer Department in Florida has used rod sounding in addition to other techniques (Terrero, et al., 2011).

Ground Microphones

Examples of utility use of ground microphones found in literature involved the technology as a method of pinpointing or confirming the presence of leaks, rather than as a primary method of condition assessment:

- In 2009, Birmingham Water Works Board in Alabama initiated a project to investigate a 36-inch diameter, low-pressure, concrete cylinder pipe main that provides approximately 60% of the water per day to the City of Birmingham using free-swimming in-line acoustic leak detection technology. Two acoustic anomalies resembling leaks were found with the technology. Though pinpointing the location of the suspected leaks was difficult due to the unknown grade of the pipe and the overgrown, varying topography of the area, above ground listening devices were used to find the leaks, which were then confirmed with excavation (Goodwin & Carroll, 2010)
- Bay County Utility Services Department in Florida used free-swimming in-line acoustic leak detection technology to find air pockets and leaks in two large diameter PCCP raw water mains. Eight acoustic anomalies were identified with characteristic of leaks and were confirmed using ground microphones (Murray, Carroll, & Higgins, 2009).
- In Salem, Oregon, a 36 inch RCCP and steel water supply main was assessed with a ground microphone to find a suspected leak. The pipe alignment was located using as-built maps, field locates, ground reference points, and a GPS unit. A trained technician with a ground microphone was able to confirm that the majority of leaks were concentrated at roadway and railway crossings (Bowers, et al., 2011).

Noise Correlators and Noise Loggers

Interestingly, only one example of use of noise correlators for condition assessment of drinking water pipelines by utilities was found in literature, and its use was not successful. After a 108 inch diameter PCCP raw water force main failed a series of hydrostatic pressure tests, which may be indicative of the presence of high pressure leakage, the City of Dallas Water Utilities, Texas, attempted to find the leak using noise correlators in conjunction with internal and external visual inspection. When the attempt was unsuccessful, other technologies were tried (Larsen, Mergelas, Bengtsson, Lawrence, & Thomas, 2005).

Two examples of utility use of noise correlators for the emerging practice of measuring pipe wall stiffness with acoustic waves were found:

- The Las Vegas Valley Water District in Nevada conducted a pilot study in which a 6 inch diameter AC pressure pipe wall was stiffness tested with the use of acoustic velocity measurements. The result was a measurement of a 0.73 to 0.74 inch wall stiffness, which was confirmed by excavating the pipe and measuring the wall thickness and stiffness of a coupon sample. The physical stiffness of the pipe excavated was 0.75 inches, and when phenolphthalein dye testing was done, the actual stiffness of the pipe corresponded very closely with the acoustically measured stiffness of 0.73 inches. Following the successful pilot study, Las Vegas Valley Water District used the same methodology to analyze a significant length of steel and asbestos concrete pipe. The results of the study were used to estimate the remaining life of the AC pipe and thus cut back the utility's AC sampling program (Bracken, et al., 2011).

- As part of a program for assessment of water transmission laterals constructed before 2000, the Southern Nevada Water Authority carried out acoustic testing on ACPP to determine pipe wall stiffness using noise correlators. For most of the lateral inspections, the distance was too long between access structures to make this testing possible; therefore, potholes were provided to connect wires to the pipe for additional listening stations (Ratliff & Russo, 2010).

In-Line Acoustic Leak Detection

From examination of literature reviewed, in-line acoustic leak detection technologies appear to be extremely popular and successful in assessment of drinking water pipelines. In an attempt to test and compare the tethered and free-swimming versions in 2008, Denver Water simulated leaks in an 11.7 mile long section of riveted steel and reinforced concrete cylinder pipe water transmission main of 60 to 66 inches in diameter. Both technologies were good at hearing the simulated leak. The tethered technology was excellent at locating the leak, while the free-swimming technology was deemed "good" (Turney, 2010).

Tethered In-Line Acoustic Leak Detection

Examples of utility use of tethered in-line acoustic leak detection are numerous and geographically wide-spread. In some cases, this is the technology that the utility turned to when another technology was unsuccessful at finding the source of a leak. Many pipeline materials are represented in the literature, but most are ferrous. Examples of utility use of tethered in-line acoustic leak detection are as follows:

- The City of Dallas, Texas, is the largest user of in-line acoustic leak detection technology in North America. After a 2004 pilot study, tethered, in-line acoustic leak detection technology was selected as its primary technology for large diameter mains. The current results of this program show that large volumes of water can be recovered from a relatively small number of leaks in large diameter mains (water savings from 43 leaks identified since 2004 was 3.5 MGD) (Laven & Kler, 2011).
- In 2007, Philadelphia Water Department in Pennsylvania began to use tethered, in-line acoustic leak detection technology for assessment of large diameter water transmission mains. This methodology has been particularly helpful in situations where accessibility or depth of the pipeline is an issue (Laven & Kler, 2011).
- Ogden, Utah carried out a condition assessment of 4.1 miles of 24-inch and 36 inch steel pipeline located in a canyon. Leakage inspection using tethered, in-line acoustic leak detection covered just over 50% of the pipeline (all of the 24" and about 20% of the 36"), finding 15 leaks on the 24" line and leading to the belief that there are probably additional leaks in the portion of pipeline that was not tested. However, results of the condition assessment identified potential savings to the City of about $20 million over the

replacement of the pipeline with new construction (Livingston, Champenois, & Frisbee, 2009).

- El Paso Water Utilities was one of the first utilities to implement a comprehensive condition assessment program for its water transmission mains using a variety of condition assessment technologies. One of the utility's primary goals is water conservation. It has used tethered, in-line acoustic leak detection technology to validate the integrity of SCCP, PVC, Steel, and Cast Iron water transmission mains, prioritize capital expenditures, and selectively rehabilitation individual pipe (Mergelas, Xiangjie, Roy, & Balliew, 2005).
- After a 108 inch diameter PCCP raw water force main failed a series of hydrostatic pressure tests, which may be indicative of the presence of high pressure leakage, the City of Dallas Water Utilities, Texas, attempted to find the leak using visual inspection and noise correlators. When these attempts were unsuccessful, tethered in-line acoustic leak detection technology was used to successfully pinpoint two leaks on the line (Larsen, et al., 2005).
- The Department of Water Affairs and Forestry has undertaken tethered in-line acoustic leak detection in various utilities in South Africa due to the fact that the technology is well suited to the conditions in the area because it is cost effective, has been proven in other markets, and can be performed while the pipeline is in service, as many water systems in the region are non-redundant. In South Africa, there is typically poor keeping of water pipeline records, limited budgets require that the inspection system be deployed using installed pipeline infrastructure only, and the topography of the land means that water lines typically run for very long distances at high pressures. For example, Bloem Water's 1170 mm Diameter PCP is in the process of being inspected with this technology. A total of 30 insertions were undertaken to inspect 32 km of the pipeline, and a total of five medium to large leaks were located on the pipeline. Numerous pipeline bends and air pockets were also detected and logged successfully during the inspection (Webb, et al., 2009).
- A strategic, 32 km long bulk water steel pipeline linking power stations in the Mpumalangha Province in South Africa was inspected with tethered in-line acoustic leak detection technology using 30 insertion points provided at existing air valves. At each insertion point, the pressure and flow rate were measured by removing the air valve and fitting a pressure gauge and inserting an insertion-style flow meter into the pipeline. Only 2 leaks were detected and located on the entire length of inspected pipeline (Webb, et al., 2009).
- A sliplined portion of an 80-year old steel pipeline with a current inside diameter of 560 mm was inspected with tethered inline acoustic leak detection to find the source of pressure loss experienced since the rehabilitation work done. Attempts to find the leak with several other technologies had been unsuccessful, but the tethered, in-line acoustic leak detection technology successfully pinpointed the leak (Webb, et al., 2009).

- Thames Water in the UK was the first user of in-line acoustic leak detection technology and has now run nearly 1,500 surveys averaging about 1,600 feet in length, mostly on cast iron water mains with lead joints. Over 1,250 leaks have been located with a reported accuracy rate of nearly 100% (Laven & Kler, 2011).
- An in-line leak detection program commenced recently in Manila, Philippines, and in less than two months of inspections, 72 leaks had been found (frequency of 6 leaks per mile of pipeline). The leak detection efforts are employed in conjunction with in-line video to detect illegal connections (Laven & Kler, 2011)

Free-Swimming In-Line Acoustic Leak Detection

Use of free-swimming in-line acoustic leak detection is less prevalent, though equally successful as the tethered in-line acoustic leak detection technology. This is perhaps attributable to the fact that the free-swimming version is best for use in long stretches of pipelines, of which there is less length than pipelines of distribution systems. Examples of free-swimming in-line acoustic leak detection for use by utilities in drinking water pipeline condition assessment are as follows:

- The Washington Suburban Sanitary Commission has experienced several premature, catastrophic failures of PCCP installed during the 1960's and 1970's and thus implemented a PCCP management program. The first step of the program involves the use of free-swimming, in-line acoustic leak detection technology to locate pipeline joint and barrel leaks before dewatering the pipelines and conducting internal inspections (Fick & Wagner, 2010).
- In 2009, Birmingham Water Works Board in Alabama initiated a project to investigate a 36-inch diameter, low-pressure, concrete cylinder pipe main that provides approximately 60% of the water per day to the City of Birmingham using free-swimming in-line acoustic leak detection technology. Two acoustic anomalies resembling leaks were found with the technology. Though pinpointing the location of the suspected leaks was difficult due to the unknown grade of the pipe and the overgrown, varying topography of the area, above ground listening devices were used to find the leaks, which were then confirmed with excavation (Goodwin & Carroll, 2010)
- Louisville, Kentucky assessed a 24-inch diameter cast iron pipeline with mortar lining with free-swimming in-line acoustic leak detection technology as a demonstration of the technology's ability not only to identify leaks but assess the pipe wall stiffness by measuring the velocity of a low frequency pulse as it propagates along the pipe. Pulsers are attached to typical fittings and valves found on the pipes. The technology was able to detect 12 natural leaks and simulated leaks in three pits. Though it is unlikely for this added feature of the technology to identify individual pits in a pipeline, it is an effective tool to highlight areas where a cluster of pits compromises hoop stiffness or where there is a general deterioration of the pipe wall, as well as being able to identify and locate the joints along the pipeline by recognizing the change in stiffness at each joint (Paulson & Nguyen, 2010).

- Bay County Utility Services Department in Florida used free-swimming in-line acoustic leak detection technology to find air pockets and leaks in two large diameter PCCP raw water mains. Eight acoustic anomalies were identified with characteristic of leaks and were confirmed using ground microphones (Murray, et al., 2009).
- Toho Water Authority used free-swimming in-line leak detection to assess an above-ground 36-inch diameter PCCP reclaimed water transmission main. This leak detection technology was chosen because of the need to keep the line in service and because of the need to use a cost-efficient technology for inspection of the entire 21 km length of the pipeline. The inspection was completed in approximately 8.5 hours and identified one leak (Po & Xing, 2011).

Acoustic Monitoring Systems

Both the older, less useful, array based acoustic monitoring systems and the newer fiber optic monitoring systems were found mentioned in literature with examples of utility use. However, mention of the use of the fiber optic systems was far more prevalent than mention of the use of the array based systems. Examples of utility use of fiber optic acoustic monitoring systems for condition assessment of drinking water pipelines are as follows:

- Fiber optic monitoring systems have been found to be advantageous due to their low cost, better spatial resolution, negligible attenuation of signals, low energy requirement, and the fact that a single system is capable of monitoring 80 miles of pipelines (Agarwal & Sinha, 2010).
- As part of Washington Suburban Sanitary Commission's PCCP management program, 77 miles of PCCP 48 inches or greater in diameter are inspected with a variety of technologies, then the necessary repairs and/or replacements are made, then an acoustic fiber optic monitoring system is installed to detect wire break activity within the in-service pipeline. The AFO cable is inserted inside the pipeline and connected to an external data acquisition system that not only contains the light source for the AFO cable, but a monitoring system that detects, records, and filters all detected acoustic activitiy in the pipeline. Acoustic events are sent via email to WSSC as well as published on the web (Fick & Wagner, 2010).
- Both the San Diego County Water Authority and San Francisco Public Utilities Commission in California have used acoustic fiber optic monitoring systems, and have found that rapid refill of the PCCP following the shut down and dewatering process causes stress and unusually high numbers of wire breaks. A slow refill process prevents this from happening (Stroebele, et al., 2010).
- An acoustic monitoring system installed by Providence Water in a 102-inch PCCP aqueduct that had catastrophically failed in 1996 resulted in the realization that depressurization resulted in stress on the pipeline and an unusually high number of wire breaks (Stroebele, et al., 2010).
- The very long, above-ground PCCP water transmission line that is the Great Man Made River Project in Libya was initially inspected with electromagnetic technologies, but now

consumer demand is such that dewatering the pipeline to perform electromagnetic inspection is no longer an option. The system now primarily relies upon fiber optic acoustic monitoring, which makes it possible to monitor large sections of the line and process the results to effectively manage the system while under normal operation. Since 2004, there have been 17 interventions to repair or replace the pipe based solely on acoustic monitoring. The system is also used to monitor the effectiveness of the retrofitted cathodic protection system, by showing the deterioration trends leveling out after its installation (O. Essamin, Bubteina, Lenghi, Feghi, & Wrigglesworth, 2011).

- The City of Houston, Texas, uses acoustic fiber optic monitoring systems to monitor approximately 4,500 feet of an 84-inch diameter PCCP and 24,000 feet of a 66-inch diameter line. To install the cable, the lines had to be isolated, drained and cleaned. The cost of modifications to the pipe required to permit installation required significant commitment from the City, because the cable must exist the pipe at each end and on each side of in-line isolation valves. A protocol for the analysis of data and assessment of risk associated with an acoustic event, and corrective action to be taken was developed, making the monitoring system part of the systems Emergency Action Plan for failed pipelines (Morris, Henry, & Gruber, 2010).

Examples of utility use of array based acoustic monitoring systems for condition assessment of drinking water pipelines are as follows:

- In 1979, Howard County, Maryland's PCCP inventory began experiencing failures. The utility implemented an array-based acoustic monitoring program in 2000 to evaluate the condition of approximately 18 miles of PCCP for a minimum of three months at a time. By using a number of sensor configurations, development of signal attenuation curves have been developed for different diameter PCCP. The sensor spacing has been found to be critical to the success of the acoustic monitoring program (Diaz, Campbell, & Holley, 2005).
- The City of Houston also uses array based monitoring systems to monitor various prioritized PCCP lines for a minimum of four months at a time as part of the City's condition assessment program (Henry & Long, 2009).

Impact Echo and Spectral Analysis of Surface Waves (SASW)

These technologies were found in literature mentioned as being used in conjunction with multiple other technologies for condition assessment of drinking water PCCP lines. Examples of this type of use are as follows:

- The Washington Suburban Sanitary Commission has experienced several premature, catastrophic failures of PCCP installed during the 1960's and 1970's and thus implemented a PCCP management program. 77 miles of PCCP 48" and above in diameter are inspected on a seven year cycle with manned internal electromagnetic inspections in conjunction with visual, sounding, sonic, and ultrasonic testing. The sonic/ultrasonic direct and resonant frequency measurements are obtained using a small projectile impact energy source, and a hand-held four sensor array, which determines if the contrete lining and/or core is experiencing loss of strength or experiencing micro-cracking, and provides information on the condition and thickness of the outer coating of mortar on PCCP. Limited when analyzing short pipe sections, entry ports, adapters or sections with outlets, blow offs, or air relief valves because these pipe sections are constructed differently than traditional pipes and values considered normal for PCCP do not apply. Does not identify the presence of broken prestressing wires (Fick & Wagner, 2010).

- The Metropolitan Water District of Southern California implemented a PCCP condition assessment program in 1996 which included internal inspections that uses impact echo in conjunction with direct visual assessment and rod sounding. Since that time, additional technologies have been added to the PCCP inspection process (Harren & McReynolds, 2010).
- In order to avoid catastrophic failure, protect structural integrity of pipelines, determine condition and extend service life, and develop strategies for maintenance and renewal, the San Diego County Water Authority uses impact echo testing as one of many technologies for inspecting PCCP lines (Grigg, 2006).
- The New Jersey Water Supply Authority conducted an impact echo (sonic/ultrasonic) survey to assess the condition of a 108 inch diameter PCCP force main. This technology is liked because it provides a more holistic approach than sounding, acoustical emission, and magnetic surveys, which may only find pipe with broken wires. Impact echo testing detects anomalies in the concrete that may lead to future failure as well as delaminated coating, improper bedding, and overloaded pipe. Approximately 5% of the pipes in the line inspected exhibited anomalous readings that gave rise to varying degrees of concern. Based upon the results, a pipeline was excavated and found to have several longitudinal cracks that extended through the entire concrete coating (Fisk & Marshall).

Ultrasonic Testing Methods

While mention of ultrasonic wall thickness measurement for utility condition assessment of drinking water pipelines was found during the literature review, there was no mention of use of long range guided ultrasonic wave technology.

<u>Ultrasonic Wall Thickness Measurement</u>

Ultrasonic wall thickness measurement was mentioned primarily as a method to test the thickness of steel pipelines. Examples of utility use of this technology for drinking water pipeline condition assessment are as follows:

- Ogden, Utah carried out a condition assessment of 4.1 miles of 24-inch and 36 inch steel pipeline located in a canyon. Twelve locations were excavated and ultrasonic wall thickness testing performed along with coupon sampling. There were indications of significant pitting on the 24 inch diameter line but not on the 36 inch diameter line. The results of this investigation provided the City with potential savings of $20 million over the replacement cost (Livingston, et al., 2009).

- During the condition assessment of a 36 inch diameter, steel water supply main in Salem, Oregon excavated parts of the steel pipe had the pipe wall thickness measured by taking ultrasonic thickness measurements (Bowers, et al., 2011).
- To investigate a trunk main failure, Water Corporation in Australia used ultrasonic testing to test metal thickness in conjunction with internal camera and visual inspection and coating integrity investigations. A large number of external defects were found to be present, mostly where third party infrastructure impinged on the main and included damage to the coating, gouge marks, chain marks, and pitting (Marlow, et al., 2007).
- Following a corrosion-related failure, Southern Nevada Water Authority in Nevada did direct assessment in 2008 as part of assessment of a large diameter cement mortar lined and coated steel line. Based on previous indirect assessment results, four sites exhibiting the highest risk or corrosion were excavated and broadband electromagnetic as well as ultrasonic testing was used to measure the pipe wall thickness. BEM was used to evaluate its capabilities in lieu of ultrasonic wall thickness measurement for future assessments. BEM measured the wall thickness over a two inch square but did not require removal of the mortar before use. Ultrasonic was more precise, but required the exposure of the steel pipe wall for use (Ratliff, Russo, Frechette, & Fox, 2009).

Electric and Electromagnetic Based Methods

The primary method used for condition assessment of drinking water pipelines within this category of technologies is remote field technologies.

Remote Field Technologies

There were two examples of remote field technology being used by utilities for assessment of drinking water pipelines that were not constructed of PCCP. One example used a man-entry tool, and the other used a hand-held version for measurement externally:

- Following an initial investigation which identified stray current failures within 300m sections of twin 54” steel mains in New Territories, China, man entry RFT condition assessment was performed to attain more detailed information. The results of the inspection helped to determine that a fully structural polyethylene liner was needed to rehabilitate the 300m sections of main. The detailed condition assessment allowed the utility to selectively rehabilitate the necessary sections, lowering the total replacement costs and the risk of failure of the main (Ferguson, 2010).
- A section of an 80-year old cast iron water main in Sydney, Australia was excavated and exposed to determine the “original” wall thickness of the pipe using a hand-held RFT tool. This technology was used as the pipe had undergone external graphitization and ultrasonic wall thickness measurement could therefore not be used (Ferguson, 2010).

The many other mentions of use of RFT involve the technology’s use for assessment of PCCP.

- The Washington Suburban Sanitary Commission has experienced several premature, catastrophic failures of PCCP installed during the 1960's and 1970's and thus implemented a PCCP management program. 77 miles of PCCP 48" and above in diameter are inspected on a seven year cycle with manned internal electromagnetic inspections in conjunction with visual, sounding, sonic, and ultrasonic testing (Fick & Wagner, 2010).
- The Metropolitan Water District of Southern California initiated a PCCP condition assessment program in 1996 and added RFTC to its condition assessment tools in 2000 (Harren & McReynolds, 2010).
- Since experiencing a catastrophic failure in a PCCP, Denver Water has conducted condition assessment of the pipeline using RFTC. In addition to using structural analysis, sections of the pipe were destructively tested to determine the accuracy of the electromagnetic readings. After electromagnetic testing and dissection of the pipelines in 1999 and in 2003, it was found that between 11% and 40% of the wire breaks predicted were found. The overestimation of the actual number of prestress wire breaks is partially attributable to the lack of field calibration of the electromagnetic response of the equipment to the actual pipe designs and construction. The testing procedure is also subject to interferences from pipe construction features (Bambei & Lewis, 2005).
- After several major failures of the very long, above-ground PCCP water transmission line that is the Great Man Made River Project in Libya, it was determined that the cause was chloride-induced corrosion of the prestressing wires. An extensive survey was undertaken which included, at the beginning of the program, external rod sounding and potential surveys. Use of RFT inspection was introduced in 2000 (Omar Essamin, et al., 2005). The collected condition information has been used to create a pipeline deterioration model.
- After finding a leaking PCCP, Elizabethtown Water Company in New Jersey decided to perform a non-destructive electromagnetic internal, manned inspection using RFT. Based on the results of the inspection, which reported information on broken wires, the utility elected to perform selective replacement and rehabilitation of portions of the pipeline (Lewis & Schaefer, 2004).
- El Paso Water Utilities was one of the first utilities to implement a comprehensive condition assessment program for its water transmission mains using a variety of condition assessment technologies. One of the utility's primary goals is water conservation. It has used RFT inspection to establish the baseline condition of its PCCP lines, followed by inspection with acoustic emissions sensors (Mergelas, et al., 2005).
- The Tarrant Regional Water District in Texas operates two 120km long large diameter PCCP lines to supply water to over 1.5 million people. Both have suffered failures due to corrosion, hydrogen embrittlement, and inadequate thrust restraint and about 800 pipe segments are damaged. The pipes were assessed with manned internal RFT, requiring pipe dewatering, and the results were used in a model to determine the remaining strength

of the damaged pipe. About 100 pipe segments were damaged enough to be at high risk of failure and replaced immediately and 250 more were in a state in which further damage would put them at risk of failure. A fuzzy risk model was used to prioritize the replacement of the lines (Marshall, Zarghamee, Mergalas, & Kleiner, 2005).

- The City of Houston uses electromagnetic inspections to assess a baseline level of prestressing wire deterioration in their large diameter water transmission PCCP lines as part of a water transmission line condition assessment program. Limitations found include the importance of good calibration and the fact that it only provides a snapshot of broken wires, but not a rate of deterioration. A rate of deterioration can be obtained by performing multiple surveys over a number of years, but this is costly and disruptive to the water system (Henry & Long, 2009).
- As part of a program for assessment of water transmission laterals constructed before 2000, the Southern Nevada Water Authority performed internal RFT inspections on PCCP lines (Ratliff & Russo, 2010).
- In order to avoid catastrophic failure, protect structural integrity of pipelines, determine condition and extend service life, and develop strategies for maintenance and renewal, the San Diego County Water Authority, California, uses RFT as one of many techniques for inspecting PCCP lines (Grigg, 2006)
- Providence Water, Rhode Island, implemented a condition assessment project for inspection of a 102" PCCP aqueduct in 2005 and 2006 including an internal, manned RFTC inspection in conjunction with visual and sounding inspections, resistivity testing of PCCP wires (requiring excavation to the crown of the pipe, chipping hammer to expose the prestressing wire, and a resistance meter used to measure the resistance of a prestressing wire loop, which if high, indicates that it is broken), and acoustic fiber optic monitoring system (Higgins, et al., 2007).

Two examples of utility use of the free-swimming version of this technology were found, and are as follows:

- After failure of a large diameter PCCP water main, Miami-Dade Water and Sewer Department in Florida initiated inspection of large diameter PCCP and PCP water mains with a free-swimming RFT tool, which was necessary to carry out a rapid inspection with minimal operation downtime and thus not adversely affect customers. Approximately 40 miles of large diameter transmission mains had been inspected in 2011 with 2% showing evidence of broken prestressing wires. (Terrero, et al., 2011).
- Dallas County/Parks Cities Municipal Utilities District in Texas assessed the condition of a 36 inch diameter PCCP with a free-swimming RFT tool. It was necessary to use a tool that did not require the pipeline to be taken out of service for a long period of time, as the line is currently the only water supply transmission line for two major communities in the area. Based on the inspection results, the rehabilitation that had been planned for the line can be deferred to future years (McDaniel, 2010).

An in-line, robotic version of an RFT tool that can operate in flow conditions was made available commercially in the past few years, and there are two examples of utility use of this version of the technology:

- Dallas Water Utilities initiated a proactive condition assessment program for large diameter PCCP water mains after a major failure in 2001, utilizing RFT technologies that required the lines to be dewatered first. After a failure on an 84" PCCP that was very difficult to dewater because of its lack of drain valves in early 2009, a contractor mobilized an emergency RFT inspection with a robotic inspection vehicle that required only one access point to be dewatered so it could be set up, then could conduct the rest of the inspection underwater. The line had taken 3 months to dewater in 2004. After the emergency inspection, the Utility immediately requested the remaining 13 miles be inspected. The ability to be able to perform condition assessments under river crossings is critical for the utility (Payton, Larsen, & Arredondo, 2010).
- To inspect 99-inch diameter PCP owned and operated by the Organismo de Cuenca de Aguas del Valle de Mexico, manned inspections had been performed with RFTC in 2007 and 2008. However, there were dewatering difficulties so not all sections could be inspected, and the pipeline did not have blow offs at all the low points and could only be taken out of service for 36 hour periods, so complex dewatering methods were not an option. However, the development of a large diameter robotic internal RFTC tool that requires only a section of the pipe to be dewatered allowed the successful condition assessment of the pipeline. Difficulties included a power outage that caused the tool to flop over while on a 16% slope (technicians were able to pull the tool back and right it) and some difficulties in setting up the tool at access points with high water levels (divers were used), and the tool becoming stuck on an obstruction 400 feet from an insertion point (divers freed the device) (Psutka & Kong, 2009).

An RFT tool that can be used for condition assessment of PCCP externally was also developed recently, and there is one example of utility use of that tool for condition assessment of a drinking water pipeline. Greater Cincinnati Water Works used RFT to inspect a 48" transmission main installed inside an abandoned subway tunnel where it is exposed to the elements within the tunnel as well as to anything that leaks through the road above, including undiluted road salt. The main has been covered in plastic where necessary to minimize these problems. In 2008, a portion of the main was dewatered and inspected with manned RFT. The robotic system was not used due to the logistical challenges of bringing it into the subway tunnel. Since two sections could not be dewatered sufficiently for manned access, they were not inspected at that time. By 2009, and external RFT tool had been developed and was used successfully and enabled the utility to save the time and cost of dewatering the pipeline. Another suggested use for the external RFT tool is confirming and/or refining results of wire break estimations made by other tools through excavation (Biggar, 2010).

One example of utility use of BEM for condition assessment of drinking water pipelines was found: Following a corrosion-related failure, Southern Nevada Water Authority in Nevada did direct assessment in 2008 as part of assessment of a large diameter cement mortar lined and coated steel and PCCP line. Based on previous indirect assessment results, four sites exhibiting the highest risk or corrosion were excavated and broadband electromagnetic as well as ultrasonic testing was used to measure the pipe wall thickness. BEM was used to evaluate its capabilities in lieu of ultrasonic wall thickness measurement for future assessments. BEM measured the wall thickness over a two inch square but did not require removal of the mortar before use. Ultrasonic was more precise, but required the exposure of the steel pipe wall for use (Ratliff, et al., 2009).

Ground Penetrating Radar (GPR) and Pipe Penetrating Radar

No examples of use of pipe penetrating radar for inspection of drinking water pipelines were found during the literature review. However, two examples of use of GPR for condition assessment of drinking water pipelines were found during the literature review, and they are both quite unique. The examples are as follows:

- As part of a program for assessment of water transmission laterals constructed before 2000, the Southern Nevada Water Authority plans to perform ground penetrating radar testing for RCP lines excavated at sites exhibiting the highest potential of deterioration due to previously determined internal and/or external conditions. The GPR unit sits directly on top of the concrete structure and characterizes the condition through the wall (Ratliff & Russo, 2010).
- In order to map tunnel lining conditions and locate concrete deterioration and voids, GPR surveying was carried out with a custom built cart in a water supply tunnel in Victoria, Canada. The tunnel is 8.8 km long and 2.3 meters in diameter and was surveyed in both directions in two days. Major anomalies were drilled to verify interpretations of voids behind the liner. Five major types of anomalies were identified, including variations in water content, void spaces, embedded wood, faults, and metallic objects. The processed data provided a great deal of information on the condition of the tunnel lining (Parkinson & Ekes, 2008).

Electrical Continuity Testing

Two examples of electrical continuity as a condition assessment method for PCCP were found during the literature review, and two examples of electrical continuity for use with other types of pipelines were found. The examples found are as follows:

- The electrical continuity of a 36 inch diameter steel water supply main in Salem, Oregon was assessed during a corrosion assessment of the line. At six test pits, test stations were installed. Brackets were welded onto the steel pipe and wire test station leads were run from the brackets into a valve box installed at grade. A substantial current was induced in the pipeline at a test station and the influence was verified at the adjacent test stations, confirming electrical continuity along most of the steel pipeline (Bowers, et al., 2011).
- As part of a program for assessment of water transmission laterals constructed before 2000, the Southern Nevada Water Authority performed electrical continuity surveys (Ratliff & Russo, 2010).
- To verify the results of RFTC inspection of water mains, Miami-Dade Water and Sewer Department in Florida has used electrical continuity testing for PCCP that does not have

shorting straps under the prestressing wire and with non-cylinder PCP (Terrero, et al., 2011).

- Continuity testing was performed on PCCP previously assessed with RFTC technologies by Aurora Water in Colorado. An attempt was made to relate wire continuity measurements to RFTC results. The correlation of the continuity tests with the number of RFTC-indicated broken wires varied from pipe to pipe. However, the continuity testing was able to determine the presence and location of broken wires and is a viable ND technology for that purpose (Catalano, Parks, & Vidmar, 2009).

Flow Based Methods

Flow based methods for condition assessment were not prevalently mentioned with examples of utility use in the literature review. When flow was mentioned, it was typically in conjunction with the use of SCADA.

Flow Meters

The only example of utility use of flow for drinking water pipeline condition assessment found was from Salem, Oregon. The utility took daily SCADA meter readings to and from a 36 inch diameter RCCP and steel water supply main when a leak was suspected (Bowers, et al., 2011).

Physical Force Based Methods

Physical force based methods of condition assessment were also not commonly mentioned as utility practices for drinking water pipelines during the literature review. Transient pressure monitoring was the only force based method for which a literary example of utility use was found.

Transient Pressure Monitoring

While reports and other literature suggest that pressure monitoring is a commonly used tool for condition assessment of drinking water pipelines, only one example of utility usage of this methodology was found in the literature review. The City of Houston uses transient pressure monitoring as part of its water transmission line condition assessment program. Potential areas of distress are identified by running models to determine where pressure transients have occurred in the past. This method is one of many condition assessment techniques used to provide a full picture of the system's condition (Henry & Long, 2009).

Rod Sounding

See section on Acoustic Based Methods for more information.

Impact Echo and Spectral Analysis of Surface Waves (SASW)

See section on Acoustic Based Methods for more information.

Temperature Based Methods

Temperature based methods of condition assessment for drinking water pipelines is another category of condition assessment technique that did not produce many examples of utility use.

Infrared Thermography

The only example found involving a temperature based methodology for condition assessment of a drinking water pipeline involved use of infrared thermography and took place almost 30 years ago. In 1983, infrared thermography was used by Metropolitan St. Louis Sewer District, Kentucky, to locate a leak in a buried water pipeline. Prior to the inspection, utility personnel had observed street pavement sinking up to 6 inches along a 600 foot section of a downtown street. In-sewer visual inspections had located only 3 dime-sized water infiltration points in the large diameter sewer located alongside the pressurized water line in the street. During the infrared thermographic inspection, a cool area was located perpendicular to the buried water pipe, starting at the water line and spreading outward toward the sewer line. The cooler surface area was determined to be caused by the heat sinking ability of the water plume as it spread out from the water line leak and flowed down the outside of the nearby sewer. An erosion area above the water line was also located with the IR thermographic inspection, visible as a warmer signature in the thermographic image. The water line leak had been carrying soil into the infiltration points of the sewer line and the void area had caused the pavement sinking that had been observed (Weil & Graf, 1991).

Environmental Testing

By characterizing the environment surrounding a pipeline, one of the most important components for predicting that pipeline's life can be ascertained (Lillie, Reed, Rodgers, Daniels, & Smart, 2004). Considering this factor, though there were a great deal of examples of environmental testing used by utilities as part of a condition assessment of a drinking water pipeline, it is surprising that more were not found.

Soil and Groundwater Testing

Many examples of utility soil testing to determine the potential for corrosion of nearby pipelines were found:

- The Metropolitan Water District of Southern California requires pre-construction soil corrosivity evaluations, which generally rule out mortar coated steel or PCCP as a pipeline option in corrosive soils (Harren & McReynolds, 2010).
- Soil resistivity measurements are taken around the Great Man Made River project PCCP lines in Libya for combination with other condition assessment inspection data and use in a pipeline deterioration model (Omar Essamin, et al., 2005).
- Following a corrosion-related failure, Southern Nevada Water Authority in Nevada used a soil corrosivity evaluation in 2007 as part of assessment of a large diameter cement mortar lined and coated steel pipe. As part of the evaluation, an electromagnetic conductivity survey was performed at all accessible locations along the entire alignment and based on analysis of these results, soil and groundwater (if encountered) was sampled and tested at 23 locations. Soil was tested for resistivity and moisture levels (Ratliff, et al., 2009).
- As part of a corrosion assessment for a 36" diameter steel water supply main, Salem, Oregon had soil resistivity, pH, and redox potential of samples around the line tested in 2009. A 1.2 mile segment of the line was identified as being susceptible to failure due to seasonal soil corrosion or oxidation reduction corrosion (Bowers, et al., 2011).
- As part of a program for assessment of water transmission laterals constructed before 2000, the Southern Nevada Water Authority performed soil corrosivity evaluation testing

which included soil resistivity testing, soil sampling and testing, and groundwater sampling and testing, when groundwater was encountered. Samples were analyzed and classified as 1) severely corrosive to ferrous metals; 2) aggressive with respect to exposure of cement-mortar or concrete embedded steel to the mitigation of chloride; and 3) subject to severe sulfate attach alone. Groundwater was encountered and sampled at only one of the 26 sites identified for sampling (Ratliff & Russo, 2010).

- To assess the condition of an 80-year old cast iron water main in Sydney, Australia, 103 small soil samples at pipe depth were taken along the length of the pipe and tested with linear polarization resistance. The results were used in algorithms to determine probabilities and times to failure for different sections of the main (Ferguson, 2010).
- Because of the existence of many utility lines with cathodic protection systems parallel to North Texas Municipal Water District water mains, protecting the utility's water mains from corrosion was very important. Part of what must drive choices involves testing soil and determining soil corrosivity based on criteria including soil resistivity, pH, sulfate content, and chloride content (Maughn, Sibert, & Scott, 2011).

One example of utility use of groundwater testing was found, though the example was somewhat unique. After a 66-inch diameter steel water main in the City of Houston was damaged during unassociated concrete pile driving construction activities, the line was excavated for condition assessment. Water present at the excavation was sampled and screened in the field for chlorine content, and found to be free to chlorine. Therefore, the water was not likely attributable to a leak in the water main (Saenz & Card, 2011).

