EPA/600/R-09/049 | May 2009 | www.epa.gov/nrmrl

United States
Environmental Protection
Agency

Condition Assessment of Wastewater Collection Systems

WHITE PAPER


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

United States Environmental Protection Agency
Office of Research and Development
Washington, DC 20460
Final Report
May 2009
EPA/600/R-09/049

EPA

White Paper on Condition Assessment of Wastewater Collection Systems

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Contract No. EP-C-05-058
Task Order No. 59

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Disclaimer

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed, and collaborated in the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for publication. Any opinions expressed in this report are those of the author(s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Symbols and Acronyms

2D	Two dimensional
3D	Three dimensional
A	Access point
ACI	American Concrete Institute
AET	Acoustic emission testing
AwwaRF	American Water Works Association Research Foundation (now Water Research Foundation)
B	Broken
BEM	Broadband electromagnetic methodology
BW	Brick work
C	Crack
CARE-S	Computer Aided Rehabilitation Program for Sewers
CCTV	Closed-Circuit Television
CDMA	Code Division Multiple Access
CMOM	Capacity, Management, Operation and Maintenance
CWA	Clean Water Act
D	Deformed or deposits
DVD	Digital video discs
ECT	Eddy current testing
EDGE	Enhanced Data Rates for Global Evolution
EPA	Environmental Protection Agency
F	Fracture
FELL	Focused Electrode Leak Location System
FL	Longitudinal fracture
FMEA	Failure Mode and Effects Analysis
ft.	feet
GIS	Geographic Information System
gpm	gallons per minute
gpm/in-mile	gallons per minute per inch diameter per mile length
GPR	Ground penetrating radar
GPRS	General Packet Radio Service
GPS	Global positioning system
H	Hole
HDPE	high density polyethylene
HSV	Hole with visible soil
I	Infiltration
I/I	Inflow and infiltration
in.	inches

IP	internet protocol
IRT	Infrared thermography
IS	Intruding seal material
J	Joint
KPI	Key performance indicator
L	Line
LED	Light-emitting diode
LF	Lining failure
M	Miscellaneous
MACP	Manhole Assessment Certification Program
MCU	Camera underwater
MFL	Magnetic flux leakage
NA	Not applicable
NACWA	National Association of Clean Water Agencies
NASSCO	National Association of Sewer Service Companies
OB	Obstacles
O&M	Operations and Maintenance
ORD	Office of Research and Development
PACP	Pipeline Assessment Certification Program
PCCP	Pre-stressed concrete cylinder pipe
PR	Point repair
psi	pounds per square inch
PTZ	Pan-Tilt-Zoom
PVC	Polyvinyl chloride
R	Roots
RCP	Reinforced concrete pipe
RFEC	Remote field eddy current
RFEC/TC	Remote field eddy current/transformer coupling
S	Surface damage
SASW	Spectral Analysis of Surface Waves
SCADA	Supervisory Control and Data Acquisition
SCRAPS	Sewer Cataloging, Retrieval, and Prioritization System
Sonar	Sound navigation and ranging
SSET	Sewer scanning evaluation technology
SSO	Sanitary sewer overflow
T	Tap
TC	Transformer coupling
U.S.	United States of America
USEPA	United States Environmental Protection Agency
VCP	Vitrified clay pipe
V	Vermin

VR	Vermin including rats
WEF	Water Environment Federation
WERF	Water Environment Research Federation
WF	Weld failure
WRc	Water Research Centre (United Kingdom)
X	Collapse

Executive Summary

In 2007, the United States Environmental Protection Agency (USEPA) finalized a research program entitled "Innovation and Research for Water Infrastructure for the 21st Century" that will generate the science and engineering knowledge needed to improve and evaluate innovative technologies to reduce the cost while improving the effectiveness of operation, maintenance, and replacement of aging and failing drinking water and wastewater treatment and conveyance systems (USEPA, 2007). Task Order 59, Condition Assessment of Wastewater Collection Systems, is one of several projects being conducted under this research initiative.

Overview

The objectives of Task Order 59 are to comprehensively review condition assessment technologies and to investigate condition assessment approaches for wastewater collection systems. Specific project objectives include:

- Identify and characterize the state of condition assessment technology for wastewater collection systems.
- Research and evaluate performance and cost of innovative and advanced infrastructure monitoring technologies including wireless and remote sensing approaches developed in other industries and their applicability to wastewater collection sewers.
- Identify and evaluate innovative closed-circuit television (CCTV) technologies currently used by more advanced wastewater utilities for transfer to utilities at large.
- Prepare protocols, metrics, and site selection criteria for field demonstration of selected innovative condition assessment technologies and decision-support systems.

This White Paper is one of the first work products created under Task Order 59 and was used as a basis for discussions at the project's Technology Forum in September 2008. The White Paper summarizes the current state of condition assessment technologies, reviews mechanisms of pipe failure, discusses emerging and innovative technologies for sewer inspection, and presents a summary of the Technology Forum. It incorporates feedback received at the Technology Forum.

Condition Assessment

The primary components of any asset management program include the identification, location, and condition of assets. Condition assessment provides the critical information needed to assess the physical condition and functionality of a wastewater collection system, and to estimate remaining service life and asset value. After the field inspection, pipe defects are classified using a standard coding system and pipe condition is assessed using a systematic method to produce consistent, useful information. Following data analysis, condition assessment information is used to make estimates of a pipe's remaining useful life and its long-term performance, and to make decisions about pipe rehabilitation, pipe replacement and/or further inspections.

Dynamics of Wastewater System Failure

In conducting condition assessment, it is important to understand the dynamics of pipe failure including the level, type, and severity of a failure mechanism. Failure can be a sudden, catastrophic collapse of a pipe, restricted hydraulic capacity, or a variety of other performance conditions that result in the inability of the pipe to perform as necessary for the minimum acceptable level of operation of the system. The purpose of condition assessment is to detect pipe defects which indicate the likelihood of pipe failure, as well as to assess the collection system's performance. This section discusses the mechanisms of pipe failure, the various types of pipe defects, and the relationship between the condition of a pipe and its performance. It is important to understand that the mechanisms and impacts of pipe failure are highly dependent upon the pipe material and type of sewer (i.e. force main, gravity line).

Inspection Technologies

There are a variety of technologies available for assessment of collection systems. These technologies, summarized in Table ES-1, include:

- CCTV is a well-established and common industry method used for inspecting pipes. It provides visual data on leaks, location of service laterals, and sediment and debris accumulation. The primary disadvantages to CCTV technology are that it only provides a view of the pipe surface above the waterline; it does not provide any structural data on the pipe wall integrity; and it does not provide a view of the soil envelope supporting the pipe. For inspections of gravity lines, basic CCTV systems are not able to measure slope. There are needs for higher resolution cameras with better lighting; and improvements in crawler technology to better negotiate obstructions, grease, and off-set joints. The quality of defect identification and pipe condition assessment using CCTV is highly dependent on many factors including operator interpretation, picture quality, and flow level. Innovative camera technologies include zoom cameras, digital inspection, push cameras, and advances in crawler technology.
- ***Acoustic technologies*** use measuring devices to detect vibrations and/or sound waves. In pipeline assessment, acoustic sensors are used to detect signals emitted by defects. Three types of acoustic technologies are used for pipeline assessment: leak detectors, which are used to detect the acoustic signals emitted by pipeline leaks; acoustic monitoring systems, which are used to evaluate the condition of pre-stressed concrete cylinder pipe (PCCP) by detecting the signals emitted by breaking pre-stressed wires; and sonar, or ultrasonic systems, which emit high frequency sound waves and measure their reflection in order to detect a variety of pipe defects.
- ***Electrical/Electromagnetic*** currents are the basis of several sewer evaluation techniques. The electrical leak location method is used to detect leaks in surcharged non-ferrous pipes. Eddy Current Testing (ECT) and Remote Field Eddy Current (RFEC) technology identify defects in ferrous pipes. Magnetic Flux Leakage (MFL) inspection is widely used in the oil and gas industry to measure metal loss and detect cracks in ferrous pipelines.
- ***Laser profiling*** uses a laser to create a line of light around the pipe wall, highlighting the shape of the sewer. This technique allows for the detection of changes to the pipe's shape, which may be caused by deformation, corrosion, or siltation. Laser inspection can only be used to inspect the portions of a pipe wall that are above the water line. To assess the entire internal surface of a pipeline requires the pipe to be taken out of service. Lasers are often used in combination with other inspection methods, most commonly CCTV and/or sonar.
- ***Innovative methods*** based on a variety of technologies are currently being developed for the evaluation of sewer collection systems. Gamma-gamma logging is a technique used primarily to evaluate cast-in-place concrete pilings and can provide information on the average bulk density of the concrete and the location of voids. Ground Penetrating Radar can detect underground voids, and is potentially useful for examination of pipe bedding and to locate leaks. Infrared Thermography involves the use of an infrared camera to measure the temperature differential across an object and is a potential method of detecting sewer defects such as leaks and voids. Micro-Deflection is a nondestructive technology used to evaluate general conditions and joint integrity of brick, concrete, and clay structures using a load to create a slight deformation or micro-deflection in the test material. Impact Echo and Spectral Analysis of Surface Waves (SASW) are acoustic wave techniques for locating and measuring cracks, delaminations, voids, and honeycombing in concrete and masonry.

Summary of Technology Forum

A technology forum was held on September 11 and 12, 2008 in Edison, New Jersey to discuss the state of the science for condition assessment of wastewater collection systems and to identify critical gaps in current knowledge. A draft of the White Paper was distributed to participants in advance of the meeting and served as a basis for forum discussions. The objective of the forum was to present the findings of the research and obtain direction for additional research and further evaluation during the field demonstration tasks. The forum included discussions on data needs for conducting condition assessment and making asset management decisions; use of flow monitoring for asset management; systematic approaches to condition assessment; the importance of understanding the mechanisms of pipe failure; and tools and models available for conducting risk-based decision making related to wastewater assets.

Critical gaps in our knowledge of inspection technologies, and our ability to diagnose and predict infrastructure failures were identified at the Technology Forum and summarized below.

1. Research is needed to further define the costs and benefits of pipe inspection and rehabilitation as part of a utility's condition assessment program. Methods of determining the impact of deteriorating collection systems on municipal budgets are needed.
2. Inspection technologies need to be identified for the following applications:
    a. Reduce use of confined space entry during sewer system inspections and investigations.
    b. Affordable inspection technology that utilizes multi-sensor devices on a small transportable package.
    c. Inspecting pipes below the waterline.
    d. Inspecting force mains that are in service.
    e. Inspecting laterals.
3. Data management methods and models are available, but a lack of data standardization makes it difficult to compare historical data collected with different inspection technologies that have proprietary data structures.
4. Research is needed to improve how asset condition is tracked over time. Geospatial information (with a high degree of accuracy) needs to be collected along with pipe condition data in order to link historical inspection data with an exact physical location.

Information transfer to practitioners was identified as a critical industry need. Practitioners need training on topics such as infrastructure failure mechanisms; using historical inspection data for condition assessment applications; applying the Pipeline Assessment Certification Program (PACP) coding system to characterize pipe defects; developing a condition assessment program; and preparing accurate record drawings for new and rehabilitated pipe. In addition, practitioners need simple condition assessment tools (i.e. scattergraphs for analyzing flow data, decision trees, rules of thumb).

Table ES-1: Summary of Emerging and Innovative Technologies

Technology	CCTV				Acoustic			Electrical & Electro-magnetic			Laser	Innovative Technologies				
	Conventional	Zoom camera	Digital scanning	Push-camera inspection	In-line leak detectors	Acoustic monitoring systems	Sonar/ultrasonic	Electrical leak location	Remote field eddy current	Magnetic flux leakage	Laser profiling	Gamma-gamma logging	Ground penetrating radar	Infrared thermography	Micro-deflection	Impact echo/SASW
Application																
Pipe type	G	G	G	S	G, F	F	G, F	G, F, S	G,F,S	G,F,S	G, F	G,F,S	G,F,S	G,F,S	G	G
Pipe material	Any	Any	Any	Any	Any	PCCP	Any	NF	F	F, PCCP	Any	C	Any	Any	B	B, C
Pipe size	>6”	>6”	6”-60”	1”-12”	≥4”	≥18”	≥2”	≥3”	≥2”	2”-56”	> 4”	Not yet defined	Not yet defined	Not yet defined	Not yet defined	>6’
Defects Detected																
Sediment, debris, roots	●	●	●	●			●				●					
Pipe sags & deflections	●	●	Partial	●			●				●					
External pits & voids							●					●			Partial	●
Corrosion & metal loss			Partial				●		●	●	●					
Off-set joints	●	●	Partial	●												
Pipe cracks	●	●	●	●			●	●	●	●						●
Leaks	●	●	●	●	●			●	●				●	●		
Broken pre-stressed wires						●			●							
Wall thickness									●							●
Service connections	●	●		●								●				
Bedding condition												●	●			
Bedding voids												●	●	●	Partial	
Deteriorated insulation														●		
Overall condition															●	

Pipe type: G – Gravity line F – Force main S – Service lateral

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

1.0 Overview of Task Order 59

In 2007, USEPA finalized a research program entitled "Innovation and Research for Water Infrastructure for the 21st Century" that is being implemented by the Office of Research and Development. It will generate the science and engineering knowledge needed to improve and evaluate innovative technologies to reduce the cost while improving the effectiveness of operation, maintenance, and replacement of aging and failing drinking water and wastewater treatment and conveyance systems (USEPA, 2007). Task Order 59, Condition Assessment of Wastewater Collection Systems, is one of several projects being conducted under this research initiative.

1.1 Project Background

In 2002, the USEPA Office of Water published a report entitled "Clean Water and Drinking Water Infrastructure Gap Analysis" (USEPA, 2002). The Gap Analysis report identified a critical shortfall in funding of the nation's water and wastewater infrastructure including a $270 billion gap for wastewater infrastructure for the years 2000-2019. The deferred maintenance approach to operating and maintaining the nation's aging wastewater infrastructure has become a paramount concern of the Agency.

Failing wastewater infrastructure can pose a significant threat to public health and the environment. Wastewater infrastructure may include sanitary and combined sewer components, but this project is focused only on sanitary sewer systems. Systems with inadequate hydraulic capacity and/or blockages may lead to sanitary sewer overflows (SSOs) and may cause flooding damage to private property or release untreated sewage to receiving waters. Some of the health hazards associated with basement flooding by untreated wastewater include the potential presence of pathogenic microorganisms such as viruses, bacteria, and protozoa.

USEPA and State regulators have taken legal action against utility districts for property damage and SSOs. For example, in 2005, a settlement of $300 million was reached with the Washington Suburban Sanitary Commission to implement a program to reduce occurrences of basement flooding. This joint settlement was reached among the utility district, USEPA, State of Maryland, and five local citizens groups. In 2004, Knoxville Utility Board reached a settlement with the State of Tennessee for a capital improvements program of $350 million to eliminate flooding due to hydraulic restrictions. In 2004, Hamilton, Ohio reached a settlement to implement a program to eliminate SSOs and basement flooding that was estimated to cost approximately $1.5 billion.

1.2 Purpose and Scope

The objectives of Task Order 59 are to comprehensively review condition assessment technologies and to investigate condition assessment approaches for wastewater collection systems. The primary goal of the project is to develop more efficient and cost-effective means to conduct condition assessment and to use the information as part of a risk-based asset management approach to planning. Specific project objectives include:

- Identify and characterize the state of condition assessment technology for wastewater collection systems.
- Research and evaluate performance and cost of innovative and advanced infrastructure monitoring technologies including wireless and remote sensing approaches developed in other industries and their applicability to wastewater collection sewers.
- Identify and evaluate innovative CCTV technologies currently used by more advanced wastewater utilities for transfer to utilities at large.

- Prepare protocols, metrics, and site selection criteria for field demonstration of selected innovative condition assessment technologies and decision-support systems.

To meet these project objectives, a stakeholder group was established to review all task products, and a technology forum was convened to help compile and assess the current state-of-the-art and evolving technologies including any critical gaps in performance, affordability or applicability to wastewater collection systems. During the literature review for the White Paper, internal camera inspection technologies were researched and evaluated for immediate transfer to utilities at large; advanced integrity assessment technologies that apply non-contact, remote sensing approaches were also reviewed. In the main portion of the project, protocols/metrics for field demonstration of selected technologies will be developed, as will criteria for selecting demonstration sites. Finally, field demonstrations of select technologies will be conducted.

The work products resulting from the project will include:

- White paper summarizing current state of the technology.
- Summary of technology forum discussions and findings.
- Comprehensive inventory of condition assessment technologies.
- Information transfer document on internal camera inspection technologies.
- Information transfer document on advanced integrity monitoring technologies.
- Quality assurance project plan for conducting field demonstrations and data analysis.
- Technical memoranda summarizing each task.
- Final project report.

A draft white paper was prepared and used as a basis for discussion at the project's Technology Forum held in Edison, NJ on September 11 and 12, 2008. It was distributed to the expert panel, stakeholders and other participants in advance of the meeting. This final white paper incorporates feedback received at the Technology Forum.

1.3 Definition of Terms

A wastewater collection system or sanitary sewer system is defined as the network of pipes and pumping systems used to convey sanitary flow to a wastewater treatment facility for treatment prior to discharge to the environment. A wastewater collection system is designed to convey only sanitary flow, whereas a combined system is designed to convey sanitary and stormwater flows.

A gravity line is a sewer pipe that is sloped to convey flow via gravitational forces. Typical design standards are based on open channel flow equations under normal flow conditions utilizing Manning's equation. Design criteria for a gravity line generally take into consideration anticipated defects as a pipe remains in service. An allowable rate of inflow and infiltration expressed in terms of gallons per minute per in. diameter per mile length (gpm/in-mile) is included in hydraulic design of gravity lines. It is also typical to select a frictional coefficient that is based upon a sediment accumulation at the invert of the pipe. The minimum diameter of a gravity line (excluding service laterals) is typically 8 inches (in.); however, large interceptors can have diameters in excess of 12 feet (ft). Older systems may contain 6-in. gravity lines.

Service laterals are the gravity lines that convey wastewater from a building's foundation to the sanitary line, or main, in the street. The ownership of the service lateral varies widely from area to area. It may be defined by property line limits, with the private sewer lateral extending from the house or building foundation to the property line and the municipal or public lateral located within the public right of way. In other cases, the property owner may own the service lateral all the way to the main.

A force main is a pressure line used to convey pumped sewage. The Water Environment Research Federation (WERF) 2004 survey indicated that force mains comprise, on average, 7.5% of a collection system. This percentage does vary considerably depending on the region and the topography. Approximately 46% of the force mains have diameters less than 12-in. and 20% are greater than 36-in. The most common pipe materials for force mains are cast iron and ductile iron.

Asset Management - The primary components of any asset management program include the identification, location, and condition of assets; the determination of their useful life and their valuation. The key to asset management is to understand the types, frequency, and costs of failure. Asset management often employs a risk-based management approach that utilizes information on asset failures as part of a decision making model to manage funding and maintenance priorities. One risk model often employed is Failure Mode and Effects Analysis (FMEA). FMEA analyzes a system's potential failure modes so they can be classified by severity or determination of the effect upon the system. It is widely used in manufacturing as a risk mitigation tool in various phases of product life cycle and product quality planning.

The Water Research Foundation (formerly the American Water Works Association Research Foundation (AwwaRF)) and the Water Environment Federation (WEF) have both produced guidance documents on asset management and risk-based analysis of assets. The Capacity, Management, Operation and Maintenance (CMOM) program also outlines the framework necessary to develop an information-based strategy on managing assets. Such approaches are not unique to the wastewater industry. Developing an understanding of the risks and potential costs of system failure can aid in the decision making process.

Condition assessment is one of the core components of an asset management program. It provides the critical information needed to assess the condition and remaining useful life and long-term performance of a piping system. Condition assessment can also be used to determine the functionality of the pipes in meeting their design criteria. 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 (USEPA, 2007).

The type of pipe defect varies depending on the pipe material and pipe diameter, as discussed in Section 3.2. The most prevalent defects are as follows: cracks/broken pipe, root intrusion, sediment, grease build-up, off-set joints, corrosion, manhole frame and cover leaks, and pipe sags.

Pipe failure includes collapse, which may cause extensive property damage and/or discharge of untreated sewage, severe hydraulic restrictions, and severe decrease in hydraulic capacity. Other less severe pipe conditions could also be considered "failure" depending on the performance standards set for the system.

The term inspection technologies in this white paper refers to the various methods used for detecting pipe defects, structural and operational condition, and environmental conditions that could potentially impact pipe condition. These technologies, discussed in Section 4.0, have varying abilities for detecting and quantifying specific types of pipe defects. Inspection technologies may have limited applications depending on pipe material and/or pipe diameter. A robust condition assessment method would likely include a variety of inspection technologies, based on the specific characteristics of a utility's sewer network.

1.4 Critical Gaps in Inspection Technologies and Condition Assessment

A previous research project (Thomson et al., 2004) surveyed large wastewater utility districts to determine critical gaps in condition assessment of gravity pipelines and force mains. The survey found that 100% of the 31 survey respondents relied almost exclusively on CCTV as the primary means to inspect pipes. The general limitations of current CCTV technology were the focus of the identification of critical gaps. There were also several respondents who expressed concerns with the inability to measure the structural integrity of the pipe wall and the inability to measure crown corrosion of concrete pipe and internal corrosion for ferrous pipes.

1.4.1 Gravity Line Inspection

The majority of sewer pipeline inspection activities performed by utilities involve gravity pipelines. In the 2004 utility survey (Thomson et al. 2004), critical gaps for inspection technologies for gravity lines were defined as follows:

- The needs for improvements to CCTV - higher resolution cameras with better lighting; improvements in crawler technology to negotiate obstructions, grease, offset-joints; and cameras for inspection of laterals.
- Ability to monitor in surcharged (i.e., flooded) conditions.
- Inability to obtain information on pipe wall thickness.
- Inability to measure slope.
- Inability to locate manholes[1].
- Inability to locate soil voids above or below a pipe segment.
- Inability to quantify corrosion (e.g., internal, external).

1.4.2 Pressure Line/Force Main Inspection

Inspection of force mains is currently limited to pipelines that are taken out of service. For this reason, force mains are infrequently inspected by utilities, primarily because of the inability to take the line out of service without costly by-pass pumping. Other critical gaps in inspection of force mains include the limited number of inspection technologies suitable for use in force mains; and the inability to determine wall thickness, cracking, and pitting with currently available inspection technologies (Thomson et al. 2004).

1.4.3 Condition Assessment Protocols

Based on a survey of twenty-four Canadian sewer agencies using condition assessment protocols, Rahman and Vanier (2004) identified the lack of consistent, standard condition assessment protocols as a critical gap. The survey results showed 68% of the respondents used a protocol based on that of the National Water Research Council. The biggest gaps identified were systematic collection of data and use of formal risk assessment methods to prioritize resources for maintenance and rehabilitation activities. Research has focused on the use of models to standardize the risk-based decision-making process.

1.5 Research Questions

The following key research questions relating to sewer inspection and condition assessment have emerged from EPA research (USEPA, 2007). These questions reflect critical gaps in our knowledge of the performance of innovative inspection technologies, our understanding of proven condition assessment techniques, and our ability to diagnose and predict infrastructure failures.

- Can emerging and innovative inspection technologies be identified and demonstrated in field settings to improve our understanding of their cost-effectiveness, technical performance, and reliability?

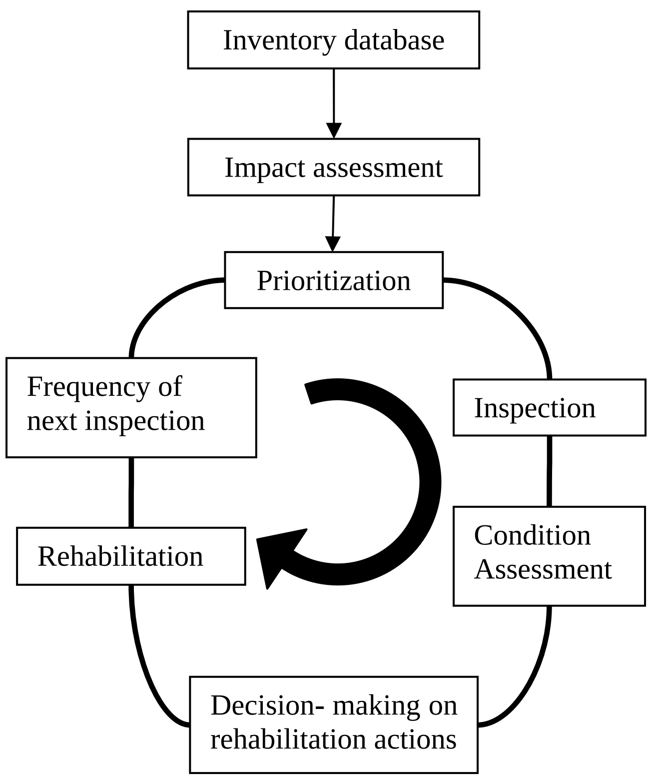
[1] Other sources indicate that manholes can be located via CCTV inspection. CCTV crawlers can be equipped with radio transponders to aid in manhole location.