Pipe to Soil Potential/Stray Current Mapping

Potential tests and stray current mapping were found to be quite common during the literature review of utility practices for drinking water pipeline condition assessment. Examples found in the literature are as follows:

- The Metropolitan Water District of Southern California has corrosion crews test for the presence of stray currents from surrounding foreign pipeline cathodic protection systems and upgrade stray current mitigation and cathodic protection systems as areas at risk of corrosion are identified (Harren & McReynolds, 2010).
- After several major failures of the very long, above-ground PCCP water transmission line that is the Great Man Made River Project in Libya, it was determined that the cause was chloride-induced corrosion of the prestressing wires. An extensive survey was undertaken which included, at the beginning of the program, potential mapping in conjunction with external rod sounding. Additional technologies were introduced in 2000 (Omar Essamin, et al., 2005).
- Following a corrosion-related failure, Southern Nevada Water Authority in Nevada used a pipe potential survey in 2007 as part of assessment of a large diameter cement mortar lined and coated steel and PCCP line. Nineteen test stations were installed along the pipe and nine at appurtenances, and the opportunity was taken to perform direct assessment at those locations. Electrical continuity testing confirmed that the steel pipe was continuous

through appurtenances with one discontinuity. Baseline potential testing established a baseline reference to monitor future changes in potentials in order to be able to estimate the probability that corrosion is occurring and evaluate corrosion control, if installed. A close-interval survey was conducted on 31,000 feet of pipeline to identify anodic areas, where the pipe is likely corroded to protect adjacent cathodic areas. During this survey, a significant amount of stray current was measured (Ratliff, et al., 2009).

- Pipe-to-soil potential was measured for a 36" diameter steel water supply main in Salem, Oregon, as part of a corrosion assessment for the line. The pipe-to-soil potential was measured at six test stations, and an over-the-line potential survey was conducted where the steel pipe was found to be discontinuous. Areas which have a high probability for corrosion to occur were identified (Bowers, et al., 2011).
- As part of a program for assessment of water transmission laterals constructed before 2000, the Southern Nevada Water Authority performed soil corrosivity evaluation testing with included a soil-to-pipe potential survey and stray current survey (Ratliff & Russo, 2010).
- As an initial investigation technique, stray current failures were detected in twin 54" steel mains in New Territories, China in 2003 and 2003. This information was used to follow-up with a more detailed assessment (Ferguson, 2010).

Other Methods

Coupon and Lining Sampling

Examples of coupon sampling as part of utility condition assessment for drinking water pipelines are as follows:

- Ogden, Utah carried out a condition assessment of 4.1 miles of 24-inch and 36 inch steel pipeline located in a canyon. Twelve locations were excavated and ultrasonic wall thickness testing performed along with coupon sampling. Coupons were tested for wall thickness and yield strength. The results of this investigation provided the City with potential savings of $20 million over the replacement cost (Livingston, et al., 2009).
- A 36-inch diameter RCCP and steel water supply main in Salem, Oregon had samples cut from excavation sites as part of a condition assessment program for the line. The wall thickness of the concrete and steel pipe samples were measured and the coating and lining characteristics of the steel pipe inspected (Bowers, et al., 2011).
- Scottish Water, UK, uses both opportunistic and planned pipe sampling to assess its water main conditions and develop models of pipe condition and performance. Overall, the models have been built up from 7,000 pipe samples, with sampling being focused on problem pipe materials and less on sampling from plastics. In an average year, 200 samples are taken and used to refine deterioration curves (Marlow, et al., 2007).

One example of a utility removing much larger samples of pipeline for condition assessment purposes was found as well. After five failures had occurred in a 250 mm diameter cast iron water main, CSIRO in Australia removed five sections of the pipe wall, each approximately one meter long. Each section was grit blasted to remove graphitized corrosion product and expose the remaining metallic material. A grid pattern was scribed on the outer surface of each exhumed section and the remaining wall thickness was measured in each section of the grid with calipers (Marlow, et al., 2007).

State-of-the-Art Practice Review for Technology Use

In addition to a literature review, a practice review of condition assessment technology and methodology use with drinking water pipelines was performed. The practice review involved obtaining information directly from utilities regarding their use of condition assessment techniques.

Definition of Scope

The practice review focused on gathering information directly from utilities about their experiences with use of certain technologies and/or methodologies for condition assessment. The focus was on the choices made regarding these condition assessment techniques as well as the advantages and limitations of the techniques within certain projects or programs. While some information was gathered on costs, surrounding regulatory issues, data analysis, and the place of the condition assessment work done within the larger umbrella of asset management, the focus of the practice review centered on information that could be mined to help other utility personnel understand and choose the available techniques for condition assessment of drinking water pipelines.

Methods for Data Mining

Data mining began with the creation of guiding questions for utilities, which were intended for use during meetings with utilities and utility follow-up to further guide the utilities in the type of information sought by the research team. The guiding questions consisted primarily of open-ended questions in order to discourage a survey-like response and to get the most information on the subtleties of use of different condition assessment technologies and their advantages and limitations according to the region of use, the size of the utility, the pipeline material and diameter, and other aspects of the work.

The research team members located and targeted experienced utilities of varying sizes and geographical locations in the United States. Fifteen international utilities were also targeted. When requested, Virginia Tech signed Memorandums of Understanding (MOUs) with utilities across the nation. The MOUs protect utility information shared with the research team. The information cannot be shared until utility approval is obtained.

The utility data mining process was as follows: A knowledgeable contact from the utility was identified and a meeting with this contact and others the contact deemed appropriate was held. The aim of this meeting was to share the project objectives with the utility, to request the utility's participation in the project, and to discover the extent of the utility's experience with pipeline condition assessment. If the utility agreed to participate in the project, research team members set up and held interviews with appropriate managers, staff members and/or consultants in order to data mine experiential information and request all relevant documentation on the condition assessment technology or methodology. In this manner, detailed information on utility experiences was captured in addition to anecdotal information. Because of time constraints, it was often not possible for the research team to cover all of a single utility's experiences. In these cases, the research team focused on data mining information on as many categories of condition assessment technologies as possible and asked about unique experiences.

Utility Practices Covered

The utility practices covered are summarized in Table 2.

Table 2. Summary of Utility Practices Covered

Utility, State (number of case studies)	Condition Assessment Techniques Employed
Aurora Water, CO (3)	Rod Sounding Ultrasonic Wall Thickness Measurement Direct Assessment Probing Remote Field Technologies Acoustic Monitoring Systems Transient Pressure Monitoring
Baltimore City Bureau of Water and Wastewater, MD	Direct Assessment Rod Sounding Remote Field Technologies
Baltimore County Department of Public Works, MD	Direct Assessment Remote Field Technologies
Billings Department of Public Works, MT	Noise Correlators and Noise Loggers
Dover Utilities Commission, NH	Noise Correlators and Noise Loggers
Fairfax Water, VA	Soil Testing
Howard County Department of Public Works, MD (2)	Rod Sounding Acoustic Monitoring Systems Direct Assessment Remote Field Technologies Soil Testing
Korea Water Resources Corporation, South Korea	Analysis of Existing Data
Massachusetts Water Resources Authority, MA	Noise Correlators and Noise Loggers Ground Microphones
Metropolitan Water District of Southern California, CA	Remote Field Technologies
Miami-Dade Water and Sewer Department, FL	Remote Field Technologies
Montgomery County Water Services Department, OH	Analysis of Existing Data
Philadelphia Water Department, PA	In-Line Acoustic Leak Detection
Portland Water Bureau, OR (3)	Noise Correlators Ultrasonic Wall Thickness Measurement Direct Assessment Hand-held Digital Camera
San Francisco Public Utilities Commission, CA (2)	Magnetic Flux Leakage In-Line Acoustic Leak Detection
Seattle Public Utilities, WA (2)	Remote Field Technologies Direct Assessment Analysis of Existing Data
Sydney Water, Australia (2)	Ultrasonic Wall Thickness Measurement Direct Assessment Magnetic Flux Leakage Soil Testing
Washington Suburban Sanitary Commission, MD (4)	Acoustic Monitoring Systems Remote Field Technologies In-Line Acoustic Leak Detection

These utility practices are broken down by technology and further explained below.

Direct Assessment

Case study information was gathered from utilities about the practice of direct assessment. The utilities from which information was gathered are illustrated in Figure 2. Aurora Water provided information on direct assessment of two large diameter water pipelines with manned entry. Baltimore City Bureau of Water and Wastewater provided information on the internal direct visual assessment of a 54-inch diameter PCCP water transmission main in conjunction with rod sounding and electromagnetic inspection. Portland Water Bureau provided information on direct visual assessment above ground for high risk drinking water pipeline bridge crossings. Sydney Water provided information on use of direct visual assessment for inspection of a buried cast iron water main at specific excavation sites. Seattle Public Utilities provided information on their internal direct visual assessment of large diameter steel water pipes that was performed in 1977 and involved rating the pipeline on a 10 point scale to record its condition. Howard County Department of Public Works provided information on their PCCP inspection program, which covers water transmission mains, and was started in 1999 with manned entry for visual inspections and rod sounding and then moved on to more advanced techniques.

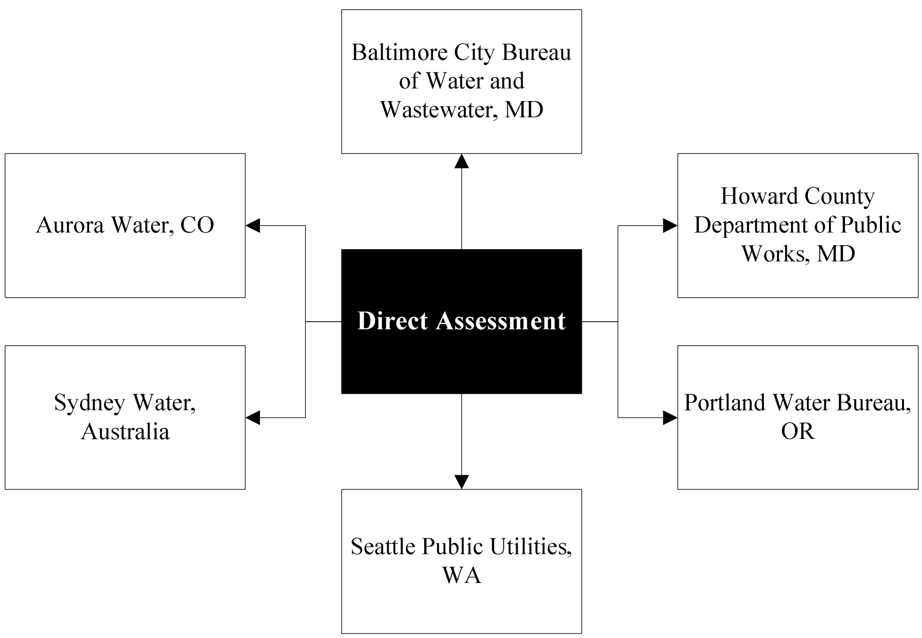

Figure 2. Utilities from which Information on the Practice of Direct Assessment for Condition Assessment of Drinking Water Pipelines was Gathered

Hand-Held Digital Cameras

As shown in Figure 3, Portland Water Bureau was the only utility that provided direct information on use of a hand-held digital camera for condition assessment of drinking water pipelines. Portland Water Bureau used the camera in combination with direct assessment to capture the condition of all drinking water pipeline bridge crossings. Each pipeline was assigned a preliminary risk rating based upon likelihood of failure and consequence of failure, then pipes that were rated as medium, high, or extreme risks were inspected to confirm the condition estimate. Pipelines were taken to document the pipeline and site conditions when it was warranted.

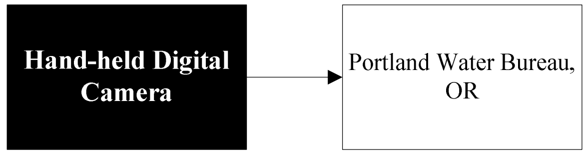

Figure 3. Utilities from which Information on the Use of Hand-Held Digital Cameras for Condition Assessment of Drinking Water Pipelines was Gathered

Rod Sounding

Information on the use of rod sounding for condition assessment of drinking water pipelines was gathered from two utilities, as shown in Figure 4. Howard County Department of Public Works initially used rod sounding in conjunction with manned entry and visual inspection as a standard part of their program for inspection of large diameter PCCP water transmission lines, but later moved on to more advanced technologies. Aurora Water provided information on the use of rod sounding in conjunction with other techniques for the inspection of two particular stretched of PCCP. Baltimore City Bureau of Water and Wastewater provided information on the use of rod sounding in conjunction with direct internal visual assessment and electromagnetic inspection of a 54-inch diameter PCCP water transmission main.

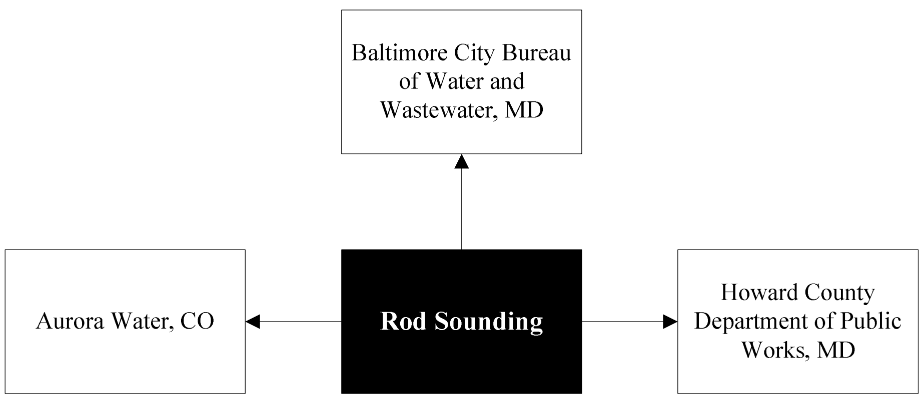

Figure 4. Utilities from which Information on Use of Rod Sounding for Condition Assessment of Water Pipelines was Gathered

Aurora Water used sounding as part of an internal inspection on a 66-inch diameter pipeline consisting of both welded steel pipe and PCCP. The sounding was done with a ball-peen hammer on the PCCP section of the pipeline in order to find evidence of core decompression or other structural distress. If a problem found was widespread, the general stretch of pipeline in which it was located was noted. If a defect found was singular, its location was noted using a previously established numbering system created for another project.

Aurora Water also used sounding as part of an internal inspection of a 4.2 mile long section of a 54-inch PCCP raw water transmission main. The sounding inspection was varied out in conjunction with manned entry and direct visual assessment and remote field, electromagnetic inspection. A hollow sounding area was found, measuring 58 inches longitudinally and 17 inches circumferentially, produced a sound that, though hollow, did not match that of a pipe with a large amount of broken prestressing wires. Three other regions produced a slightly different pitch in the lining when sounded; however, a true hollow area could not be discerned. Additional areas were detected to have hollow sounding areas, and two other areas were found with circumferential cracks; however, these observations did not appear to be indicative of potentially distressed pipe. In some of the hollow sounding areas, review of the US Pipe Line Layout sheets showed that the hollow-sounding areas were a result of the pipes being steel replacement pipes or specials. There was no cracking associated with the hollow sounds in the pipe. When hollow sounding areas on the interior surface of embedded cylinder prestressed pipe are found with active longitudinal cracks, which have deposits of carbonate leached from the concrete, those hollow sounding areas almost invariably indicate a lack of concrete compression and possible structural deterioration. Hollows that indicate distress are caused by separation of the lining from the embedded steel cylinder. The compressive stress in the steel cylinder that is caused by this separation is greater than the stress in the concrete core, due to the shrinkage and creep of the concrete that occurs after prestressing. When the prestressing is lose, the elastic strain in the cylinder combined with the internal pressure can exceed the concrete tensile strength of the outer core and cause it to crack. The expansion of the cylinder away from the inner core causes the separations or hollows detectable by internal sounding.

Ground Microphones

Two drinking water utilities provided use of ground microphones for condition assessment, as shown in Figure 5. Both Philadelphia Water Department uses ground microphones for detection of leaks in their smaller diameter water pipelines, while Massachusetts Water Resources Authority uses ground microphones to survey larger diameter pipelines.

Figure 5. Utilities from which Information was Gathered on Use of Ground Microphones for Drinking Water Pipeline Condition Assessment

Philadelphia Water Department (PWD) has operated a traditional, above-ground, acoustic leak detection program for inspection of its water distribution system, employing ground microphones in conjunction with noise correlators and loggers, for many years. The PWD Leak Detection crew manually surveys roughly one third of the system's 3,144 miles of pipelines for leaks annually. PWD repairs approximately 800 water main breaks each year. Over 3,000 leaks are encountered each year. A portion of these are repaired by PWD while others, located on customer service lines, are referred to those customers to arrange for repairs. This traditional leak detection program surveys the smaller water distribution mains and water system service connections. Different technologies are used for larger pipelines, due to accessibility issues as well as the fact that many of the leak sounds in larger mains are more subtle and therefore more difficult to detect.

Massachusetts Water Resources Authority is a water wholesaler and therefore only maintains 300 miles of transmission mains that have an average diameter of 36 to 48-inches. Therefore, the utility uses ground microphones in conjunction with noise correlators and loggers to detect leaks in their larger diameter lines and also helps locals if there is a suspected leak in their smaller diameter water distribution line. Massachusetts Water Resources Authority has had a lot of success using these technologies for leak detection.

Noise Correlators and Noise Loggers

The utilities which provided information on the use of noise correlators and noise loggers for condition assessment of drinking water pipelines are illustrated in Figure 6. Philadelphia Water Department has used noise correlators and loggers in conjunction with ground microphones to detect leaks in their water distribution system for many years, while Massachusetts Water Resources Authority uses the same technologies to detect leaks in larger diameter water transmission lines. Dover Utilities Commission puts out noise correlator and logger pods at nighttime to listen for leaks on their water mains. Billings Department of Public Works has been able to reduce leakage in their drinking water distribution system to less than half of its previous level using noise correlators to detect and locate leaks. Portland Water Bureau provided information on a specific contract for performing a leak detection surveys with noise correlators and loggers on 20 miles of the utility's large diameter water mains in 2010, as well as information on a condition assessment pilot project that involved using passive cross-correlation of leak vibrations in a 16-inch diameter steel pipeline.

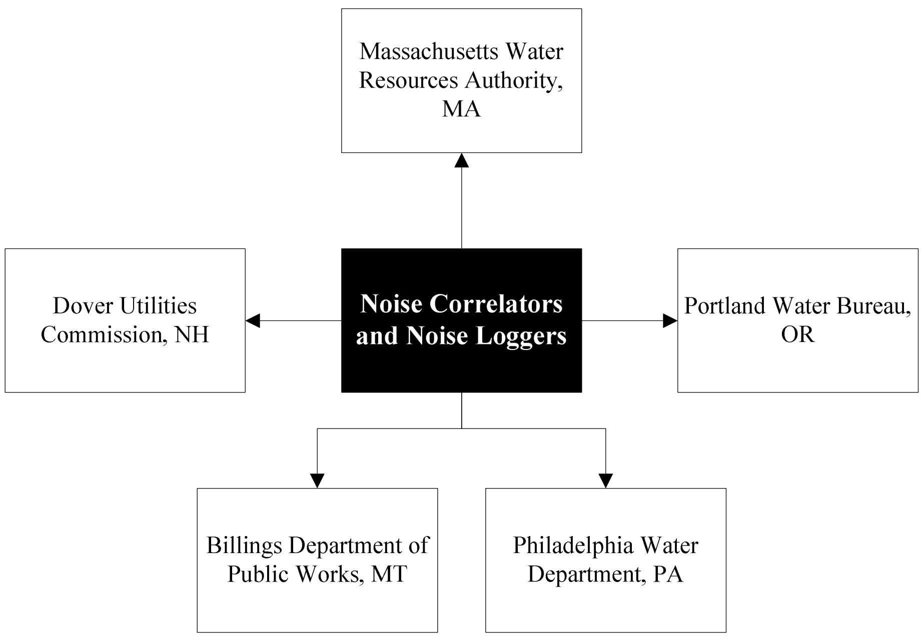

Figure 6. Utilities from which Information on Use of Noise Correlators and Noise Loggers for Condition Assessment of Drinking Water Pipelines was Gathered

Billings water mains are mostly cast iron, some with an age of over 100 years. Given the system age, leakage is a frequent problem. The Billings Public Works Department has been performing almost continuous rehabilitation and replacement of water mains since 1979. The rehabilitation and replacement program includes the implementation of an aggressive approach for locating and repairing leaks in water mains, utilizing electronic noise correlators. The use of noise correlators allows for an accurate location of the leak. Depending upon on the leak size and condition of the pipe, a decision is made in each case on whether to repair the leak or replace the pipe segment.

After a leak has been located, an open cut excavation is made in the area. The utility tests for leakage preferably those water mains located in an area where street improvement projects are taking place in order to minimize public disruption. Also, specific system sections are scheduled together for water main renewal, in order to minimize the spread of working areas throughout the City.

Portland Water Bureau commissioned leak detection surveys of 23.05 miles of water mains, ranging in diameter from 24 to 60 inches and of various materials including concrete cylinder pipe, ductile iron, cast iron, and polyvinyl chloride. Pipes were chosen for leak detection survey because they were considered as having a high risk of failure. Five potential leaks and three points of interest were found during the survey. Three leaks were found in 60-inch diameter CCP, one in 36-inch diameter DI pipe, and one in 30-inch diameter CI pipe. Two points of interest were found in 60-inch diameter CCP, and one in 57-inch diameter CCP.

Portland Water Bureau also provided information on a condition assessment methodology using passive cross-correlation method based on passive leak noise detection using sensors. Sensors are mounted at different locations on the pipe or on pipe fittings such as valves. The basis of this condition assessment methodology is not to locate leaks, but to be able to estimate the remaining average pipe wall thickness from accurate measurement of noise travel times at different sensors. Noise travel time depends on pipe stiffness, which is related to wall thickness. While an average wall thickness was estimated based on this technology, there was no additional condition assessment information available for verification of the results.

In-Line Acoustic Leak Detection

Utilities which provided information on their use of in-line acoustic leak detection for condition assessment of drinking water pipelines are shown in Figure 7. San Francisco Public Utilities Commission and Philadelphia Water Department provided information on their use of tethered, in-line acoustic leak detection. Washington Suburban Sanitary Commission provided information on their use of free-swimming, in-line acoustic leak detection. While Philadelphia Water Department used in-line acoustic leak detection as a contracted service for inspection of as many large diameter metallic lines as possible, both San Francisco Public Utilities Commission and Washington Suburban Sanitary Commission used in-line acoustic leak detection as a methodology for assessment of specific PCCP lines.

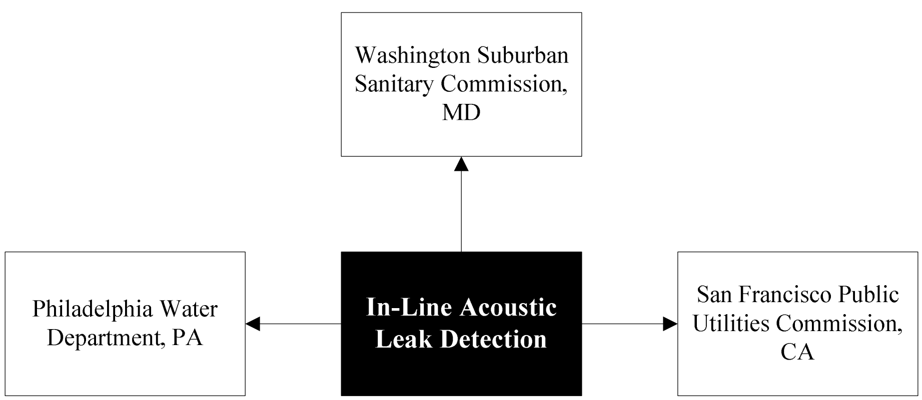

Figure 7. Utilities from which Information on Use of In-Line Acoustic Leak Detection for Condition Assessment of Drinking Water Pipelines was Gathered

Washington Suburban Sanitary Commission (WSSC) provided information on their use of free-swimming, in-line acoustic leak detection to survey a 96-inch PCCP which is a critical pipeline in the supply of drinking water to southern Prince George County, Maryland. After suspecting a leak in this pipeline, WSSC chose the free-swimming, in-line acoustic leak detection technology because it is ideally suited to long leak detection surveys typically requiring only one insertion and retrieval point, and had a lower total project cost to survey the entire reach of the almost six miles of pipeline.

To ensure adequate headroom in the predetermined extraction location, WSSC was required to core a chamber roof slab. Small acoustic sensors were adhered directly to any available metal surfaces of pipeline appurtenances available on the pipe and remained for the duration of the survey. These sensors allowed better location of the tool within the pipeline. A total of four chambers were dewatered for access to insertion points and points where sensors were adhered for the survey. Flow had to be controlled during the survey to ensure the inspection tool's safe travel through the pipeline, which required the closing of all significant connections on the main

The first insertion was intended to gather acoustic condition assessment related data on 29,830 feet of the PCCP in a single day; however, due to inline obstructions, possibly attributed to the reduced diameter at the slip lined section of the pipeline, the device stopped moving when less than 10% of the pipeline was inspected and could not be retrieved. Thus, the data recorded on that device was lost.

A second insertion of the device was done the following day at a further station of the pipe, and the rest of the pipeline was inspected successfully. Two large leaks were identified on the pipeline. At the time the report on the results of this survey was developed, in mid-December 2008, these leaks had the largest acoustic energy ever recorded by the technology. It was concluded that the leaks were expected to be in the range of 20 to 50 gpm. Both leaks appeared to coincide with points where the PCCP transitioned to steel slip lining. A thorough inspection of those locations during a pipeline dewatering was recommended. Due to the large size of the recorded leaks, it is possible that the extremely strong acoustic signal they created overpowered the acoustic signal of smaller leaks located within 500 ft of the reported leak locations.

Most of Philadelphia Water Department's water transmission and distribution system is metallic. Philadelphia Water Department (PWD) piloted and then implemented a tethered, in-line acoustic leak detection system for inspection of large diameter water transmission lines under contract in 2007. The contract was written to employ this methodology for a time period of four years. During that time period, almost 30 miles of pipeline were inspected. In that pipeline length, 63 leaks were pinpointed, averaging two leaks per mile of pipeline. It has been estimated that some of the repairs to these leaks that were detected as a result of this program have prevented catastrophic pipeline ruptures.

Sahara® is particularly applicable to PWD's situation because there are a relatively large number of transmission mains in the City's water infrastructure with existing connection points that were tapped into the pipe originally as flow gauging points in the early 1900s and already typically have manholes built around them, making them excellent locations for permanent access points for the tethered, in-line acoustic leak detection deployment. While there are a relatively large number of these connection points in the large diameter water transmission mains of PWD, and these connection points can be used for more traditional, above-ground acoustic technologies, they are still too far spaced to be used to comprehensively test transmission mains. While a typical above-ground noise correlator may bracket a maximum of 500 feet of pipeline, tethered, in-line acoustic leak detection technology has been used in Philadelphia to test up to more than 4000 feet of pipeline in a single deployment.

While the existence of the tether lends itself to the opportunity to double-check acoustic signals as the tool is retracted back through the pipeline to be retrieved, PWD has found that it also has some disadvantages. Once, when retracting the cable, it became tangled in the pipeline. Though this is not a common situation, it did happen, and it created an issue with the service provider. The pipeline had to be shut down and depressurized in order to untangle the line and remove it.

Of the 71 suspected leaks that were detected with this leak detection system in Philadelphia over the duration of the four year contract, 61 (75%) were confirmed to be leaks. Six of the confirmed leaks were on neighboring mains or service connections. One suspected leak is awaiting repair and one suspected leak repair has been deferred. Eight of the suspected leaks (11%) were confirmed to be false positives. Of the detected leaks that were false positives, many were explained by mitigating factors such as extraneous noise. All in all, PWD is satisfied with the results obtained using the tethered, in-line, acoustic leak detection system.

Acoustic Monitoring Systems

Utilities which provided information on their use of acoustic monitoring systems for condition assessment of drinking water pipelines are shown in Figure 8. Washington Suburban Sanitary Commission provided information on their use of fiber optic cable for acoustic monitoring of a large diameter PCCP. Aurora Water provided information on their use of acoustic monitoring with arrays on a large diameter PCCP raw water transmission main. Howard County Department of Public Works has monitored their large diameter PCCP water transmission lines with first arrays and then with fiber optic cable as part of a PCCP inspection program since 2000.

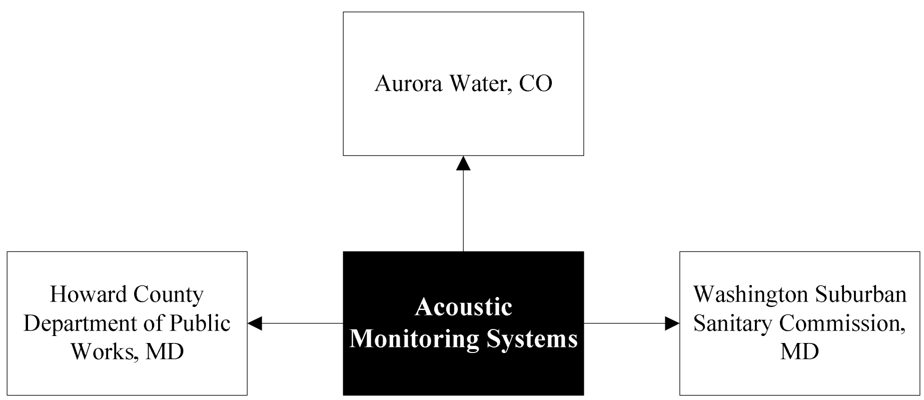

Figure 8. Utilities from which Information on Use of Acoustic Monitoring Systems for Drinking Water Pipeline Condition Assessment was Gathered

WSSC used an acoustic fiber optic monitoring system to detect broken prestressing wires in a 96-inch diameter PCCP line following an electromagnetic inspection that had identified many wires broken in a single pipe section of that line. Eight wire breaks were detected by the monitoring system on one pipe section in less than ten hours. The accelerated rate of wire breaks, with six wire breaks occurring in a half hour indicated that the pipe had advanced to a condition close to fast failure. WSSC found that the active wire break activity captured by the acoustic fiber optic monitoring system was an indication of the pipe deterioration; however, there was inconsistency between the actual wire breaks found with forensic investigation and the reported wire break numbers by the acoustic monitoring system.

Howard County Department of Public Works started using acoustic monitoring array systems to monitor almost 60,000 feet of their PCCP pipelines in 2000. However, around 2005, the arrays began to be taken out of service, because the maintenance issues related to the systems were becoming challenging. For example, the cables attached to the hydrophones were deteriorating in the lines, and beginning to break. It was necessary to stop flow and break a connection in order to slip a hydrophone through. When a cable broke, the hydrophones would float down the pipe and be lost. Eventually, it got to the point where cables were being lost as well. The manufacturing process for hydrophones is relatively difficult and expensive, so the arrays were removed properly before the hydrophones were lost. There were other reasons to remove hydrophones as well. In one situation, there was multiple wire break activities in a pipe that the vendor and contractor that had installed the system wanted to remove the array in it. When a pipe bursts, the array cables have to be cut and then all the cables and hydrophones in that pipe are lost. The company feared that this pipe would burst soon. After the cables and hydrophone arrays were removed, Howard County Department of Public Works hired a contractor to excavate the pipe for inspection. The pipe was still in operation when it was excavated. When the pipe was exposed, it began to visibly expand. The major factor that had been keeping the pipe from bursting was the confining pressure from the surrounding soil. The pipe was taken out of service and replaced. By 2006, all the arrays had been removed. Eventually, that particular vendor and contractor stopped manufacturing arrays altogether, since they were expensive to manufacture, and deteriorated or were lost too frequently to be cost effective.

In 2007, Howard County Department of Public Works began using a fiber optic acoustic monitoring system on a PCCP that had previously had an array monitoring system installed, and it has worked quite well. Thus far, it has been easy for the data analysts to determine differences between wire break sounds and other sounds (such as someone entering a manhole). To date, there are no problems with surrounding sounds from traffic. The utility is now looking into performing short term monitoring (about three months) of the entire PCCP system. If activity is seen in the system, the monitoring will be continued selectively. Howard County Department of Public Works currently enjoys the fact that all wire break information can be seen and managed by utility personnel by logging in through the vendor and contractor's website.

Ultrasonic Wall Thickness Measurement

Utilities which provided information on their use of ultrasonic wall thickness measurement as part of the condition assessment of drinking water pipelines are illustrated in Figure 9. Aurora Water provided information on a 2007 inspection of a suspended 66-inch diameter welded steel pipe with ultrasonic wall thickness measurement in conjunction with internal direct visual assessment, probing, and lining thickness measurements. Sydney Water provided information on condition assessment of a specific pit cast iron gravity-fed water pipeline using ultrasonic wall thickness measurement in conjunction with an external direct visual assessment and magnetic flux leakage testing.

Figure 9. Utilities from which Information on Use of Ultrasonic Wall Thickness Measurement for Condition Assessment of Drinking Water Pipelines was Gathered

Sydney Water excavated a 20-inch diameter concrete lined pit cast iron water main at six sites. At each of these sites, the pipe was excavated so that the entirety of the 360 degrees of pipe wall could be accessed. Ultrasonic wall thickness measurements were taken externally.

Aurora Water provided information on a 2007 inspection of a suspended 66-inch diameter welded steel pipe with ultrasonic wall thickness measurement to measure loss of thickness in some locations due to corrosion in conjunction. The ultrasonic wall thickness measurements were taken from inside the pipeline.

Remote Field Technologies

Utilities which provided information on their use of remote field technologies for condition assessment of their drinking water pipelines are provided in Figure 10. Both Baltimore City Bureau of Water and Wastewater and Aurora Water provided information of their use of modified remote field technology to find wire breaks in a large diameter water transmission PCCP. Howard County Department of Public Works also provided information on their testing of a modified remote field technology as part of their PCCP inspection program. Washington Suburban Sanitary Commission provided information on the use of a modified remote field technology for inspection of a 42-inch diameter PCCP water transmission main, focusing on the calibration process for the inspection. Miami-Dade Water and Sewer Department provided information on their use of both manned and free-swimming remote field technology as part of a condition assessment of 75 miles of large diameter PCCP lines. The Metropolitan Water District of Southern California provided information on their use of two commercially available remote field technologies modified for use with PCCP on the same pipe sections in 2004 and 2009, and the comparison of the results. Seattle Public Utilities provided information on the utility's use of an internal, free-swimming remote field electromagnetic tool to assess the condition of three sections of 8-inch diameter cast iron water pipelines. San Francisco Public Utilities Commission used electromagnetic testing on PCCP pressurized water pipelines from 36 to 96-inches in diameter. The electromagnetic testing had calibration issues at the time which required costly field calibrations, and also had limited accuracy detecting broken wires where the bell overlapped the spigot.

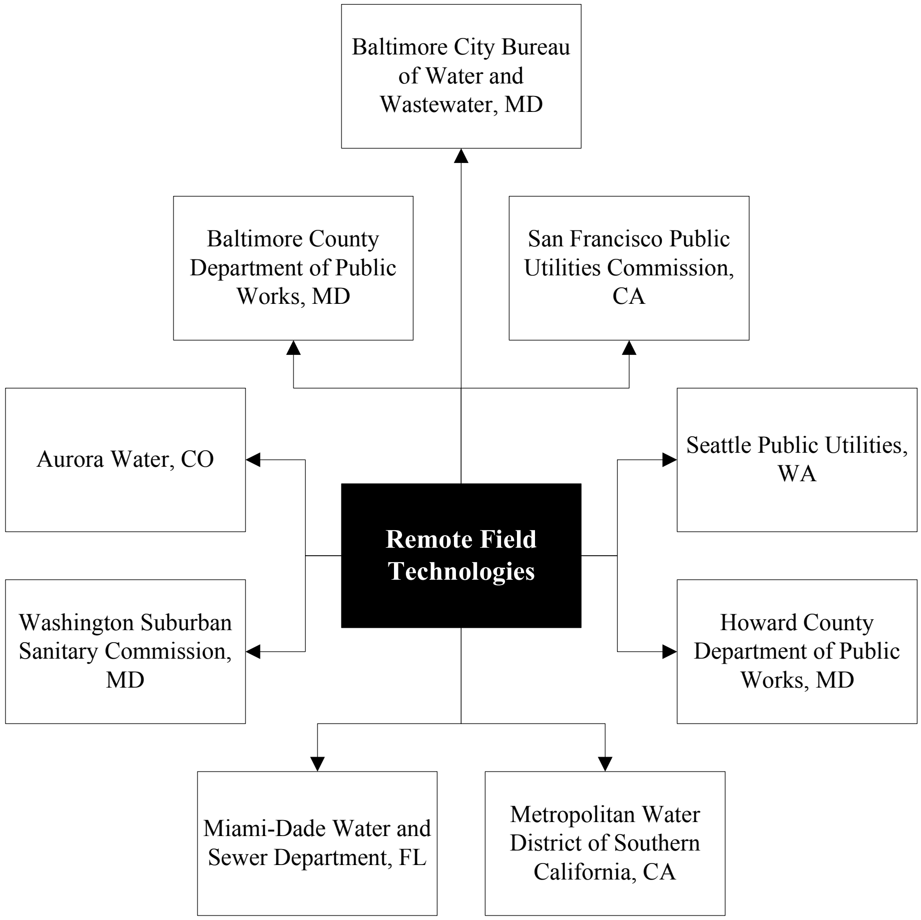

Figure 10. Utilities from which Information on Use of Remote Field Technologies for Condition Assessment of Drinking Water Pipelines was Gathered

Aurora Water inspection of a PCCP required an inspection cart to be assembled inside the pipe and several short passes performed to configure the cart's hardware settings. The RFEC/TC equipment generated an electromagnetic field inside the pipeline with a transmitter coil on one side of the pipe. The field was transmitted to the other side of the pipe using the prestressing wire. A receiver coil on the opposite side of the pipe was used to measure and record the electromagnetic signature of each pipe section. The data collected was reviewed to identify pipe sections with an anomalous electromagnetic response. In order to identify anomalies, the data was compared to calibration data, anomalies found in other pipelines, and excavation data from other mains. Wire break estimates were made based on the size of the anomalies found and the number of wire wraps per foot on the pipe that was inspected. In total, 1,079 pipe sections were inspected in three days. Fifty-one of these pipe sections (4.7%) were found to have electromagnetic anomalies consistent with wire break damage. In the initial analysis of these 51 pipe sections, two pipes exhibited electromagnetic anomalies consistent with 50 or more broken wires. However, upon further review and comparison with calibration pipes, the initial damage levels were reduced, such that no pipes are now thought to have more than 50 broken wires. It was recommended that the pipeline with the highest numbers of wire breaks should be monitored for additional estimated wire breaks, hollow areas, or longitudinal cracks, which may signal incipient failure.

As a pilot program, Seattle Public Utilities performed the inspection of three sections of 8-inch diameter cast iron water lines in 2003 using free-swimming, internal remote field inspection. The three deepest pitting areas and the thinnest circumferential loss area were identified for each pipe length. The condition assessment work also included an economic analysis and list of prescribed restoration measures that provided a possible estimated savings of 68% to the full replacement cost of the pipelines. The company that was contracted to do the condition assessment guaranteed the performance of pipeline for the next 15 years if their prescribed restoration measures were implemented.

Magnetic Flux Leakage

Two utilities provided information on their use of magnetic flux leakage for condition assessment of drinking water pipelines, as shown in Figure 11. Sydney Water provided information on their use of magnetic flux leakage for external scans of a 20-inch diameter pit cast iron gravity-fed water main in conjunction with direct visual assessment and ultrasonic wall thickness measurements for a 2009 condition assessment of the line. San Francisco Public Utilities Commission developed an internal tool to inspect large diameter mortar-lined water transmission mains with magnetic flux leakage technology. As magnetic flux leakage, which was originally developed for oil and gas utility pipelines which are not typically lined, cannot traditionally be used to scan metallic pipeline through a mortar lining, this development is significant.

Figure 11. Utilities from which Information on Use of Magnetic Flux Leakage for Condition Assessment of Drinking Water Pipelines was Gathered

Sydney Water excavated a 20-inch diameter concrete lined pit cast iron water main at six sites. At each of these sites, the pipe was excavated so that the entirety of the 360 degrees of pipe wall could be accessed. At each of these sites, a series of scans was carried out with a high flux magnetic inspection system designed specifically for use on ferrous pipelines. The tool used to test the pipeline was created for use on pipelines 12 inches in diameter and above, in areas where a 360 degree inspection of a pipe section in one pass would not be practical. The tool is used to inspect discrete axial segments of the pipe wall. It is traversed circumferentially around the pipe wall to inspect the entire pipe surface or to provide the selective inspection data. Because of its use of magnetic flux leakage, this tool provides a very detailed understanding of the pipeline condition locally.

Due to encrustation obstructing the tool, the invert of the pipe could not be scanned in all cases. After spending a considerable amount of time removing the encrustation on the pipe, the technicians were instructed by Sydney Water personnel to leave the remaining encrustation on the pipe and continue with the condition assessment. External pitting corrosion was identified at all the inspection locations. The pitting ranged from 1.0 mm in depth to through wall corrosion. Significant internal location was not identified at any location. During the on-site inspection, areas of the pipe were described as “soft”. Three of these locations were weeping water. Several potentially through wall defects were found in the scan data at three of the sites. At these locations, the technicians did not fully dig out the defect for fear of causing the pipeline to leak.

Transient Pressure Monitoring

As shown in Figure 12, one utility provided information on its use of transient pressure monitoring for condition assessment of drinking water pipelines. Aurora Water used remote transient pressure monitoring in conjunction with an array-based acoustic monitoring system to monitor a large diameter PCCP raw water transmission main.

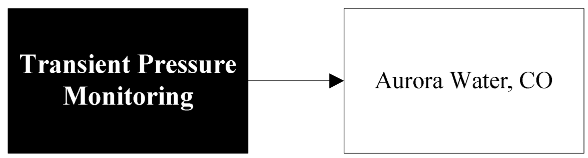

Figure 12. Utilities from which Information on Use of Transient Pressure Monitoring for Condition Assessment of Drinking Water Pipelines was Gathered

Aurora Water used remote transient pressure monitoring in conjunction with an acoustic monitoring system in order to monitor a PCCP that had previously been inspected with visual, sounding, and electromagnetic inspection. The baseline condition of the pipeline had been found by the previous inspection to be acceptable, but further monitoring was recommended in order to understand the pipeline’s rate of deterioration and prevent failures. The transient pressure monitoring was performed in conjunction with acoustic monitoring in 2008 and lasted approximately six months.

Numerous pressure transients were recorded during the monitoring period along the main. These events were reviewed and classified as false events, noise, or transient events. False events are those events caused by external factors, such as tampering with the remote transient pressure monitoring (RTPM) valves or low power in the RTPM batteries. Both cases cause a sudden recorded drop in pressure, but do not show a transient event in the pipeline. Noises are events with an insignificant overall change in pressure. These are defined by transients that differ by less than 5 psi from the operating pressure. Transient events are sudden increases or decreases in pressure. There were 145 transient events. The largest transient event during the monitoring period occurred on April 15, during the period when the pipeline was being pressurized and the transient increased from 62.2 psi to 190.3 psi, an overall increase of 128.1 psi or 206%. This event exceeded the recommended maximum pressure limit of the pipeline, as did one other transient event recorded during this time period. Because of these transient events, it was recommended that periodic remote field technology inspections be performed on this line.

Probing

One utility provided information on the use of probing for condition assessment of its drinking water pipelines, as shown in Figure 13. Aurora Water conducted an inspection of a large diameter, suspended portion of a welded steel pipeline with visual inspection in conjunction with probing of the pipeline’s lining and joint ring with screwdrivers. Lining anomalies, approximate areas of disbondment, and overall liner condition were recorded with a measured station location in the pipeline. The lining failure was found to be highly variable, but it covered the majority of the suspended portion of the pipeline.

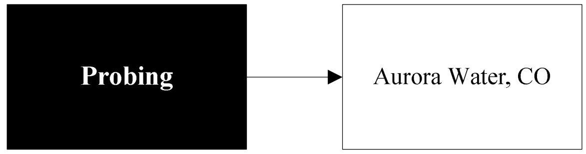

Figure 13. Utilities from which Information on Use of Probing for Condition Assessment of Drinking Water Pipelines was Gathered

Soil Testing

Utilities which provided information on the use of soil testing as part of condition assessment of drinking water pipelines are shown in Figure 14. Sydney Water provided information on their use of soil testing in conjunction with magnetic flux leakage, ultrasonic wall thickness measurements, and visual inspection at excavated pits around a 20-inch diameter pit cast iron gravity-fed water pipeline. Fairfax Water provided information on a planned distribution system sustainability program that will involve taking soil samples and testing for resistivity. Howard County Department of Public Works provided information on their corrosion testing program, which was implemented in 2005.

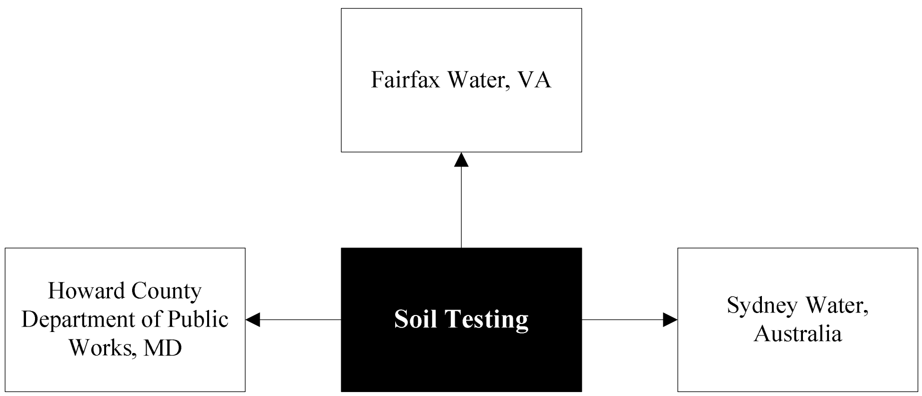

Figure 14. Utilities from which Information on Use of Soil Testing for Condition Assessment of Drinking Water Pipelines was Gathered

Sydney Water soil samples were tested for several variables, including water content, resistivity, chloride content, electrical conductivity, vertical heterogeneity, redox potential, pH value, sulphate content, and pipe to soil potential. Linear polarization resistance soil samples were taken at each excavation site and at additional intermediate sites.

Coupon/Lining Sampling

One utility provided information on use of lining sampling, as shown in Figure 15.

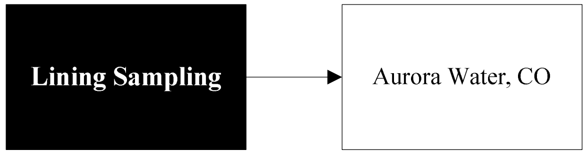

Figure 15. Utilities from which information on Lining Sampling for Condition Assessment of Drinking Water Pipelines was Gathered

Aurora Water sampled the lining of a 250-foot long, 66-inch diameter welded steel pipeline that was suspended over a channel in 2007 to determine the extent of its degradation and to evaluate and recommend re-lining alternatives. The lining material was tested for the presence of lead and polychlorinated biphenyls (PCB) in order to best address regulatory requirements if the existing lining requires removal and to characterize the loss of wall thickness in the pipeline segment.

Seven lining samples were taken from the Aurora Water pipeline, each of which displayed one of the following characteristics:

- Blistering and disbondment in the suspended pipe
- Thin flaking at field and expansion joints
- Thicker lining from the buried steel pipe (at the end of the suspended section)

Each sample tested positive for PCBs. The PCB was determined to be Aroclor 1254, which was most likely used as a stabilizer in the original lining material. Since the PCB concentrations found in each sample were higher than 50 ppm, the lining, once removed, must be disposed of in a hazardous waste landfill in accordance with the EPA Resource Conservation and Recovery Act (RCRA).

Five of the samples tested positive for lead. This lead was most likely used as a primer and bonding agent for the original lining. Municipal and nonhazardous waste landfills will accept materials containing total lead concentrations of less than 100 ppm. Some of these samples therefore exceeded the EPA RCRA standard, and typically must be analyzed by a toxicity characteristic leachate procedure prior to disposal to determine the leachable quantity of lead. However, the presence of PCBs already required disposal of the lining in a hazardous waste landfill regardless of lead content, so this analysis was not required.

Analysis of Existing Data

A number of utilities provided information on analysis of existing data on drinking water pipelines for condition assessment use, as shown in Figure 16. Korea Water Resources Corporation (K-water) provided information on their estimation of water pipeline condition with use of condition assessment models. This method is used because the utility has found that direct inspection technologies are too expensive. Data used to estimate condition includes pipe thickness, corrosion depth, and lining along with laboratory test results of soil properties and structural properties of different types of pipe walls. Montgomery County Water Services Department is in the beginning stages of implementation of a program to estimate the condition of water lines based upon age, soil conditions, pipe material, and break history. Neither utility typically uses direct forms of condition assessment.

Figure 16. Utilities from which Information on Analysis of Existing Pipeline Data for Condition Assessment of Drinking Water Pipelines was Gathered

Synthesis of Practice Reviewed

Analysis of Pipe Materials and Diameters

The drinking water utility practices reviewed showed that the majority of focus was on PCCP, PCP, and steel pipelines, and less on CIP, DIP, and PVC. Part of the reason for this may be based on the fact that a number of utilities expressed concerns related to the condition of their Class IV PCCP, manufactured in the late 1970's and early 1980's, which is particularly susceptible to scattered wire breaks due to non-standard hydrogen embrittlement and appears to demonstrate poorer performance than other types of PCCP. However, the main reason PCCP, PCP, and steel pipelines were the focus of the practice review may be that these are materials commonly used for larger diameter pipelines. The practices reviewed focused, in vast majority, on larger diameter pipelines, due to their criticality and cost. Larger diameter pipelines, particularly PCCP lines, are more prone to fail catastrophically than smaller diameter pipelines, and in that failure, they may cause much greater damage to the surroundings and may cut off water supply to a much larger number of people than smaller pipelines. Additionally, large diameter PCCP lines are more likely to fail catastrophically than large diameter pipelines constructed of ferrous materials.

Analysis of Condition Assessment Techniques Used

The condition assessment techniques used for smaller diameter lines found during the practice review primarily involved soil testing, use of above ground leak detection technologies such as ground microphones, and noise correlators and noise loggers. In one pilot study, internal, free-swimming remote field technology was used for a small diameter cast iron pipeline; however, this is not thought to be a common practice.

In larger diameter lines, the vast number of practices involved direct assessment, either through man entry in conjunction with rod sounding, or through above-ground inspection. However, in utilities with more advanced condition assessment programs, these are no longer as commonly practiced, and much more prevalence is placed upon use of remote field technologies, and, to a lesser extent, acoustic monitoring systems and in-line acoustic leak detection tools.

Coupon sampling was found to be a prevalent practice for assessment of drinking water pipelines through the literature review, but the practice review revealed no examples of a utility using coupon sampling for pipeline condition assessment. One utility did provide information on sampling of the lining of a large diameter water pipeline. The reason for this discrepancy is unknown, and can only be determined through the further data-mining of utility practices.

Though there were no examples of utility use of magnetic flux leakage for condition assessment of drinking water pipelines found through the literature review, two were obtained through a practice review. Magnetic flux leakage, which was originally developed for the condition assessment of unlined, ferrous gas and oil pipelines and requires direct contact with the ferrous pipe wall surface, has traditionally been much more difficult to use for condition assessment of ferrous drinking water pipelines, which are typically lined and may have build-up on the internal pipeline walls. Therefore, use of this technology for assessment of drinking water pipelines has, until recently, involved excavation of the pipeline for external use of the technology. One of the utility experiences found during the practice review illustrates this use of magnetic flux leakage. The other involves a very unique utility experience, in which an internal magnetic flux leakage condition assessment device was developed specifically for use in large diameter, lined drinking water pipelines. The development of this inspection tool is significant and may signal a change in the trend of use of magnetic flux leakage for pipeline condition assessment in the future.

The concern about catastrophic failure of aging PCCP was easily discerned from the utility practices reviewed. Remote field technology was the most prevalent advanced condition assessment tool for assessment of large diameter pipelines encountered during the practice review, and all of the non-pilot examples of use of remote field technologies involved condition assessment of PCCP. However, this use of remote field technology produces only a snapshot of the number and position of broken wires within the PCCP at the time of inspection. The usefulness of this type of assessment appears to be limited. The usefulness of this type of inspection would increase if combined with acoustic monitoring techniques, which do not provide quantitative baseline information on the wire breaks existing in the pipe, but provide information on the rate of breaks in prestressing wire of PCCP. Some utilities are practicing this combination of technologies. Additionally, it remains to be determined if there is a better indicator for condition of PCCP than the quantity and location of broken wires within the pipeline. Examples of utilities using in-line acoustic leak detection to find defects in PCCP were encountered during the practice review, and one example of a utility using transient pressure monitoring in conjunction with acoustic monitoring, to help determine the reasons behind wire breaks, was included in the practice review.

Condition Assessment as a Secondary Goal

In one case, condition assessment techniques were used for something other than assessing the condition of the pipeline. Aurora Water sampled the lining of a large diameter water pipeline not to learn more about the condition of the lining, which had already been ascertained by an internal visual inspection and probing, but to test the sample for the presence of PCBs and lead in order to be able to address regulatory requirements.

Geographical Trends

No geographical trends were noted as far as prevalence of condition assessment techniques was concerned. However, larger utilities with more resources and a higher population density tended to have more advanced condition assessment programs and used newer technologies. Therefore, in accordance with the population densities of the United States, more advanced condition assessment programs were found along the east and west coasts of the United States than in the mid-western states.

Considerations When Selecting Condition Assessment Techniques

The information gathered from Montgomery County Water Services Department leads to interesting questions regarding the reasons why certain condition assessment techniques are adopted more readily than others. The Montgomery County Water Services Department's condition assessment of the utility's drinking water system has only just begun, and involves only an analysis of existing data on the network's pipeline characteristics. Meanwhile, larger utilities, with bigger budgets, larger pipelines, larger and denser populations, and a greater chance of negative publicity in cases of catastrophic failure, tend to branch out more and use more advanced technologies for condition assessment.

Lessons Learned

From the described experiences of utilities, a variety of repeating themes were discovered. These themes reveal a trend in the current mindset of experienced utility personnel that may serve as lessons learned for other utilities.

- It is very useful to have the results of a condition assessment, no matter what the technology is. However, using multiple condition assessment technologies provides a much clearer picture of the condition of a pipeline than use of a single technology does. For example, Seattle Public Utilities found that high leakage rates and poor pipe interior conditions are not necessarily related. Use of multiple condition assessment techniques can show that while one aspect of a pipeline is in good condition, there are problems elsewhere. Information from Washington Suburban Sanitary commission, Aurora Water, and Howard County Department of Public Works also demonstrated this idea.
- A baseline condition assessment is necessary for better asset management, as the baseline condition can be compared with the results of future condition assessments. Models and simulations are very useful in better understanding pipeline condition using the data obtained with the currently available technologies. At the same time, while simulation is useful, it is not 100% effective. Monitoring a pipeline's condition over time is the key for understanding a pipeline's life cycle. This key lesson was demonstrated in information obtained from Miami-Dade Water and Sewer Authority, Portland Water Bureau, the Billings Department of Public Works, Howard County Department of Public Works, and the Washington Suburban Sanitary Commission.
- Pipeline related data collection and the tracking and management of that data is important, and it is necessary to develop standard methods for this purpose. A GIS based system is very useful for data management, and has been found to be critical by some utilities. Systematic data collection and tracking is useful when using models and simulations. Information gathered from Fairfax Water, K-Water, Portland Water Bureau, Aurora Water, and Sydney Water supports this key lesson.
- As environmental factors are a major consideration in the length of a pipeline's operational life, information obtained through soil sampling and testing is important and should be kept. Information from Howard County Department of Public Works supports this idea.
- Cost is a critical factor to many utilities. Condition assessment techniques can save a utility a great deal of cost in eliminating unnecessary rehabilitation and/or replacement work. Information from San Francisco Public Utilities Commission, Philadelphia Water Department, and Seattle Public Utilities demonstrates this idea.

- It is important for utilities to focus, in a holistic way, on having an effective asset management system rather than simply chasing leaks or assessing condition as a reactive action. This lesson was demonstrated by the information gathered from Miami-Dade Water and Sewer Authority.

Conclusions and Recommendations

The use of drinking water pipeline condition assessment practices in the U.S. has expanded as a result of rapidly aging and deteriorating pipelines, increased regulation, publicized catastrophic failures, and the resulting need for more robust, intensive asset management practices. As data obtained during utility condition assessment continues being acquired, it is important that there is a focus on standardizing data management and information sharing between utilities so that life cycles of pipelines with regard to environmental conditions, materials, manufacturing history, and operating conditions can be better understood. A group effort to collect, combine, and better understand condition assessment data will enable utilities to better handle the problem of aging and deteriorating wastewater pipelines.

Future work should involve the development of a data standard for collection and reporting of information on pipeline condition assessment projects. Future work should also involve the direct collection of condition assessment information from additional utilities, as this direct data-mining tends to lead to greater understanding of the asset management process. Information on condition assessment experiences should be shared between utilities.

Acknowledgements

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CONDITION ASSESSMENT TECHNOLOGIES FOR WASTEWATER PIPELINES: STATE-OF-THE-ART LITERATURE AND PRACTICE REVIEW

Abstract

Aging and deteriorating wastewater pipelines have become a major problem in the United States. To save costs associated with reactive renewal of wastewater pipelines, utilities have been taking a more proactive approach to effectively manage their wastewater pipeline assets. Condition assessment is a key component of this approach, providing critical information needed to assess the remaining useful life and long-term performance of a piping system and allowing utilities to prioritize renewal work. While information on the tools and techniques available for condition assessment are readily available from the vendors providing these products, more in-depth information on uses of these condition assessment tools with regard to applicability, success, and limitations for particular utility characteristics, can only be obtained from utilities that have experience with them. This paper gives a brief background on available condition assessment tools and techniques for wastewater pipelines, but also provides a synthesis of literature reviewed on utility uses of condition assessment techniques for wastewater pipelines, as well as a synthesis of information obtained directly from utilities on experiences with condition assessment techniques for wastewater pipelines.

Introduction

Aging and deteriorating wastewater pipelines have become a major problem in the United States. In 2009, the ASCE graded America's wastewater infrastructure with a *D-* (Report Card for America's Infrastructure, 2009). The deterioration of gravity wastewater pipelines may allow wastewater to contaminating ground and surface waters directly. The deterioration of gravity wastewater pipelines may also allow rain water to enter the pipelines, increasing the flow in the pipeline, causing wastewater treatment plants to have to treat extra volumes, and increasing the change of occurrence of a Sanitary Sewer Overflow (SSO). SSOs can also occur due to a blockage in the sewer. SSOs cause environmental problems and public health issues, and the Environmental Protection Agency's (EPA's) Clean Water Act prohibits them. Gravity wastewater pipelines that have deteriorated to the extent of collapse may cause major depressions in roads and properties.

The deterioration of large diameter pressurized wastewater force mains is even more risky, as pressurized pipelines are at a greater risk of catastrophic failure that may cause major consequences with regard to damage to property, the environment, society, and public health. Historically, rehabilitation has been prompted by repairing failures rather than preventing them (Wirahadikusumah, Abraham, Iseley, & Prasanth, 1998). However, as national wastewater systems deteriorate, a more proactive approach has become necessary and, in fact, minimizes cost when compared to a reactive approach. Still, maintenance and repair is not inexpensive and wastewater pipeline systems are extensive; thus, renewal and maintenance work must be prioritized. Developing an understanding of the risks and potential costs of system failure can aid in the decision making process.

This is where condition assessment of sanitary sewer pipes comes in. Condition assessment is one of the core components of an asset management program, providing critical information needed to assess the remaining useful life and long-term performance of a piping system (Feeney, Thayer, Bonomo, & Martel, 2009). USEPA has defined "condition assessment" as the collection of data and information through the direct inspection, observation, and investigation and in-direct monitoring and reporting, and the analysis of the data and information to make a determination of the structural, operational and performance status of capital infrastructure assets (Innovation and Research for Water Infrastructure for the 21st Century: Research Plan, 2007).

Condition assessment is a key component of good asset management practices. Reliable information on the condition of assets is important in the process of understanding long-term performance measures, accurately estimating the remaining life of assets, and prioritizing further investigation or renewal activities. Understanding which condition assessment technologies and methodologies are available and being cognizant of the advantages and limitations of these techniques is important in choosing the appropriate condition assessment practices for a specific utility's needs. Though much information is available from technology vendors on the specifications of the technologies they provide, this information does not always represent the wholeness of a technology's interactions with various characteristics of pipeline networks, flow characteristics, environmental conditions, or utility capabilities. A more accurate understanding of the available condition assessment techniques can be gained through analysis of utility experiences. In addition to a brief background on the available technologies for condition assessment of wastewater pipelines, the below sections provide a synthesis of literature reviewed on utility uses of condition assessment techniques for wastewater pipelines, as well as a synthesis of information obtained directly from utilities on experiences with condition assessment techniques for wastewater pipelines.

Condition Assessment Technologies

In order to more effectively discuss condition assessment technologies, a classification set was created for the available technologies for both drinking water and wastewater pipelines. The classification set divides technologies into categories based upon their primary mode of operation. These classifications are further described in Table 3.

Table 3. Description of Pipeline Condition Assessment Technology and Methodology Categorization

Category	Description
Visual and Camera Methods	These technologies primarily utilize visual images as a way to understand pipeline condition. Includes CCTV and other cameras, as well as smoke and dye testing.
Acoustic Based Methods	These technologies use sound waves to obtain data about pipeline condition. This includes sonic and ultrasonic technologies, acoustic monitoring technologies, and leak detection technologies.
Laser Based Methods	These technologies use a laser to obtain pipeline condition related data.
Electric and Electromagnetic Based Methods	These technologies use electricity or electromagnets to obtain data related to pipeline condition. Remote field technologies, ground penetrating radar, magnetic flux leakage, and sonde & receiver technologies are included in this category.
Flow Based Methods	These technologies and methodologies measure flow volume and/or velocity.
Physical Force Based Methods	This category includes technologies and methodologies that primarily use physical force to obtain data related to condition. This includes pressure related and deflection related technologies and methodologies.
Temperature Based Methods	This category includes technologies and methodologies that use a measurement of temperature to obtain pipeline condition data. Included are infrared technologies and flow temperature measurements.
Environmental Testing	Technologies and methodologies that assess the pipeline environment as part of the condition assessment process. This includes soil and water measurements and stray current analysis.
Other Methods	Analysis of existing data, destructive technologies, and any other technology that does not fit into the other categories.

Visual and Camera Methods

Visual and camera based techniques for condition assessment are considered those that primarily utilize visual images as a way to understand pipeline condition. In addition to direct visual assessment, this category includes various types of camera inspection, as well as smoke and dye testing, which rely mainly on visual cues to be effective.

Direct Assessment

Direct assessment is the practice of visually inspecting a pipeline and drawing conclusions based upon visual clues that were observed. This is a very simple method of condition assessment, involving no tools besides the human eye and a light source, if needed. Direct assessment can be performed above ground, through excavation, or through manned entry:

- Above ground inspections typically involve an inspector walking the alignment of a pipeline, looking for clues to indicate that there are condition issues, such as depressions in the ground above a pipeline, pools of standing water, or sources of stray current.
- Excavation for direct assessment involves excavating a section of pipeline in order to look for visual signs of issues having to do with condition. This usually has to do with the condition of the exterior wall of the pipeline, but may also involve visual assessment of the conditions of the soil and/or groundwater surrounding the pipeline or the bedding conditions. Excavation for direct assessment is usually performed in conjunction with testing using other tools for condition assessment (*Condition Assessment Inspection Techniques*, 2005). This technique is usually performed opportunistically rather than being performed on a regular basis (Sunarho, 2009).

- Manned entry for direct assessment can be done with large diameter pipelines. This method involves an inspector entering a pipeline in order to look for visual signs of pipeline condition in the interior pipeline walls and joints. Man entry is one of the most common methods used for inspection of pipelines (Sunarho, 2009). Like excavation, it is also typically performed in conjunction with the use of other condition assessment tools (*Condition Assessment Inspection Techniques*, 2005).

Direct assessment may be performed on any material or diameter pipeline. The technique's primary limitations come from the fact that it is visually based and involves subjective interpretation of visual data (Sunarho, 2009).

For more information on the use of direct visual assessment for condition assessment of wastewater pipelines, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Hand-Held Digital Cameras

Hand-held digital cameras are sometimes used to capture visual data on the external condition of above-ground wastewater lines. However, they are more commonly used for reporting purposes, or in the creation of a utility system inventory (Strauch, 2004). Man entry inspections also often involve the use of hand-held digital photographs to record various conditions (Strauch, 2011).

Like many other visual based condition assessment tools, hand-held digital cameras can be used for pipelines of any diameter or material, but the technique is limited both by the fact that it captures only visual data, and by the fact that it involves subjective interpretation of visual clues.

Traditional Closed Circuit Television (CCTV)

Traditional closed circuit television, or CCTV, is the most prevalent method of condition assessment used for sanitary sewer pipeline assets. In a 2007 survey of wastewater utilities, 100% of respondents claimed using traditional CCTV as the primary method of assessing condition of their pipeline assets (Feeney, et al., 2009). CCTV involves the use of a robot-mounted, forward-looking pan/tilt and zoom camera as well as a lighting system mounted on a wheeled carriage that travels between two manholes, operated by certified operators trained to control the camera and interpret video streams (Rizzo, 2010). It is typically used only in gravity sewer lines, but can be used in force mains if they are depressurized and drained.

CCTV technology is limited in the fact that it can only provide a visual representation of the inside surface of a pipe above the water line, and this data is subject to interpretation by the operator and may suffer due to picture quality, lighting, and flow level (Feeney, et al., 2009). Though there has been progress in the automation of video processing techniques, it is still necessary for a real time assessment of the captured CCTV video footage to be made (Costello, Chapman, Rogers, & Metje, 2007). The fact that results of CCTV are subjective due to the need for operator interpretation has been mitigated with the development of the National Association of Sewer Service Companies (NASSCO) Pipeline Assessment and Certification Program (PACP), which standardizes the reporting and interpretation of CCTV-obtained visual data.

Cleaning may be necessary before use of CCTV to remove blockages and to allow the camera to traverse the line as well as to provide an unobstructed view of the pipeline walls. This combined with the need for an operator to interpret the real-time data means that use of CCTV is a relatively time-consuming and expensive condition assessment technique.

For more information on CCTV for condition assessment of wastewater pipelines, see U.S. EPA Reports *Innovative Internal Camera Inspection and Data Management for Effective Condition Assessment of Collection Systems*, *Report on Condition Assessment of Wastewater Collection Systems*, *Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems*, and *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF reports *Inspection Guidelines for Ferrous Force Mains* and *Methods for Cost Effective Rehabilitation of Private Sewer Laterals*, *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*, and *Reducing Peak Rainfall-Derived Inflow and Infiltration Rates: Case Studies and Protocol*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Zoom Cameras

Zoom camera inspection refers to inspection using a camera on a stationary mount such as a tripod, pole, or boom. Zoom camera technology typically utilizes a diagnostic video camera with a high-powered tele-objective zoom lens coupled with high-intensity lighting (Lee, 2005b). Zoom cameras have been in use in the US since about 1995 (Di Tullio & Milley, 2005). They were historically used for manhole inspections, but now can pan 360 degrees and zoom in up to 100 to 700 feet depending upon pipeline diameter (Feeney, et al., 2009). Now, stand-alone zoom trucks are available, and all-terrain vehicles permit inspection of manholes and pipeline that were previously inaccessible (Di Tullio & Milley, 2005). Because zoom cameras are deployed through manholes, their use is limited to gravity flow sewer lines.

Like traditional CCTV, zoom cameras only capture visual information above the flow line (Feeney, et al., 2009). Zoom cameras do not collect as detailed visual data as traditional CCTV due to limitations in image resolution, lighting, and optical zoom capabilities (Feeney, et al., 2009), but zoom camera inspection is typically faster and more efficient than traditional inline CCTV (Lee, 2005b). The set-up of zoom cameras eliminates the need for cleaning lines before inspection (Feeney, et al., 2009). A zoom camera inspection crew can typically inspect about one mile of pipe per day, versus about 1,500 feet per day using in-line camera inspection equipment (Di Tullio & Milley, 2005). However, zoom cameras are not designed to replace traditional CCTV, but rather to help prioritize further investigation and renewal. Zoom camera use has been recommended as a step to narrow down problem areas in the assessment of an entire sewer network, as a step after the less expensive technique of flow monitoring and before the more expensive techniques of man entry for direct visual assessment or in-line camera (Wade & Buonadonna, 2010). Zoom cameras eliminate the need for confined space entry certification needed if inspection is being done through direct visual assessment via man entry, and eliminates the need for pipe cleaning before inspection necessary for many in-line camera inspections.

Cleaning the pipe before the inspection may remove important clues in helping to determine the initial cause of a structural or operational problem. About 80% of defects are within 15-20 feet of the manhole (Joseph & Di Tullio, 2003). A survey of utilities showed that use of zoom cameras for inspection were reported at 1/3-1/4 of the time needed to inspect using traditional CCTV, and costs of zoom camera inspection was reported to be ½ to 2/3 less than the cost of cleaning plus conventional CCTV inspection (Martel et al., 2010).

For more information on zoom camera use in wastewater pipelines, see U.S. EPA Reports *Innovative Internal Camera Inspection and Data Management for Effective Condition Assessment of Collection Systems*, *Report on Condition Assessment of Wastewater Collection Systems*, *Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems*, and *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Pushrod Cameras

Pushrod camera inspection involves the inspection of a pipeline via a small diameter camera which produces video of the pipeline. Conventional pushrod camera systems involve a camera/probe, cable/reel, and computer/recorded/controller (Feeney, et al., 2009). These cameras are designed for use in laterals and small diameter force mains, inaccessible to crawlers due to their larger size. Their primary limitations are image quality, lighting, and ability to move past obstructions (Feeney, et al., 2009).

For more information on the use of pushrod cameras in wastewater pipelines, see U.S. EPA Reports *Innovative Internal Camera Inspection and Data Management for Effective Condition Assessment of Collection Systems* and *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF reports *Methods for Cost Effective Rehabilitation of Private Sewer Laterals* and *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Digital Scanners (Optical Scanners)

Digital scanners, also called optical scanners, involve lights mounted parallel to one or two high resolution digital cameras with wide-angle lenses on a crawler. The cameras scan hemispherical images of the entire internal pipe surface during inspection, which is then transmitted to a surface station where it can be viewed in real time and recorded(Feeney, et al., 2009). Digital scanners provide the same information as CCTV, with the added benefit of being able to unwrap the pipe image and do post-processing of images (Rizzo, 2010) instead of relying on an operator to zoom into critical areas for further review. While it is still necessary to manually interpret results, much progress has been made towards automating this procedure using image processing and artificial neural networks (Costello, et al., 2007). Digital scanning is primarily used for gravity sewer lines greater than six inches in diameter, but also has limited applicability in out-of-service, drained force mains and larger diameter service laterals (Feeney, et al., 2009).

For more information on the use of digital scanning technology in wastewater pipelines, see U.S. EPA Reports *Innovative Internal Camera Inspection and Data Management for Effective*

Condition Assessment of Collection Systems, *Report on Condition Assessment of Wastewater Collection Systems*, *Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems,* and *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF report *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Smoke Testing

Smoke testing is used to identify defects and illicit connections that allow extraneous flow into the collection system. In order to effectively use smoke testing in sewers, records of sewer connections must be well known. Therefore, smoke testing is used more in Australia and America where records of sewers are reasonable accurate, but of less use in European sewers (Elswirth, Heske, Hotzl, Schneider, & Burn, 2000).