- Can advances in remote monitoring and wireless technologies be applied to reduce confined-space entry requirements for sewer system inspection and investigation?
- What measurements or operational data can be used to determine and track the condition of assets over time?
- Can standard technical guidelines, uniform data requirements, and indicators be developed for condition assessment of sewers and non-sewer assets, including manholes, service laterals, and pipe joints?
- Can technical guidance be developed for establishing an overall wastewater infrastructure inspection program, including inspection prioritization, inspection frequency, inspection type (physical vs. visual, maintenance vs. structural), inspection by asset type, and inspection cost-effectiveness?
- How can a municipality determine the impact of deteriorating collection systems on their financial budgets?
- Can infrastructure failure mechanisms be better characterized to improve risk assessment models?

2.0 Condition Assessment

Condition assessment has gained considerable attention in recent years amongst municipalities and utility districts as a component of an asset management program. It can be used to prioritize infrastructure projects based on relative risk, thereby easing the financial burden on wastewater utilities and their customers. WERF estimates that wastewater utility purveyors spend approximately $4.2 billion annually to rehabilitate sanitary pipelines. Local and state governments are required to tabulate the value of their public assets (i.e., buildings, roads, utilities, etc.) to support the development of a unified cost accounting system, per the Governmental Accounting Standards Board Bulletin 34. This program requires detailed financial accounting of all assets, however, the level of detail to which it is implemented can vary from city to city. Condition assessment can also assist utilities in implementing USEPA's proposed guidance for evaluating the Capacity, Management, Operation, and Maintenance (CMOM) program for sanitary sewer collection systems (USEPA, 2005). The CMOM program requires a municipality that operates a sanitary sewer system to provide adequate conveyance capacity for all parts of the system and to take all feasible steps to stop and mitigate the impacts of sanitary sewer overflows.

A variety of processes have been developed for performing condition assessments, ranging from simple to complex. They generally follow a similar progression of steps: setting objectives for the condition assessment, identification of assets and available data, asset inspection, data analysis, and decision making. Specific condition assessment processes are described in the WERF publication "Condition Assessment Strategies and Protocols for Water and Wastewater Utilities" (Marlow et al., 2007) and in the National Research Council's "Guidelines for Condition Assessment and Rehabilitation of Large Sewers" (McDonald and Zhao, 2001). Figure 2-1 illustrates the steps in the condition assessment process.



Source: McDonald and Zhao, 2001

Figure 2-1: Condition Assessment

2.1 Program Development

The development of a condition assessment program must first consider the program drivers and objectives. The drivers may include regulatory compliance, operation and maintenance efficiency, risk management, and/or financial budgeting forecast. Often, the primary driver for wastewater utilities is investigation of sources of infiltration/inflow (I/I) that would require a system-wide condition assessment program. Other utilities are more concerned with identifying high risk pipes for which a catastrophic failure could lead to extensive service disruptions and environmental damage. A risk-based condition assessment program would focus on specific pipes that present these types of risk.

Objectives for performing the condition assessment should be explicitly stated, so that the program's effectiveness can be evaluated. The objectives will also establish how the results of the condition assessment will be used in the decision making process, the final step of condition assessment. Key performance indicators (KPIs), metrics used to determine the utility's progress to defined goals, would be defined at this step. Objectives for performing a condition assessment could be to understand the structural condition, performance, and/or progression of deterioration (i.e. remaining service life) of the asset.

The costs of conducting condition assessment must be documented and compared to the anticipated benefits in order to justify the program. The costs are typically easier to quantify but should include both the direct costs of inspection and the indirect costs to the utility and other parties of carrying out the inspection work and collecting and analyzing the data. The benefits are more difficult to quantify and derive mainly from the reduction in the risk of failure (likelihood times consequences of failure) and from the knowledge that allows maintenance, rehabilitation and replacement to be carried out on the most cost effective schedule. More specifically, the costs of condition assessment include:

- Equipment and labor costs to conduct field inspections including excavation, traffic control, road surface restoration, monitoring equipment and data collection.
- Labor costs before and after field work for planning, data analysis and reporting.
- Cost of service disruptions due to inspection work.

Specific benefits of a condition assessment program may include:

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

Comparing the costs to benefits for gravity sewers and force mains, it has been reported (Thomson 2008) that:

- The cost of inspection of gravity sewers is typically low with respect to the value of the asset (e.g. the cost of inspection of a 12-in diameter sewer at 13-ft depth is less than 1% of the asset value) and the proportion decreases with increasing depth and diameter of sewer.
- The benefits from inspection of gravity sewers are likely to exceed costs for all but small diameter sewers at shallow depths.

- The cost of inspection of force mains is high with indirect costs often exceeding the direct costs of inspection (emptying the line, providing temporary bypass, accessing the line).
- The monetary benefits of inspection may be less than the cost of inspection for smaller lines in less populated areas (fail and fix approach may be chosen) although this ratio may change in environmentally sensitive areas. The benefits increase greatly for larger diameter force mains and urban areas due to the increased risk of major consequences.

When performing condition assessment, it is essential to compile an inventory of assets and existing system data (i.e. pipe material, size, age, maintenance history, inspection records). The utility should understand the content and form of existing data, and should identify data gaps at this step. System maps and geographic information system (GIS) databases are good information resources. Inspection and testing records may include I/I studies: flow data, smoke testing, flow isolation studies, and/or dye tracer studies. Failure data from within the system or from research on similar conditions (e.g., soil bedding type, material, age) in utility districts can be used to define risk of failure. Data gaps identified in this step are used to plan the inspection program.

A key difficulty in developing a rational inspection, condition assessment, and asset management program is that some of the most critical elements of the sewer infrastructure are the most difficult and expensive to inspect. For example, large diameter sewers have continuous and high levels of flow that make bypassing the sewer difficult or impossible. They may contain large debris that hinder inspections unless the pipes are cleaned first, and they may not have been inspected for decades. Similar conditions exist for force mains in terms of the consequences of failure vs. the ability to inspect.

2.2 Asset Inspection

The primary purpose of an inspection is to define the current condition of an asset, in order to detect and evaluate the progression of deterioration and to make informed decisions on asset management. A well developed inspection plan will maximize the value of the program, while minimizing the cost of inspection. A detailed work plan and quality assurance project plan should also be established at this step to outline how the proposed inspection program would meet the program objectives. The inspection plan should focus on what assets to inspect, when they should be inspected, and what technologies will be used for inspection. Ideally, an inspection would occur at a point prior to failure where an intervention could effectively renew the asset. For a buried pipeline, there is limited ability to obtain a warning indicator as to the appropriate time and location to perform an inspection. It is this unknown state that is the inherent risk in managing buried assets.

2.2.1 Selection of Assets for Inspection

It may be considered cost prohibitive to inspect every linear foot of a wastewater collection system especially when confronting the need to inspect a large system with little prior inspection history. It is for this reason that condition assessment programs generally use a planned approach to focus on high consequence/high risk pipes or to utilize statistical sampling to select assets for inspection. Decisions on which assets to inspect should be related to the objectives and KPIs defined in the program development phase of the condition assessment process. For example, if the objective or KPI is to reduce SSOs, then a utility may focus on service lateral, which are often a large source of I/I. If the objective or KPI is to reduce risk of failure of high consequence pipes, then a utility may focus on pipes with higher impact and probability of failure, and not inspect service laterals, as they are not high risk or high consequence.

2.2.2 Prioritization of Assets

Two models for prioritizing assets for inspection are described below:

- The National Research Council's approach (McDonald and Zhao, 2001) utilizes an "impact assessment" to prioritize assets for inspection. Impact assessment is a weighted average of six separate impact factors: location, soil support, size, depth, sewer function, and seismic factors. Impact assessment can then be directly calculated in a uniform approach based on a weighted average.
- SCRAPS (Sewer Cataloging, Retrieval, and Prioritization System) is based on the general approach of defining risk factors based on consequence of failure and likelihood of failure (Merrill et al., 2004). The term "Consequence of Failure" is defined as the impact of a failure in terms of repair cost, disruption to the public and economy, impairment of system operation, regulatory compliance, public health and safety, and damages to the environment. The same terminology can also be applied to the decision making process used in applying condition assessment to asset management. The impact of a failure must be understood and quantified. If the impact can be quantified in dollars, then it can be compared to both the cost of condition assessment and the cost of replacement and/or rehabilitation.

2.2.3 Asset Inspection

The type of inspection performed depends on the objective of the condition assessment program. The selected inspection technique needs to be consistent with the type of asset to be inspected and provide the information and data required to support decision making. Flow monitoring is usually utilized when conducting I/I studies, to evaluate hydraulic capacity and determine hydraulic restrictions. CCTV is the most commonly used method of inspecting sewers for structural defects; however, there are a variety of technologies available for this type of inspection; these technologies are discussed in-depth in Section 4.0. A detailed work plan and quality assurance project plan should be established; these documents ideally would outline how the proposed inspection program would meet the program objectives.

2.3 Data Management

A successful condition assessment program as part of an asset management program requires that the data collected are organized, analyzed, and maintained in a database system. This important step allows a utility to develop an understanding of trends. There are three general approaches to database management that have varying degrees of cost and complexity but all of which use commercially available software:

1. Software specifically designed for condition assessment and asset management.
2. Database software that is not specifically designed for condition assessment.
3. Spreadsheet software.

2.3.1 Condition Assessment/Asset Management Software

There are numerous commercially available data management programs for condition assessment that range in level of complexity and cost. The primary component is a database to store defect coding on pipe segments both spatially and over time. The commercially available systems can also incorporate additional elements such as cost accounting, develop work orders for maintenance calls, and order parts to maintain required spare parts. Another useful feature is the incorporation of GIS functionality into the system. The GIS component highlights the geo-spatial distribution of the data, and can provide a very effective tool for the utility to plan subsequent inspections and/or rehabilitation activities. The benefit of the commercially available programs is that they are designed specifically for the intended purpose. However, the cost of system maintenance can be significant, as can licensing costs, depending upon system complexity.

Another type of commercially available software is designed to summarize the results of a CCTV inspection and the resulting defect code data. This has become standard practice in the industry. The National Association of Sewer Service Companies (NASSCO) licenses software programs to be consistent using the PACP and Manhole Assessment Certification Program (MACP) rating systems, which are discussed in Section 2.4.2. The certification programs allow commercial providers to submit their pipe assessment software for evaluation and certification to ensure that their software adheres to NASSCO standards. It is important to verify the software has been approved to decrease the set-up time required to enter ranking and coding information. Pipeline inspection software is used simultaneously with pipeline inspection hardware to accurately document the status of sewer pipe, storm drains, or water pipelines. The software gives access to text data, video, and still photos all of which help the user identify the condition of the pipe and precisely complete a pipeline inspection. Defects can be quickly categorized by location, type, and severity. The software compiles this data into a searchable database which can be distributed into printed reports.

2.3.2 General Database Management Software

Utilization of commercially available database software requires a utility to design a database specific to their needs. The benefit would be the reduced initial licensing cost of the software. Most utilities would have database software as part of their professional software packages licensed for their operating system. Another benefit is that it may cost less to maintain than the condition assessment software described above. A drawback to this approach is the significant up-front work and required expertise to design a database system for the intended purpose.

2.3.3 Spreadsheet Software

Spreadsheet software is the least costly of the three systems; however, it also has the most limitations. This type of software is readily available and likely exists at each of the utilities. A simple yet effective system can be designed to collect and store data. However, spreadsheets are a flat file system and are very limited in usefulness as the database expands. It can become overly cumbersome if multiple spread sheets are required.

2.4 Data Analysis

The data resulting from inspection may quantify the level of service and/or structural defects. It does not, however, provide any ability to reduce risk or define the significance of the finding. The follow-up step is to process and analyze the inspection data. There are two general analysis methods used, based on the type of inspection performed. If flow monitoring was employed as the inspection technology, an analysis of hydraulic capacity is performed, using hydraulic modeling techniques. If an inspection of structural defects utilizing CCTV or one of the other non-destructive technologies was performed, analysis is generally performed by coding defects in accordance with one of the various methods available, such as the Water Research Centre (WRc)'s system or NASCCO's PACP and MACP programs

2.4.1 Hydraulic Capacity/Hydraulic Restrictions

Hydraulic capacity is the primary performance measure for a wastewater collection system. Flow data gathered by flow meters has been used to guide sewer system management for at least three decades.

Advancements in technology and software have brought a new level of condition assessment information to utility managers. The purpose of this section is to discuss the use of flow data as a tool in condition assessment. A description of improvements in flow meter technology is discussed in Section 4.5.

Historically, flow data have been used in Sewer System Evaluation Survey (SSES) as a screening tool to prioritize areas for further study. Flow data presented over a period of time are useful in demonstrating the system impacts due to rainfall or elevated groundwater. It provides the required information to calibrate a hydraulic model or conduct I/I studies. The hydraulic model can then be used as a predictive tool to project overflow and/or surcharged conditions for various design storms.

The following is a list of the most common indirect measurements that allow an operator to assess the general condition or rate of I/I:

- Average Daily Dry Weather Flow includes the average flow from a sewershed, which is composed of the wastewater production rate and base infiltration of the system.
- Base Wastewater Flow is estimated on the number and type of sewer users, domestic water usage records, and predicted diurnal flow variations. It equates to the anticipated flow rate of only wastewater in the system.
- Groundwater infiltration is determined by subtracting the estimated Base Wastewater Flow from the Average Daily Dry Weather Flow.
- Capture coefficient or percentage of rainfall that enters the sewer.
- Relationship between rainfall and peak flow rate.

The I/I values are valuable for planning purposes, providing a good indicator of pipe conditions upstream of a flow meter. As the sub-areas for which data are collected increase in size, flow data are less useful as a predictive tool for condition assessment. It does, however, provide the data to quantify groundwater infiltration and wet weather derived flow for the area tributary to the metering location.

The real value of flow monitoring data of sewers is developing a database on long-term historic trends in order to determine seasonal variations and impacts of wet weather. Flow data provide the direct correlation needed to determine if performance measures are being attained. Flow data are also useful as a screening tool to determine problems areas of a system that require further study by other means.

The traditional method of viewing flow data is hydrographs, which reveal information on condition upstream of flow meters. Alternatively, flow data can be viewed as scattergraphs, which provide information on hydraulic conditions downstream, or in the vicinity of, a flow meter. Scattergraphs are created by plotting flow depth versus flow velocity data. When flow meters are working correctly, a normal pipe curve is plotted unless normal open channel flow is not occurring. In these cases, the scattergraph data can be used to identify such hydraulic restrictions as silt or obstacles, bottlenecks, and negative grade pipe, as well as surcharged conditions.

2.4.2 Structural Condition

For wastewater collection systems, analysis of inspection data generally involves coding the defects based on both the type and severity of defects. Structural pipe defects and hydraulic restrictions encountered during the inspection need to be ranked by severity level based on the potential to negatively impact the system's hydraulic capacity.

The WRc, located in the United Kingdom, developed a set of standards to rank the severity of pipe defects found in an inspection. European authorities adopted these standards as their benchmark pipe defect coding standard. In 2001, NASSCO developed a set of coding standards based on the WRc system (NAASCO, 2001). The NASSCO PACP standards have successfully become the industry standard for coding pipe defects. NASSCO has also developed the MACP, which is similar to PACP but applies to manholes instead of pipelines. NASSCO has training programs to certify and train inspection professionals in PACP and MACP. NASSCO has begun work on developing a coding system for service laterals.

The PACP coding system categorizes defects and features into five sections: continuous defect coding, structural defect coding, operational and maintenance coding, construction features coding, and miscellaneous features coding. For each type of defect, the PACP uses a combination of capital letters to describe the type of defect and a number to rank the severity of the defect. An example is "FL" for a longitudinal fracture. Defect codes are recorded on a standardized form along with pertinent system data including defect type, continuous distance of the defect, severity, size, circumferential location (clock location), joint number, image/video reference number, and comments.

A brief description of the PACP defect coding system is described below:

- **Continuous Defect Coding:** Continuous defect coding is made up of two separate coding classifications. The first is called "Truly". Truly continuous defects are defects that run along the sewer for a minimum distance of three ft. These defects include longitudinal fractures and cracks. "Repeated" continuous defect coding defects are continuous defects that occur at regular intervals along the pipe. These usually occur at pipe joints and include encrustation, open joints, and circumferential fractures. Continuous defect coding can be used in conjunction with other types of coding to accurately describe defects on the PACP form.

- **Structural Defect Coding:** Structural defect coding is made up of a number of separate coding classifications. This section uses coding to define the type of defects that are related to structural degradation of the pipe due to various reasons. The coding under structural defects are as follows: crack (C), fracture (F), broken (B), hole (H), deformed (D), collapse (X), joint (J), surface damage (S), lining failure (LF), weld failure (WF), point repair (PR), and brick work (BW). Under each of these subtitles there are also other letters to further define the type of defect. For example: HSV is for a hole with visible soil.

- **Operational and Maintenance Defect Coding:** This section uses coding to define the type of defects that are related to lack of maintenance on the pipe system. Operational and maintenance defect coding is made up of a number of separate coding classifications as follows: deposits (D), roots (R), infiltration (I), obstacles (OB), and vermin (V). Under each of these subtitles there are also other letters to further define the type of defect. For example: VR designates that there are vermin, specifically, rats in the pipe.

- **Construction Features Coding:** This section uses coding to define construction features located in or around the pipe system. Construction features coding is made up of a number of separate coding classifications as follows: tap (T), intruding seal material (IS), line (L), and access point (A). Under each of these subtitles there are also other letters to further define the type of defect. For example: AMH designates that there is an access point in the line that is a manhole.

- **Miscellaneous Features Coding:** Miscellaneous features coding is made up of a number of separate subcoding classifications. This section uses coding to define miscellaneous (M) features in the pipe system. Under this subtitle there are also other letters to further define the type of defect. For example: MCU designates that the camera is underwater.

The PACP uses a numerical grading system to define the severity of pipe defects. Condition grades for structural defects and operation and maintenance (O&M) defects are assigned based on the risk of further deterioration or failure. The numerical system uses numbers ranging from 1 to 5 with 1 being the best and 5 being the worst. The severity ranking considers the immediate defect, risk of failure, and rate of deterioration.

- Grade 5 – Pipe segment has failed or will likely fail within the next five years. Pipe segment requires immediate attention.
- Grade 4 – Pipe segment has severe defects with the risk of failure within the next five to ten years.
- Grade 3 – Pipe segment has moderate defects. Deterioration may continue, but not for ten to twenty years.
- Grade 2 – Pipe segment has minor defects. Pipe is unlikely to fail for at least 20 years.
- Grade 1 – Pipe segment has minor defects. Failure is unlikely in the foreseeable future.

Pipe ratings are based on the number of occurrences for each condition grade and are calculated separately for both structural and O&M defects for each pipe segment. Each pipe segment will be assigned a segment grade based on the number of occurrences of each graded defect. The graded defect is multiplied by the number of occurrences, and this equals the segment grade. The overall pipe rating is calculated by adding all of the segment grades per pipeline. The structural defects are added separately from the O&M grades, so each pipeline receives two separate grades.

The PACP also uses a quick grading system, which is a shorthand method of expressing the number of occurrences for the 2 highest grade levels. The quick grading system uses four characters:

1. The first character is the highest severity grade occurring along the pipe length.
2. The second character is the total number of occurrences of the highest severity grade. If the total number exceeds 9, then alphabetic characters are used as follows: 10 to 14-A, 15-19-B, 20 to 24-C and so on.
3. The third character is the next highest severity grade occurring along the pipe length.
4. The fourth character is the total number of the second highest severity grade occurrences, which is formatted the same way as the second character.

For example, a code of 3224 would equate to two grade 3 defects and four grade 2 defects in a pipe segment. This also shows that no grade 4 or 5 defects were found. The quick grading system allows the pipe defects to be summarized in an efficient manner. As with the longhand method, structural defects are graded separately from O&M defects.

2.5 Decision Making

Decision making for condition assessment of a wastewater collection system entails understanding the possible risks and determining at what point a utility should intervene to avoid a failed condition with an unacceptable cost and/or consequence. It is important to note that condition assessment alone does not provide any benefit in risk reduction. The follow-up decision making process that leads to prioritization ranking and rehabilitation ranking followed by action to fix problems and upgrade the system is what leads to risk reduction.

The purpose of this section is to highlight and summarize the decision making process, the final step in the condition assessment process. In addition to inspection data, the utility requires supplemental data on long-term asset performance to aid in the decision making process.

Marlow et al. (2007) posed the following questions that need to be addressed to provide the required information for decision making:

- What are the consequences of asset failure?

- What are the costs to replace/rehabilitate the assets?
- What alternatives exist, given the results of the condition and performance assessment (e.g., replacement, deferment, rehabilitation, non-structural maintenance)?

Important definitions to consider are failed condition and service life. The American Concrete Institute defines service life as the period of time following installation during which all properties exceed minimum accepted standards when routinely maintained.

- Technical service life – period of time until an unacceptable condition is reached.
- Functional service life – period of time until the system element no longer provides functional service.
- Economic service life – period of time until it becomes economically more effective to replace or rehab than to continue to operate in its current condition.

The objective for the decision making model is to understand risk and to determine when to intervene to avoid unacceptable consequences (e.g., economic, socio-economic, environmental). However, it is not possible to have a robust decision making model without obtaining sufficient condition data to track pipe deterioration and to understand the pipe or system failure modes.

In general terms, decisions on pipe rehabilitation/replacement can be made based on one or more of the following: engineering calculations, probability of failure, and remaining life estimation.

- **Engineering Calculations:** Inspection data are interpreted deterministically. An example would be to calculate structural condition of a pipe segment directly based on measured minimum wall thickness, actual loading conditions, and existing soil bedding. A second example of this methodology is the calculation of hydraulic capacity. Flow data can provide direct measurement of actual flow conditions; and then be interpolated using a hydraulic model to calculate hydraulic capacity of a pipe segment under current or projected conditions. Both of these examples illustrate a direct calculation of the condition or performance of the pipe segment. If it does not meet the required design conditions or performance conditions, then replacement or rehabilitation is required.

- **Probability of Failure:** This type of output would ideally provide a direct forecast of pipe deterioration over time. If a utility have the data to support this type of forecast, then an intervention could be implemented before an unacceptable level of service occurred. In practice, it is difficult and potentially costly to directly determine the probability of failure. However, the American Concrete Institute (2000) did reference studies and models to predict failure rate in reinforced concrete pipe. Regression forecasts and models were developed to predict failure of reinforced concrete pipe (RCP) based on chloride concentrations, extent of spalling and mechanical loading conditions, and sulfate concentration. Repeated data collection and analysis over time are required to obtain the decay curves based on the different paths to failure and the system or environmental conditions that exacerbate each failure mode.

- **Remaining Life Estimation:** Remaining life estimation is commonly used to characterize condition of buried assets. Remaining life is defined as the duration of time until an unacceptable condition exists or an asset no longer meets its primary function. Standard coding systems are used to define condition and performance. NASSCO's PACP system, discussed in Section 2.4.2, has become the standard to follow in the United States for wastewater pipe systems.

A variety of decision making models have been developed for sewer assets. WERF is developing a web-based model based on remaining economic life of water and wastewater pipes. T-WARP is a software program that uses fuzzy logic to analyze the possibilities of pipe failure. The European Union's Computer-Aided Rehabilitation Program for Sewers (CARE-S) is a software program that supports efficiency in rehabilitation decisions. McDonald and Zhao (2001) propose a matrix approach for decision making based on asset condition grades and an impact assessment rating as summarized in Table 2-1. The term impact assessment is defined by the authors as a weighted average of six separate impact factors: location, soil support, size, depth, sewer function, and seismic factors.

Table 2-1: Condition Assessment Matrix

Asset condition grade*	Implication of asset condition	Impact assessment	Action	Inspection frequency
5	Failed or imminent failure	1 to 5	Immediate	NA
4	Condition poor, high risk of structural failure	5	Immediate	NA
		1 to 4	High	2 to 6 years
3	Condition poor, moderate structural risk	4 to 5	Medium	3 yrs
		1 to 3	Low	5 to 10 years
2	Fair condition, minimal structural risk	5	Medium	5 years
		1 to 4	Low	10 to 15 years
0 to 1	Good condition	5	Not required	10 years
		1 to 4		15 to 25 years

* Condition grade is based on WRc coding system (Manual of Sewer Condition Assessment, WRc 2003).