To perform smoke testing, sewer ends are blocked to inhibit smoke from migrating into non-test sewer sections. Then an air blower is placed over a manhole at one or both ends of the test sewer section, a smoke source is placed inside the manhole(s) with the blower connection, and the sewer pipeline is allowed to fill with smoke (Strauch & Wetzel, 2005). Inspectors must then visually observe the area for emissions of smoke from drainage appurtenances, through the ground, or through other structures. These emissions provide evidence of a through-defect in a pipeline or a connection to the tested sanitary sewer section.

Smoke testing can only be performed in gravity sewer systems. This technique must be performed during dry weather periods so that soil moisture does not prevent the smoke from penetrating through the soil (Thomas, Schroeder, & Johnson, 2010). Smoke testing should also be conducted with unfrozen ground conditions (Strauch & Wetzel, 2005). It is limited by the fact that it cannot show through-wall defects in sagging sections of pipe, or in areas where debris covers defects.

For more information on the use of smoke testing for condition assessment of wastewater pipelines, see WERF report *Methods for Cost Effective Rehabilitation of Private Sewer Laterals* and *Reducing Peak Rainfall-Derived Inflow and Infiltration Rates: Case Studies and Protocol*.

Dye Testing

Dye testing is a system that was first used in the 1960s, and relied on injecting a fluorescent dye (often Rhodamine) into the system at a known concentration, and measuring the dilution rate downstream (Gokhale & Graham, 2004). The dye testing technique can act as a form of monitoring where infiltration is suspected, but attempts have also been made, by adding a flow meter at the point of sampling, to quantify amounts of exfiltration (Gokhale & Graham, 2004).

For more information on the use of dye testing for condition assessment of wastewater pipelines, see WERF report *Methods for Cost Effective Rehabilitation of Private Sewer Laterals* and *Reducing Peak Rainfall-Derived Inflow and Infiltration Rates: Case Studies and Protocol*.

Acoustic Based Methods

Acoustic based methods are those condition assessment technologies and methodologies that primarily use sound waves to obtain data about pipeline condition. This category of condition assessment includes sonic and ultrasonic technologies, acoustic monitoring technologies, and leak detection technologies.

Rod Sounding

Rod sounding, or hammer sounding, is the most basic, first, and most-used method for PCCP inspection (Rizzo, 2010). It involves striking the pipe wall with a hammer or rod and listening to the resulting sound. Rod sounding can either be performed by dewatering a pipeline and entering the pipeline or externally, if the external wall of the pipeline is accessible. If a "hollow sound" is heard after striking the pipeline with the rod, it can be associated with the detachment of the steel cylinder from the concrete core and the delamination of the outside mortar coating (Rizzo, 2010).

Ground Microphones

The use of ground microphones is a traditional, passive approach to detect leaks in pipelines(Rizzo, 2010) which relies on the fact that when a fluid leaks from a pipeline, it generates an acoustic signal. These devices can be placed on pipe fittings, hydrants, or service connections to detect the sound produced by the leak (Fanner et al., 2007). A listening stick, which involved the use of a rod to transmit the sound of a leak up to the operator's ear, is the historical precursor to the ground microphone. Later, geophones were used to pick up on the sound and allow it to be recorded for future reference (Costello, et al., 2007). Modern electronic devices have added signal amplifiers and noise filters; however, the most important factor for success in using listening devices is that the inspector using the device has good hearing and is well trained and experienced in interpreting the sounds picked up by the device (Fanner, et al., 2007).

In order for ground microphones to be effective, one must first know the location of the pipeline and, to a lesser degree, the location of the suspected leak (Costello, et al., 2007). It is also important to minimize background noise when using this technology (Costello, et al., 2007). Recent research involving acoustic leak detection have focused on sound wave propagation in plastic water mains (Costello, et al., 2007).

For more information on use of ground microphones for condition assessment of wastewater pipelines, see U.S. EPA report *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Noise Correlators and Noise Loggers

Noise correlators typically consist of a receiver unit and two sensors equipped with a radio transmitter (Fanner, et al., 2007). These devices have been used for leak detection since the 1980s (Feeney, et al., 2009). The sensors are placed on each side of the suspected leak and pick up the leak sound from the pipe being tested. The leak noise travels at a constant velocity depending upon the pipe's material and diameter, and will arrive first at the sensor it is closest to, then at the other sensor. The correlator uses the time difference between the arrival times to calculate the leak location (Rizzo, 2010). Leak noise correlators have been found to be successful when used in distribution mains, but have had limited success when used in large diameter pipelines (Costello, et al., 2007).

Noise loggers are installed at fittings. They are turned on at night to monitor system noise and listen for acoustic signals produced by leaks. The purpose for use overnight is that, at night time, higher pressures result in increased intensity of leak noise and, at night, there is less chance of interference from ambient sound (Fanner, et al., 2007). These devices do not pin-point the location of a leak, but rather give an indication that there is a leak present within the vicinity of the logger (Fanner, et al., 2007).

More recently, noise correlators have been used to test the wall thickness of pipelines (Bracken, 2010).

For more information on noise loggers and correlators for condition assessment of wastewater pipelines, see U.S. EPA report *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

In-Line Acoustic Leak Detection

There are two modes of in-line acoustic leak detection: tethered and free-swimming. For both tethered and free-swimming in-line acoustic leak detection systems, a minimum pressure and flow velocity are required to successfully carry the inspection device through the pipelines, requiring extensive planning and knowledge of the pipeline system characteristics before testing. These systems are restricted to use in force mains.

Tethered In-Line Acoustic Leak Detection

The commercially available tethered in-line acoustic leak detection system consists of a sensor head with a hydrophone (used to detect sound under water) attached to a cable which carries sounds detected to processing equipment above ground (Feeney, et al., 2009). The sensor head is inserted into a pipe through any access point of appropriate diameter and is carried through the pipe, with the help of an attached parachute, by the pressure of the flow through the pipe. As the sensor head is transmitted through the pipe, acoustic signals are sent back to the processing equipment and interpreted based on their characteristics. After inspection, the sensor head is retracted through the pipe with the cable and retrieved through the original insertion point.

The commercially available tethered in-line acoustic leak detection tool can also be adapted for work in no-flow conditions by using a winch and a pull-tape to pull it through the pipeline (Webb, Mergelas, & Laven, 2009).

For more information on the use of tethered in-line acoustic leak detection systems for assessment of wastewater pipelines, see the U.S. EPA Report, *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Free-Swimming In-Line Acoustic Leak Detection
The commercially available free-swimming in-line acoustic leak detection technology involves a foam ball equipped with an aluminum inner core that contains several sensors that measure acoustic signals, temperature, and pressure as well as a microprocessor with an ultrasonic transmitter, a data logger, and a DC battery (Feeney, et al., 2009). The ball is inserted into the pipeline and propelled by the flow within the pipeline, then retrieved at a pre-arranged retrieval location where it is captured with a net.

For more information on the use of free-swimming in-line acoustic leak detection systems for assessment of wastewater pipelines, see the U.S. EPA Report, *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Acoustic Monitoring Systems
Research done in the late 1980's and early 1990's by the United States Department of the Interior, Bureau of Reclamation, first investigated the use of continuous acoustic monitoring to track the deterioration of PCCP (Fitamant, Lewis, Tanzi, & Wheatley, 2004). Acoustic monitoring systems are installed along PCCP to provide continuous monitoring of the general condition of the pipe by detecting the acoustic signal that is produced when prestressing wires break within pipes (Feeney, et al., 2009). When a wire breaks, the redistribution of stress in the material causes the release of transient elastic waves (an acoustic emission), which are then detected by sensors like piezoelectric transducers, hydrophones, or accelerometers (Rizzo, 2010).

There are arrays of sensors available commercially for use in pipe monitoring (Rizzo, 2010). The location of each acoustic event can be determined by correlating the arrival time of the sound to the sensors that were involved in detection. Fiber optic cable monitoring systems are also commercially available. Because the entirety of the fiber optic cable acts as a sensor, very lengthy sections of pipeline can be monitored with these systems from a single access point and the distance of the sensor from an acoustic event is never greater than a single pipeline diameter (Agarwal & Sinha, 2010). Because the sensor does not contain electronics, there is little or no background noise created by the monitoring system (Feeney, et al., 2009).

For more information on acoustic monitoring systems available for condition assessment of wastewater pipelines, see U.S. EPA Reports *Report on Condition Assessment of Wastewater Collection Systems* and *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Impact-Echo and Spectral Analysis of Surface Waves (SASW)
Impact-echo and spectral analysis of surface waves (SASW) methods are widely used in assessment of concrete structures, and can detect delamination as well as determining thickness (Tuccillo, Jolley, Martel, & Boyd, 2010). The method involves mechanically impacting the surface of the pipe to propagate sound waves into the material, then a simple signal processing

technique is used to provide the thickness, depth of delamination, and sound velocity inside the concrete (which indicates the concrete quality) (Rizzo, 2010).

The impact-echo technique can be used on PCCP, RCP, and clay pipe, and can detect delamination and cracks in various interfaces between concrete and mortar and steel. It either requires dewatering and human access into the pipe, or external access to the pipe wall (Rizzo, 2010).

For more information on the use of impact echo as a condition assessment tool for wastewater pipelines, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Sonar

Sonar is a technique that emits a burst of sound and measures the time it takes to travel from the source to the target and back again. The knowledge of the velocity of sound through an appropriate medium is used to find the distance from the source to the target (Rizzo, 2010). This technology is used to inspect pipe surfaces below the water line and map the accumulation of debris and sediment, provide information on pipe geometry, and provide information on the existence of pipe wall deflections, pits, voids, and cracks (Tuccillo, et al., 2010).

The technology can be applied to any pipeline material, and can be applied to gravity sewers as well as sewage force mains without taking them out of service (Tuccillo, et al., 2010). Its prevalence in conjunction with CCTV for gravity sewer inspection has led to the plan for upcoming versions of NASSCO's PACP will have added data fields for sonar inspections (Derr, 2010).

The downfalls of sonar are that it can be applied in air or water, but not both simultaneously, and that it sometimes has difficulty detecting longitudinal cracks (Feeney, et al., 2009).

For more information on the use of sonar as a condition assessment tool for wastewater pipelines, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report, Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems,* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Also, see WERF report *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Ultrasonic Testing Methods

Ultrasonic testing methods are based on the propagation of ultrasonic stress waves through one or more probes to send broad-band or narrowband mechanical waves through a medium (Rizzo, 2010). Ultrasonic methods require pipe cleaning prior to inspection to remove debris (Costello, et al., 2007).

Ultrasonic Wall Thickness Measurement

Ultrasonic wall thickness testing uses bulk waves to test a small region within the ultrasonic probe (Rizzo, 2010). Ultrasonic wall thickness measurement equipment can be used to measure the remaining wall thickness of metallic, ceramic, plastic, and composite pipelines but performs best on steel and ductile iron pipelines (Tuccillo, et al., 2010). When using this technique with cast iron pipes, false internal reflections can skew test results due to the in homogeneity of the material (*Condition Assessment Inspection Techniques*, 2005).

Ultrasonic wall thickness measurement requires point-by-point measurements, so can be slow. These tools also require exposure of a clean area to allow direct contact of the transducer to the material surface, and also require relatively clean and dry test conditions (Tuccillo, et al., 2010). An adaptation of ultrasonic testing is being developed in Europe, in which a series of ultrasonic sensors are mounted in a ring and placed on a crawler to allow the full circumference of the pipe to be tested as the crawler traverses the pipe. This testing must be done in a drained, out-of-service pipeline (Derr, 2010).

For more information on the use of ultrasonic wall thickness measurement for wastewater pipeline condition assessment, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Long Range Guided Ultrasonic Wave (LRGUW)

When ultrasound waves propagate into a bounded media, a guided ultrasonic wave, or a wave that travels along the medium guided by the medium's geometric boundaries, is generated, and may travel along a pipeline, exciting the whole longitudinal direction and cross section of the pipeline (Rizzo, 2010). This method of ultrasonic testing can detect cracks and measure the wall thickness of a metal pipeline across a long distance (Tuccillo, et al., 2010).

This method has been used on industrial piping in manufacturing as well as in the oil and gas sector, and has been successfully field tested on water mains, but has not yet been used on wastewater pipelines (Tuccillo, et al., 2010).

For more information on the use of LRGUW for wastewater pipeline condition assessment, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Laser Based Methods

Laser-based condition assessment technologies are those that primarily involve the use of a laser to obtain pipeline condition related data.

Laser Profiling

Laser profiling is the most commonly used laser technology at this point. The technology is used to determine the shape of a sewer and any ovality or vertical deflection caused by the interaction of sewer defects and external loads (*Condition Assessment Inspection Techniques*, 2005). This gives information about the sewers structural integrity, information that affects the design of liner systems, and, when compared to the expected pipe shape, information about the extent of corrosion of and/or build-up on the internal wall of pipes.

Laser profiling can only provide data above the flow line, and are often used in conjunction with other technologies, most commonly CCTV and/or sonar (Feeney, et al., 2009).

For more information on the use of laser profiling as a condition assessment tool for wastewater pipelines, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report, Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems,* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF reports *Inspection Guidelines for Ferrous Force Mains* and *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Light Detection and Ranging (LIDAR)

Light detection and ranging, or LIDAR, works by bouncing photons of light off an object and measuring the time it takes for that light to return to the LIDAR scanner. This measured time can be converted to a distance measurement. The photons of light are sent out by the scanner at many angles and directions, and the individual measurements can be assembled into a full 3D model of the pipe interior. This 3D model is called a "point cloud", and can be analyzed to highlight areas where the pipe contains defects (Lipkin, 2012).

Electric and Electromagnetic Based Methods

Electric and electromagnetic based condition assessment techniques are those that primarily use electricity or electromagnets to obtain data related to pipeline condition.

Eddy Current Testing

Eddy current testing can be used in pipelines that are made of electrically conductive materials or in reinforced concrete and PCCP, to qualitatively assess the steel reinforcement (Rizzo, 2010). Eddy current testing involves the use of a magnetic coil with an alternating current, which induces a time-varying magnetic field in the pipe that causes an electric current to be generated in the material (Rizzo, 2010). The currents that are generated in the pipe produce magnetic fields in the pipe material that oppose the original magnetic field and change the impedance of the magnetic coil. As the eddy current traverses the pipe, the change in impedance is measured, which has the potential to produce data that can measure wall thickness and find discontinuities that lie in the planes transverse to the currents (Rizzo, 2010). The main disadvantage of eddy current testing is the limitation in depth of penetration of the alternating current, which limits the depth to which defects can be found in a pipe wall at a given frequency (Rizzo, 2010).

For more information on eddy current testing for use in condition assessment of wastewater pipelines, see U.S. EPA report *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Remote Field Technologies

The remote field eddy current (RFEC) method was proposed to overcome the disadvantage of eddy current testing, in which the depth of penetration of the alternating current at a given frequency limits the depth to which defects can be found in a pipe wall (Rizzo, 2010). RFEC involves the deployment of a probe consisting of multiple magnetic coils, an exciter coil and one or more detector coils, through the pipeline. Eddy currents are induced in the pipe wall with the exciter coil, and these currents attenuate quickly as they flow along the pipe wall towards the detector coil, which is located approximately two to three pipe diameters away from the exciter coil. A second magnetic field passes from the exciter to the outside of the pipe and flows along the outer pipe wall, then back into the interior of the pipe to reach the detector (Feeney, et al., 2009). At a distance of about three pipe diameters, the field in the pipe wall is stronger than the field within the pipe, and sensors positioned in this "remote field region" can detect minor variations in the field strength (*Condition Assessment Inspection Techniques*, 2005).

Remote field technologies are used primarily for assessment of ferrous pipe walls, and can detect pitting, corrosion, leaks, and cracks. These technologies can be used in any flow conditions and over a large range of diameters (Feeney, et al., 2009). However, certain commercially available tools using remote field eddy currents have been developed specifically to detect and quantify broken prestressing wires in PCCP. In these tools, the electromagnetic field generated by the exciter coil is amplified by the wires in the pipeline (Feeney, et al., 2009). During this type of inspection, the magnetic field of interest is very small. Interferences such as motion caused by impacts or uneven pipe floor, variations in pipe joints, the presence of steel sheeting or other steel structures adjacent to the pipeline, and changing wire diameter or pitch can distort measurements (Fitamant, et al., 2004).

Another version of an RFEC inspection tool uses broadband electromagnetic (BEM) induction techniques to record data over a broad range of frequencies (*Condition Assessment Inspection Techniques*, 2005). BEM's frequency independence allows operation of the device to be modified based upon the material being investigated and the site conditions, which in turn reduces the likelihood that the device will be affected by electromagnetic noise (Feeney, et al., 2009). BEM can be used through thick coatings and linings to detect cracks and anomalies in the pipe wall, as well as to measure wall thickness, quantify graphitization, and locate broken wires in PCCP (Feeney, et al., 2009). BEM can be used externally or inside a dewatered pipeline (Feeney, et al., 2009).

Pipeline condition assessment tools utilizing remote field technology are available commercially in the form of manned and unmanned internal inspection tools for full and dewatered pipes, in the form of pigs for inspection in pressurized pipes, and as tools that move along the outside of a pipeline (Biggar, 2010).

For more information on remote field technologies for use in condition assessment of wastewater pipelines, see U.S. EPA report *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF reports *Inspection Guidelines for Ferrous Force Mains* and *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Electrical Leak Location (Electro-scanning)

The electrical leak location method was first developed in 1981 for the inspection of geomembrane liners, but was developed specifically for detecting leaks in pipelines in 1999 (Feeney, et al., 2009). This method is also known as electro-scanning, and can be used for finding leaks in pipelines with materials that are electrical insulators, i.e., non-ferrous pipes (Feeney, et al., 2009).

Electro-scanning locates pipe defects by measuring the electrical resistance of the pipe wall. A fixed electric voltage is applied between an electrode in the pipe, called a sonde, and an electrode on the surface, which is usually a metal stake pushed into the ground (Harris & Dobson, 2006). The pipe is kept full of water at the sonde location, resulting in a situation in which the electrical resistance of the current path between the sonde and the surface electrode is very low except through the pipe wall, which keeps electrical current from flowing between the two electrodes unless there is a defect in the pipe that leaks the current, and thus would also leak water (Harris & Dobson, 2006).

For more information on the use of electro-scanning for condition assessment of wastewater pipelines, see the U.S. EPA Report *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report, Field Demonstration of Condition Assessment Technologies for Wastewater Collection Systems,* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF reports *Methods for Cost Effective Rehabilitation of Private Sewer Laterals* and *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Ground Penetrating Radar (GPR) and Pipe Penetrating Radar

Ground penetrating radar, or GPR, is a technique that uses electromagnetic radiation in the microwave band. The microwave signals are pulsed from the ground surface, propagate into the ground at a velocity related to the electrical properties of the subsurface materials (Ratliff & Russo, 2010), and are then reflected from subsurface structures. Transducers or antenna are used as transmitters and receivers (Rizzo, 2010).

GPR can detect soil voids. The technology can be used to identify leaks by detecting cavities or disturbed ground created by a leak or by detecting the presence of water from the leak (Fanner, et al., 2007). GPR is good for assessing rebar in reinforced concrete (Rizzo, 2010). Current technology allows GPR to sit directly on top of concrete structures to characterize the condition of the structure through the wall (Ratliff & Russo, 2010). Highly trained and experienced individuals are required to interpret the data resulting from a GPR inspection (Koo & Ariaratnam, 2006).

An in-pipe GPR tool, referred to as pipe penetrating radar, has been developed and used successfully, though to a limited extent, for pipeline condition assessment (Koo & Ariaratnam, 2006).

For more information on ground and pipe penetrating radar technologies for use in condition assessment of wastewater pipelines, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF reports *Inspection Guidelines for Ferrous Force Mains* and *Methods for Cost Effective Rehabilitation of Private Sewer Laterals* and *An Examination of Innovative Methods Used in the Inspection of Wastewater Systems*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Magnetic Flux Leakage (MFL)

Now a technique widely used for gas and oil pipelines, magnetic flux leakage (MFL) detection was first developed in the 1920's and 1930's for materials testing (Feeney, et al., 2009). The first MFL in-line inspection tool for pipelines was introduced in 1965 (Rizzo, 2010).

Magnetic flux leakage is done by magnetizing a pipe wall and scanning its surface with a flux-sensitive sensor. Magnetic lines of force, or flux lines, are contained within the pipe wall; however, if there is a defect or anomaly in the pipe wall, the magnetic surface is disrupted and the flux "leaks" out of the discontinuity, which can then be detected through measurements of change in the pipe's magnetic permeability (Rizzo, 2010).

MFL pigs can be used in buried or surface cast iron and steel pipes to detect metal loss from corrosion and find circumferential and longitudinal cracks (Rizzo, 2010). Magnetic flux leakage is best used for smaller diameter, unlined cast iron and steel pipes. It has no problem finding small defects, but has difficulties regarding short and shallow defects, which lends the data obtained a degree of uncertainty (Costello, et al., 2007).

For more information on the use of magnetic flux leakage as a condition assessment tool for wastewater pipelines, refer to the U.S. EPA Report *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Flow Based Methods

Flow based technologies and methodologies are those that measure flow depth, volume, and/or velocity as a primary way to determine information about the condition of a pipeline. These techniques include various uses of flow meters and precipitation measurement.

Flow Meters

Flow meters typically operate by direct measurement of depth and velocity, from which flow is calculated based upon the continuity equation (Feeney, et al., 2009). The data obtained is then analyzed, many times in conjunction with rainfall data. In collection systems, this method is typically used to screen for problem areas in order to support planning for further assessment or rehabilitation, and is particularly useful in systems where there are concerns about infiltration and inflow (I/I) (Tuccillo, et al., 2010). Flow meters can be installed in a collection system to learn flow rates at different points in the system and find unexpected surpluses or deficits of flow. Flow meters can also be used to measure dry weather and wet weather flow rates in a system and compare the rates to find the quantity of I/I (Tuccillo, et al., 2010).

For more information on the use of flow data analysis to assess the condition of wastewater pipelines, see the U.S. EPA Reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems.*

Also, see WERF reports *Reducing Peak Rainfall-Derived Inflow and Infiltration Rates: Case Studies and Protocol* and Using Flow Prediction Technologies to Control Sanitary Sewer Overflows.

Night Flow Isolation

At night time, flows in gravity sanitary sewers are very low. Some utilities use this fact to determine if there may be I/I problems. This is done by waiting for a significant wet weather event, then checking night time flow rates and comparing the rates to flows typically generated at the same time during dry weather. This method does not involve any tools besides visual inspection and assessment, and is therefore not able to quantify flow changes. It is used as a general indicator of a problem with an area.

Physical Force Based Methods

Condition assessment techniques that are primarily carried out with the use of physical force are included in this category. This includes condition assessment techniques that are pressure related or involve impact or hardness testing.

Gas or Liquid Pressure Testing

Pressure testing is a widely used method in new pipe installations, and is also often used to evaluate the leak-tightness of existing sewers. In this process, a section of the line is plugged on both sides of a joint, and a fluid (air or water) is inserted into it under a pressure. If the pressure stays above a certain level for a specific period of time, the pipeline “passes the test” (Sterling et al., 2006).

This process has some shortcomings. Namely, joints immediately adjacent to service connections cannot be sealed or tested; the results of the testing does not provide a quantifiable measurement of a defect, so rehabilitation work may be done to seal joints that are not cost-effective to seal; and the process is very time consuming (Harris & Tasello, 2004).

For more information on the use of pressure testing for condition assessment of wastewater pipelines, see WERF report *Methods for Cost Effective Rehabilitation of Private Sewer Laterals*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Transient Pressure Monitoring

Pressure monitoring is done on pressure lines to examine the stresses that are occurring on a pipeline. These stresses are compared to the design stresses for the pipeline to help determine if changes should be made to the line or the operational practices. Transient pressure monitoring systems typically sample pressure data once per minute and also continuously monitor for pressure transients or negative pressures. When these events occur, sampling rates go up to once every 0.01 seconds (Weare, 2007).

Micro-Deflection

Micro-deflection involves the application of a load onto a brick, concrete, or clay structure to create a slight deformation, which is then measured and displayed graphically as a plot of load versus deflection. A structurally sound material would be expected to have a consistent micro-deflection profile for various loads, while deteriorated or defective structures would not (Tuccillo, et al., 2010).

For more information on the use of micro-deflection for wastewater pipeline condition assessment, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Probing

Probing simply involves putting pressure on the lining or wall of a pipeline to determine its condition through resistance to the pressure. This is an informal method of condition assessment.

Rod Sounding

See section on Acoustic Based Methods for more information.

Impact Echo and Spectral Analysis of Surface Waves (SASW)

See section on Acoustic Based Methods for more information.

Temperature Based Methods

Temperature based methods of condition assessment involve temperature measurement as a primary way to obtain pipeline condition data. This category of tools and techniques includes infrared technologies and flow temperature measurements.

Infrared Thermography

Infrared thermography works on the principle that when a material is heated, infrared radiation flows from warmer to cooler areas at a rate dependent upon the material's insulating properties. An infrared camera is used to measure the infrared radiation across the surface of an object. Uneven heating or cooling can indicate variations in pipe wall thickness, variations of the bonding of a liner to the pipe wall, or the presence of soil voids outside the pipe (Tuccillo, et al., 2010).

For more information on the use of infrared thermography for wastewater pipeline condition assessment, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

Also, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Flow Temperature Testing

Some utilities practice opening manholes after wet weather events to measure the variations in flow temperature. A change to a much colder flow from one manhole to another may indicate the presence of rainfall derived I/I.

Additionally, an increase in temperature of an effluent due to a new wastewater connection may contribute to a more aggressive internal pipeline environment that could contribute to the likelihood of increased risk of internal corrosion (Thomson, Morrison, Sangster, & Hayward, 2007).

For more information on the use of soil and groundwater testing for use in condition assessment of wastewater pipelines, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Environmental Testing

This category of condition assessment involves methodologies that assess the pipeline environment to obtain indirect information about the pipeline's condition as well as to make predictions about its future condition. These techniques include testing samples from the pipeline's external or internal environment as well as field analyses.

Soil and Groundwater Testing

The soil and groundwater conditions have a great bearing on the likelihood of external corrosion of a ferrous pipeline, even to the point of being recognized in numerous codes and guides as being a key factor when screening for likelihood of failure due to external corrosion (Thomson, et al., 2007).

Relevant parameters to test soil for include soil resistivity, in-situ hydrogen ion content (pH), chloride ion content, soluble sulphate ion content, presence of sulfides, and oxygen reduction (redox) potential of soils (Clothier, Oram, & Kubek, 2011). Groundwater levels are important because wetted soils have different properties than dry soils (Thomson, et al., 2007).

For more information on the use of soil and groundwater testing for use in condition assessment of wastewater pipelines, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Gas Sensors

Hydrogen sulfide emitted from wastewater can rapidly break down a cement pipeline, rebar (N. Stubblefield, Shaw, White, Verduin, & Morrison, 2009), or a cement mortar lining (Thomson, et al., 2007). Gas sensors can be used to measure the amount of hydrogen sulfide in a sanitary sewer, providing indirect data on the causes of corrosion within a system.

For more information on the use of soil and groundwater testing for use in condition assessment of wastewater pipelines, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

In-Pipe Flow Testing

In-pipe flow testing refers to sampling and testing parameters of the fluid conveyed within a pipeline. Changes to the nature of the effluent being conveyed through pipes may create a more aggressive internal environment that would contribute to the likelihood of increased risk of internal conditions (Thomson, et al., 2007).

For more information on the use of in-pipe flow testing for use in condition assessment of wastewater pipelines, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Pipe to Soil Potential/Stray Current Mapping

Cell-to-cell potential surveys measure voltage gradients in the soil surrounding the pipe and are conducted on electrically discontinuous pipelines. They provide a snapshot of areas where active corrosion processes are taking place at the time of survey. They can also be used to detect whether stray current corrosion is occurring. When used in conjunction with resistivity and other data, cell-to-cell potential measurements can be used to pinpoint locations of greatest exposure with the highest likelihood of exhibiting observable corrosion damage. Similar to resistivity measurements, cell-to-cell potentials cannot provide a direct assessment of pipeline condition; however, high electrical potentials indicate locations of potentially significant deterioration that can be used to target at-risk infrastructure for focused condition assessment inspections (Clothier, et al., 2011).

Other Methods

This category of condition assessment techniques include coupon sampling and other types of material sampling as well as other technologies that do not fit into the other condition assessment categories previously described.

Coupon and Other Sampling

Coupon sampling typically involves the use of under pressure tapping equipment to remove a 50mm diameter coupon from a pipe wall while the pipe is still operational (*Condition Assessment Inspection Techniques*, 2005), then measuring pit depths, testing, or examining the coupon in various ways to determine the extent of corrosion of the pipeline or other parameters. Larger samples of pipe wall can also be taken; however, this involves closing down the section of pipe and so is more expensive and disruptive than coupon sampling. Samples of pipe wall for lab analysis can also be taken from failed pipelines as a part of forensic investigation. Linings of pipelines can also be scraped and sampled for further testing, as can PCCP wires.

For more information on the use of coupon sampling for condition assessment of wastewater pipelines, see WERF report *Inspection Guidelines for Ferrous Force Mains*.

Also, see ISTT report *Condition Assessment Inspection Techniques*.

Also, see NRCC report *Guidelines for Condition Assessment and Rehabilitation of Large Sewers*.

Conveyance Systems

Conveyance systems refer to those systems used to move condition assessment equipment through pipelines. These include a wide variety of mobile robots called tractors or crawlers, float rigs, and segmented robots that move like inchworms (Feeney, et al., 2009) and allow condition assessment tools to be adaptable to flow or other pipeline conditions.

For more information on conveyance systems, see U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Innovative Internal Camera Inspection and Data Management for Effective Condition Assessment of Collection Systems*.

Gamma-Gamma Logging

Gamma-gamma logging is an innovative technique primarily used to evaluate cast-in-place concrete pilings, as well as for investigation of vertical boreholes in the mining, oil, and gas industries (Feeney, et al., 2009). This technology is based upon the principle that emitted radioactive gamma rays are backscattered and detected in proportion to the density of the surrounding material. For most materials, the natural log of backscattered gamma ray particles has a linear relationship with the density of the material (Tuccillo, et al., 2010).

This equipment consists of a probe containing a small amount of radioactive material and two or more scintillation detector to detect the gamma rays. This technology has been used to identify and locate pipe bedding cavities, and has been proposed as a tool to be mounted on a robotic crawler for pipeline condition assessment (Tuccillo, et al., 2010).

For more information on gamma-gamma logging for application to wastewater pipeline condition assessment, refer to the U.S. EPA reports *White Paper on Condition Assessment of Wastewater Collection Systems: State of Technology Review Report* and *Report on Condition Assessment of Wastewater Collection Systems*.

State-of-the-Art Literature Review for Technology Use

Literature about wastewater pipeline condition assessment technologies and practices was reviewed to establish the current state-of-the-art. A web search was done, which provided publicly available articles and major reports, such as those published by the EPA. In addition to a web search, database search engines available through the Virginia Tech library were used to access literature. The most prevalently used database search engines were the ASCE Civil Engineering Database, Compendex, and Web of Science. Access to the WERF publication database was also provided for two weeks, during which time all relevant and available WERF publications were accessed. The library of the SWIM Laboratory was also searched for relevant reports and other publications.

Definition of Scope

The literature review focused on the use of pipeline condition assessment technologies by wastewater utilities. Literature reviewed was pragmatic from the viewpoint of wastewater utility personnel, involving information on actual use of the technologies and methodologies, as well as surrounding management practices and costs directly related to the use of the technologies and methodologies. The review focused less on in-depth information on modeling and data analysis practices, asset management from a larger perspective, and research related to development of new technologies and methodologies.

Major reports meant for use as reference documents by utilities were reviewed for inclusion in this literature review, as were journal articles and conference papers.

Reports Reviewed

Ten reports were found that were specifically useful and applicable to the practice of using condition assessment technologies and methodologies for gathering information on the condition of wastewater pipelines. These reports are illustrated in Figure 17.

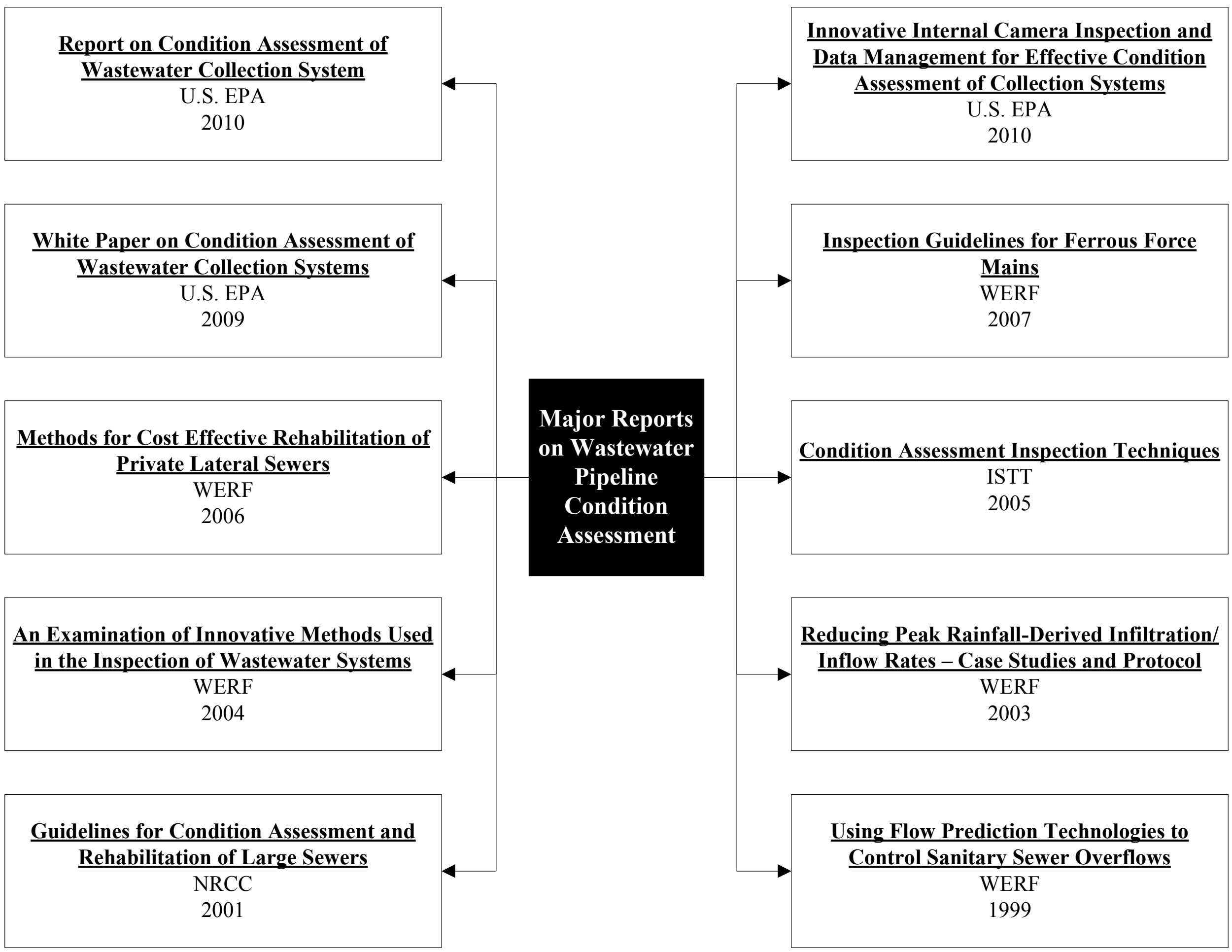

Figure 17. Major Reports Useful for Practicing Wastewater Pipeline Condition Assessment Technologies and Methodologies

Technology Use Information Found in Literature Sources Reviewed

Information was gathered from reports, journal articles, conference papers, and other literature sources on the use of various condition assessment techniques by specific utilities for wastewater pipelines. Information on specific work as well as information on trends in use found in the literature is described in this section, classified by type of condition assessment technology.

Visual and Camera Methods

Visual and camera based methods of condition assessment were found to be, by far, the most prevalently mentioned techniques used by wastewater utilities for pipeline condition assessment in the reviewed literature.