NA – Not Applicable

Source: McDonald and Zhao, 2001

3.0 Dynamics of Wastewater Collection System Failure

In conducting condition assessment, it is important to understand the dynamics of pipe failure including the level, type, and severity of a failure mechanism. Failure modes can include sudden, catastrophic collapse of a pipe or restricted hydraulic capacity. The purpose of condition assessment is to detect pipe defects which indicate the likelihood of pipe failure, as well as to assess the collection system's performance. This section discusses the mechanisms of pipe failure, the various types of pipe defects, and the relationship between the condition of a pipe and its performance. It is important to understand that pipe failure and defects are highly dependent upon the pipe material, diameter, and type of sewer (e.g. force main, gravity line).

3.1 Failure Mechanisms

Pipe failures can be grouped into three general categories according to the cause of failure: hydraulic restrictions (e.g. blockage), hydraulic capacity, and structural condition. The following sections provide additional details on these failure mechanisms.

3.1.1 Hydraulic Restrictions

The primary function of a wastewater collection system is to convey wastewater; therefore, hydraulic capacity and factors that limit it are of paramount concern. Hydraulic restrictions are the most prevalent condition encountered in wastewater collection systems. The characteristics of untreated wastewater are such that accumulation of sediment, grease, and rags is a constant maintenance item. There are situations in larger diameter sewers, especially combined sewers, when large items create obstructions and rapid hydraulic restrictions. This can lead to street and basement flooding.

Standards used for hydraulic design mandate minimum slopes for various pipe diameters to achieve scouring velocities that minimize debris accumulation. However, there are many external conditions that encourage debris accumulation (e.g. root intrusion, grease, pipe sags).

Blockages are easily detected by visual inspection. The direct cause of a blockage sometimes is not evident. For most conditions, the failure rate is slow over time. A standard maintenance program for cleaning and flushing sewers is typically adequate to control blockages. The types of defects that fall within the category of hydraulic restrictions are as follows: root intrusion, sediment accumulation, and grease build-up. It should be noted that off-set joints and pipe sags can directly impact pipe flow thereby creating low velocity conditions that are conducive to solids deposition.

3.1.2 Hydraulic Capacity

Failure due to hydraulic capacity is defined as a pipe segment not having adequate, available capacity for the designed conditions. The failure condition may be caused by excessive I/I, pipe deformation, and/or inadequate slope.

I/I have a direct impact on the capacity available to convey wastewater. The groundwater and storm water enter the collection system through direct connections or indirectly via cracks and defects. Zero I/I is not a realistic design objective. The hydraulic design of new sewers considers an anticipated level of I/I in determining pipe size.

Pipe deformation and inadequate slope directly impact the hydraulic capacity of the pipe. Flow can be calculated based on the Manning's equation for normal flow conditions:

$Q = 1/n * A * R_h^{2/3} * S^{1/2}$

Whereas

Q = Flow[2] (volume per time).

A = Cross-sectional flow area (area).

n = Manning's roughness coefficient.

R_h = Hydraulic radius (length).

S = Pipe slope.

The mathematical relationship of change in area due to pipe deformation or inadequate slope is self-evident. A decrease in flow area and/or pipe slope will result in a proportional decrease in flow capacity.

Failure due to hydraulic capacity is often a sign of other types of defects such as structural defects. Major sources of I/I can be cracks, broken pipes, leaks from manhole frames and covers, and off-set joints. Pipe sags and areas of inadequate pipe slope can be due to loss of pipe bedding or inadequate construction controls.

3.1.3 Structural Failure

Structural failure is caused by defects of the pipe wall and/or the soil envelope used to support the pipe. In general, the types of defects that are associated with structural failure include cracks, misaligned or off-set joints, pipe deflection, cracked manhole frames and covers, and internal and external corrosion. Internal corrosion is caused by hydrogen sulfide formation, and external corrosion is due to soil corrosivity.

The pipe is supported by a soil envelope that consists of the soil bedding and the cover soil. The soil bedding acts as the foundation for the pipe and distributes the vertical load around the exterior of the pipe wall. The pipe is subjected to live loads and earth loads. The goal of the bedding design is to transmit this load to the bedding and avoid point loads on the pipe. Loss of bedding can result in the pipe bridging areas of reduced bedding. This can lead to pipe deflection, pipe deformation, and longitudinal cracking. Increased traffic load or loss of soil cover is another cause of structural failure.

The type and degree of failure differ by pipe material. Some pipe material (e.g. PCCP) is susceptible to sudden failure while others fail gradually and are easily detected by visual inspections. Typical failure modes for various types of pipe material used in sewer collection systems include:

- **Ferrous Pipe (Ductile Iron, Cast Iron, Steel) -** The primary failure mode for metal pipes is internal or external corrosion, which leads to breaks or holes in the pipe wall. Cast iron in particular is brittle, making these pipes prone to cracking. Large diameter steel pipes are susceptible to collapse as well as corrosion.
- **Concrete Pipe (RCP, PCCP) -** Corrosion is often a major factor in the structural failure of concrete pipe. RCP typically fails after the interior surface of the pipe wall has deteriorated to such a degree that the reinforcing steel is exposed. As the reinforcing steel corrodes, it swells, beginning to break up the surrounding concrete and causing failure. PCCP has a distinctive failure mechanism as failure occurs when the pre-stressed wires break, generally as a result of corrosion or direct physical damage to the pipe.
- **Ceramic-based pipe (Brick, Vitrified Clay Pipe (VCP)) -** Brick pipes generally fail by collapse, often caused by weakened mortar. VCP fails when external loads create cracks in

[2] Please note a factor of 1.49 is used when utilizing British Units.

the material. Failure is often exacerbated by the loss of surrounding soil into the pipe after initial fracture leading to void formation and loss of soil support to the pipe.

- **Plastic Pipe (Polyvinyl Chloride (PVC), High-density Polyethylene (HDPE)) -** The primary failure mode of plastic pipe is environmental stress cracking, which occurs from stress developed in a deflected pipe or due to slow crack growth, a phenomenon that occurs when a pipe is subjected to long duration tensile stress. Leaking joints can also contribute to plastic pipe failure.

3.2 Pipe Defects

Sewer defects are generally categorized as service or structural. Structural defects include cracks, fractures, breaks, deformations, collapses, joint displacements, and open joints. Service defects include tree roots, obstructions, debris, and encrustation. Pipe defects can also be classified by whether they are defects of the internal pipe surface, a pipe wall defect, a leak, or an alignment defect. Thomson et al. (2004) classify defects as internal pipe surface (sediment, debris, and roots), pipe wall (pipe sags and deflections, pits and voids, corrosion and metal loss, off-set joints, pipe cracks, broken pre-stressed wires, wall thickness, service connections and deteriorated insulation), leakage, and pipe support (bedding condition and voids).

The most prevalent defects in wastewater collection systems are cracks/broken pipe, root intrusion, sediment, grease build-up, off-set joints, corrosion, frame and cover leaks, and pipe sags. However, pipe defects vary with the pipe material and pipe diameter. Because gravity lines and force mains are generally constructed of different materials, they are susceptible to different types of defects.

Gravity pipes are usually constructed of VCP or PVC which are prone to grease build-up and joint misalignment/leakage. However, VCP is likely to experience cracks/breaks and root intrusion, whereas PVC is more likely to have excessive deflection, grade and/or alignment issues, and lateral connection defects.

Unlike gravity pipes, most force mains are constructed of ferrous materials (i.e., welded steel, ductile iron, or cast iron) or plastic (PVC, HDPE). Large diameter force mains have also been constructed of PCCP. While ferrous pipes tend to experience defects similar to VCP and PVC, internal and external corrosion are the primary defects. Table 3-1 provides a summary of the most common pipe defects by pipe material from a recent utility survey (Thomson et al., 2004).

Table 3-1: Most Common Pipe Defects Identified

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

1 – Liner separation, weld failure

2 – Missing bricks, soft mortar, vertical deflection, collapse

3 – Lateral connections

4 – Pressure capacity (force mains only)

Source: Thomson et al. (2004). Reprinted with permission from WERF.

3.3 Correlations between Assessed Conditions and Performance Measures

The measure of performance for a wastewater collection system can be based on four critical areas: service level, regulatory compliance, public health and safety, and environmental protection (Fleury and Warner, 2007). The subsections below describe how these performance measures can be correlated to pipe condition.

- **Service Level:** Wastewater utilities strive to provide continuous, efficient service for their customers. Pipe conditions that affect service level include defects or conditions that affect the available hydraulic capacity to convey current and future planned wastewater flows. Excess hydraulic capacity in a newly constructed piping system can diminish over time due to many types of defects: corrosion, I/I, sediment accumulation, pipe deflections, and cross-connections.

- **Regulatory Compliance:** Wastewater utilities must comply with existing regulations. The Clean Water Act (CWA) prohibits discharges of pollutants to waters of the U.S., unless authorized by a National Pollutant Discharge Elimination System permit. Unpermitted discharges from the sanitary sewer system constitute a violation of the CWA. Non-compliance with the SSO regulations, specifically the CMOM provisions, will result in enforcement actions including mandated O&M programs and fines. Pipe conditions that affect regulatory compliance may include defects or conditions that cause sewage overflows or back-ups.

- **Public Health and Safety:** Wastewater utilities protect public health and safety by minimizing conditions where the public can be exposed to untreated sewage such as receiving waters used for drinking water sources, fishing, and/or contact recreation such as swimming. Pipe conditions that affect protection of public health include defects or conditions that cause sewage overflows, back-ups or catastrophic pipe failure.

- **Environmental Protection:** Pipe failure may cause extensive property damage and/or discharge of untreated sewage. Failures of large diameter pipes and force mains contribute to the formation of sinkholes that may lead to damage and/or disruption to roadways and utilities, as well as the creation of hydraulic restrictions. Pipe conditions that affect environmental protection efforts are similar to those listed above—defects or conditions that cause sewage overflows, back-ups, or catastrophic pipe failure.

Utilities use pipe condition information to assess how well they are meeting each of these performance measures and to identify and prioritize system needs. The goal is to provide the best possible service in a cost-effective manner. Utilities need to know what is an acceptable level of performance that can provide regulatory compliance, environmentally acceptable performance, and operational effectiveness at the lowest possible life cycle cost? Inspection and condition assessment provide key information for helping the utility address these questions and balance system needs and costs.

4.0 Inspection Technologies

Inspection technologies and their use in condition assessment for wastewater collection systems are presented in this section. Each technology is briefly described, and commercially available and emerging products utilizing the technology are discussed. Table 4-1 provides a summary of typical applications for each technology.

Table 4-1: Inspection Technology Overview

Technology		**Sewer type**			**Pipe material**	**Pipe diameter**	**Defects detected**			
		Gravity	**Force main**	**Lateral**			**Internal condition**	**Pipe wall**	**Leakage**	**Pipe support**
Camera	Digital cameras	•			Any	6-in.-60-in.	•	•	•	
	Zoom cameras	•			Any	>6-in.	•	•	•	
	Push-camera			•	Any	1-in.-12-in.	•	•	•	
Acoustic	In-line leak detectors	•	•		Any	≥4-in.			•	
	Acoustic monitoring systems		•		PCCP	≥18-in.		•		
	Sonar/ultrasonic	•	•		Any	≥2-in.	•	•		
Electrical/ electromagnetic	Electrical leak location	•	•	•	Non-ferrous	≥3-in.			•	
	Remote field eddy current	•	•	•	Ferrous, PCCP	≥2-in.		•	•	
	Magnetic flux leakage	•	•	•	Ferrous	2-in.-56-in.		•		
Laser	Laser profiling	•	•		Any	4-in.-160-in.	•	•		
Innovative technologies	Gamma-gamma logging	•	•	•	Concrete	Not yet defined				•
	Ground penetrating radar	•	•	•	Any	Not yet defined			•	•
	Infrared thermograph	•	•	•	Any	Not yet defined			•	•
	Micro-deflection	•			Brick	Not yet defined		•		•
	Impact echo/SASW	•			Brick/ Concrete	>6-ft.		•		

4.1 Camera Inspection

CCTV inspection is a very effective method of evaluating and creating a permanent video record of underground pipe conditions. The visual inspection of sanitary sewer lines enables a CCTV operator to locate and identify specific defects that contribute to the infiltration of groundwater into the collection system and exfiltration of sewage into the substrate surrounding a pipeline. This is a well established and common industry method for pipeline assessment. In a recent survey report (Thomson et al., 2004), 100% of survey respondents from large wastewater utility districts relied on CCTV as their primary method of collection system inspections; hence, it is not surprising that the critical gaps identified in this survey parallel the limitations of CCTV inspection. CCTV provides a means to inspect a pipeline that is either too small or hazardous for direct human entry inspection. The primary disadvantages to the technology are that it only provides a view of the pipe surface above the waterline and does not provide any structural data on the pipe wall integrity or a view of the soil envelope supporting the pipe.

The technology and level of ancillary equipment used for CCTV inspection of sewer systems varies significantly based on the diameter of the line being inspected. In general, CCTV technology uses a video camera with lighting to provide a visual recording of the inside condition of a pipeline. The means to convey the camera through the pipeline vary in complexity from simple pushrod cameras (pushcams) to complex remote controlled robot crawlers. The level of optical control on the camera also varies in complexity. The ability to pan, tilt, and zoom has become the industry standard for sewer inspection because it allows the operator to gain a full circumferential view of the pipe.

Data obtained from CCTV inspection include:

- Evidence of sediment, debris, roots, etc.
- Evidence of pipe sags and deflections.
- Off-set joints.
- Pipe cracks.
- Leaks.
- Location and condition of service connections.

As noted above, CCTV technology does have limitations due to its ability to only provide a visual representation of the inside surface of a pipe above the waterline. Additionally, the quality of defect identification and pipe condition assessment using CCTV is highly dependent on many factors including operator interpretation, picture quality, and flow level. In terms of benefits, it is a cost-effective technology providing the broadest base level of data used in condition assessment. For example, many technologies exist (as described in later section) that provide data on the structural condition of the pipe wall, and other technologies exist that can determine the condition of the soil surrounding the pipe. However, these technologies are unable to provide visual data on leaks, location of service laterals, and sediment and debris accumulation. It is for this reason that CCTV will remain an important inspection tool in any condition assessment program for wastewater collection systems.

The following sections present innovative technologies specific to CCTV and its use in condition assessment for wastewater collection systems. Each technology will be briefly described, noting manufacturers and/or providers of the technology and typical applications. The technologies described in this section include:

- Zoom Camera Inspection.
- Digital Scanning.
- Camera Deployment.

4.1.1 *Zoom Camera Inspection*

Like traditional CCTV inspection, zoom camera inspection technology involves the generation of still imagery and/or recorded video imagery of a pipe. The key difference is that in zoom camera inspection, the camera mount is stationary. The technology does not require the camera equipment to pass though the entire length of the pipe segments being inspected. Instead, the camera is mounted either on a truck, crane, pole, or a tripod. The equipment is then lowered into a manhole to perform the inspection and the camera "zooms" down any pipe entering or exiting the manhole.

Historically, zoom cameras have been utilized to perform manhole inspection and inspect a few ft down the pipe utilizing a camera mounted on the end of a telescopic pole. This technology is commonly referred to as a down look camera. Newer zoom cameras can pan 360 degrees and zoom up to 100-ft. in 6-in. diameter pipe and up to 700-ft. for larger pipe diameters.

This technology involves setting up the zoom camera at each manhole and inspecting the manhole and pipes. Potentially, the technology could allow for the inspection of an entire section of pipe from one manhole to the next. Zoom camera inspection has some of the same limitations as traditional CCTV pipe inspection in that it cannot inspect what is beneath the fluid being conveyed through the pipe. It is not designed to replace conventional CCTV systems, but rather to screen and prioritize pipes for further conventional CCTV work and/or cleaning pipelines. The technology does not provide the detailed visual evaluation of conventional CCTV. The primary advantage to the technology is improved production rate. The set-up eliminates the need for cleaning prior to the inspection, as well as the inevitable down-time associated with an obstruction to a crawler mounted camera. An inspection crew can move through a service area in an expeditious manner and highlight segments requiring a more detailed inspection.

Zoom camera inspection is a very efficient, cost-effective method of performing manhole inspections, which has been its primary use. It is, however, limited in its ability to inspect pipe segments. Image resolution, lighting, and limitation in optical zoom are the primary disadvantages of this technology. The technologies described below attempt to overcome these limitations with improvements to lighting and zoom ability. This technology also increases the production rate of sewer inspections, as it collects data at a speed several times faster than traditional CCTV inspection. This is in part because pipes generally do not have to be flushed and cleaned prior to inspection.

Zoom camera inspection is only useful for inspecting gravity sewers because its access to the sewer is via a manhole. Force mains and/or service laterals do not have the required access points to deploy this technology. As with all camera inspection technologies, zoom camera inspection can be used with any pipe material.

Zoom camera inspection services are available from a variety of service providers. Both regional and national service providers have the ability to provide this service. It is not known if the use of the longer range cameras with increased zoom capabilities is a commonly used inspection tool in the industry. Provided below is a description of four manufacturers of zoom cameras used for the inspection of gravity sewers.

No new zoom camera technologies under development have been specifically identified as emerging technologies. Likely, the identified manufacturers will continue product development and increase optical and digital zooming capabilities. It is also likely that the technology will be equipped with a digital inspection system as described in Section 4.1.2. Table 4-2 provides a summary description of the zoom camera technology.

Table 4-2: Zoom Camera Inspection Summary

SUMMARY	
Sewer type	Gravity sewers only
Material	Any
Pipe size	> 6-in.
Defects detected	Cracks, leaks, root intrusion, overall surface condition of pipe/manholes
Original application	Manhole inspection
Status	Commercially available
Advantages	High production rate, effective/efficient at prioritizing segments requiring more detailed inspection/maintenance
Disadvantages	Inability to inspect manhole to manhole for average diameter lines, potential to miss significant defects

CUES IMX - Truck Mounted Zoom Camera

The CUES-IMX truck-mounted zoom camera provides video inspection for manholes and pipelines. The CUES-IMX camera offers imaging technology with a 25:1 optical zoom that is stabilized and remotely controlled by a telescopic boom. The camera can record images from up to 300' into the pipeline. The camera mounting fork is designed to pan the camera head 360° continuously, tilt mechanically 45° up or 90° down, and tilt optically 166°. The camera imager, optics, mechanics and electronics are housed in a damage resistant, waterproof, rugged enclosure that is 7-in. in diameter and 16-in. in length. The CUES-IMX system includes the camera, high intensity discharge lighting heads, mast system and controller. The manufacturer indicates that the system can be mounted within an inspection van, all-terrain vehicle, or a trailer.

The system is equipped with data collection, GIS software and global positioning system (GPS) equipment. The GIS software and GPS equipment are used to create sewer maps in the field and create an asset management database for the system. Defects detected during the inspection can be stored in a database along with photos and video clips. All data is geo-referenced to the field collected GPS coordinates. This is common to the industry and the subject of further discussion in a later section.

The objective of the CUES-IMX camera system is to increase the production rate of the inspection process, as compared to traditional CCTV. The manufacturer indicates that an inspection process using zoom technology has a production rate of five to eight times higher than traditional CCTV and is a useful tool to efficiently characterize a collection system and prioritize segments for further inspection and/or cleaning. Inspections using the CUES-IMX camera provides mapping, inventory and condition information that can be used immediately to reduce system operation and maintenance issues by quickly identifying areas of high-risk due to blockage or structural defects. The risk of backups or overflows can be assessed and addressed rapidly.

GE Technologies - Ca-Zoom PTZ and QuickView

GE Technologies offers three truck-mounted Everest Ca-Zoom Pan-Tilt Zoom (PTZ) cameras for sewer inspection. Each camera has a different PTZ camera head. The PTZ 140 has a 300:1 zoom capability (optical 25:1, digital 12:1) and is equipped with two high-power 35-watt lights. The camera has the ability to record imagery up to 250 ft down a pipe segment with diameters between 15 in. and 60 in. The PTZ100 has 40:1 zoom capability (10:1 optical, 4:1 digital), and four 5-watt light-emitting diode (LED) lights. The PTZ270 also has a 40:1 zoom capacity, but has eight 5-watt LED lights.

The smaller hand-held QuickView unit is a pole mounted camera with a total zoom capability of 216:1 (18:1 optical, 12:1 digital). It has the ability to zoom to between 75 and 250 ft within pipe diameters of 6 in. to 60 in. The unit is mounted on an 18 foot telescoping pole.

The benefits and limitations of these cameras are similar to those of the CUES-IMX camera system as described above.

CTZoom Technologies - PortaZoom

Innovative Technology Products, Inc. offers sewer inspection with the PortaZoom camera, manufactured by CTZoom Technologies. The PortaZoom is housed in a compact enclosure, just 6 in. in diameter. The camera pans more than 350° and has a 312:1 zoom capability (26:1 optical, 12:1 digital). The camera has full-circumference integrated lighting, including peripheral lighting to reduce shadows. The PortaZoom is operated by a computer, joystick and keyboard. The PortaZoom can be mounted to any vehicle or hand-held pole, and can zoom approximately 100 ft to 200 ft into pipes.

AquaData, Inc. - AquaZoom

AquaData Inc. also manufacturers zoom camera inspection equipment. They manufacture the AquaZoom system though it is not commercially available. The AquaZoom can be used on pipes with diameters of 6 in. or larger and can inspect pipelines for approximately 100 ft. It is normally mounted on either a truck or tripod, which is claimed to provide better stability compared to pole mounted devices. It also utilizes a built-in control center and video recording equipment to perform pipe inspections.

Aries Industries – HC3000 Zoom Pole Camera

The Aries HC3000 Zoom camera has a 432:1 zoom ratio (36:1 optical, 12:1 digital). The camera has two LED lights, and is mounted on a 6-foot to 18-foot telescoping pole. The camera can view up to 100 ft into the pipeline being inspected. The image is transmitted via radio frequency technology to a media case, which houses a radio frequency receiver and monitor. A small portable monitor is also available for viewing the images as the camera zooms down the pipe. The pole mounted device provides easy portability and rapid setup.

4.1.2 Digital Scanning

Digital scanning is a state-of-the-art technology within the camera inspection industry. Like conventional CCTV, digital cameras are transported through sewer lines using self-propelled crawlers. Unlike conventional CCTV systems, digital scanning uses one or two high-resolution digital cameras with wide-angle lenses in the front, or front and rear, section of the housing. During pipe inspections, parallel mounted lights are triggered at the same position in the pipe. The hemispherical pictures scanned are put together to form 360° spherical images. There is one specific manufacturer that utilizes a single camera with a wide angle lens to accomplish the same result.

During the scanning process, data are transmitted to a surface viewing station where it can be viewed in real-time and recorded for later evaluation. The major advantage to digital scanning technology is that it is possible for the data to be assessed independently of the real-time sewer inspection. By comparison, conventional CCTV relies on a camera operator to pan, tilt, and zoom into critical areas for further review. The image, as controlled by the operator, is stored. Therefore, if the operator does not see a defect, the camera is not stopped for further investigation.

Digital scanning develops a full digital image of the pipe segment. This allows the individual reviewing the images to control the direction of the PTZ features and to stop the image at any point to capture video clips and images. The inner pipe surface can be “unfolded” providing a view of pipe conditions, which permits computer-aided measurement of defects and objects. Digital scanning provides a more consistent and complete assessment of pipe condition. It provides a second level of quality control in the review process and allows other individual(s) involved in the process to gain insight into the pipe condition (e.g., designers, rehabilitation contractors, and utility owners).

Digital scanning technology is primarily used for gravity lines in the 6-in. to 60-in. diameter range. Its applicability for use in inspecting sewer laterals is limited since laterals are typically less than 6 in. in diameter and access is generally through a small diameter clean-out. It is also limited in its ability to inspect force mains. Like conventional CCTV technology, digital scanning is only able to provide useful images above the waterline; force mains would have to be taken out of service and drained before digital recording. Access to force mains also typically restricts the use of digital and CCTV technology. Force mains are pressurized and do not have access manholes to insert CCTV equipment. Digital scanning can be used with any pipe material. Table 4-3 provides a summary description of the digital camera scanning technology.