Direct Assessment

Direct visual assessment can involve an above-ground inspection during which look for indirect signs of pipeline condition, an excavation of a pipeline to visually assess the condition of the exterior pipe wall, or a manned entry into a large diameter pipeline to visually assess the condition of the interior pipe wall. Manned entry direct visual inspection was the most frequently mentioned method of direct assessment in the literature reviewed. Because of the characteristics of wastewater, manned entry into a sanitary sewer pipe often involves a great deal of precautionary measures to ensure the safety of the inspectors:

- As part of a proactive condition assessment and pipeline management program implemented following a catastrophic failure of a PCCP force mains, Middlesex County Utilities Authority in New Jersey carried out visual internal inspections of their large diameter pipelines in 2003. Members of the inspection team had to be OSHA-certified to enter confined spaces, all OSHA CFR 17910.146 permit requirements were fulfilled, and the three-man inspection team carried self-contained breathing apparatus and oxygen and toxic gas meters. HAZMAT crews were located at the entry and exist manholes to provide emergency rescue if required. Safety protocol and the inspection procedures were reviewed prior to the inspections, and ventilation and inspection sequencing were established (Fitamant, et al., 2004).
- A 54” PPCP force main was assessed with manned visual inspection in 2008 in Regina, Saskatchewan, Canada. In 1999, approximately 75 feet of the pipeline had failed and was replaced with HDPE pipeline. The inspection was conducted downstream of this failed section. Man entry involved various safety procedures such as forced air ventilation, a safety line, supplied air, and self breathing apparatus (Mak, 2011).
- The City of Hamilton, Ontario, Canada inspected with combined CCTV and sonar in 1998, and then followed up this inspection with man entry to confirm the presence of cracking, from which it was determined not to be as critical as noted in the earlier inspection report. In order to carry out the continuous man-entry inspections for the deep, high-flowing, large diameter sewer, extensive safety procedures were documented and training was undertaken for all team members, including confined space entry, fall arrest, specialized equipment, and mock rescue scenarios. A full scale dry run operation was undertaken to confirm the ability to safely lower and raise both men and equipment down the 28 m deep manhole shaft, which was monitored by team members as well as an outside safety consultant. Minor issues were identified during the dry run and addressed with solutions that were implemented into the confined space entry and rescue plan. To ensure the safety of the in-line crew, a live communication link between the command truck and technicians working in the sewer was established, including the use of military-quality rescue ropes containing a communication line (Crowder, Bauer, & Bainbridge, 2010).
- Scranton Sewer Authority, PA, used specialized inspection crews to provide confined space entry and detailed inspection services of internal equipment during inspection of combined sewers (Strauch, 2011).

Manned entry for visual assessment into large diameter wastewater pipelines also has the disadvantage of possibly being ineffective due to dirty pipe walls:

- The City of Hamilton, Canada's follow-up inspection with man entry required heavy debris cleaning prior to carrying out the inspection work. Specialized cleaning equipment had to be used, as standard cleaning operations would not be effective due to the depth of the sewer and the high flow levels (Crowder, et al., 2010).
- During Middlesex County Utilities Authority visual internal inspections of their large diameter PCCP in 2003, it was found that sludge build-up on the walls hampered the visual portion of the inspections (Fitamant, et al., 2004).

Manned entry for direct visual inspection of wastewater pipelines is time-consuming and costly, as well. Because man entry and CCTV costs for large diameter sewers (over 900 mm) was prohibitive, a UK utility (MWH) developed a risk-based approach for prioritization, using failure likelihood and a failure consequence assessment. The limitation to this approach was that to cover the entire asset set, much of the base data using the calculations was inferred from rules of thumb, and this asset data will be updated with real survey data when either CCTV or man-entry surveys are completed(Rolfe-Dickinson, 2010).

Manned entry visual inspections were found paired with other inspection technologies for inspection of specific pipelines in literature. Many manned visual inspections were also found to be part of larger condition assessment programs, which combined many types of technology:

- A manned visual inspection of 54" PPCP force main in 2008 in Regina, Saskatchewan, Canada, was conducted in conjunction with traditional CCTV. The inspection found five pipe sections under severe corrosion attack where the interior concrete surfaces near the crown of the pipe had deteriorated exposing reinforcing, as well as nine sections that showed early signs of H2S attack (Mak, 2011).
- A large diameter PCCP force main inspection program in Greater Lawrence Sanitary District, Massachusetts, performed in-line direct visual inspection in conjunction with rod sounding (Weare, 2007).
- Water Care Services Limited in New Zealand, conducts walk-through inspection for larger diameter mains and larger duplicate siphon pipes as part of a much larger condition assessment program (Marlow et al., 2007), and also conducts these walk-throughs when a particular sewer pipe is prioritized because of danger of failure.
- Scranton Sewer Authority, PA, addressed an Order for Compliance from the EPA to address the order including requirements relating to the existing NDES Permit, which required physical identification of the combined sewer system, including location of the discharge point, description of the regulator system, description of the outfall structure, and field verification of deteriorated sewers and other areas of concern (Strauch, 2011).

Some cases in literature were found which involved excavation for direct assessment. In these cases, multiple methods of condition assessment were used in conjunction with direct visual assessment:

- Based upon condition ratings of the City of Virginia Beach's pressurized force mains, test pits were dug to directly assess the pipelines under various conditions and utilize the results to indirectly assess the remaining portions through inference. The selected inspections included a good balance of both CI and DI pipelines, as well as of mains in less corrosive environments to assess performance in relatively benign conditions. AC pipe test pit locations were also selected to verify the hypothesis that the soil chemistry determined during an earlier corrosion program would not significantly corrode the AC pipelines (Clothier, et al., 2011).
- The City of Wilmington, North Carolina, excavates key locations along its PCCP force mains and performs visual inspections along with hammer soundings as part of the utility's sanitary sewer condition assessment program (Miles, 2007).

Hand-Held Digital Cameras

Man entry inspections often involve the use of hand-held digital photographs to record various conditions, as was done by Scranton Sewer Authority (Strauch, 2011). Besides this example, specific mention of use of hand-held digital cameras was not found during the literature review. However, it was evident in many cases that digital photography was used to report and record certain conditions, many times in conjunction with management of a GIS program.

Traditional Closed Circuit Television (CCTV)

Traditional CCTV was found mentioned in many literature sources describing utility condition assessment of wastewater pipelines, most of which are not mentioned here. Though CCTV is typically used for assessment of the condition of gravity sanitary sewer lines, there were mentions of use of CCTV in other types of pipeline, including large diameter PCCP (Mak, 2011), pressurized reclaimed water lines (Villalobos & Najar, 2005), and even storm sewers (Ekes, Neducza, & Henrich, 2011).

In many situations, CCTV was found not to provide satisfactory results:

- The City of Redding has owned a CCTV unit since 1976 and has inspected most of its gravity sanitary sewer system at least once. The inspections have shown that the structural condition of the collection system is generally good; however, CCTV could not detect pipe joints or service connections that were suspected to be a major contributor of infiltration into the Redding system unless water is flowing through the joint during or shortly after a high rainfall period, when the pipes are usually too full to CCTV in Redding because of extremely high wet weather flows in the City (Harris & Tasello, 2004).
- The City of Hamilton, Ontario, Canada inspected with combined CCTV and sonar in 1998, then followed up this section with man entry to confirm the presence of cracking which was determined not to be as critical as noted in the earlier inspection report (Crowder, et al., 2010).
- Salt Lake City, Utah began to prioritize inspection of larger sanitary sewers following a catastrophic failure. However, the utility realized traditional CCTV, while helpful in

identifying structural failure and corrosion, could not quantify the magnitude of corrosion. The utility ended up using high def imaging/laser profiling/sonar combined technology (Graham, Brown, & Larson, 2010).
- A frequently leaky, 14 to 16 inch diameter reclaimed water line of WSP, DIP, and ACP in Incline Village, California, was televised as part of a condition assessment program. The interior surfaces of the joints were a particular concern, but the video inspections did not reveal any significant signs of corrosion except in areas where large sections of the cement mortar lining had fallen off due to third party damage (Villalobos & Najar, 2005).

However, in some cases, CCTV was specifically selected as the best tool for the job. For example, to assess the condition of 11,000 linear feet of 33 and 48 inch gravity sewer pipe and a low flow water depth of 25-30% pipe diameter, the City of Santa Clara, California, determined that traditional CCTV, which is typically limited to a single inspection distance of 2000 linear feet and has the ability to record defects above the flow line, was the most effective way to accomplish a thorough inspection (Avon, Kalkman, Taylor, & Amin, 2010).

In some cases, CCTV was used as the primary condition assessment technique for gravity sanitary sewers:

- Bellevue Utilities in Washington has an aggressive sewer CCTV inspection program. Two video trucks are owned in-house and approximately 10% of the wastewater system is inspected yearly. The pipeline videos are used for the purpose of coordination with street asphalt overlays and other CIPs so that needed sewer repairs can be made prior to other planned projects; inspection of critical pipelines with high failure consequences; determination of maintenance effectiveness activities and determination of need of adjustment of maintenance intervals; inspection of work performed by contractors; and investigation of wastewater system failures. Pipeline condition is rated using NASSCO PACP standard. This information is combined with a consequence of failure rating to prioritize sewer work (Heubach, 2011).
- The County of Los Angeles Consolidated Sewer Maintenance District, CA, initiated a program in 2005 with a 10 year goal to inspect the condition of over 4900 miles of sewer and proactively address maintenance and structural deficiencies. Between 2005 and 2010, the program has logged over 1300 miles in CCTV inspection videos using NASSCO PACP. Approximately 7.5% of segments analyzed are sent to maintenance crews for corrective action. A 34% reduction in SSOs has resulted from this program (Swartz, Villaluna, & Eskridge, 2010).

In many other cases, CCTV was utilized in conjunction with other condition assessment techniques, and was many times used as part of a larger condition assessment related program:

- The Columbus Division of Sewerage and Draining in Ohio used CCTV in conjunction with smoke testing, dye testing, and flow monitoring as part of investigation of potential I/I sources on private property (Lehmann, Schroeder, & Fallara, 2010).

- The City of Miami Beach, FL, used CCTV (and NASSCO PACP) as part of an SSES program, in conjunction with smoke testing and visual manhole inspections (Thomas, et al., 2010).
- The City of Toronto had a 2008 experience using non-man entry, single pass inspection methodology to obtain integrated CCTV, laser profiling, sonar profiling, and gas measurement data for trunk sewers (Sarrami & Doherty, 2009).
- Water Care Services Limited in New Zealand assesses its trunk sewer network using CCTV in conjunction with man entry and sonar to obtain condition data for use in risk analysis. The complete 300km system trunk network was inspected from 2000 to 2005 with CCTV and visual inspection, at an approximate cost of AU$1.5 million (Marlow, et al., 2007).
- CCTV was used as part of SSES plans in Oak Creek, WI; Honolulu, HI; LOTT, WA; King County, WA; McCandless Township Sanitary Authority, PA; and Milwaukee Metropolitan Sewerage District, Wisconsin (Merrill, Lukas, Roberts, Palmer, & Rheenan, 2003).

Zoom Camera

Many utilities were found to use zoom camera technology as an initial inspection technique, used to prioritize more in-depth inspections, and beneficial for its quick production rate and ability to provide assessment information without requiring the expensive process of cleaning, as well as for the ability for zoom cameras to be adapted to assess hard-to-access locations:

- After several force main failures and overflows impacted beach areas on a holiday weekend, the need for sewer rehabilitation became a focus of the media in coastal Wilmington, North Carolina. A priority –setting process for rehabilitation was implemented quickly, and zoom cameras were used as a cost-effective, investigative technique to acquire gravity sewer condition information up to 50-70 feet from the manhole through which the camera is inserted (Miles, 2007).
- The Town of Stoneham, Massachusetts; Dallas Water Utilities, TX; the City of Hamilton, Ontario; and the City of Quebec have zoom/clean/inspect programs (Di Tullio & Milley, 2005).
- The City of Hamilton, Ontario has implemented zoom camera screening programs in order to inspect their entire system and prioritize pipes for further inspection using other methods (Martel, et al., 2010).
- A pilot project performed in Dallas, Texas, used zoom camera technology and found that 70% of its pipes did not need cleaning, CCTV inspection, or other attention (Martel, et al., 2010).
- A mid-Atlantic utility implemented use of zoom cameras to investigate some of their major interceptors that were reaching the end of their design lives and were found through flow monitoring to be too small to convey current wet weather flows. These interceptors were difficult to access, as they were located beneath a major four-lane

highway right-of-way. The interceptors, ranging from 20” to 66” in diameter, would have been extremely difficult and extremely costly to assess through traditional cleaning and CCTV (Lee, 2005b).

- Zoom cameras were used by the Scranton Sewer Authority in Pennsylvania as part of compliance with its NPDES permit. After inspection of regulators in the combined sewer system, zoom cameras were used to provide images of adjacent piping to locate cracked, misaligned, or collapsed sewers, and blockages (Strauch, 2011).

In some cases, the use of zoom cameras was found to be unexpectedly beneficial over CCTV. After implementing zoom camera inspection on difficult-to-access interceptors that experienced significant corrosion, a mid-Atlantic utility found that collapse was imminent in many locations in the interceptor, and that if inline CCTV was used instead of zoom camera technology, the high pressure wash that would have been used to pre-clean the interceptor before CCTV-ing would likely have increased the possibility of collapse. In this case, the use of zoom camera inspections provided the information needed to make the necessary decisions in a cost-effective manner (Lee, 2005b).

Sometimes, zoom cameras were used as a method to help locate and record parts of a system rather than to inspect for condition:

- In addition to using zoom camera as part of a plan to locate and reduce I/I sources, the Town of Auburn, Massachusetts additionally used the zoom camera inspection data to assign structural and O&M service codes (Martel, et al., 2010).
- Hillsborough County Water Resources Services, Florida, implemented a zoom camera screening program in order to locate manholes and cleanouts, inspect manholes and pipelines, establish the condition of manholes and pipelines, and identify immediate maintenance and structural needs (Martel, et al., 2010).

Pushrod Cameras

Pushrod cameras are typically used to gather data on the condition of small diameter pipelines, such as in wastewater laterals. These cameras are used in this manner to find sources of I/I in the City of Jeannette Municipal Authority in Pennsylvania (Strauch, 2002).

Recently, push cameras have been further developed as an answer to a CCTV type technology for inspecting in-service pressurized lines. Though most case studies found in literature describe the use of this technology on water lines, there was one case study involving a pressurized wastewater line. Dallas Water Utilities conducted a CCTV inspection of a 6” ductile iron wastewater force main by inserting the CCTV sensor through a “Y” joint in the pipe. Fresh water was pumped into the force main while it was being recorded to reduce the turbidity of the water, which resulted in reasonable quality video inspection data on the pipeline (Jo, Laven, & Jacob, 2010). The paper in which this case study was presented concluded that current tethered inline video technology can be helpful in some general asset management decision making, but the quality of the video was not high enough to service as a consistent station-by-station visual inspection of the pipe. As the technology is developed with a better light source and better control over the camera, its usefulness may become more extensive (Jo, et al., 2010).

Digital Scanners (Optical Scanners)
Very few literature sources offered case study information on the use of digital scanning for condition assessment of wastewater pipelines. Digital scanning has been used in Europe and Asia for several years, but has a limited history in North America (Martel, et al., 2010). This could have been explained by the added cost of digital scanning over CCTV; however, recently, it has been found that the cost of digital scanning is similar to that of CCTV (Rizzo, 2010).

The City of Hamilton, Ontario, conducted a pilot test with digital scanning for sewer pipes in 2006 and was pleased with the quality of the data over CCTV data. However, the added cost of the highly detailed inspections provided by digital scanning was not justified in pipes less than 36 inches in diameter, as consequence of failure for smaller pipes was much lower. Unfortunately, in the larger, more critical pipes, SSET was not as effective. More recently, the cost of SSET has come down and now is more comparable to CCTV cost in Hamilton (Martel, et al., 2010).

Smoke Testing
Smoke testing is an investigative method traditionally employed with a number of other methods to determine sources of I/I (Lee, 2005a). Smoke testing is part of a typical SSES program, used in a targeted way to identify potential inflow sources in areas narrowed by a flow metering program (T. B. Wagner, 2011). This was demonstrated by almost all literature sources reviewed that mentioned use of smoke testing for wastewater pipeline condition assessment:

- The City of Miami Beach, FL carried out an SSES which involved smoke testing to identify inflow sources to the gravity sewer system. The smoke testing portion of the SSES was initiated in October 2007, completed in December 2007, tested about 75,100 linear feet of mainline gravity sewer, and identified a total of 40 defects which consisted primarily of missing cleanout caps on private property which allowed localized stormwater to illicitly drain into the sanitary system (Thomas, et al., 2010).
- The City of Jeannette Municipal Authority in PA uses smoke testing as part of a program to eliminate sources of I/I (Strauch, 2002).
- The City of Columbus Division of Sewerage and Drainage in Ohio used smoke testing as part of a 2009-2010 program to study more than 250 miles of sanitary sewer collection system and identify causes of overflows as well as to find sources of I/I and develop remediation plans (Lehmann, et al., 2010).
- The City of Miami Beach, Florida, a volume sewer customer of Miami-Dad Water and Sewer Department, used smoke testing as part of an extensive SSES project that was implemented as part of compliance with requirements set force by the Miami-Dade County Volume Sewer Customer Ordinance. Smoke testing was used to identify and understand the public and private sources of I/I, structural pipe defects, and O&M related defects in the system (Thomas, et al., 2010).
- In order to reduce rainfall-derived I/I, the communities of Banks, Cedar Hills, Cornelius, and Forest Grove used analysis including smoke testing in conjunction with flow metering, precipitation measurement, visual inspection, and cameras between 1991 and 1999 (Merrill, et al., 2003).

- Honolulu, HI, also used smoke testing in their SSES program to minimize I/I in conjunction with CCTV, visual manhole inspections, and mini-basin flow monitoring (Merrill, et al., 2003).
- King County, Washington completed an SSES program around 1987 that included smoke testing and CCTV inspection of sewers (Merrill, et al., 2003).
- The Milwaukee Metropolitan Sewer District also used smoke testing as part of SSES investigations, in addition to above-ground manhole inspections, sewer televising, building inspection, and dye testing (Merrill, et al., 2003).

Only one case was found that mentioned smoke testing used for condition assessment, but not as part of an SSES program. Beaufort-Jasper Water and Sewer Authority, SC used smoke testing after acquiring wastewater systems located on Military installations adjacent to wetlands and water bodies to determine the locations of inaccessible manholes, breaks in the line, and undetermined cross-connections (to the storm sewer) in the gravity sewer lines (Flynn & Sexton, 2011).

Smoke testing was reported to be insufficient for finding some sources of I/I by utilities:

- In Berkeley, California, a project was completed in the 1980s in which 250 laterals were tested with various inspection methods, and the results were compared with results of smoke testing performed previously on the same laterals. The comparison showed that smoke testing identified less than a third of lateral leaks. This has been the experience of many agencies, and is attributed to the fact that smoke testing does not identify sources of I/I associated with traps, sags, leaves and deposition, and high water levels (Sterling, et al., 2006).
- The City of Redding, California used smoke testing in conjunction with CCTV extensively on sections of the collections system showing dramatic increases in flow during storm events to find sources of I/I. The type of flow sources usually located were inflows from roof drains, open-cut clean-outs or leaky manhole covers that became submerged during peak wet weather conditions, Repairing these sources did not reduce the wet weather flow (Harris & Tasello, 2004).

Dye Testing

Dye testing is one of the traditional investigative procedures that has been employed to determine sources of infiltration and inflow (I/I) in wastewater pipeline systems (Lee, 2005a). It is a technique typically used for condition assessment of wastewater pipelines as part of a sewer system evaluation survey (SSES) program (T. B. Wagner, 2011), as was demonstrated by descriptions of the use of the technique during the literature review:

- Dye testing has been combined with internal CCTV inspection, smoke testing, and direct assessment in the sanitary sewer systems of the City of Hagerstown, Maryland; Washington County Water and Sewer Department; the US Military Academy at West point, and the Defense Distribution Depot (DDSP) (Strauch, 2004).

- The City of Jeannette Municipality Authority in Pennsylvania has been actively implementing a CMOM-type program since the early 1990s as part of compliance with a Consent Order and Agreement with the Pennsylvania Department of Environmental Resources, which required a corrective action plan to address hydraulic overloading at the wastewater treatment plant and periodic discharges of untreated sewage. Dye testing was just one of a variety of condition assessment techniques used to perform an I/I evaluation survey (Strauch, 2002). Dye testing was not only used on main gravity lines, but also was performed selectively during a pilot study of private building sewers and laterals to identify potential I/I sources such as sump pump, floor drain, and downspout interconnections (Strauch, 2002).
- The City of Columbus Division of Sewerage and Drainage in Ohio used dye testing as part of a 2009-2010 program to study more than 250 miles of sanitary sewer collection system and identify causes of overflows as well as to find sources of I/I and develop remediation plans (Lehmann, et al., 2010).
- The McCandless Township Sanitary Authority in Pittsburgh, Pennsylvania conducted dye testing to determine houses that had illegal connections to the sewer system as part of an SSES Program (Merrill, et al., 2003).
- The Milwaukee Metropolitan Sewerage District in Wisconsin performed an SSES investigation which included dyed water flooding of suspected source identified during smoke testing (Merrill, et al., 2003).
- Dye testing was also carried out to identify I/I sources in both the City of Lafayette, LA, and Dallas Water Utilities, TX, in 2003 (Sterling, et al., 2006).

One unusual case mentioned that in the City of Salem, Oregon, dye testing was used in order to detect if a house has more than one lateral. During the test, dye is added to each fixture in the house and a CCTV camera is inserted into the lateral close to the house foundation while an operator monitors for the appearance of dye in the lateral (Sterling, et al., 2006).

Acoustic Based Methods

Acoustic methods of detection were less prevalent that visual and camera based methods for condition assessment of wastewater pipelines. The use of above ground leak detection tools like ground microphones and noise correlators was not found during the literature review at all; nor was impact echo technology, spectral analysis of surface waves, or long range guided ultrasonic wave technology. Since many acoustic technologies rely on pressurization to work, those used for wastewater pipeline condition assessment tended to be those technologies that could be used for large diameter force main assessment.

Rod Sounding

The use of rod sounding for assessment of large diameter PCCP force mains was not prevalent in literature, but examples of this practice were found. Two examples describe similar PCCP condition assessment programs, for which rod sounding was carried out internally in conjunction with manned visual inspection:

- After the catastrophic failure of a 102 inch PCCP sewer force main, a PCCP condition assessment program was implemented by Middlesex County Utilities Authority, New Jersey. One of the condition assessment technologies used was rod sounding, which was performed internally in conjunction with a visual inspection in 2003 (Fitamant, et al., 2004).
- After witnessing the experiences of Middlesex County Utilities Authority and understanding that their PCCP was from the same time period, a similar PCCP condition assessment program involving rod sounding in conjunction with manned visual inspection was implemented by Greater Lawrence Sanitary District, Massachusetts in 2005 (Weare, 2007).

One example of the use of rod sounding externally was found in the case of rod sounding assessment done in conjunction with external visual assessment at key excavated locations along sections of PCCP force mains in Wilmington, North Carolina, as part of the utility's sanitary sewer condition assessment program (Miles, 2007).

In-Line Acoustic Leak Detection

In-line acoustic leak detection techniques were originally produced for use in water mains, but now have been piloted in wastewater applications. However, using these technologies in wastewater force mains adds a level of complexity due to the nature of the fluid conveyed through wastewater pipelines and the lower pressure encountered (Clothier, et al., 2011). A number of considerations come into play when utilities decide to use these technologies. Having available insertion points for the technologies, pipeline geometry and fittings that allow the condition assessment work to be more efficient, an appropriate flow velocity and volume, record drawings that indicate the vertical pipe configurations, and appropriate pipeline diameters are among the many concerns inherent in using these technologies.

In-line acoustic leak detection technologies are useful for wastewater force mains, which are less frequently designed with redundancy or access for internal inspection and thus cannot easily be taken out of service for inspection (Derr, Hubbard, Nzainga, & Varga, 2009). In-line acoustic leak detection technologies are applicable to all pipe materials, but require a minimum pressure and flow rate to be used.

Tethered In-Line Acoustic Leak Detection

Tethered in-line acoustic leak detection technology has been used in wastewater systems in the U.K. since 2005 with reported success and there have been several applications in North America since 2006 (Derr, et al., 2009). However, typical insertion equipment, which was originally designed for high pressure water systems, is heavy and difficult to transport and set up for lower pressure wastewater systems. Lighter and less expensive insertion methods appear to be easily feasible from a design standpoint (Derr, et al., 2009). The parachute that helps to propel the in-line sensor through the pipeline can be a concern if solids from the wastewater keep it from being retrieved through the insertion point. This was an occurrence in pilot tests performed for Hampton Roads Sanitation District, but was solved by detaching and releasing the parachute, resulting in the loss of the parachute but the saving of the sensor (Derr, et al., 2009).

In theory, tethered in-line acoustic leak detection can be deployed from a single point and gather data over a length of pipeline equal to that of the length of the cable with which the sensor is tethered. In actuality, the actual inspection distance per insertion is strongly dependent on the flow velocity and the number of bends and other fittings in the pipeline which must be negotiated (Derr, et al., 2009).

Pilot tests performed with tethered in-line acoustic leak detection in the Hampton Roads Sanitation District sewer system in coastal Virginia determined that the technology could successfully be inserted and retrieved from the system force mains and that useful information could be obtained on active leaks and air pockets in the system. However, two of the eight sites chosen for the pilot tests did not have an adequate flow velocity relative the number of fittings and bends in the segment to be tested. In cases where an adequate flow velocity was not consistently attained, and the pumping stations tributary to the segment were not able to attain higher pumping rates to meet the minimum velocity criteria during the test, it was not possible to use this technology (Derr, et al., 2009). Hampton Roads Sanitation District has only a fraction of force mains that meet the required criteria. The relative ease of deployment through existing 2-inch air release valve (ARV) taps make the technology an attractive one to use, where feasible, but other technologies will have to be employed where minimum flow velocities are unattainable (Derr, et al., 2009).

Wastewater force mains have few inspection stations, and the lack of easily accessible insertion and retrieval ports greatly increases the cost and difficulty of a wastewater force main inspection program (Derr, 2010).

In 2009, the Metropolitan St. Louis Sewer District carried out a trial test of tethered, in-line acoustic leak detection technology for the particular purpose of inspecting a pipeline that typically experiences unacceptably high flows in the system during high river stages. The technology was advantageous in that it allowed inspection during high river level conditions, unlike CCTV, and thus the utility hoped that it would identify the sources of inflow to the pipeline. The inspection results showed several sections of the pipeline that contained trapped air; however, there were no audio sounds that resembled a leak or infiltration found. In two locations, the velocity in the pipeline was no sufficient to carry the sensor. Therefore, it was concluded that there was a potential source of inflow in the interceptor downstream of this location that caused the velocity to decrease at the location of the insertion (Livingston, 2010).

Free-Swimming In-Line Acoustic Leak Detection

Free-swimming in-line acoustic leak detection technologies are deployed at one location and retrieved in a second, pre-planned location. In wastewater systems, the ball can be retrieved at an open discharge point such as a manhole or the headworks chamber in a wastewater treatment facility (Derr, et al., 2009). This type of technology is useful for wastewater force mains, which have few inspection stations. The lack of easily accessible insertion and retrieval ports greatly increases the cost and difficulty of a wastewater force main inspection program (Derr, 2010). Three examples of use of free swimming in-line acoustic leak detection for condition assessment of wastewater pipelines were found during the literature review:

- In order to inspect a 36-inch diameter ductile iron sewage force main which had experienced two unexplainable failures in a two year time span, the Milwaukee

Metropolitan Sewerage District, Wisconsin, assessed the pipeline's condition with free-swimming, in-line acoustic leak detection technology. Four sensors were installed on the force main to help locate the inspection device. The tool was inserted into a check valve at a pump discharge and traveled through the two miles of pipeline in approximately four hours, and then was recovered with a screen at the gravity sewer manhole at the terminal end of the force main. The results of the leak survey indicated no leaks and three air pockets (Noran & Obenauf, 2010).

- In 2008, the City of San Jose used free-swimming, in-line acoustic leak detection to survey approximately 1.5 miles of a 24-inch diameter ductile iron force main, as this technique allowed the force main to remain in service during assessment. Force main cleaning was conducted with a pig, four sensors were placed on the line to help locate the inspection device, and then the free-swimming in-line acoustic leak detection technology was inserted at a lift station. Due to insufficient wet well level at the lift station, pressure and flow could not be maintained over the entire run of the device through the line, and the pumps had to be shut down temporarily a few times towards the end of the run. The device was retrieved at the discharge box at the treatment facility. Fourteen gas pockets were identified, but no leaks were found (Wurst, Lee, & Shenkiryk, 2010).
- In 2008, Bay County Utility Services Department, Florida, released a free-swimming in-line acoustic leak detection device into a 42 inch subaqueous industrial waste PCCP force main and a 36 inch diameter subaqueous domestic wastewater HDPE force main, for the purpose of locating potential air pockets and leaks. No acoustic anomalies were found during this inspection (Murray, Carroll, & Higgins, 2009).

Acoustic Monitoring Systems

Though there were no examples of utility use of fiber optic monitoring systems for wastewater pipeline condition assessment found, there were three examples of pipeline condition assessment with the use of array based acoustic monitoring systems:

- As part of a proactive pipeline condition assessment program implemented after a catastrophic failure of a PCCP force main, Middlesex County Utilities Authority, New Jersey, installed a surface mounted acoustic emission monitoring system on a PCCP pipeline in 2004 to detect wire breaks. This system was found to be desirable because of the provision of real time information on the pipe deterioration rate, and was found to be remarkably accurate at locating and quantifying wire breaks (Fitamant, et al., 2004). Information on broken PCCP wires was followed by structural analysis which determined the likelihood of failure of the PCCP based on the number and locations of broken wires, loading factors, and pipe pressure factors (Fitamant, et al., 2004).
- A similar condition assessment program in Greater Lawrence Sanitation District in Massachusetts involved the installation of a single underwater hydrophone and six surface-mounted sensors installed on a PCCP. A wireless transmitter was used to capture acoustic event data. This monitoring system was purchased by the utility to provide a

permanent acoustic monitoring system and alerted the utility to three pipe sections of concern resulting in the dewatering and further inspection of one of those sections (Weare, 2007).

- In the City of Lake Worth and the City of West Palm Beach, FL, segments of higher risk 36 to 48-inch diameter PCCP were identified for monitoring with acoustic emissions testing and were monitored for a 700 hour period. Based on data collected during this period, it was determined that the force main was not deterioration in five out of the six monitored locations. At the sixth location, two prestressing wire related acoustical events were detected, indicating that there may be some distress present at that site (N. D. Stubblefield, Glaus, White, Morrison, & Shields, 2008) and (Mergelas, Stubblefield, Craig, Morrison, & White, 2007).

Sonar

Sonar is mainly used in wastewater management to provide evidence of sewer condition below the flow line (Rizzo, 2010). Because of this fact, it is often used in combination with CCTV and other technologies:

- Salt Lake City Public Utilities initiated a master plan study of their sewer collection system in 2008. Soon it was found that traditional CCTV inspection activities already performed by the City were helpful in identifying existing structural failure and corrosion but could not identify the magnitude of the corrosion. Therefore, a technology incorporating high definition imaging with laser profiling and sonar was used. The sonar results measured quantifiable amounts of sediment in the pipeline segments that were inspected, which was useful information to the City. Using the inspection results, a group of pipelines in Salt Lake City have been identified for appropriately prioritized renewal (Graham, et al., 2010).
- Water Care in New Zealand used a laser profiler mounted on a float with a sonar unit attached underneath. The sewer flow propelled the float, and the speed was controlled by a winch at the upstream manhole. Again, the sonar inspection provided data on various levels of silt build-up in the sewer. The data's accuracy was confirmed during the resultant sewer cleaning operation (Sunarho, 2009).
- The City of Toronto also used a non-man entry, single pass inspection methodology to obtain integrated CCTV, laser profiling, sonar profiling, and gas measurement data for trunk sewers in 2008. A minimum flow depth was required to submerge the sonar pulse generator head. When the flow level was too low, sonar readings could not be obtained. However, when it provided data, the sonar component of the multi-sensor inspection allowed conclusions and recommendations to be made on cleaning requirements (Sarrami & Doherty, 2009).
- The City of Baltimore used sonar in their condition assessment of large diameter outfall sewers which conveys wastewater flow from Baltimore City to a wastewater treatment plant. Due to the flow and sediment depth within these pipelines, traditional crawler type

> CCTV camera technologies were not chosen to conduct the condition assessments. Instead, a combination of CCTV above the flow line and sonar below the flow line was used in conjunction with hydrogen sulfide and temperature levels. The inspection crew coordinated with a nearby pump station, as the flows within the sewer were turbulent while the pump station was discharging flow. The most significant defect observed during the inspection was the sediment buildup along the length of the pipeline, which became increasingly dense and composed of gravel and debris along the length of the line. The survey had to be abandoned near a junction structure due to the inadequate flow levels and dense sediment (T. Wagner, Qadri, Slifko, & Braswell, 2009).

One example of use of sonar without combination with other assessment technologies was found during the literature review. In Ottawa, an outfall sewer between 84 and 95 inches in diameter, comprised of concrete lined tunnels, operates under continuously surcharged conditions. To address the concerns that the abnormal surcharging under otherwise low dry weather flow conditions might lead to excessive sediment buildup in the relatively flat interceptor, the region chose to undertake sonar inspection. Because of the surcharged conditions, only sonar was used. The inspection equipment was inserted by creating a short period of non-surcharged flow by briefly reducing the storage depth at the wet well. Sonar images clearly showed, in the sections inspected, that the invert of the pipe was, in fact, particularly well scoured and free of silt build-up (Andrews, 2010).

Ultrasonic Testing Methods

<u>*Ultrasonic Wall Thickness Measurement*</u>

While there are few technologies available for in-service inspection (which is excellent for non-redundant pipelines, ultrasonic is one that can be used. However, it is best for coverage of smaller portions of the pipe wall to detect individual defects at a level of great detail. It is best used for spot checks with statistical extrapolation (Wu, 2010). Examples of use of ultrasonic wall thickness measurement in ferrous and asbestos concrete pipelines are as follows:

- The City of Virginia Beach did assessment of ferrous pipelines that were exposed during an assessment program that involved digging test pits. The test pit locations were based upon condition ratings determined from existing data, and the exposed pipelines in test pits were sampled. In locations where the external condition of the pipe was conducive for accurate ultrasonic thickness measurements, the measurements were taken (Clothier, et al., 2011).
- Ultrasonic thickness measurements were taken as part of a corrosion investigation on a 22 mile long 14-inch and 16-inch diameter WSP, ACP and DIP reclaimed water pipeline near Incline Village, California. The Incline Village General Improvement District initiated the condition assessment rather than continuing to make emergency repairs on the pipeline. Ultrasonic measurements were taken at four locations (12, 3, 6, and 9 o'clock) on the DI pipe at each of the five areas of excavation and the thickness measurements were consistent with the original wall thicknesses. Calculations were

performed based on the estimated minimum and maximum surge pressures in each area (Villalobos & Najar, 2005).

- As part of a condition assessment project to investigate approximately 150km of uncoated grey cast and ductile iron pipes and coal tar enamel wrapped steel pipes in Singapore in 2004, the pipeline was excavated in some sites to determine "original" wall thickness of the pipe using a hand-held RFTC technology in conjunction with ultrasonic wall thickness measurement (Ferguson, 2010).