Table 4-3: Digital Camera Scanning Inspection Summary

SUMMARY	
Sewer type	Gravity sewers, limited applicability for force mains and service laterals
Material	Any
Pipe size	6-in. to 60-in.
Defects detected	Cracks, leaks, root intrusion, overall condition of pipe
Original application	Inspection of piping
Status	Commercially available, new applications under development
Advantages	Increased QA/QC control, additional project personnel able to review/control data imagery, able to make digital measurements of defects, can compare data directly from one inspection to the next
Disadvantages	More costly then CCTV, lower production rate compared to traditional CCTV, only works above waterline.

Digital scanning camera systems are available from a variety of vendors. Several commercial applications are specifically designed for the investigation of water, storm drain, and sewer pipelines. The following are descriptions of some of the products available from several vendors.

Blackhawk-PAS - Sewer Scanning Evaluation Technology (SSET)

SSET was developed in Japan in 1994, and introduced through field trials in the United States in 1997. The third-generation SSET was refined by Blackhawk-PAS for commercial marketing. SSET uses two digital image capture devices mounted on a remotely controlled tractor. One of the cameras records a forward view of the pipeline while the other camera scans the side of the pipe to create a spiral, perpendicular view. SSET can be used in pipes ranging from 8-in. to 36-in. diameter, operating at a rate of approximately 13 ft per minute.

RapidView – IBAK, USA - Panoramo

The RapidView-IBAK, USA Panoramo system was developed by IBAK Helmut Hunger GmbH & Co. KG of Kiel Germany in partnership with RapidView, LLC. The application was first developed and used in 2002. The first application in the United States was in 2007.

The Panoramo system uses two high-resolution digital photo cameras with 186° wide-angle lenses fit into the front and rear section of the housing. During pipe inspections, parallel mounted xenon flashlights are triggered at the same position in the pipe. The hemispherical pictures scanned are put together to form 360° spherical images. The Panoramo can scan 8-in. to 48-in. diameter pipes at a speed of up to 70 ft per minute in forward or reverse motion.

During the Panoramo scanning process, the data are transmitted digitally to the inspection vehicle and are at the operator's disposal. The scans can be viewed as live pictures for orientation purposes and for locating any obstructions. In addition, the data are stored in the form of "PANORAMO films", on removable hard disks or digital video discs (DVDs).

This image scanning method makes it possible for the pipe inspection to be assessed by personnel away from the field. The reviewer has the ability to pan, tilt, or zoom in on potential defects as if in the truck with the field crew. The reviewer can stop at any position, turn a full circle, zoom, and complete the data analysis. An unfolded view of the inner pipe surface which is available simultaneously gives the reviewer a rapid view of the state of the pipe and permits computer-aided measurement of the position and size of objects. The Panoramo system works in conjunction with WinCan Scan Explorer Software Version 8.

Envirosight - DigiSewer

The Envirosight DigiSewer system was originally developed by DigiSewer and manufactured by IPEK (provider of crawlers and cameras to Envirosight). The DigiSewer was originally designed to be used for borehole inspection and was first used in Europe in 2003. It was officially released to the North American market in April 2007.

The DigiSewer uses one high-resolution photo cameras with 180° wide-angle fisheye lens, integrated into the front of the rover crawler. The DigiSewer can scan pipes from 6-in. to 60-in. diameter at a scan speed of 70 ft per minute. The DigiSewer can scan pipes over a length of approximately 650 ft.

Emerging Technologies

No digital scanning applications have been specifically identified as emerging technologies. Likely, the identified manufacturers will continue product development and increase optical and digital zoom capabilities. The technology is four to five years old in Europe and Asia; however it has a limited history in North America. The manufacturers and users listed above are constantly developing new ways to use these products. Our research indicates that future research will focus on enhancements to the software used for defect recognition and digital defect measurements. RapidView and Envirosight are developing manhole inspection capabilities with the use of the digital scan cameras. Envirosight is also planning to increase the scan distance to approximately 1,650 ft by fall 2008 and provide improved scanning rates.

4.1.3 Camera Deployment

In a CCTV inspection, cameras are deployed into pipelines in a variety of ways. Mobile robots called crawlers or tractors are available in a variety of sizes and configurations, thus enabling their use in a host of pipes sizes. These are typically introduced into the sewer via a manhole. Cameras can also be mounted to float rigs for inspecting large diameter pipes partially filled with water. Pushrod cameras are typically used in smaller diameter pipes (6 in. and less) such as service laterals and are typically introduced into the sewer through a cleanout.

This section describes innovations to vehicles used to carry CCTV cameras as well as technologies that can be added to the conventional camera vehicles to further assist in CCTV inspection.

A variety of innovations have been applied to the tractors or crawlers which carry CCTV cameras. These innovations include extra long range tractors/floats compared to the typical applications in use, smaller than typical tractors that can be used for some laterals, tractors that are able to dispatch smaller lateral cameras from the main line, and segmented robots that can bend around odd angles in small diameter pipes.

Different camera tractor innovations are available from a variety of vendors. Several commercial applications are specifically designed for the investigation of water, storm drain, and sewer pipelines. Pushcams are used almost exclusively in smaller diameter sewers such as service laterals. Tractor innovations have been broken down into four groups: small diameter tractors, long range tractors, segmented tractors, and lateral launchers - tractors that can launch lateral cameras off of the main inspection vehicle.

Pushcams

Pushrod camera, or pushcam, technology involves the inspection of pipeline via a small diameter camera mounted to a pushrod and reel setup which produces video of the pipeline. This technology is primarily designed for laterals and small diameter force main applications. Conventional pushcams use straight view cameras capable of inspecting pipes of 2-in. or greater. Advancements include pushcams capable of inspecting pipes smaller than 2-in. as well as steerable and pan/tilt pushcams.

Pushcams are typically used in an environment where it is otherwise impossible to get photographs or video footage such as a small diameter water, sewer, or drain pipes. Typically, they are used in applications where crawlers/robotic camera vehicles are unable to function due to their larger size. Conventional pushcams systems are comprised of a camera/probe, cable/reel, and computer/recorder/controller. The probe used to advance the camera is usually a semi-rigid rod, constructed of fiberglass. The primary limitations are image quality, lighting, and ability to move past obstructions. Table 4-4 summarizes a variety of commercially available pushcams.

Table 4-4: Pushcam Product Comparison

PRODUCT (VENDOR)	PIPE DIAMETER	INSPECTION LENGTH	NOTES
CrystalCam Push Camera (Inuktun)	>2-in.		High resolution low lux camera – highly effective in low light environments. Can be tractor mounted, can be used as a reverse camera
Flexiprobe (Pearpoint)	1-in. to 8-in.	500-ft	
Hydrus (Rapidview-IBAK, USA)	>2-in.		Straight view camera only
Orion (Rapidview-IBAK, USA)	>4-in.		Pan and tilt functions
Orion L (Rapidview-IBAK, USA)	>4-in.		Pan and tilt, includes “steer stick” allowing device to be steered around bends or turns
Push Camera (Insight Vision)	1-in. to 12-in.	300-ft	Uses Clearview line of camera heads, large 10.4 in. LCD monitor

Tractors/Crawlers

Tractors and crawlers are mobile robots used to deploy CCTV through a pipeline. Most are wheeled or tracked, and are tethered via a cable to a controller unit located near the point of entry to the sewer system. Conventional CCTV inspection tractors are larger vehicles that are not able to get into smaller pipes or laterals. Many of the tractors are not steerable and can only inspect pipe runs of 300 to 500 ft. Advancements in technologies now include lateral launchers that are able to deploy smaller diameter pushcams into laterals; small diameter tractors that can be deployed in pipes as small as 4 in. in diameter; long range tractors that can inspect pipes at great distances from the point of entry; and segmented robots that can bend around odd bends or angles in small diameter pipes. Tables 4-5, 4-6, and 4-7 summarize a selection of commercially available innovative tractor and crawler technologies.

Table 4-5: Lateral Launcher Product Comparison

PRODUCT (VENDOR)	MAINLINE		LATERAL		NOTES
	Pipe diameter	Inspection length	Pipe diameter	Inspection length	
IBAK LISY 150-M (RapidView-IBAK, USA)	>6-in.				Tungsten carbide wheel for grip
LAMP (CUES)	6-in. to 24-in.		2-in. to 6-in.	≥80-ft	
Lateral Evaluation Television System (Aries Industries)	>8-in.	800-ft	3-in. to 6-in.	80-ft	Can ID pipe locations with locator beacon
Lateral Inspection System (RS Technical Services)	8-in. to 24-in.	1,000-ft	4-in. to 8-in.	100-ft	

Table 4-6: Small Diameter Tractor Product Comparison

PRODUCT (VENDOR)	PIPE DIAMETER	INSPECTION LENGTH	NOTES
ELK T100 Mini (Pearpoint)	4-in. to 10-in.	500-ft	
KRA 65 (RapidView – IBAK, USA)	>4-in.		Steerable, electric stabilizing function
Mighty Mini Transporter (RS Technical Services)	4-in. to 12-in.	500-ft	
Rovver 100 (Environsight-IPEK)	4-in. to 12-in.	660-ft	Steerable, PVC wheel with titanium spikes for traction
Versatrax 100 (Inuktun)	>4-in.	600-ft	Tracked crawler
Xpress Silver-Bullet Crawler (Insight Vision)	4-in. to 15-in.	600-ft	4-wheel drive crawler

Table 4-7: Long Range Tractor Product Comparison

PRODUCT (VENDOR)	PIPE DIAMETER	INSPECTION LENGTH	NOTES
Versatrax 300 VLR (Inuktun)	>12-in.	6,000-ft	Modular construction for onsite customization, optional reverse camera can be mounted on crawler
Responder (RedZone)	>36-in.	5,280-ft	Skid steer enabled tractor, Kevlar reinforced buoyant cable, submersible to 500-ft

Segmented Robots

Electromechanica, Inc. designs custom inspection robotics and other applications on an as needed basis. For example, the client may have a specific type of small diameter pipe system containing tees or wyes, or other angles that a typical tractor or crawler would not be able to navigate. One such development is the Internal Pipe Inspection Robot. This design uses a unique “inchworm” movement which optimizes movement within the pipe. The robot itself consists of three arm linkages that expand radially to force the different segments to grip the inside of the pipe and move it along. The multiple segments also can be useful in overcoming obstacles or looking down laterals. The robot uses pneumatic cylinders to provide force to move the robot through the pipe. The robot can be outfitted with cameras, sensors or tools to achieve many different types of jobs in pipes including pipe inspection. As stated above, this is not a commercial product, but one that must be custom ordered for the client’s specialized needs.

Emerging Technologies

- ***Pushcams*** **-** The IPEK Agilios pushcam system was developed for small diameter pipes and has pan/tilt capability. It works in conjunction with the vision control unit and is battery powered.
- ***Autonomous Crawlers*** **-** An autonomous crawler does not require a real-time remote operator. The crawler's behavior is programmed in advance of deployment. The vehicle is programmed to cue off of particular environmental landmarks. For instance, RedZone Robotics, a Pittsburgh, Pennsylvania based company, has designed a robot that constantly monitors the diameter of the pipe as the robot progresses through the pipe. Infrared sensors atop the vehicle sense when the distance to the roof of the pipe alters radically, which the robot then interprets as a manhole. The vehicle may be programmed to stop at the first manhole it encounters, or stop after encountering some specified number of manholes. Autonomous crawlers are beginning to enter the marketplace.
- ***Autonomous Floaters*** **-** Automatika, Inc. based in Pittsburgh, Pennsylvania, is developing the prototype of a neutrally buoyant, untethered pipe inspection robot called PipeEye. The robot is a 12-in. sphere designed to float in pipes greater than 24 in. in diameter. Cameras and lights will operate above the waterline, and ultrasonic transducers will operate below the waterline. The PipeEye system is derived from an oil/gas pipeline inspection module co-developed by Automatika and Shell Oil. Currently, the system does not yet have a product status.

4.2 Acoustic Technologies

Acoustic technology in general terms uses measuring devices to detect vibrations and/or sound waves. In pipeline assessment, acoustic sensors are used to detect signals emitted by defects and are utilized by a variety of commercially available products. Acoustic technologies are used extensively for inspection of water mains; therefore, this category of inspection technology can also be used for force main inspection. There are three distinct classifications of acoustic technologies:

- Leak detectors, which are used to detect the acoustic signals emitted by pipeline leaks.
- Acoustic monitoring systems, which are used to evaluate the condition of PCCP.
- Sonar, or ultrasonic, systems, which emit high frequency sound waves and measure their reflection off the pipe wall in order to detect a variety of pipe defects.

Table 4-8 summarizes these classifications of acoustic technologies.