Ultrasonic methods can be used for PCCP inspection to determine the possibility of wire breakage, though its accuracy is not yet known. Velocity and frequency of pipe resonance are measured to determine concrete quality and detect lamination or cracks. This method seems to be good for testing selected uncovered PCCP sections from the outside. Because concrete is more attenuative than metals, the area inspected by conventional UT or GUWs is smaller than in metal pipes and lower ultrasonic frequencies used must be lower (Rizzo, 2010). Examples of use of this technology for PCCP inspection are as follows:

- Wilmington, North Carolina excavates key locations along its PCCP force mains and implements ultrasonic thickness testing to look for thinning due to hydrogen sulfide corrosion as part of the utility's sanitary sewer condition assessment program (Miles, 2007).
- A 60 inch diameter PCCP force main in central Virginia was excavated at multiple sites to allow for ultrasonic thickness measurements from the outside of the pipe in 2003 and 2004. This testing was intended to determine any thinning due to hydrogen sulphide attack (Lewis & Fisk, 2005).

Laser Based Methods

While the use of laser profiling by utilities for condition assessment of wastewater pipelines was easily found during the literature review, no case studies about the use of LIDAR were found. This

Laser Profiling

Though gaining popularity in the Unites States, laser profiling still appears to be more prevalent internationally than domestically. Some utilities used laser profiling for the main purpose of characterizing and quantifying the corrosion of the internal pipeline wall:

- As part of their sewer collection master plan, and in order to be able to quantify the extent of their system's corrosion, Salt Lake City used a joint laser profiling, sonar, and high definition imaging tool to inspect their large diameter gravity pipelines, ranging from 33 inches to 108 inches in diameter (Graham, et al., 2010).
- Sydney Water in Australia has utilized laser profiling as a means of inspection of concrete sewers, chosen for its ability to accurately measure the depth and extent of internal corrosion (Sunarho, 2009).

- Tauranga City Council in New Zealand used laser profiling to quantify the internal corrosion of a 24-inch diameter concrete sanitary sewer main (N. H. Bennett & Logan, 2005).
- To determine where corrosion was most severe in a semi-elliptical concrete sewer pipeline, Water Care in New Zealand used laser profiling before commissioning rehabilitation work (N. H. Bennett & Logan, 2005).

Other utilities were more interested in the ovality of their pipelines, which might indicate loading or structural problems:

- The City of Toronto used a single pass inspection methodology that integrated laser profiling with sonar profiling, CCTV, and gas measurement for large diameter trunk sewer inspections in 2008. Toronto was mainly interested in the ovality information obtained by the laser profiling technology (Sarrami & Doherty, 2009).

Other utilities were interested in the ovality or condition of their sewers to assess the pipeline's readiness for rehabilitation:

- The Fairfax County Maintenance and Stormwater Management Division in Virginia used laser profiling to assess the true ovality of a structurally compromised 21-inch concrete storm sewer pipe that was located in a residential easement. The planned rehabilitation method involved use of a very thick CIPP liner in conjunction with excavation and replacement of the worst sections of the pipeline. Laser profiling demonstrated that the ovality was not as bad as originally thought, and that the CIPP wall thickness was over-designed. This use of laser profiling saved initial construction costs as well as the social cost of excavation activities in backyards (Lee, Schell, & Hofer, 2009).
- In Louisville, Kentucky, laser profiling was used to verify the ovality of a newly installed 42-inch diameter HDPE storm water pipeline (N. H. Bennett & Logan, 2005).
- Laser profiling was used by the City of New Orleans to verify the condition of a 990 foot long large diameter sewer pipeline before rehabilitation with sliplining. The results revealed that there were over 30 misaligned joints in the section that would have been an impediment to the sliplining process, and an alternative trenchless rehabilitation technology was chosen as a result (Smith, 2009).
- Laser profiling was used in the City of Gladbeck, Germany, to verify the size of a pipeline before relining it. Previous investigations of the pipeline had suggested that there was a change in diameter through a section of the pipeline to be relined (N. H. Bennett & Logan, 2005).

In an example of use of laser profiling to confirm how much of a CIPP liner had distorted after the liner imploded during the installation process, the City of Portland used laser profiling to determine the maximum and minimum diameters inside the pipeline (N. H. Bennett & Logan, 2005).

Additionally, laser profiling was used as a new construction inspection technique by the New Castle County Department of Special Services in Delaware. The utility used laser profiling to verify the quality of the installation of a 42-inch gravity sewer pipeline. The ability to measure the exact deformation of the new pipeline after backfill and restoration correlated directly to a determination of expected design life (Lee, et al., 2009).

Electric and Electromagnetic Based Methods

Electric and electromagnetic based methods as used for utility condition assessment of wastewater pipelines were adequately represented during the literature review, except in the case of magnetic flux leakage, for which no examples of use could be found.

Eddy Current Testing

One example of use of eddy current testing was found during literature review. The use of eddy current testing is rare, and is mainly mentioned as a precursor to the development of remote field technologies. The example found in literature took place in Singapore. Approximately 150km of uncoated grey cast and ductile iron pipes and coal tar enamel wrapped steel pipes in Singapore were pigged as part of a condition assessment project in 2004 using near field technique intelligent pigging at strategic locations. This eddy current technique uses varying frequencies. It is much slower than RFTC pigging as measurements are made while the pig is stationary (Ferguson, 2010).

Remote Field Technologies

Literature examples of utility use of remote field technologies involved examples of the use of the standard technology, examples of the use of the modified technology for inspection of PCCP, and examples of the use of BEM. Examples of utility use of standard remote field technology are as follows:

- In Las Virgenes Municipal Water District, California, a free-swimming remote field technology was selected to inspect two 6 inch diameter ductile iron force mains for loss of material due to corrosion, feared because of the presence of corrosive soils in the area. This technology was more useful than MFL or UT would be due to the presence of a cement mortar lining and the possibility of tuberculation on the pipe walls, both of which prevented the MFL and UT technologies from being as close to the pipe walls as was necessary for an accurate assessment. A total 3,200 corrosion pits were detected, with more than 200 penetrating completely through the pipeline walls (though there were no leaks, either due to graphitization or the presence of the cement mortar lining) (Lippman, Ellison, & Romer, 2010).
- As part of a condition assessment project to investigate approximately 150km of uncoated grey cast and ductile iron pipes and coal tar enamel wrapped steel pipes in Singapore in 2004, the pipeline was excavated in some sites to determine “original” wall thickness of the pipe using a hand-held RFTC technology in conjunction with ultrasonic wall thickness measurement (Ferguson, 2010).

Examples of use of RFT for inspection of PCCP are as follows:

- Middlesex County Utilities Authority, New Jersey conducted Polar-Wave electromagnetic testing in a 102-inch diameter PCCP concurrently with visual and sounding inspections as part of its pipeline condition assessment program. The equipment was assembled within the pipeline and pushed through at walking speed. The results of the assessment revealed that 14% of the pipe segments inspected had 20 or more wire breaks (Fitamant, et al., 2004).
- A similar program in the Greater Lawrence Sanitation District in Massachusetts conducted an electromagnetic inspection to quantify the number of broken PCCP wires in 2005. It was found that an important aspect of this inspection was to properly calibrate the equipment for the type and size of pipe being inspected, in order to improve the accuracy of the results. In their case, Pure Technologies removed a portion of the pipeline segments to be tested in order to calibrate their equipment. Based on the results of the electromagnetic inspection as well as other condition assessment inspection results, one of the pipe sections was determined to be in imminent danger of failure and emergency repairs were implemented(Weare, 2007).

Only one example of use of Broadband Electromagnetic (BEM) scanning by a wastewater utility was found during the literature review. In order to assess the condition of the ductile iron (DI) portion of a wastewater force main with shared ownership by the City of Lake Worth and Palm Beach County, FL, used a variety of condition assessment techniques including BEM. The DI portion of the force main was 9.65 miles and of a diameter ranging from 42 inches to 54 inches. Because the main is manifolded, it serves as the primary conduit of wastewater to the treatment plant. It has no redundancy or bypass lines and cannot be taken out of service for more than a few hours or incoming flow would be forced to spill to an ocean outfall. Due to recent failures of the DI portion, BEM was used to make measurements of the existing DI pipe wall thickness including a profile of the wall at selected locations. Using historical O&M data, a determination was made regarding useful life of the pipeline, likely failure points, remaining wall thickness of ductile iron pipe segments, and what areas should be replaced (N. D. Stubblefield, et al., 2008).

Electrical Leak Location (Electro-scanning)

Examples of utility use of electro-scanning for pipeline condition assessment are mostly about use of the technology after other technologies are unsuccessful:

- After use of flow monitoring, television inspection, joint air pressure testing, and smoke testing for more than 20 years for infiltration assessment and location; repairing all detected leaks; and still ended up with collection system wet weather flows consistently 300% greater than dry weather flows, the City of Redding, California, chose to try electro-scanning. Electro-scanning was done as a pilot program on 25,000 feet of main line sewers in a sub-basin with particularly high wet weather flows. The electro-scanning was performed under surcharged conditions and spot excavations were used to verify the results, making it possible to repair any confirmed leaks during excavation. Pipe defects found with electro-scanning were found to be accurate and the pipeline was repaired at each of the spot excavations. It is speculated that the primary source of leaks was likely to be the large number of service connections and associated joints that could not be tested with more traditional techniques used for detecting sources of I/I, but could be found with electro-scanning. Also, the sewer rehabilitation program formulated using the electro-scan data was much more cost effective than any other wet weather flow reduction program carried out by the City of Redding (Harris & Tasello, 2004).

- In Vallejo, California, nine laterals were tested using electro-scanning in December 2004, and the agency's personnel reported that they liked the technology and found the results easy to interpret (Sterling, et al., 2006).
- In Sarasota, Florida, in March 2005, ten laterals were tested and the city engineers were impressed with the fact that the inspection was able to pinpoint leaks that were not visible with the City's lateral CCTV. The ease of use and apparent short training time required for personnel use was also appealing to the agency (Sterling, et al., 2006).
- In Miami-Dade County, Florida, 12 laterals were tested using electro-scanning in April 2005, and the system identified leaks in two laterals that had successfully passed an air pressure test. These false positives are believed to be the result of metal clamps that had been used to repair those laterals and were interpreted as leaks (Sterling, et al., 2006).

One utility used electro-scanning in another capacity. Athens-Clarke County Public Utilities Department in Georgia used electro-scanning as part of implementation of capital improvements. Approximately 9,200 feet of 36 inch diameter RCP was to be rehabilitated with CIPP. Traditionally, the line would have been cleaned and televised with CCTV twice – once during design activities to confirm the feasibility of the planned rehabilitation approach and again just prior to rehabilitation, which would have cost an estimated $100,000 per event. However, by inspection the pipeline with electro-scanning technology during the design activities rather than cleaning in conjunction with CCTV, approximately $85,000 was saved. Electro-scanning was performed under normal flow operating conditions rather than surcharged conditions due to access and slope constraints, and due to the fact that the purpose of the investigation was to confirm suspected joint leakage, which could be done with only partially full conditions (Moy, Coleman, & Wilmut, 2006).

Ground Penetrating Radar (GPR) and Pipe Penetrating Radar

Examples of use of both GPR and pipe penetrating radar for condition assessment of pipelines by utilities were found. Pipe penetrating radar examples are as follows:

- The earliest reported in-pipe survey took place in 2004 when the city of Phoenix, AZ approved a pilot project using combined GPR and digital scanning system. The system carried one GPR antenna, suitable to 30" and 36" pipe sizes with a maximum cable length of 250 feet and inspected approximately 6,000 feet of PVC-lined concrete sewer pipe, locating defects at the 12:00 pipe position. It is speculated that, as the technology advances, it could have other applications including the assessment of reinforcing bars within a pipe wall and determination of pipe thickness (Koo & Ariaratnam, 2006).
- Greater Vancouver Sewerage and Drainage District commissioned a high frequency pipe penetrating radar (PPR) survey to investigate a rectangular 30-inch storm sewer pipe.

The objective of the survey was to confirm the existing pipe wall thickness, the existence and spacing of reinforcement and locate any unforeseen obstacles or obstructions above the obvert using PPR. Since no information was available about the construction method and condition of the pipe, PR data provided critical baseline information for selecting the appropriate maintenance and rehabilitation strategy. A simultaneous CCTV recording accompanied the survey in order to provide a visual record of the inspection. The PPR data were of excellent quality with 16-24 inches signal penetration, and found the pipe wall thickness and reinforcement of the pipe walls, as well as the locations of rebar in the pipeline (Ekes, et al., 2011).

Examples of use of GPR by utilities for wastewater pipeline inspection are as follows:

- To inspect a deep, high-flowing, large diameter sewer in the City of Hamilton, Ontario, a combined CCTV/Sonar inspection was done in 1998, which found significant cracking. To confirm the results of the inspection, a man entry inspection was done in 1999, which confirmed the presence of cracking but found that it was not as critical as noted in the earlier inspection report. During the man entry, a single ground penetrating radar unit was also used and found that there was the presence of voids both around the pipeline, in the soil, as well as within the pipe wall. The voids within the pipe wall were explained as likely being a result of the concrete pouring practices used in the 1960's when the sewer was constructed. Due to the cracking in combination with the potential expansion of the voids found by the GPR, the City of Hamilton identified the sewer as a critical asset (Crowder, et al., 2010).
- GPR was also used to assess a large PCCP in central VA. The highest points of the pipeline appeared to have the most loss of pipe wall thickness. To avoid the danger associated with excavating the PCCP at the test pits at these high points, ground penetrating radar was used to locate voids or wet regions around the pipeline that might indicate partial pipe collapse or leakage. Only one anomaly was observed in this survey, which consisted of an area of higher moisture content within the soil in the vicinity of an 8" sewer line installed perpendicular to, and above, the PCCP pipeline (Lewis & Fisk, 2005).

Flow Based Methods

Flow based methods by utilities for condition assessment of wastewater pipelines were extremely commonly mentioned in literature. However, the techniques always had to do with the use of flow meters. No literature-based examples of use of night flow monitoring were found.

Flow Meters

There is much information on utility use of flow meters for wastewater pipeline condition assessment available in literature. For the most part, flow meters were used as part of SSES programs, or to identify sources of I/I. Examples are as follows:

- The City of Redding has nine permanent flow monitors located at lift stations and uses 28 portable flow monitors to cover the 380 miles of its collection system. Attempts to localize sources of I/I by monitoring smaller and smaller sub-basins in the City have required years due to the variability of rainfall events in the area and the fact that data analysis requires out-of-house expertise. Obtaining data to show the effectiveness of rehabilitation work has been found by the City of Redding to be equally complex, time consuming, and expensive. Flow monitoring has been found to be useful in showing the volume and general extent of infiltration, but not useful in designing an infiltration mitigation project for the City (Harris & Tasello, 2004).
- The City of Columbus Division of Sewerage and Drainage, Ohio, used flow monitoring in conjunction with other traditional techniques to help identify locations and causes of overflows, surcharging, and sewage backups, as well as to identiy I/I problems. Flow metering was done as a the first inspection technology used to understand the sewershed sub-basins (Lehmann, et al., 2010).
- The City of Miami Beach, Florida also used flow monitoring as part of the first phase of its SSES project, in order to identify and eliminate sources of I/I (Thomas, et al., 2010).
- Hampden Township, Pennsylvania, conducted a flow meter study in 2002 prior to the start of an aggressive I/I removal program to generally identify areas of the Township with significant I/I. After these areas were identified, a five year pilot program began in the identified areas involving CCTV as well as continued flow monitoring at pumping stations and with five open channel flow meters. After rehabilitation work was performed, the Township completed a second flow meter study to compare to the initial flow meter study results and quantify the I/I removed (Strauch, Miller, & Campbell, 2008).
- The Unified Sewerage Agency of Washington County, Oregon started its RDII reduction program in 1990, and uses flow meters to evaluate basins and evaluate the amount of I/I in each basin. If the expected reduction is greater than 70%, the utility will estimate the cost of rehabilitating areas of the basin, and if the cost of rehabilitation to achieve removal of the predicted amount of RDII is less than $2.00 per gallon of RDII removed, the project will proceed (Merrill, et al., 2003).
- Oak Creek, Wisconsin, collected flow monitoring data both before and after a sewer rehabilitation project intended to eliminate RDII. Before construction, a depth-monitoring device was installed at the downstream end of the basin to measure flows during dry and wet weather, and then the flows were computed using Manning's equation and pipe characteristics. It was important to make sure a backwater hydraulic condition did not prevent the pipe from flowing at a normal depth during the monitoring period, since this can subject information derived from depth-only flow meters to error. After construction, a velocity (and depth) flow meter was used to measure flows for the project site. Manual depth measurements were taken at the same time to confirm the flow meter

data and the velocity and depth sensors were cleared of any apparent debris weekly (Merrill, et al., 2003).

- The Lacey, Olympia, Tumwater, and Thurston (LOTT) Wastewater Partnership basins underwent a RDII reduction study that involved installation of a velocity and depth measuring flow meter at the outlet of the basin as an initial RDII investigation step (Merrill, et al., 2003).
- King County, Washington, did an I/I Pilot project in two areas. Before rehabilitation, in 1988 and 1999, flow monitoring was conducted on the sewer systems of these areas and was found to produce little usable data due to the fact that the metering probes were chronically clogged and the depth of the low flows did not cover the velocity/depth probe placed in the invert of the sewer (Merrill, et al., 2003).
- McCandless Township Sanitary Authority in Pennsylvania performed an I/I abatement program in an area of their sewer system in 1999. The authority began a flow monitoring program approximately three years before the I/I abatement program, which acted as a snapshot of the infiltration issues in the systems. Flow monitoring was also conducted post-construction to evaluate the success of the I/I program and has been ongoing (Merrill, et al., 2003).
- Metropolitan Council Environmental Services in Minnesota has collected wastewater flow data for the purpose of billing more than 100 communities in the twin cities metropolitan area for many years. In the early 1990's, several years of data from seven flow meters were analyzed to determine the system-wide impact of RDII (D. Bennett et al., 1999).
- The Bureau of Environmental Services in Oregon collected system flow data for calibration of models to be used in combined sewer and system-wide facility planning, including estimation of RDII within the sanitary sewer system (D. Bennett, et al., 1999).

In one example, a utility used flow meters as a tool to determine the condition of a single pipeline. Las Virgenes Municipal Water District uses flow meters on both ends of an 8-inch diameter cast iron force main that, though installed in 1993, has a history of failure. If a pre-determined deviation in flow is observed between the two meters, the pumps are to be shut down and the pipeline surveyed for evidence of failures (Lippman, et al., 2010).

In another example, a utility used flow meters to direct future growth and improvement. Montgomery Water Works and Sanitary Sewer Board in Alabama collected sewer flow data to focus its sewer system rehabilitation and for sewer system improvement planning (D. Bennett, et al., 1999).

Physical Force Based Methods

Not many examples of utility condition assessment of wastewater pipelines using a method based upon physical force were found. However, the most commonly encountered method in this category was joint pressure testing.

Gas or Liquid Joint Pressure Testing

Pressure testing use for condition assessment of a force main, a gravity sewer, and of laterals were found during the literature review. The Las Virgenes Municipal Water District used water pressure testing on an 8-inch diameter ductile iron force main after it had experienced two major failures caused by microbiologically induced corrosion. This method was used to find areas where the pipeline was bad and replacing those sections rather than replacing the whole line. Pipeline sections were methodically pressurized between isolation valves up to 150% of the pipeline's working pressure. Results indicated no structural failures or leaks. This pressure testing is now repeated on a regular basis to monitor the integrity of the system (Lippman, et al., 2010).

The City of Redding used air pressure testing extensively as part of its program to detect I/I sources in its gravity system. The testing method involved an in-pipe packer to isolate a joint and the application of air pressure to test the joints. However, after using this methodology in conjunction with smoke testing and CCTV and repairing every leak detected, it was found that there was still an extremely high level of wet weather flow in the sewer system. It has been speculated that this may be due to the fact that joints immediately adjacent to service connections and service connections cannot be tested with this methodology, and this is where many of the I/I sources are located (Harris & Tasello, 2004).

Examples of utility use of pressure testing for lateral condition assessment are as follows:

- In both Miami-Dade County, Florida and in the City of Burlingame, California, specific air pressure testing procedures have been developed to verify the leak-tightness of sewer laterals (Sterling, et al., 2006).
- In both the City of Key West, Florida and in the City of Burlingame, California, a particular hydrostatic pressure testing procedure has been developed in order to verify the leak-tightness of upper laterals (Sterling, et al., 2006).

Transient Pressure Monitoring

Only two examples of use of transient pressure monitoring as part of condition assessment by a wastewater utility were found. The examples are as follows:

- A transient pressure monitoring system was permanently installed as part of the Greater Lawrence Sanitation District, Massachusetts, pipeline condition assessment program. Based on the some of the unexpectedly high pressure surges found, the utility prioritized the rehabilitation of the old surge control valves on their pumps, which effectively reduced the magnitude of the pressure surges (Weare, 2007).
- A hydraulic analysis was done as part of a corrosion investigation on a 22 mile long 14-inch and 16-inch diameter WSP, ACP and DIP reclaimed water pipeline near Incline Village, California. The Incline Village General Improvement District initiated the condition assessment rather than continuing to make emergency repairs on the pipeline. The minimum wall thickness required to withstand surge pressures was calculated and it was found that though the steel had retained most of its original strength, the thickness of the walls was not sufficient for certain segments. Samples were send to a laboratory for

mechanical and chemical testing and the results concluded that the pipeline was of satisfactory condition (Villalobos & Najar, 2005).

Micro-Deflection

Micro-deflection was used to assess the condition of brick sewers in Montreal in the mid-1990's (Makar, 1999). No other examples of use of micro-deflection for condition assessment of wastewater pipelines have been found.

Probing

Only one example of utility use of probing for determining condition of a wastewater line was found during the literature review. The City of Santa Clara, California, performed penetration tests at manholes on a 13,000 foot long gravity pipeline consisting of both lined and unlined RCP , DIP, and Techite pipe and ranging from 33 to 48 inches in diameter. The line had experienced significant corrosion problems. The penetration tests were used to assess the condition of the concrete. The information was used in conjunction with other condition assessment technology derived information to determine the areas of the line at the most risk (Avon, et al., 2010).

Temperature Based Methods

No information on wastewater utility use of temperature based methods for condition assessment of pipelines was found during the literature review.

Environmental Testing

Soil Testing

In most utility case examples of soil testing, the work was done as part of condition assessment of a particular pipeline. Many pipeline materials were covered by these examples, which are as follows:

- Soil samples were collected around a PCCP by the Greater Lawrence Sanitation District in 2005 to determine if environmental conditions were detrimental to the structural condition of the pipe. In one location, the soil quality was found to be aggressive. In this section, the pipeline was in poorer condition than the rest of the line (Weare, 2007).
- The City of Hamilton, Ontario had boreholes drilled from the surface around a pipeline that was being inspected in order to confirm the soil strata around the pipe and to determine the groundwater table level (Crowder, et al., 2010).
- CSIRO in Australia conducted soil testing as part of condition assessment of a 300mm AC pressure sewer pipe constructed in 1978. Seven locations were sampled, tested for soil aggressiveness, and used to carry out a preliminary analysis to identify sections of the pipeline with high probability of failure. Several of these positions were then recommended for core sampling (Marlow, et al., 2007).
- Soil resistivity analysis was done as part of a corrosion investigation on a 22 mile long 14-inch and 16-inch diameter WSP, ACP and DIP reclaimed water pipeline near Incline Village, California. The Incline Village General Improvement District initiated the condition assessment rather than continuing to make emergency repairs on the pipeline. Soil samples were taken and the evaluation of the samples showed that the majority of

the pipeline was in negligibly corrosive soils, but one area near a marshland contained high concentrations of chlorides, which prompted a recommendation to replace 100 feet of the pipeline in this area. The level of sulfates at the DIP discharge area reduced the soil resistivity to a level considered corrosive to metallic pipes (Villalobos & Najar, 2005).

In one case, soil testing was mentioned as part of a full program to evaluate the corrosion potential for a utility's critical pipelines. After evaluating existing data, it was found that there was not sufficient information to assess the full potential impact of environmental factors on the City of Virginia Beach's critical inventory, which was predominantly iron. Therefore, a Corrosion Evaluation Program, approximately 5 months in duration, included detailed field and laboratory analyses to characterize the corrosivity of the soils. Soil samples were collected at approximately every 500 feet along critical force main infrastructure. In-situ resistivity and pH measurements were taken at approximately every 200 feet along the critical force main infrastructure. Since the presence of chlorides, sulfate ions, sulfides, and redox potentials measured within the limits of the City's program were well below industry thresholds, they were not considered to be significant factors in the deterioration of the City's critical infrastructure (Clothier, et al., 2011).

In another case, soil testing was used as a forensic measure. Following a 2003 force main rupture, Middlesex County Utilities Authority did soil sampling and testing along the line to determine whether aggressive soil conditions existed along the entire line or in isolated areas (Fitamant, et al., 2004).

Groundwater Testing

In two examples of utility use of groundwater testing, the work was done to determine the aggressiveness of the environment and possible resulting damage to the pipeline assets:

- Groundwater sampling was done by the Greater Lawrence Sanitation District in Massachusetts as part of a pipeline condition assessment condition to determine if environmental conditions were detrimental to the structural condition of a PCCP. One of the samples was found to be aggressive, and this sample corresponded to the section of pipeline displaying signs of being in poor condition (Weare, 2007).
- Wilmington, North Carolina takes groundwater samples along with soil samples at key points along their PCCP force mains in order to determine the aggressiveness of environmental conditions, which may indicate potential for external corrosion. This is part of the utility's sanitary sewer condition assessment program (Miles, 2007).

In one case, groundwater sampling was used forensically. Following a 2003 force main rupture, Middlesex County Utilities Authority did groundwater sampling and testing along the line to determine whether aggressive soil conditions existed along the entire line or in isolated areas (Fitamant, et al., 2004).

In one other example found, groundwater was sampled for yet another purpose: The City of Hamilton, Ontario sampled groundwater after cleaning and during man entry inspections of a large diameter sewer pipeline. Samples were taken from the inside of the pipe, as the ground water was infiltrating into the line, and were used to determine sediment accumulation and estimate a rate of groundwater infiltration to the pipe (Crowder, et al., 2010).

Gas Sensors

Only two examples of utility use of gas sensors as part of condition assessment of a wastewater pipeline were encountered during the literature review. The City of Toronto used a single pass inspection methodology that integrated gas sensors for measurement of hydrogen sulphide with sonar profiling, CCTV, and laser profiling for large diameter trunk sewer inspections in 2008 (Sarrami & Doherty, 2009).

The City of Santa Clara, California, used hydrogen sulfide sampling on a gravity sanitary sewer that suffered from extensive corrosion. The pipeline ranged in diameter from 36 to 48 inches and was constructed of lined and unlined RCP, DIP, and Techite pipe. Eight manholes along the 13,000 foot length of the pipeline were selected for hydrogen sulfide monitoring based upon the findings from previously completed manhole inspections (which consisted of wastewater sampling, penetration testing, and concrete sampling). Monitoring of those eight manholes was conducted in 2009 over a 7 day period in June. Suspended hydrogen sulfide gas monitors were set up at all eight locations and left for the duration of the monitoring period. The results showed that, because there is no air gap for the hydrogen sulfide to escape downstream, it flows to the manhole nearest to the interceptor, creating a lethal concentration that was above the limit that could be measured by the monitor (Avon, et al., 2010).

In-Pipe Flow Testing

Two examples of in-pipe flow testing were found during the literature review. For the City of Santa Clara, California, the work was undertaken as part of work to assess the risk of corrosion to a main gravity sewer line. Wastewater samples were taken at each manhole using confined space entries. The samples were tested for dissolved sulfides (Avon, et al., 2010).

Alternately, in Incline Village, California, the wastewater flowing inside a water reclamation pipeline of 14 to 16 inches in diameter, constructed of WSP, DI, and AC, was sampled and the Langelier Index calculated. The Langelier Index evaluates the calcium carbonate saturation capabilities present in the water. A positive index value indicates that the water would form a protective layer of calcium carbonate on the inside surfaces of the pipe, while a negative value would indicate that the water would dissolve calcium carbonate and not form a protective layer. The results showed an average value of -1.4, indicated that effluent wastewater will continue to leach out of the lime in the mortar lining the pipe (Villalobos & Najar, 2005).

Pipe to Soil Potential/ Stray Current Mapping

Only two examples of utility use of potential surveys and stray current mapping were found during the literature review. Both sources involved work done to estimate the corrosion potential to the pipeline:

- The City of Virginia Beach's Corrosion Evaluation Program was implemented after finding there was insufficient information to fully assess the potential impact of environmental factors on the City's critical force main infrastructure, which predominately consisted of iron pipelines. The program included cell-to-cell potential surveys which were allowed, by site conditions, to be conducted along approximately

44% of the critical force main infrastructure. The remaining infrastructure was either inaccessible within 10 feet due to a paved surface or another ferrous pipeline was located between the critical infrastructure and the point of measurement. Measurements were taken every 4 feet along the entire critical inventory and detected numerous locations where spikes in the survey profile showed anodic activity at rates greater than 25 millivolts which is usually indicative of significant corrosion activity. No sources of stray DC current were identified in any of the potential measurement surveys(Clothier, et al., 2011).

- In 2009, a survey of the galvanic cathodic protection system installed on a 24-inch ductile iron force main in San Jose, California, was done. The results of pipe-to-soil potentials indicated an electrical discontinuity, which could possibly be the cause of the force main not receiving adequate cathodic protection. Soil resistance was also measured to assist with the rehabilitation of the pipeline's cathodic protection system, and the results indicated that the soil was highly corrosive to buried metallic pipelines (Wurst, et al., 2010).

Other Methods

Coupon and Other Sampling

Many examples of physical sampling of a pipeline network in order to determine the conditions of a pipeline were found. Coupon sampling and core sampling was prevalent. Examples include the following:

- In the City of Virginia Beach, as part of a condition assessment program for force mains, test pits were dug in locations set by condition ratings determined using existing data. In places where external ultrasonic wall thickness measurements were not available due to the condition of the pipeline, coupon samples of the ferrous inventory at the test pit sites were taken and direct wall thickness measurements were made. Samples were then grit-blasted to remove graphitized portions of the pipe with no remaining structural value and pit depth measurements were made (Clothier, et al., 2011).
- Coupons are sometimes used during force main investigations in Wilmington, North Carolina's sanitary sewer condition assessment program as a means of calibrating and verifying non-destructive testing results at critical locations (Miles, 2007).
- Coupon sampling was done as part of a corrosion investigation on a 22 mile long 14-inch and 16-inch diameter WSP, ACP and DIP reclaimed water pipeline near Incline Village, California. The minimum wall thickness required to withstand surge pressures was calculated and it was found that though the steel had retained most of its original strength, the thickness of the walls was not sufficient for certain segments. Pipe wall samples were sent to a laboratory for mechanical and chemical testing and the results concluded that the pipeline was of satisfactory condition (Villalobos & Najar, 2005).
- For test pits of the AC inventory in Virginia Beach's condition assessment program for critical force mains, samples were cut into excavated sections to allow for cement

degradation testing across the cross-section of the pipe. When applied to structurally sound cement pipe, phenolphthalein indicator solution turns fuchsia in color while degraded cement with no structural integrity remains colorless. The remaining wall thickness of structural cement is then measured to determine the rate of material degradation due to cement-leaching and estimate anticipated remaining life.

- The City of Hamilton, Ontario had concrete cores extracted from pipe walls inside a sewer that was being inspected with man entry in order to confirm concrete thickness and strength (Crowder, et al., 2010).
- Following soil sampling and testing, CSIRO in Australia took core samples of a 300mm AC pressure sewer pipe constructed in 1978. After cores were taken, the residual tensile strength of the pipe wall was assessed and used to derive a probability density function to quantify the variation in deterioration rate for two distinct soil environments. The function was then used with a physical failure model to assess the asset's propensity toward failure (Marlow, et al., 2007).

Two examples of testing of cement mortar lining were found in the literature review:

- The Greater Lawrence Sanitation District in Massachusetts sampled mortar from a PCCP in 2005 along with soil and groundwater from the same areas and found that, in one section, the mortar coating was poor and not protecting the pipe from the aggressive environment surrounding it. This section of pipe was demonstrating multiple signs of being in bad condition (Weare, 2007).
- Cement mortar lining sampling was done as part of a corrosion investigation on a 22 mile long 14-inch and 16-inch diameter WSP, ACP and DIP reclaimed water pipeline near Incline Village, California. The cement mortar lining samples were analyzed to find pH and alkalinity, and the pH of the cement mortar exposed to the effluent was lower, which may indicate that the wastewater acidity may have leached out some of the lime in the mortar. The alkalinity testing showed that the mortar has retained most of its original alkalinity (Villalobos & Najar, 2005).

In one case, concrete was scraped from the walls of manholes. In Santa Clara, California, two samples of concrete were taken from within each manhole on a 13,000 foot long lined RCP, unlined RCP, DIP, and Techite pipe line ranging from 36 to 48 inches in diameter. The line had experienced serious problems with corrosion. The first sample in each manhole was to be taken from the corroded concrete, while the second sample was to be taken from the solid concrete underneath, after all the loose corroded concrete was removed from the sample area. Samples were to be tested for pH (Avon, et al., 2010).

In another example, prestress wires collected from a Middlesex County Utilities Authority, NJ, PCCP line that had failed catastrophically in 2003 underwent metallurgical testing to determine the material properties and condition of the wire (Fitamant, et al., 2004). It was found that there were some pre-existing wire splits that would not currently pass manufacturing standards, caused by manufacturing processes that also result in hydrogen embrittlement sensitivity. Hydrogen sensitivity and the existence of pre-existing weak spots in wire are characteristics typical of Interpace manufactured Class IV PCCP wire during the 1970's, but are also found in Class III wire (Fitamant, et al., 2004).

Synthesis of Literature Reviewed

The literature reviewed showed the prevalence of use of certain technologies by wastewater utilities for condition assessment of pipelines. The prevalence of flow meters as well as visual and camera based technologies appears to be in accordance with the oft-recommended progressive condition assessment approach for large diameter sewers to identify sources of I/I, in which the assessment starts with flow monitoring, proceeds to zoom camera inspections in areas identified during flow monitoring, which then narrows the group of pipelines to be inspected with CCTV inspections, smoke testing, and dye testing (Wade & Buonadonna, 2010). Because these technologies are typically used for assessment of gravity sewers, which are typically of lower criticality than force mains, the prevalence of their mention is surprising.

Of the methods are available for evaluating the condition of small diameter force mains, most methods infer the condition of the pipe, either from samples of the pipe or from measurements of the corrosive environment (Lippman, et al., 2010). Accordingly, the literature review echoes this with a large quantity of information on coupon and other sampling and environmental testing. There was also a great deal of information available on the technologies applied for the assessment of the condition of PCCP, which utilities appear to have a great deal of trouble with.

State-of-the-Art Practice Review for Technology Use

In addition to a literature review, a practice review of condition assessment technology and methodology use with wastewater pipelines was performed. The practice review involved obtaining information directly from utilities regarding their use of condition assessment techniques.

Definition of Scope

The practice review focused on gathering information directly from utilities about their experiences with use of certain technologies and/or methodologies of condition assessment. The focus was on the choices made regarding these condition assessment techniques as well as the advantages and limitations of the techniques within certain projects or programs. While some information was gathered on costs, surrounding regulatory issues, data analysis, and the place of the condition assessment work done within the larger umbrella of asset management, the focus of the practice review centered on information that could be mined to help other utility personnel understand and choose the available techniques for condition assessment of wastewater pipelines.

Methods for Data Mining

Data mining began with the creation of guiding questions for utilities, which were intended for use during meetings with utilities and utility follow-up to further guide the utilities in the type of information sought by the research team. The guiding questions consisted primarily of open-ended questions in order to discourage a survey-like response and to get the most information on the subtleties of use of different condition assessment technologies and their advantages and limitations according to the region of use, the size of the utility, the pipeline material and diameter, and other aspects of the work.

The research team members located and targeted experienced utilities of varying sizes and geographical locations in the United States. Fifteen international utilities were also targeted. When requested, Virginia Tech signed Memorandums of Understanding (MOUs) with utilities across the nation. The MOUs protect utility information shared with the research team. The information cannot be shared until utility approval is obtained.

The utility data mining process was as follows: A knowledgeable contact from the utility was identified and a meeting with this contact and others the contact deemed appropriate was held. The aim of this meeting was to share the project objectives with the utility, to request the utility's participation in the project, and to discover the extent of the utility's experience with pipeline condition assessment. If the utility agreed to participate in the project, research team members set up and held interviews with appropriate managers, staff members and/or consultants in order to data mine experiential information and request all relevant documentation on the condition assessment technology or methodology. In this manner, detailed information on utility experiences was captured in addition to anecdotal information. Because of time constraints, it was often not possible for the research team to cover all of a single utility's experiences. In these cases, the research team focused on data mining information on as many categories of condition assessment technologies as possible and asked about unique experiences.

Utility Practices Covered

The utility practices covered are summarized in Table 4.

Table 4. Summary of Utility Practices Covered

Utility, State (number of case studies)	Condition Assessment Technique(s) Employed
Aurora Water, CO (3)	Ultrasonic Wall Thickness Measurement Direct Assessment Sonar Traditional CCTV Laser Profiling Gas Sensors
Baltimore County Department of Public Works, MD (2)	Remote Field Technologies Direct Assessment Zoom Camera
City of Des Moines Public Works, IA	Traditional CCTV Flow Monitoring Smoke Testing Dye Testing
City of Jeffersonville Wastewater Department, IN	Traditional CCTV Smoke Testing Flow Monitoring
Johnson County Wastewater, KS	Direct Assessment Hand-Held Digital Camera
City of Phoenix Water Services Department, AZ (3)	Traditional CCTV
City of Virginia Beach Department of Public Utilities, VA (2)	Traditional CCTV Smoke Testing Night Flow Isolation Flow Monitoring Dye Testing
City of Worthington Public Services Department, OH	Traditional CCTV Smoke Testing Flow Monitoring
County of Los Angeles Department of Public Works, CA (1)	Traditional CCTV
Dover Utilities Commission, NH	Traditional CCTV Flow Monitoring
Grand Forks Wastewater Authority, ND (1)	In-Line Leak Detection
Howard County Department of Public Works, MD (4)	Flow Monitoring Traditional CCTV Direct Assessment Dye Testing Smoke Testing Night Flow Isolation
Massachusetts Water Resources Authority, MA	Sonar Traditional CCTV Pushrod Camera Zoom Camera
Miami-Dade Water and Sewer Department, FL (1)	Remote Field Technologies
Milwaukee Metropolitan Sewerage District, WI	Soil Testing
Montgomery County Water Services Department, OH	Traditional CCTV
Peachtree City Water and Sewer Authority, GA (1)	Traditional CCTV
San Antonio Water System, TX (1)	Smoke Testing
Sydney Water, Australia (1)	Sonar Traditional CCTV Laser Profiling

These utility practices are broken down by technology and further explained below.

Direct Assessment

Case study information was gathered from utilities about the practice of direct assessment. The utilities from which information was gathered are illustrated in Figure 18. Johnson County Wastewater, Howard County Department of Public Works, and Baltimore County Department of Public Works provided information on their use of above ground direct assessment, while Aurora Water provided information on direct assessment with man entry into the pipes to be assessed.

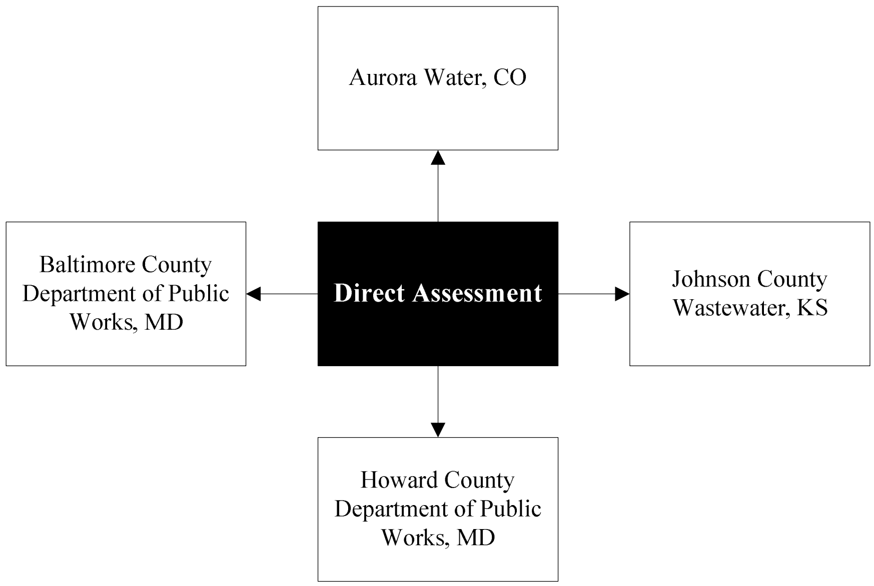

Figure 18. Utilities from which Information on the Practice of Direct Assessment of Pipelines was Gathered

Johnson County Wastewater used direct assessment to gather data about the condition of wastewater encasements, sewer pipes, and manholes above ground and exposed in stream channels or in stream beds. Direct assessment was used to find these at-risk locations and was also used to further inspect them after identification.

Howard County Department of Public Works scheduled direct assessment of sewers as part of their program to identify sources of I/I; however, the utility also used above-ground sewer and manhole inspections as a way to provide field crews with an opportunity to familiarize themselves with the areas where later tasks would be performed. Field crews walked each sewer line, located each manhole, and noted the surrounding topography. Streams and drainage culverts, areas prone to natural ponding, rain leader discharges, and any other visual clue to possible sources of I/I were documented in an above-ground manhole inspection form with a checklist.

Baltimore County Department of Public Works did an above ground assessment of a pump station force main. The inspectors walked along the alignment to look for the locations of existing valves located along the alignment as well as ground surface anomalies, including:

- Ground surface features that might be sources of electrical conductivity, such as direct current power trains, arc welding equipment, or electrical grounding systems;

- Ground surface features that may indicate force main break or settlement, such as localized soil erosion, pools of standing wastewater or evidence of standing wastewater, and odor;
- Environmentally sensitive areas such as wetlands and streams along the force main alignment.

Aurora Water used direct assessment in a man-entry operation to gather information on the condition of large diameter corrugated metal pipelines that were part of their stormwater system. The visual inspection identified representative areas of rust and defects. Those areas were then cleaned to with a wire brush to determine the extent of rust into the corrugated metal pipe material.

Hand-Held Digital Cameras

As shown in Figure 19, Johnson County Wastewater was the only utility that provided direct information on use of a hand-held digital camera for condition assessment of wastewater lines. Johnson County Wastewater used the camera in combination with direct assessment to capture the condition of all wastewater line stream crossings. The information gathered was later used to prioritize renewal activities for those pipelines that needed it.

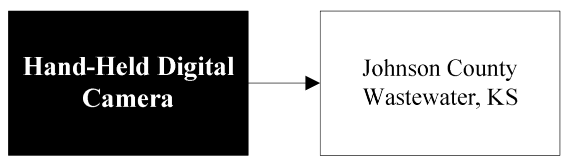

Figure 19. Utilities from which information the use of Hand-Held Digital Cameras for Condition Assessment Wastewater Pipelines was Gathered

Traditional Closed-Circuit Television (CCTV)

The use of CCTV is prevalent in wastewater pipeline inspection. Many utilities provided information on their CCTV practices. The utilities from which information on the use of CCTV for wastewater pipeline condition assessment was gathered are illustrated in Figure 20. Dover Utilities Commission and Massachusetts Water Resources Authority both own CCTV equipment and do inspection work in-house. The City of Virginia Beach Department of Public Utilities and Howard County Department of Public Works reported use of CCTV as part of an SSES program. The City of Phoenix Water Services Department reported the use of CCTV to inspect large diameter lined concrete interceptors, PVC lined concrete sanitary sewers, and unlined concrete sewers. The City of Des Moines Public Works uses CCTV as its primary method of condition assessment of its sanitary sewer system, as do Peachtree City Water and Sewerage Authority and the Montgomery County Water Services Department. Sydney Water reported use of CCTV in conjunction with laser profiling. Aurora Water used CCTV as part of condition assessment work performed on large diameter corrugated metal storm sewer pipelines. The County of Los Angeles Department of Public Works conducts CCTV inspections of the area’s sanitary sewer system and posts the inspection results online for public access. The City of Worthington Public Services Department also performs CCTV on all of its gravity sanitary sewer lines.

Figure 20. Utilities from which Information on the Use of CCTV for Pipeline Condition Assessment was Gathered

The City of Virginia Beach Department of Public Utilities reported use of traditional CCTV as part of a large SSES program:

- For SSES basin investigations triggered by exceedance of an established peak flow threshold with no wet-weather SSOs, the field investigations focus on identifying sources of I/I and structural defects within the gravity sewer system and involves using smoke testing to identify areas to be inspected with CCTV to confirm inflow sources, then further CCTV inspections based on the results of the initial CCTV footage. If the SSES basin is one that was identified as a strategic grown area by the City, CCTV of the entire gravity system within the basin is conducted.
- For SSES basin investigations triggered by unresolved SSOs caused by infrastructure defects, the logic approach for field investigation involves conducting CCTV within the

pipe segment where the SSO occurred, the upstream segment, and the downstream segment.

The City of Virginia Beach Department of Public Utilities, the City of Worthington Public Services Department, the City of Jeffersonville Wastewater Department, Montgomery County Water Services Department, and Peachtree City Water and Sewerage Authority use NASSCO PACP standards to conduct CCTV investigations and document findings.

Dover Utilities Commission recently finished inspecting all of the utility's sanitary sewer lines with CCTV, and is using that information to help make sure the information gathered is accurate in the City's GIS, with the sewer lines appropriately connected and the manholes and pipes correctly identified.

Montgomery County Water Services Department began to have a lot of sewer breaks and overflows in the early 1980s, and began doing CCTV inspections in 1985. Based upon the results of the CCTV inspections, the lines were prioritized for renewal. The utility has had great success using CCTV as its primary condition assessment technique.

Zoom Cameras

Two utilities provided information on their use of zoom cameras for condition assessment of wastewater pipelines, as shown in Figure 21. While Massachusetts Water Resources Authority reports use of zoom cameras primarily for manhole inspection, Baltimore County Department of Public Works described their use of a zoom camera for inspection of a specific force main's transition manhole and connecting gravity sewer lines.

Figure 21. Utilities from which Information on the Use of Zoom Cameras for Wastewater Pipeline Condition Assessment was Gathered

Baltimore County Department of Public Works used a zoom camera to inspect a specific transition manhole for a force main in order to identify and record hydrogen sulfide corrosion defects in the manhole and exposed interior wall of the force main and discharge sewer. The visual pipe inspections were recorded and it was found that approximately ten linear feet of the force main and discharge sewer were visible. Though there was evidence of some root intrusion, there was no evidence of corrosion and the pipelines looked structurally sound. Therefore, no additional field or data investigations were deemed necessary.

Pushrod Cameras

One utility reported the use of push cameras for inspection of wastewater pipelines, as shown in Figure 22. Massachusetts Water Resources Authority reported standard use of pushrod cameras for inspection of sewer laterals.

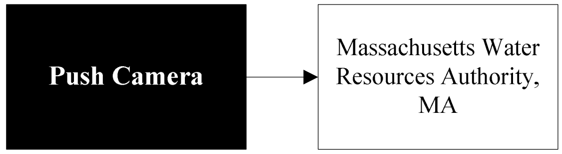

Figure 22. Utilities from which the Use of Push Cameras for Wastewater Pipeline Condition Assessment was Gathered

Smoke Testing

A number of utilities reported use of smoke testing for assessment of wastewater pipeline condition assessment. These utilities are illustrated in Figure 23. Both the City of Jeffersonville Wastewater Department and the City of Worthington Public Services Department reported use of smoke testing in their gravity sewer system to identify sources of I/I. The Howard County Department of Public Works, and the City of Virginia Beach Department of Public Utilities conduct smoke testing as part of large SSES programs. The City of San Antonio uses smoke testing to find wastewater leaks. The City of Des Moines Public Works uses smoke testing to find cross-connections.

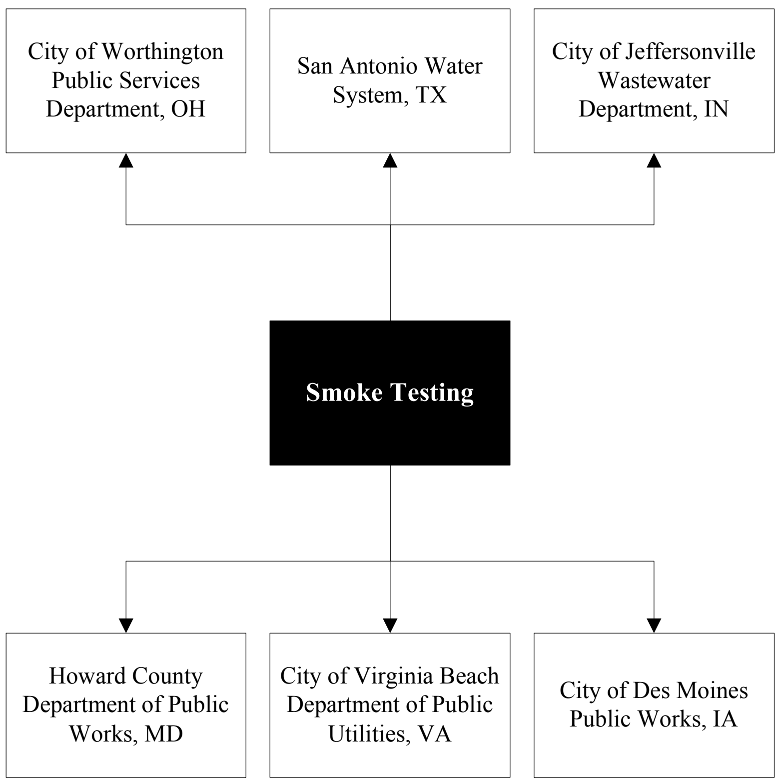

Figure 23. Utilities from which Information on Use of Smoke Testing for Wastewater Pipeline Condition Assessment was Gathered

The City of Virginia Beach Department of Public Utilities performs smoke testing in conjunction with many other inspection techniques as part of a large SSES program. After SSES basins were identified and prioritized, gravity sewer lines were smoke tested to find sources of I/I on public property that is identified as having higher amounts of impervious land surface, with runoff greater than 0.1% or as experiencing pervious land interflow with groundwater greater than 1.0%. For areas of the former description, smoke testing is expected to reveal I/I sources such as area drains, residential downspouts, or surface cracks in manhole rims. For areas of the latter description, smoke testing is used in conjunction with flow monitoring and/or CCTV to reveal I/I sources such as broken service connections and pipe, joint, and manhole failures above the active groundwater table. The City also intends to implement a plan to reduce I/I from private building laterals and private sewer systems. Though current City ordinance limit access to private property to allow performance of field investigations, if smoke testing reveals sources of I/I on private property, field personnel are required to photograph the active smoke as it vents, provide a sketch of the property identifying the address and locating major topographical and structural features, and provide a swing-tie measurement of the smoke location from three permanent structures of a GPS coordinate, recorded on the sketch.

The City of San Antonio extracts clean water from an artesian aquifer to feed its drinking water distribution system, and was concerned about possible dangers to the aquifer's water quality caused by leaking sanitary sewer pipelines. The aquifer is the only water source for the City and provides drinking water for more than two million people. In order to protect the water quality of the aquifer, and as part of wastewater collection system infrastructure improvement, the utility hired a contractor to perform smoke testing on sewer mains and laterals located on a recharge zone of the aquifer. The testing program is also required by the Texas Commission of Environmental Quality. The testing was done primarily for the purpose of locating breaks and leaks in both sewer mains and private laterals.

Dye Testing

Utility information on the use of dye testing for wastewater pipeline condition assessment was gathered. The utilities providing this information are shown in Figure 24. Both the City of Virginia Beach Department of Public Utilities and Howard County Department of Public Works use dye testing as part of large SSES programs. The City of Des Moines Public Works uses dye testing to find cross-connections in their system.

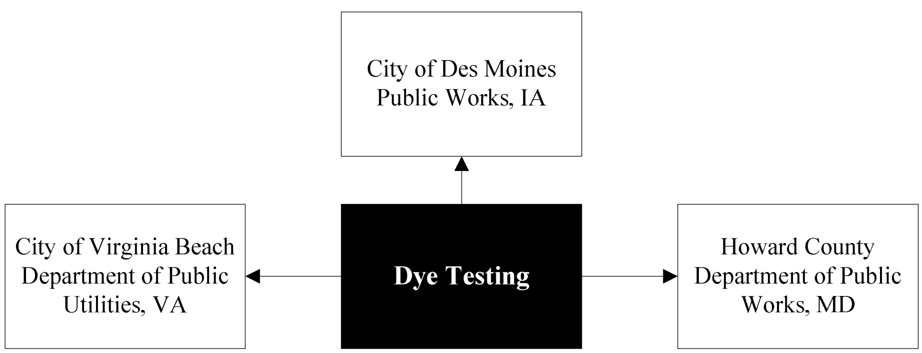

Figure 24. Utilities from which Information on the Use of Dye Testing for Wastewater Pipeline Condition Assessment was Gathered

The City of Virginia Beach Department of Public Utilities uses dye testing as an initial inspection technique in SSES basins that are investigated due to exceedance of a specific peak flow threshold. The dye testing is used to narrow down areas for further inspection with use of in-line cameras.

Howard County Department of Public Works is using dye testing in the second phase of the utility's SSES program, intended to the results of the first phase, which used flow monitoring results to identify areas of high I/I, to narrow down areas of the system for further inspection. Dye testing is one of the focused inspection tools, used to help identify sewer lines and manholes with leaks for further inspection with in-line cameras.

Flow Monitoring

The utilities that provided information on their use of flow monitoring for condition assessment of wastewater pipelines are illustrated in Figure 25. The City of Jeffersonville Wastewater Department and the City of Worthington Public Services Department use flow monitoring as method to help identify areas of their system with I/I. The City of Virginia Beach Department of Public Utilities and Howard County Department of Public Works use flow monitoring as part of large SSES programs, primarily to identify basins in need of further investigation, but also on a smaller scale for further investigation of specific basins. Dover Utilities Commission currently owns one flow meter and is in the process of installing eight permanent flow meters, but is not very advanced in the use of this technology. The City of Des Moines Public Works has an extensive flow monitoring system that extends throughout the treatment plant facilities, throughout the pipeline system, and up and down the nearby river. The utility is trying to use the gathered information to access better sustainability and calculate energy usage.

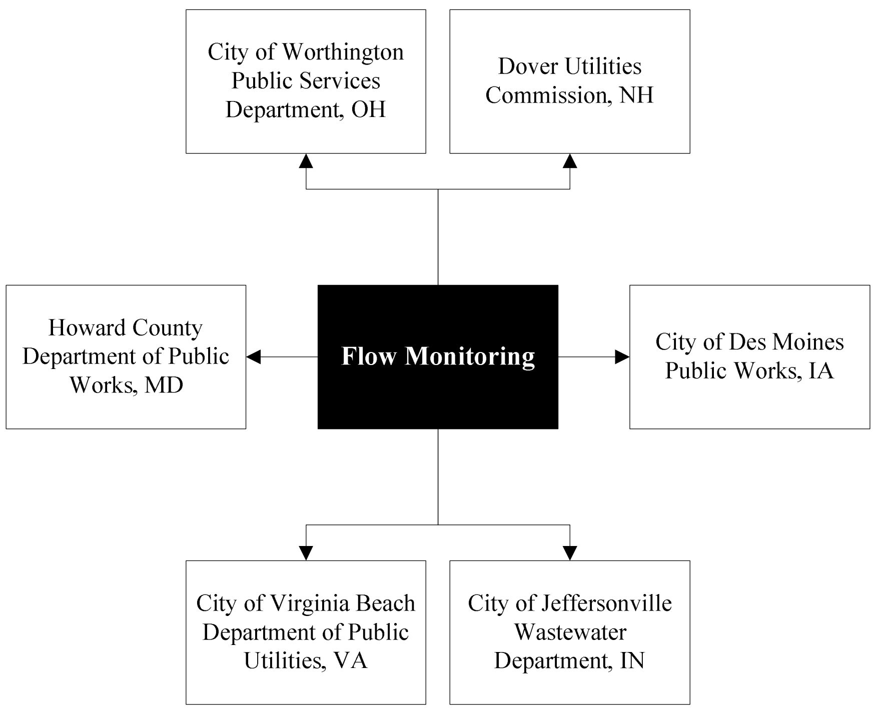

Figure 25. Utilities from which Information on Use of Flow Monitoring for Condition Assessment of Wastewater Pipelines was Gathered

Night Flow Isolation

Utilities reporting use of night flow isolation to help understand the condition of wastewater pipelines are illustrated in Figure 26. The City of Virginia Beach Department of Public Utilities and Howard County Department of Public Works both use night flow isolation as part of large SSES programs.

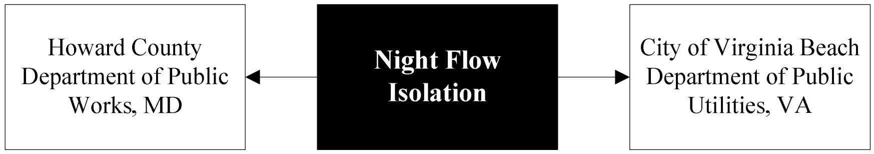

Figure 26. Utilities from which Information on Use of Night Flow Isolation for Condition Assessment of Wastewater Pipelines was Gathered

After identifying and prioritizing SSES basins for investigation, the City of Virginia Beach Department of Public Utilities has begun investigations of gravity sewer lines using night flow isolation. Night flow isolation is to be used in conjunction with CCTV in areas identified as having the hydrologic component of "Active Groundwater greater than 10.0%" and "Constant Infiltration greater than 30.0% of the wastewater flow". For areas of these descriptions, night flow isolation is expected to help identify I/I sources such as leaky joints and system failures below the active groundwater table level in gravity sewers. Night flow isolation is to be used after smoke testing or dye testing, and after CCTV inspections to pinpoint specific I/I sources.

Though current City ordinances limit access to private property for performance of field investigation techniques, if field investigations lead to the identification of a private sewer system, the field investigation personnel are required to identify, record, and provide the location of the private sewer system, the location of the connection point of the private system to the City's system, and an estimated amount of flow by observing the depth and velocity of flow and size of the pipe connected to the manhole with the date, time, and weather conditions at the time of the flow estimation calculations.

In-Line Acoustic Leak Detection

As illustrated in Figure 27, one utility provided information on their use of in-line acoustic leak detection for condition assessment of wastewater pipelines.

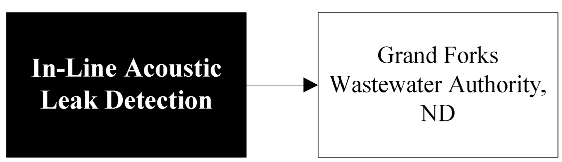

Figure 27. Utilities from which Information on Use of In-Line Acoustic Leak Detection for Condition Assessment of Wastewater Pipelines was Gathered

The City of Grand Forks inspected 8.7 miles of 24-inch to 36-inch diameter PVC and PCCP force main with free-swimming in-line acoustic leak detection technology. The inspection was completed in two days, with two deployments. A total of 15 sensor locations were deployed along the pipeline to increase the accuracy of the location of all anomalies found on the line. Six gas pockets were found on the line, ranging from two to eighteen feet in length. Eight anomalies were found that resembled leaks; however, due to the fact that the pressure on the line was below the leak detection threshold of the free-swimming, in-line, acoustic leak detection technology, these leaks could not be performed. The inspection tool was extracted once in the standard way, using under-pressure net extraction. The other extraction method involved allowing the tool to continue in the flow and be removed at the trash rakes inside the treatment plant.

Ultrasonic Wall Thickness Measurement
One utility reported the use of ultrasonic wall thickness testing, as shown in Figure 28. Aurora Water used the technology on stormwater pipelines, in a manner also applicable to wastewater pipelines.

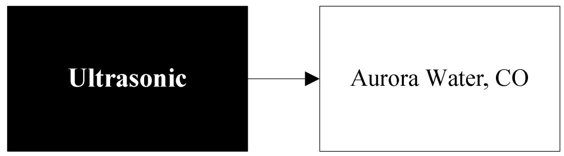

Figure 28. Utilities from which Information on Use of Ultrasonic Technologies for Pipeline Condition Assessment was Gathered

Aurora Water's intention was that ultrasonic wall thickness testing be done in conjunction with visual inspection throughout the corrugated metal storm sewer pipelines to find the remaining thickness of corroded areas. However, ultrasonic thickness measurements ended up being taken at only one rusted area within the pipeline. Rusted areas where flaking occurred were cleaned and the flakes were removed, then the area was wire brushed for testing. One reference area was tested above the corrosion, and two areas were tested in the corroded location. The reference thickness measured 0.136 inches thick and the tested areas measured 0.129 inches and 0.107 inches. At the most severely rusted locations, an ultrasonic test was not practical due to significant "flaking" or "bubbling". Efforts to clean these areas resulted in disintegration of the original pipe material.

Sonar
Utilities that reported using sonar for condition assessment of pipeline are illustrated in Figure 29. Aurora Water used sonar as a trial in conjunction with CCTV and gas sensors to collect information on the condition of a large diameter corrugated metal storm sewer pipeline. Massachusetts Water Resources Authority uses sonar on siphons of pressure pipelines. Sydney Water provided information on use of sonar for inspection of an elliptical concrete sewer.

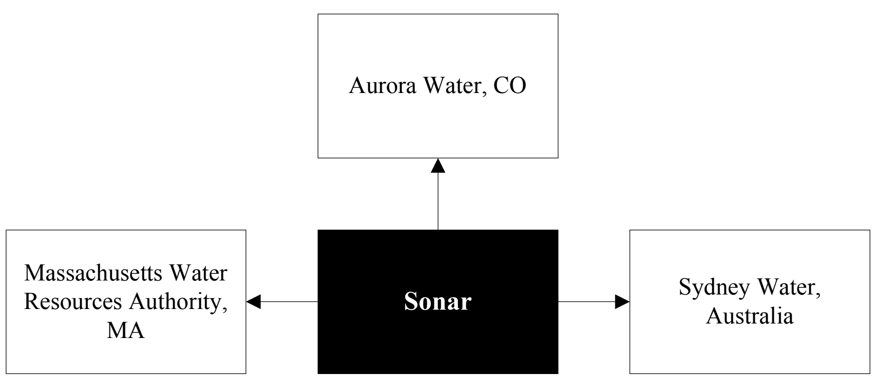

Figure 29. Utilities from which Information on Use of Sonar for Pipeline Condition Assessment was Gathered

Sydney Water used sonar in conjunction with laser profiling and CCTV on a float assembly that moved through a 62-inch by 93-inch concrete sewer pipeline with the speed controlled by a winch at the most upstream manhole. The camera and laser profiler gathered information above the flow line, which the sonar provided information on the amount of silt build-up below the flow line. The sonar measured a maximum silt build-up of 29 inches over the invert of the pipeline.

Remote Field Technologies

Utilities which reported using remote field technologies for condition assessment of wastewater pipelines are shown in Figure 30. Both Baltimore County Department of Public Works and Miami-Dade Water and Sewer Department used a free-swimming RFEC/TC technology in order to locate wire breaks in large diameter PCCP force mains.

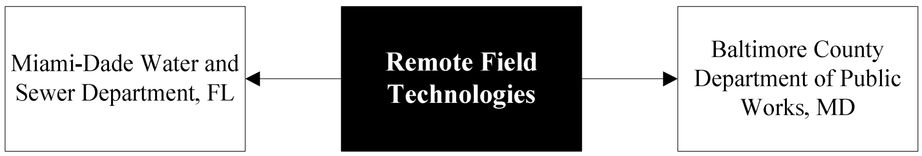

Figure 30. Utilities from which Information on Use of Remote Field Technologies for Condition Assessment of Wastewater Pipelines was Gathered

Baltimore County Department of Public Works used free-swimming RFEC/TC to traverse a 7,700 foot length of a 54-inch diameter PCCP sewer force main that was installed in 1978. The pipeline had been identified as being critical based upon Baltimore County's history of pipeline break data. A bypass line was set up for the force main and the inspection tool inserted into the force main through a flange opening. After the tool was inserted and the electromagnetic signal it was sending out tested, the pressure to the pipeline was to be increased in order to propel the tool through the pipeline. The inspection was timed for 11:00 AM, which is a high flow time, to help the tool move through the pipeline. There were some difficulties with the initial deployment of the RFEC/TC tool, but after using additional pumps and verifying that flow and pressure were adequate to launch the tool, the tool was transmitted successfully through 8,000 feet of pipeline and was retrieved 45 minutes after the launch at the pre-defined location. The results of the condition assessment work showed that the pipeline had many wire breaks. Data analysis resulted in the prediction of several break points on the pipeline. However, before decisions could be made on how to renew the pipeline, major weather events in the area contributed a great deal of inflow to the sewer system and shut down electricity to both of the pump feeders connected to the inspected line. Due to the loss of electricity, both pumps experienced rapid shutdown, and each pump very quickly closed their valves to the system, sending shockwaves to the interceptor. The force main, which was designed for 50 psi, experienced a pressure of more than 300 psi. There were a number of sanitary sewer overflows experienced, and the force main burst at one of the predicted break points. While the breakage was catastrophic, it brought positive attention to the efforts being made by the Baltimore County Department of Public Works to inspect and renew force mains.

Laser Profiling

Utilities from which information on the use of laser profiling for pipeline condition assessment was gathered are shown in Figure 31. Aurora Water provided information on the utility's use of a combined system mounted on a robot including laser scans, CCTV, and gas sensors to measure levels of hydrogen sulfide gas in a large diameter, corrugated metal storm sewer pipeline. Sydney Water provided information on their use of laser profiling in various situations.

Figure 31. Utilities from which Information on Use of Laser Profiling for Pipeline Condition Assessment was Gathered

Sydney Water provided information on their use of laser profiling in a large diameter reinforced concrete sewer and compared it to the previous year's results of a walk-through visual inspection the same sewer section, showing that the laser profiling method appears to be more accurate and minimizes the risks associated with confined space entry to personnel.

Sydney Water also performed a laser profiling inspection on a section of concrete sewer pipe before and after high-pressure cleaning, in order to illustrate the effects of cleaning. After cleaning, the corrosion detection increased significantly, with an estimated 85% of the pipe length showing corrosion at the level of the reinforcement bars, showing not only the effects of high pressure cleaning but also that laser profiling inspection provided data that enabled highly accurate determination of pipe corrosion location and extents, reducing human error significantly when compared to CCTV inspections.

Lastly, Sydney Water provided information on their use of laser profiling in conjunction with CCTV and sonar on a float assembly, showing that though laser profiling cost was still significantly higher than CCTV, the combined laser-CCTV inspection above the float line could be used in the cases where the criticality of the pipe section justifies the additional expenditure.

Soil Testing

As shown in Figure 32, one utility provided information on its use of soil testing. Instead of doing soil testing to discover the possible causes of corrosion of a pipelines, Milwaukee Metropolitan Sewerage District had soil testing done before installation of a ferrous force main, in order to help pre-empt problems caused by aggressive soil conditions.

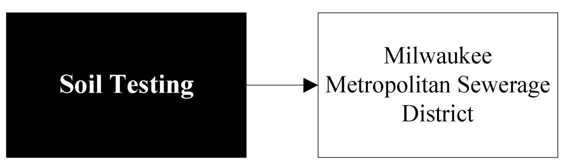

Figure 32. Utilities from which Information on Use of Soil Testing for Pipeline Condition Purposes was Gathered

Milwaukee Metropolitan Sewerage District has a pump station and 36-inch diameter ductile iron pipe (DIP) force main designed in 1981 and construction was completed in 1983. In 2007 and 2009, the force main experienced two leaks, and the utility chose to retain a contractor to provide an approach for the investigation of the condition of the force main. It was found that a pre-design soil report for the force main was completed in May 1981, which recommended polyethylene encasement for 6,200 feet of the planned pipeline due to the anaerobic bacteria activity and low soil resistivity measurements. The pipeline installed was of ductile iron with cement lining and bituminous coating on the exterior pipe, as well as a polyethylene envelope installed around the entirety of the pipeline, in excess of the recommendations following the soil testing.

Gas Sensors

As shown in Figure 33, one utility provided information on the use of gas sensors for pipeline condition assessment. Aurora Water used gas sensors to monitor for the presence of hydrogen sulfide inside a large corrugated metal stormwater pipeline system. In the case presented by Aurora Water, no traces of corrosion-causing gas were found.

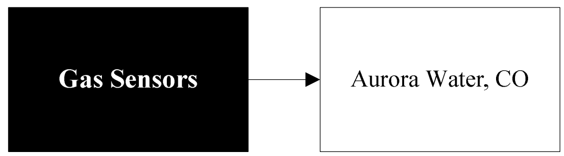

Figure 33. Utilities from which Information on Use of Gas Sensors for Pipeline Condition Assessment was Gathered

Synthesis of Practice Reviewed

Analysis of Pipe Materials and Diameters

The pipeline materials focused on in the practice review were concrete pipelines for gravity sewers and PCCP for force mains. Most information gathered was regarding gravity lines. This was surprising due to the fact that large diameter mains are far more critical than gravity sewers due to their pressurization and high consequence of failure. However, many condition assessment technologies that were originally developed for drinking water pipeline assessment have been adapted to use in wastewater pipelines in recent years, perhaps driven by highly publicized catastrophic failures and regulatory enforcement measures. The focus on PCCP in the practices reviewed for force main assessment may be related to the concerns expressed by utilities related to the condition of their Class IV PCCP, which is particularly susceptible to non-standard hydrogen embrittlement and appears to demonstrate poorer performance than other PCCP.

Analysis of Condition Assessment Techniques Used

The utility practices gathered resulted in the main focus of condition assessment techniques used for gravity lines being primarily on use of traditional CCTV. Direct above-ground visual assessment, flow monitoring, smoke testing, and dye testing were commonly used in conjunction with CCTV for SSES programs. Laser profiling and sonar were less commonly used. For force mains inspections, use of remote field technology adapted for PCCP assessment was dominant.

Based upon the extent of zoom camera use discovered during literature review, the underrepresented use of zoom cameras in the practice review was surprising. In the case of Massachusetts Water Resources Authority, zoom cameras are used only for manhole inspection. Baltimore County Department of Public Works reported use of a zoom camera at only one point – a transitional manhole at the end of a force main.

The practice of night flow isolation for use in general determination of areas with I/I problems was mentioned by two utilities in the practice review but was not found at all during the literature review. The term “night flow isolation” was used in both cases, independently. The reason for the fact that night flow isolation is not mentioned in literature is unknown. One possible explanation is that the practice is regional, as two utilities mentioning the practice were located in the same general geographical region; one utility is located in Virginia and one in Maryland.

In-line acoustic leak detection was mentioned by only one utility during the practice review. In their case, the technology was useful in identifying gas pockets within the force main tested, but because the pressure of the force main was well below the threshold needed for the technology to be able to identify leaks, no leaks were identified. It is possible that the low incidence of utility practice reviews regarding the use of in-line acoustic leak detection is due to the fact that wastewater force mains typically operate at a pressure much lower than drinking water pipelines, limiting the usefulness of the in-line acoustic leak detection technologies.

Very few utilities provided information on their use of sonar and laser profiling for pipeline inspection. Considering the satisfaction of the utilities that did report use of sonar and/or laser profiling with the data obtained by the technologies, it would be expected that the use of laser profiling and sonar would be more prevalent. However, the cost of laser profiling and sonar is higher than the cost of inspection with traditional CCTV, and it is possible that many utilities have not yet identified gravity pipelines at a level of criticality that justify the difference in cost considering the low budgets many utilities have to work with.

Condition Assessment as a Secondary Goal

In a few cases, condition assessment techniques were used for something other than assessing the condition of the pipeline. Obtaining condition assessment seemed to be secondary. For example, the City of San Antonio implemented smoke testing on sewer mains and laterals located on a recharge zone of the Edwards aquifer, which provides drinking water for more than two million people and is the only water source for the City. This smoke testing was required by the Texas Commission of Environmental Quality in order to protect groundwater quality. The use of the smoke testing as part of wastewater collection system infrastructure improvement was mentioned secondarily.

For the Milwaukee Metropolitan Sewerage District, the soil testing work done was performed before pipe installation, as a measure to prevent corrosion from occurring on the ductile iron pipeline installed. However, after experiencing leaks from the line, the soil tests were revisited to determine possible causes for the corrosion.

Des Moines reported on the use of flow monitoring with a much broader purpose than condition assessment. The flow monitoring is extensive and will be used to help improve the City's energy use sustainability.

Geographical Trends

No geographical trends were noted as far as prevalence of condition assessment techniques was concerned. However, larger utilities with more resources and a higher population density tended to have more advanced condition assessment programs and used newer technologies. Therefore, in accordance with the population densities of the United States, more advanced condition assessment programs were found along the east and west coasts of the United States than in the mid-western states.

Considerations When Selecting Condition Assessment Techniques

It appears that, when selecting a technology for condition assessment, most utilities are primarily focused on cost due to their restricted budgets. This fact is evident not only in the fact that utilities select technologies that cost less, but in the fact that utilities tend to use technologies that have a long history of use and have been proven. Only larger utilities, with bigger budgets, larger force mains, larger and denser populations, and a greater chance of negative publicity in cases of catastrophic failure, tend to use more advanced technologies for condition assessment.

It would be desirable for practices of utilities to focus on the desired data from condition assessment rather than cost when selecting an appropriate technique. However, in the United States, most utilities are public. As the public generally is unaware of issues with pipeline asset condition unless there is a highly publicized catastrophic failure, the budgets of utilities with regard to condition assessment remain low. Until the cost effectiveness of proper condition assessment data with regard to minimization of renewal work cost is fully understood, this practice of choosing the safest technology rather than the most effective will continue.

Lessons Learned

From the described experiences of utilities, a variety of repeating themes were discovered. These themes reveal a trend in the current mindset of experienced utility personnel that may serve as lessons learned for other utilities.

- For the most cost-effective renewal work, proper condition assessment is very important. This fact was demonstrated by the experiences related by the City of Phoenix Water Services Department.
- Condition assessment is a part of asset management, and effective asset management is more critical than simply locating leaks. This fact was demonstrated by the experiences related by the Miami-Dade Water and Sewer Authority.
- Collection and review of past assessments are important, as previous condition assessment data provides a baseline for future assessments. Therefore, data management is critical. Being able to transfer and manage data is very important for the continuation of effective condition monitoring. Having an industry standard for data storage is very useful. Once a standard is developed, it can possibly serve as a benchmark for future projects. The importance of data management was demonstrated in the experiences related by the City of Phoenix Water Services Department, Aurora Water, Baltimore County Department of Public Works, Howard County Department of Public Works, and the City of Virginia Beach Department of Public Utilities.
- Using a combination of condition assessment technologies results in a more complete and useful picture of a pipeline's condition than using a single condition assessment technology does. This was demonstrated by Sydney Water's experiences.
- At times, outsourcing condition assessment work is better than performing the work in-house, in terms of both performance and cost. This fact was demonstrated by the assessment work performed by Peachtree City Water and Sewerage Authority.

Conclusions and Recommendations

Wastewater pipeline condition assessment practices in the U.S. have expanded in recent years as a result of rapidly aging and deteriorating pipelines and the resulting need for more effective asset management practices. As utility condition assessment practices continue to develop and change, it is important that there is a focus on education and information sharing between utilities so that appropriate practices regarding the use of condition assessment techniques and the advantages and limitations of those techniques can be shared, and the most appropriate condition assessment technique or group of techniques can be chosen for the particular situation. Utilities should focus additionally on maintaining and managing data on the condition of pipeline assets. This focus, as well as a holistic view of the asset management process, will enable utilities to better handle the problem of aging and deteriorating wastewater pipelines.

Future work should involve the development of a data standard for collection and reporting of information on pipeline condition assessment projects. Future work should also involve the direct collection of condition assessment information from additional utilities, as this direct data-mining tends to lead to greater understanding of the asset management process. Information on condition assessment experiences should be shared between utilities.

Acknowledgements

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SUMMARY

This work involved both a review of available literature on pipeline condition assessment technologies and a review of available literature on utility experiences with various condition assessment technologies and methodologies. This work also involved an extensive utility data mining process to gather information on condition assessment experiences directly from utilities. Lessons learned regarding interaction with utility personnel during the utility data mining process are summarized in Appendix C.

Main Findings and Conclusions: Drinking Water Utility Practices

The literature review of condition assessment practices for drinking water pipelines found that the most prevalent technology categories represented were those that involved condition assessment technologies that were acoustic based, electric or electromagnetic based, and visual or camera based, as shown in Figure 34.

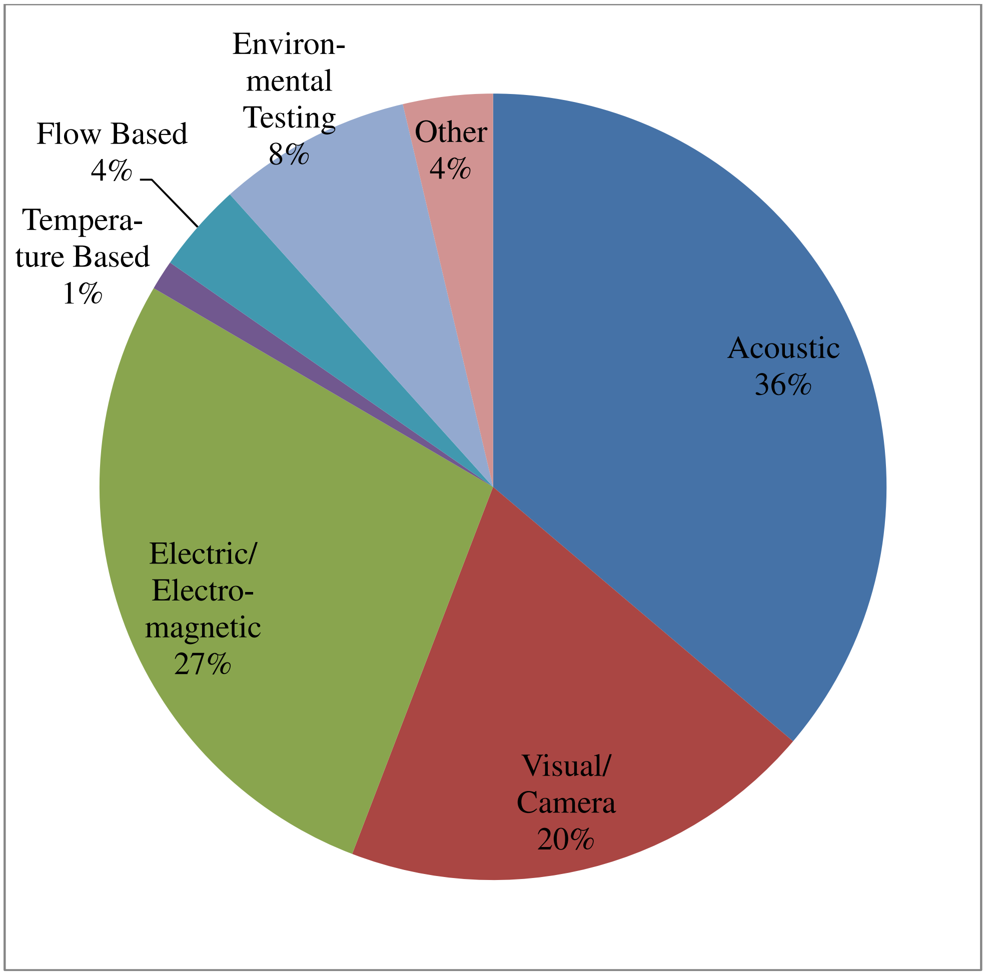

Figure 34. Technology Categories Represented in Data Gathered During Literature Review of Drinking Water Pipeline Condition Assessment Technology Utility Experience

The review of drinking water pipeline condition assessment practices gathered directly from utilities found that the technology category prevalence corresponds closely to what was found during the literature review, as shown in Figure 35.

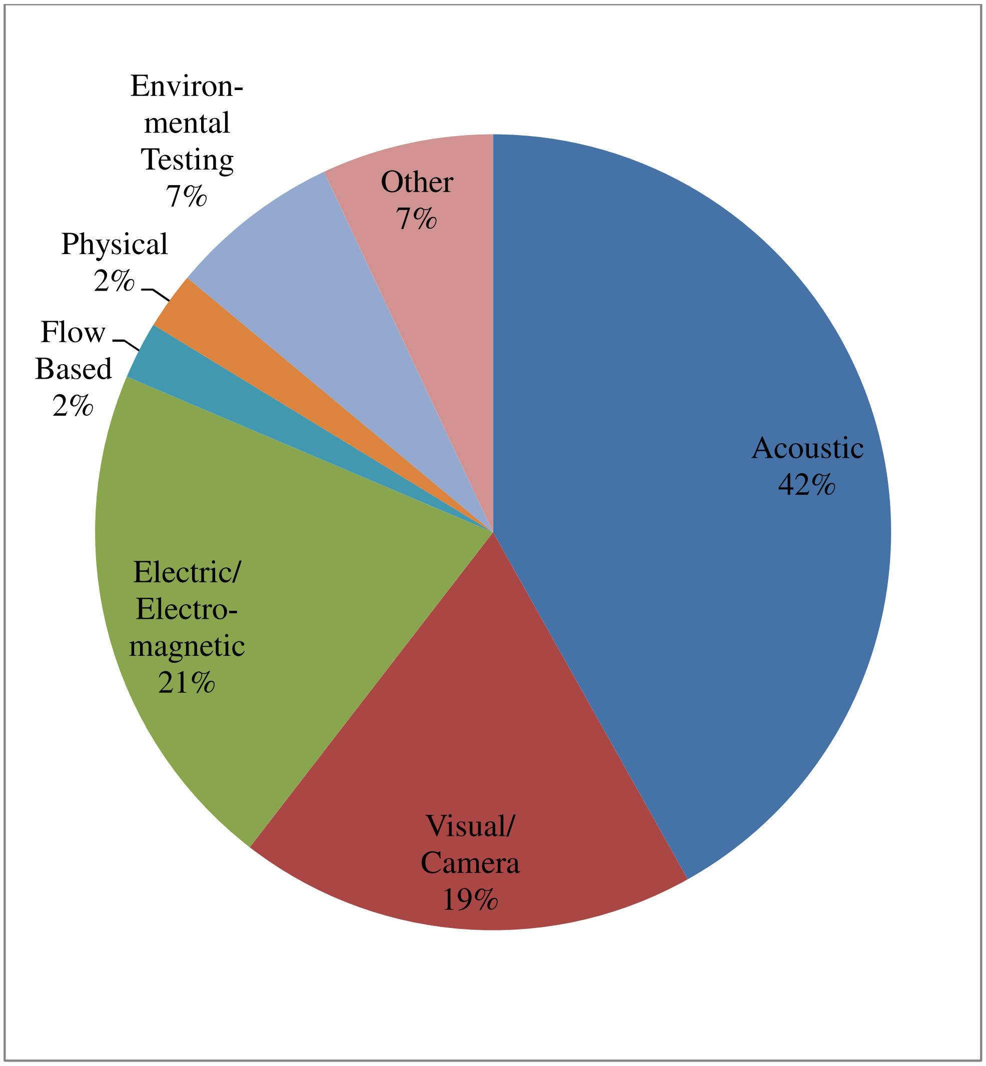

Figure 35. Technology Categories Represented in Data Gathered Directly from Utilities on Drinking Water Pipeline Condition Assessment Technology Experience

The focus of drinking water pipeline condition assessment seemed to be on those large diameter pipelines with a high consequence of failure. While large diameter condition assessment mostly involved direct assessment, the more advanced programs of larger utilities with larger budgets often also used remote field technologies and acoustic monitoring systems. The condition assessment practices related to smaller diameter pipelines mostly involved testing of environmental characteristics as well as leak detection technologies that could be performed from the ground surface. Coupon sampling was not as prevalent in practice as might be inferred through the literature review. No geographical trends were discovered.

Many utilities shared the belief that baseline condition assessment is very important for better asset management, and that the use of multiple technologies is better than just one. Utilities advised others to keep the big picture in mind and remember the importance of environmental factors, as well as the future benefit of good data management practices.

Main Findings and Conclusions: Wastewater Utility Practices

The literature review of condition assessment practices for wastewater pipelines found that the most prevalent technology categories represented were those that involved condition assessment technologies that were visual or camera based, followed by those that were acoustic based, followed by those that were electric or electromagnetic. Flow based technologies and environmental testing was also well represented, as shown in Figure 36.

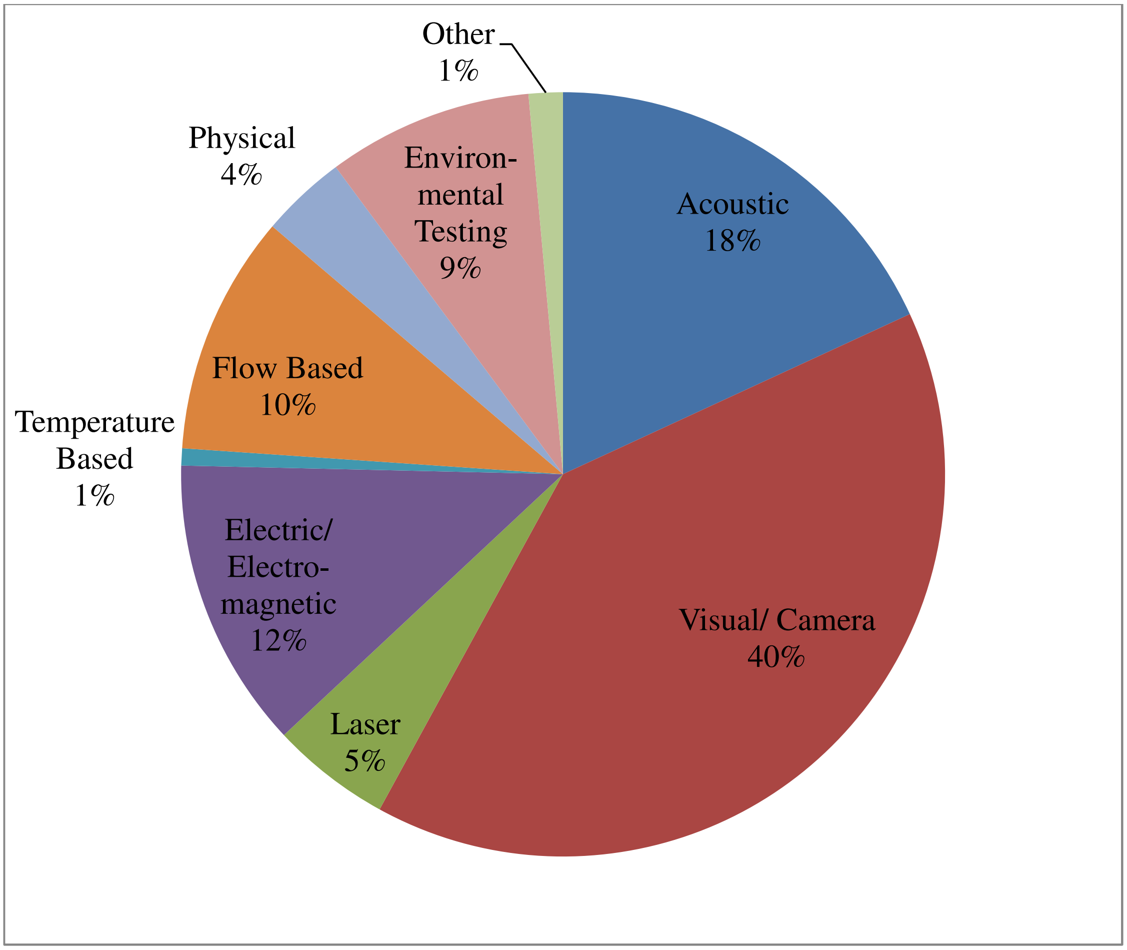

Figure 36. Technology Categories Represented in Data Gathered During Literature Review of Wastewater Pipeline Condition Assessment Technology Utility Experience

The review of wastewater pipeline condition assessment practices gathered directly from utilities found that the technology category prevalence is similar to what was found during the literature review; however, it was evident that more traditional, low-tech options for condition assessment technologies were favored as shown in Figure 37.

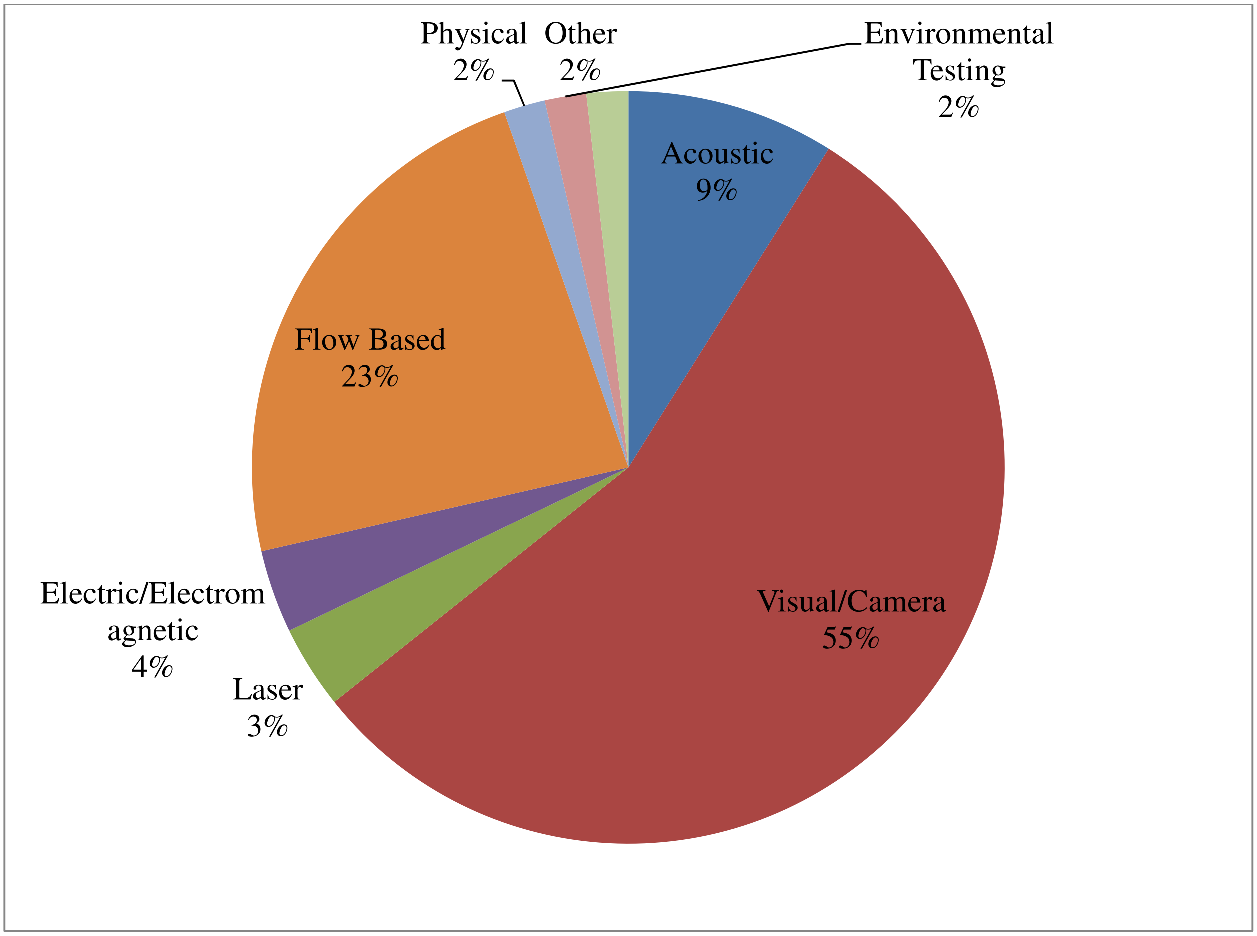

Figure 37. Technology Categories Represented in Data Gathered Directly from Utilities on Drinking Water Pipeline Condition Assessment Technology Experience

The greatest focus of wastewater pipeline condition assessment was found to be on gravity lines, which is surprising due to the high consequence of failure of force mains in comparison to gravity lines. The prevalence of SSES programs and other regulatory requirements may help to explain this pattern.

Traditional CCTV, direct visual assessment, smoke testing, and other condition assessment tools traditionally used to identify sources of infiltration and inflow were prevalent for gravity lines. The use of zoom cameras was not found to be as prevalent in the practice review as in the literature review. Also, there was a low incidence of use of sonar and laser profiling in the United States. Meanwhile, the condition assessment of larger diameter pipelines mostly involved the use of remote field technologies. Condition assessment was found to be a secondary objective in some cases, and no geographical trends were found.

Utilities typically shared the mindset that pipeline condition assessment saves money in the long run, and that the use of multiple technologies is better than the use of only one. As in the case of drinking water utilities, wastewater utilities advised that it was important to keep the big picture of asset management in mind and make sure that data management practices were appropriate.

Recommendations for Future Research

Future research on this topic should involve capturing more case studies and direct information from utility sources. A greater variety of utilities can be contacted, i.e. those with a greater variety of different service population and a greater range of budgets. Case studies may be gathered from both private and public utilities. By gathering information from a larger range of geographical regions, geographical trends relating to topography, rainfall trends, or history of an area may begin to be seen. The work can be expanded to involve more international utilities as well.

As the issue of aging, deteriorating, and failing infrastructure becomes a more important one with the increasing rate of pipeline failures and the increasing value of water resources, it is likely that new technologies will be developed at an even more rapid rate than before. It will be important to continue to keep up with new technologies and capture the advantages and limitations related to their use by utilities assessing pipeline conditions.

Additionally, network components other than pipelines, such as pumps, valves, and other appurtenances are important assets that also must be assessed and maintained. This work can be expanded to cover these appurtenances as well as to focus more on the condition assessment of pipeline joints.

CONCLUSIONS

As discussed previously, much research shows that aging water and wastewater infrastructure has become a problem and requires a substantial investment to maintain as well as to keep up with growth demands. Obtaining real information about utility practices and technology experiences is a key component to helping utilities understand the best practices to follow to optimize the renewal of these deteriorating assets.

This thesis has provided information on the background of condition assessment technologies and references to find more information about the technological background of those technologies. This thesis has also provided a comprehensive literature review of the practices of utilities regarding pipeline condition assessment. Additionally, this thesis has presented condition assessment experiences gleaned directly from utility sources, which have the benefit of containing the whole story regarding use of a particular technology. As a result, the current industry practices have been synthesized and lessons learned compiled. This work will help to educate utilities on current practices and on the best way to conduct the condition assessment portion of their asset management programs.

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APPENDIX A: GUIDING QUESTIONS FOR DRINKING WATER UTILITIES

CONDITION ASSESSMENT (CA) TECHNOLOGIES
DATA MINING—QUESTIONNAIRE
DRINKING WATER

Note: The following questionnaire will be used to facilitate data mining in the effort of producing case studies on CA Management Practices and on specific CA technologies.

1. **Background Info**

(Information from maps, plans, database information as available)

a. System size (# and length of pipeline, # of people served)
b. Materials of pipelines in system.
c. Age (installation/manufacturing).
d. Locations of replaced pipelines.
e. GIS database information available
f. Does your utility purchase water and distribute it or is it responsible for collection, treatment, distribution, etc.
g. Annual budget for CA
h. What are the definitions for lateral and service line for your utility?

2. **CA Management Practices and Prioritization**

(From responsible person(s), in-house manuals and procedures, etc.)

a. What is basis for selecting testing of pipelines?
b. Is there a Master Plan? What are the details of the Master Plan for condition assessment? What was the basis for formulating the Master Plan? (i.e. test oldest pipes first, test most important pipes first, etc.)?
c. Are there any tools (i.e. software) that are used to assist in prioritization of condition assessment?
d. Are there minimum Levels of Service that are maintained? How are these min. LOS defined (#of leaks, min. pressure, wall thickness, etc.)?
e. How are the experiences of field personnel utilized for CA? (Monthly meeting, records, etc.)
f. Do you have leak and break data and/or analysis for the system, and how are these used in CA?
g. Does your utility have training manuals to ensure standardized procedures?

3. **Condition Assessment Technologies**

Note: For each CA technologies used can you provide the following information.

a. Specific Pipe Information (i.e. Age, length size, soil type, etc. of pipes that were tested with condition assessment technologies)?
b. Performance Data
    i. Can you provide Test Reports? Specifications?
    ii. Information of duration of testing.
    iii. Information on accuracy of data.
    iv. Information on problems encountered.
c. Cost Data
    i. Direct Costs (inspection/data processing/personnel time)

a. Inspection Costs
b. Data processing Costs
c. Personnel Time (# of people and days required).
d. Can you provide work orders, contract documents, and change orders?

ii. Indirect Costs
a. Traffic stoppage costs
b. Reduced life of pipe (i.e. damage caused due to testing)\
c. Permits required? Can you provide copies?
d. Unforeseen events affect costs?
e. Other?

4. **<u>Lessons Learned</u>**
   a. What are the key points learned using this condition technology (i.e. technology worked only in certain conditions etc.)?
   b. What mistakes were made? How can these be resolved for future?
   c. How have implementing previous lessons learned improved results? What documentation is available to validate this?

5. **<u>Contact Information</u> (name, email, telephone, fax, other)**
   a. Contact Information for Water Condition Assessment :
   b. Other important points of contact:

DEFINITIONS

Service line: The line extending from the water main to the property line

Best Management Case Histories: These should include a review of the structure of the utility and how it schedules condition assessment activities and makes decisions regarding condition assessment. With this in mind, we need to collect anything that the utility has on:

- Background of the utility size and structure (is there a separate contact for each division like storm water, water and wastewater or are they combined?)
- Ownership of the assets as well as their capacity
- The components of and description of data analysis and thought processes that go into condition assessment activities.
- How they select the product or tool to be used for condition assessment – is it the utility that decides, does their consultant decide, etc.
- Understanding the components of their bid process

Technology Case Histories: In general these will paint a picture of what product was used, in what situations it was used in and whether the product was able to achieve the goals originally set for the project. With this in mind, we need to collect anything available regarding:

- Multiple uses of the same technology: we will be able to state very quickly how frequently the product is used within the utility, but due to time limitations it is not feasible to create a detailed case history for each and every use. We want to therefore concentrate on capturing what typical product use entails, any difficult project experiences or failures, any successful product uses that stand out, and any projects that pushed the limits of what the product claimed to be able to do (this could have a positive or negative outcome).

- A full, detailed description of site specific parameters (soil type, traffic loading, location, etc.). This will allow utilities to be able to find case histories for products used in similar conditions to their own and will allow us to be able to identify any major trends relating site specific parameters to successes or problems.
- What technology was used and what qualified it as the best choice for the particular project. (size restrictions, etc.)
- What were the initial expectations of the product? Documentation of how the product did or did not meet these expectations.
- The components and explanation of project-specific product design – anything that made tailoring the product to the project needs a simple, ordinary or challenging process
- Difficulties encountered during use. This could be due to manufacturing errors, damage during transportation, temperature conditions, etc.
- If applicable, once the product was used, how were service connections reinstated? Were there any difficulties with the reinstatement?
- Cost. This includes direct, indirect, quantifiable, abstract, assumptions, estimations….everything. Once we have all of the information on cost issues, it should be clearer what the best way to portray cost within the case histories will be.
- Were there any long-term effects of the product use as far as QA/QC goes?
- Quick summary of satisfaction with the product.

APPENDIX B: GUIDING QUESTIONS FOR WASTEWATER UTILITIES

CONDITION ASSESSMENT (CA) TECHNOLOGIES
DATA MINING—QUESTIONNAIRE
WASTEWATER

Note: The following questionnaire will be used to facilitate data mining in the effort of producing case studies on CA Management Practices and on specific CA technologies.

1. **Background Info**

(Information from maps, plans, database information as available)

a. System size (# and length of pipeline, # of people served)
b. Materials of pipelines in system.
c. Age (installation/manufacturing).
d. Locations of replaced pipelines.
e. GIS database information available
f. Is your system combined with storm water/wastewater or separate?
g. Does your utility purchase water and distribute it or is it responsible for collection, treatment, distribution, etc.
h. Annual budget for CA

2. **CA Management Practices and Prioritization**

(From responsible person(s), in-house manuals and procedures, etc.)

a. What is the basis for selecting testing of pipelines?
b. Is there an Asset Management Plan (or Master Plan)? What are the details of the Asset Management Plant (or Master Plan) for condition assessment? What was the basis for formulating this Plan? (i.e. test oldest pipes first, test most important pipes first, etc.)?
c. Are there any tools (i.e. software) that are used to assist in prioritization of condition assessment?
d. Are there minimum Levels of Service (LOS) that are maintained? How are these minimum LOS defined (#of leaks, capacity, etc.)?
e. How are the experiences of field personnel utilized for CA? (Monthly meeting, records, etc.)
f. Do you have break data and how are these used in CA?
g. Do have blockage and cleaning histories for your wastewater system, and how are these used in CA?
h. What are your best management practices? How are BMPs and MOPs used in CA?
i. Does your utility have training manuals to ensure standardized procedures?

3. **Condition Assessment Technologies**

Note: For each CA technology used, provide the following information (if available):

a. Specific Pipe Information (i.e. age, length, size, soil type, etc. of pipes that were tested with condition assessment technologies)?

b. Performance Data
   i. Can you provide Test Reports? Specifications?
   ii. Information of duration of testing.
   iii. Information on accuracy of data.
   iv. Information on problems encountered.
c. Cost Data
   i. Direct Costs (what the cost includes and how it is quantified)
      a. Inspection Costs
      b. Data processing Costs
      c. Personnel Time (# of people and days required).
      d. Can you provide work orders, contract documents, and change orders?
   ii. Indirect Costs
      a. Traffic stoppage costs
      b. Reduced life of pipe (i.e. damage caused due to testing)\
      c. Permits required? Can you provide copies?
      d. Unforeseen events affect costs?
      e. Other?

4. **Lessons Learned**
   a. What are the key points learned using this CA technology (i.e. technology worked only in certain conditions, etc.)?
   b. What mistakes were made? How can these be resolved in the future?
   c. How has implementing previous lessons learned improved results? What documentation is available to validate this?
5. **Contact Information (name, email, telephone, fax, other)**
   a. Contact Information for Wastewater Condition Assessment
   b. Other important points of contact

DEFINITIONS

Sewer lateral: The line extending from the sewer main to the property line

Best Management Case Histories: These should include a review of the structure of the utility and how it schedules condition assessment activities and makes decisions regarding condition assessment. With this in mind, we need to collect anything that the utility has on:

- Background of the utility size and structure (is there a separate contact for each division like storm water, water and wastewater or are they combined?)
- Ownership of the assets as well as their capacity
- The components of and description of data analysis and thought processes that go into condition assessment activities.

- How they select the product or tool to be used for condition assessment – is it the utility that decides, does their consultant decide, etc.
- Understanding the components of their bid process

Technology Case Histories: In general these will paint a picture of what product was used, in what situations it was used in and whether the product was able to achieve the goals originally set for the project. With this in mind, we need to collect anything available regarding:

- Multiple uses of the same technology: we will be able to state very quickly how frequently the product is used within the utility, but due to time limitations it is not feasible to create a detailed case history for each and every use. We want to therefore concentrate on capturing what typical product use entails, any difficult project experiences or failures, any successful product uses that stand out, and any projects that pushed the limits of what the product claimed to be able to do (this could have a positive or negative outcome).
- A full, detailed description of site specific parameters (soil type, traffic loading, location, etc.). This will allow utilities to be able to find case histories for products used in similar conditions to their own and will allow us to be able to identify any major trends relating site specific parameters to successes or problems.
- What technology was used and what qualified it as the best choice for the particular project. (size restrictions, etc.)
- What were the initial expectations of the product? Documentation of how the product did or did not meet these expectations.
- The components and explanation of project-specific product design – anything that made tailoring the product to the project needs a simple, ordinary or challenging process
- Difficulties encountered during use. This could be due to manufacturing errors, damage during transportation, temperature conditions, etc.
- If applicable, once the product was used, how were service connections reinstated? Were there any difficulties with the reinstatement?
- Cost. This includes direct, indirect, quantifiable, abstract, assumptions, estimations….everything. Once we have all of the information on cost issues, it should be clearer what the best way to portray cost within the case histories will be.
- Were there any long-term effects of the product use as far as QA/QC goes?
- Quick summary of satisfaction with the product.

APPENDIX C: UTILITY DATA MINING PROCESS

Data mining from utilities is a very difficult process. Domestic utility personnel are typically overworked and struggling to maintain an aging pipeline infrastructure to prevent catastrophic failure while fighting against an inadequate budget. If catastrophic failures related to the utility's infrastructure have been prevented so far, there is typically insufficient public and political support of the utility's work and importance due to lack of public education. To convince the under-appreciated, overworked personnel of the typical American public utility to spend their valuable time providing information to a group of research students is no easy feat. In order to do so, the credibility of the project must be established, and the project must be seen as beneficial, in the long run, to the participating utility. Additionally, the part of the participating utility personnel must be made to be as easy as possible, and those participating must be made to understand their great importance and the value of the information they have to share. The full price of their cooperation must be understood and appreciated by the research team.

The first step in the data mining process was contacting utilities. The utilities initially selected for contact had one or more of the following characteristics:

- The utility had higher-level personnel that had come into contact with one or more members of the research team and were therefore familiar with the research, or else simply familiar with the research team member and therefore willing to listen to an explanation of the research.
- The utility employed a champion of the research project or of the aggressive asset management work promoted by the project and was therefore already able to be appreciative of the benefits of the research work without much background.
- The utility had done condition assessment work on their pipelines that was known within the field. Therefore, it was unlikely that the utility personnel would be embarrassed by their lack of knowledge about the state of their assets.

An effort was made to contact utilities of a variety of sizes, in a variety of geographical regions. When further utility information was found to be necessary, utility personnel listed in industry membership directories were contacted.

The first contact of utilities was found to be most successful when the contact was performed by a research team member known to the utility employee, and the employee was a member of management within the utility and knowledgeable about the project and an advocate of advanced asset management. If a personal relationship between the utility employee and a member of the research team did not exist, contact was found to be more successful if made by a research team member with a well-known name within the industry. When this was not possible, the research team members contacting utilities had to rely on the credibility of the project, which was made more evident by the public outreach efforts made by the research team and the project's funding by the U.S. Environmental Protection Agency and support by the Water Environment Research Foundation. First contact with utility personnel was made with confidence and excitement about the project, but also with great humility. The research project was explained in the context of the utility's participation providing information that would not only further benefit the utility, but would benefit the industry as a whole.

During the utility interview process, guiding questions were used but not rigidly. It was important to allow conversations with the utility personnel to develop in a way that not only kept the conversation comfortable but also sometimes revealed interesting aspects of the utility's practices that would not otherwise be found due to use of unfamiliar vocabulary or lack of questioning on the part of the research team. It was important to be focused on what was being discussed and to show interest in the words of the utility personnel being interviewed. The research team members did well to remember the value of being able to talk to someone with field expertise and knowledge inaccessible to academics or those confined to a laboratory. Being critical of the information shared was not helpful. It was also important to remain easy to talk to while maintaining professional mannerisms and respect for the individual sharing the information. A strong background in the information being gathered was important to understand as much as possible and to be able to ask appropriate related questions.

When setting up interviews or gathering documents, it was also important to make providing information or data as easy as possible for the utility personnel. The research team members did their homework and made sure not to ask for information that was already readily available through the utility's website. Contact made by the utility was valued and was responded to quickly. "Deadlines" were given for the utility to upload their data to the FTP site provided for that purpose in order to enable scheduling and time management on the part of the utility personnel involved; however, those deadlines were flexible. The team members made themselves available to the utility personnel for questions or comments. The team followed up with un-responsive utilities in a manner that was not invasive or accusatory, keeping in mind the busy schedules of the utility personnel and their generosity in assisting the team with the project.