Table 4-8: Acoustic Technology Summary

SUMMARY	IN-LINE LEAK DETECTORS	ACOUSTIC MONITORING SYSTEMS	SONAR/ ULTRASONIC
Sewer type	Force mains, gravity sewers	Force mains	Force mains, gravity sewers
Material	Any	PCCP	Any
Pipe size	$\geq$4-in.	$\geq$18-in.	$\geq$4-in.
Defects detected	Leaks	Broken pre-stressed wires	Pipe wall deflections, corrosion, pits, voids, and cracks, debris
Original application	Leak detection in pressurized water lines	Monitoring PCCP water lines	Maritime use
Status	Commercially available for sewer inspection	Commercially available for sewer inspection	Commercially available for sewer inspection
Advantages	Can detect very small leaks.	Useful as a screening technique prior to more detailed inspection	Suitable for pipes of any material and a wide range of diameters
Disadvantages	Requires minimum flow to be carried through pipe	Only detects general distress	Only inspects pipe below the waterline

4.2.1 Leak Detectors

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

The simplest forms of leak detector are mechanical listening devices. These include listening rods and aquaphones, which are both metallic rods fitted with an earpiece. These devices are operated by placing the rod in direct contact with pipes, allowing the device operator to hear leaks through the earpiece. Geophones are another type of listening device; these are placed on soil or pavement above a pipe, allowing the operator to hear the sound from leaks as it is transmitted through the soil. Listening rod and aquaphones may also be electronic, these are similar to the mechanical devices described above but also include special elements such as noise filters, adjustable amplifiers, and sensing elements such as piezoelectric materials; leaks can be detected either by operators listening through headphones or in some cases by soundmeters that can store the sound levels emitted by leaking pipes.

Leak-noise correlators are a more complex and accurate type of leak detector, which have been used for leak detection since the 1980s. These are computer-based devices which are used to measure sound or vibration at two points on a pipe, on either side of a suspected leak. Depending on the device, the measurements are made by a vibration sensor such as an accelerometer attached to pipe contact points or an underwater microphone which is inserted into the pipe itself. Signals detected by the sensor are wirelessly transmitted to the correlator, which pinpoints the location of leaks based on the time lag between the leak signals measured from the two points.

The most complex forms of leak detectors are in-line systems, which are deployed in a pipeline and continuously monitor leakage. The rest of this section focuses on these systems. There are several commercially available in-line leak detectors which utilize acoustic technologies for pipe condition assessment. Both regional and national service providers have the ability to evaluate wastewater systems, although the technology is far more prevalent in its use for condition assessment of water distribution systems. Provided below is a description of several of these products.

Sahara® – Pressure Pipe Inspection Company

The Sahara system was originally developed by WRc for detecting leaks in pressurized water lines, and is a proven technology for that application. In the United States, the Sahara system has begun to be used for wastewater collection systems. A series of pilot studies using the Sahara for wastewater pipeline leak detection were conducted in the United Kingdom in 2005 and North America in 2006. The system is now available in the United States from the Pressure Pipe Inspection Company.

The Sahara system consists of a sensor head and a hydrophone, which is an electrical instrument used to detect or monitor sound under water. The sensor head is inserted into a pipe through any access point greater than three inches in diameter. As the sensor head is transported through the pipe line by product flow, acoustic signals are picked up at the surface by the hydrophone. The signal is then fed through a cable, and from there to processing equipment. The system operator is able to hear signals from the system directly as well as view the signal on a computer with spectrogram software. The system locates leaks by identifying acoustic signals; the size of leaks can be estimated based on the acoustic signal recorded by the device.

The Sahara system can be used in pipelines of any material to detect leaks as slow as approximately 0.25 gallons/hour. It can be used to inspect force mains 4-in. in diameter and larger. The system requires a minimum flow velocity of approximately 3 ft/s to ensure the device can move though the pipe. Additionally, pressure within the pipe must be between 10 and 150 psi in order for the system to recognize leaks.

Smartball® - Pure Technologies

The Smartball® leak detector was made commercially available by Pure Technologies in 2005. It is a proprietary system maintained by Pure Technologies. The technology is only used for inspections of pressure pipelines. It can be used for any pipeline material.

The Smartball® consists of a neutrally buoyant, foam ball equipped with an instrumented aluminum inner core. The aluminum inner core contains several sensors including an acoustic sensor, accelerometer, magnetometer, temperature gauge, and pressure gauge. The inner core also contains a microprocessor with an ultrasonic transmitter. The system is powered by a DC battery and contains a data logger. The Smartball® can be inserted into a pipeline and travel with the water flow for more than twelve hours, collecting data on the collection system with a single deployment. The Smartball® has a diameter of 2.6-in. and can be used on a pipe with 10-in. or greater in diameter. A minimum flow velocity of 1.64 ft/sec is required to convey the sensor.

The system can be inserted into a full or partially full pipe, and is carried along by the flow of water or wastewater. The Smartball® is silent; therefore its acoustic sensor can detect the sound of very small leaks in the pipeline. As the Smartball® passes through the pipe its progress can be tracked by a variety of methods, allowing for leak location to be determined within one meter of accuracy. The system can operate for up to twelve hours before it is retrieved and data downloaded.

LxSentry – LxSix Photonics, Inc.

The LxSentry pipeline monitoring system was recently introduced by LxSix, Photonics Inc. LxSentry is a highly sensitive fiber optic system designed to detect leaks in gas pipelines. Acoustical sounds are classified by the proprietary Red Alert software, which is capable of distinguishing between pipeline leaks, tampering, intrusions, and machinery and vehicles operating in the pipeline vicinity. Minimal information on the details of the operation and use of this product is currently available. No information was available on the use of the technology for water and/or wastewater systems.

4.2.2 Acoustic Monitoring Systems

Acoustic monitoring systems are installed along PCCP to provide continuous monitoring of the general condition of the pipe. PCCP has been used historically for large diameter force mains, and has been subject to failure due to internal or external corrosion. The systems work by detecting the acoustic signal produced by breaking or broken prestressed wire within pipes. While the systems do not identify individual defects, they are useful as screening techniques to determine if further condition assessment should be performed. There are currently two technologies available that provide continuous acoustic monitoring of PCCP. These products are described below.

Acoustic Emission Testing (AET) – Pressure Pipe Inspection Company

Acoustic Emission Testing (AET) is as an acoustic monitoring system used primarily to monitor the deterioration of PCCP water mains. It has also been used to evaluate sewage force mains. AET is based on the detection of the acoustic energy released when prestressed wire breaks or deflects. The system detects general distress in the pipeline by determining the frequency and number of wire breaks, or wire related events, over a period of time. The AET system determines the location of the wire related events based on the arrival time of the acoustic signals at a series of sensors within the pipe. Since the technique does not detect the number of broken wires, but rather general distress in a given section of pipeline, it is best used as a screening technique prior to utilizing other methods to pinpoint defects.

The AET system is made up of a series of units located along the pipeline. Each unit contains a sensor (either a hydrophone or an accelerometer) and a signal processor, a base station, and a precision timing device. The hydrophones are inserted into the pipeline through taps at a spacing of approximately 500 to 3,000 ft; spacing is largely dependent on pipeline diameter (smaller pipes require closer spacing than larger ones). The accelerometers are surface mounted; spacing is more flexible when this type of sensor is employed. The signal processor is a small mobile computer that is located close to the hydrophone. It monitors the signals detected by the hydrophone and transmits signals that indicate wire related events to the base station. The base station consists of a personal computer, a wireless communication module, and an internet communication module. The precision timing device, a GPS antenna and processor, provides location information on each sensor and determines the timing of acoustic events.

AET can be used to monitor active distress in PCCP 18-in. or greater in diameter. The system works while pipelines are fully operational. The technique is valuable for providing advanced warning of pipe failure, and for screening pipe networks to determine which pipes are deteriorating. However, the technique cannot detect individual defects within a pipe.

SoundPrint® - Pure Technologies

SoundPrint® is a patented acoustic monitoring technology used to provide continuous, non-destructive remote monitoring of water and wastewater pipelines, storage tanks and other structures. Introduced in 1993, the original version of SoundPrint® used hydrophones to detect breaks in prestressed wire in PCCP. The newer SoundPrint® AFO system, introduced in 2005, uses acoustic fiber-optic cable for detecting acoustic signals.

Soundprint® AFO monitoring of PCCP involves the deployment of fiber-optic cable into the pipeline. The cable is inserted into pipelines through new valves installed in manholes. Because the entire fiber-optic cable acts as a sensor, up to 12,000 ft of pipeline can be monitored from a single access point. The sensor does not contain any electronics, therefore there is little to no background noise created by the device.

4.2.3 Sonar and Ultrasonic Testing

Sonar, an acronym for Sound Navigation and Ranging, was developed in 1906, and is widely used for maritime use. The first use of sonar for inspection of pipelines was carried out by WRc in 1987. Sonar testing involves very high frequency ultrasonic sound waves that reflect off the material being inspected, allowing for the detection of defects.

Sonar/ultrasonic inspections of pipelines are accomplished by passing a sonar head through the pipe being inspected. Depending on the size and flow conditions of a pipe, the sonar head is deployed into the pipeline on a raft, skid, or robotic tractor. As the sonar head moves through the pipeline, it sends out very high frequency ultrasonic signals, which are reflected by the pipe walls and then received by the sonar head. The reflection of the signals changes when there is a change in the material it is being reflected by, allowing for the detection of defects. The time between when the signal is sent and received can be used to determine the distance between the sonar head and the pipe wall, as well as to determine the internal profile of the pipe.

Sonar inspection results in a detailed profile of the pipe wall below the water surface, which can be analyzed by a variety of methods. Sonar can detect pipe wall deflections, corrosion, pits, voids, and cracks. Sonar inspection can also detect and quantify debris, grease, and silt, and can distinguish between hard and soft debris; however, defects in the pipe wall can sometimes be obscured by grease and debris. According to Thomson et al. (2004), defects greater than 1/8 inch (3 mm) can be detected. This applies to pipe wall pitting and cracks as well as debris accumulation. Sonar does not require bypass pumping or pipe cleaning. Sonar inspection can be used in areas of poor visibility where it is difficult to use CCTV inspection. It is a versatile inspection method and can be used for inspecting gravity sewers and force mains.

One drawback to sonar is that it can only be operated in air or in water, not in both simultaneously. In some cases, a sonar system is utilized with a CCTV system, so that inspection of pipes both above and below the waterline can be accomplished simultaneously. In order to overcome this limitation, research is being done into development of systems with separate transducers, one for use in air and one in water, so that inspection of partially filled pipes can be accomplished. Additionally, longitudinal cracks in pipes can be difficult to detect.

Commercial sonar pipe inspection tools typically consist of an underwater scanning transducer, a sonar processor, and a color monitor. Table 4-9 highlights a selection of sonar-based pipe inspection products.

Table 4-9: Sonar Product Comparison

DEVICE: VENDOR	SEWER TYPE/ PIPE SIZE	DEFECTS DETECTED	NOTES
Amtec Sonar: Amtec Surveying, Ltd.	Force mains ≥21 in.	Deformations, holes, breaks, and pipe wall loss.	
A-SIS Aquacoustic	≥12 in.	Pipe size & distortion, holes, debris, scour, erosion	Combines sonar and CCTV
Envirosight	Gravity ≥4 in.	Pipe diameter, shape capacity, corrosion, cracks, debris	Attachment for CCTV
PipeEye: PipeEye International	Force mains, gravity ≥10 in.	Build-up, deformities, flow restriction, water level	
RVS2: R&R Visual	≥10 in.	Open cracks, debris, sediment	
Sonar Profiler System (submerged): CUES	Force mains ≥12 in.	Defects, blockage, debris	
Sonar Profiler System (semi-submerged): CUES	≥12 in.	Defects, blockage, debris	Combines sonar and CCTV
Sonar Sewer Profiling Attachment: Redzone	Force mains, gravity ≥36 in.	Blockages, deformations, capacity, sediment	Attachment for the Responder platform
Sonar Sweep Attachment Redzone:	Force mains, gravity ≥36 in.	Blockages, deformations, capacity, sediment	Attachment for the Responder platform
TISCIT: Amtec Surveying, Ltd.	Gravity ≥21 in.	Deformations, holes, breaks, and pipe wall loss	Combines sonar and CCTV
Ultrascan CD: GE Oil & Gas	Force mains, gravity	Axial cracks	
Ultrascan DUO: GE Oil & Gas	Force mains, gravity ≥24 in.	Wall loss and cracks	
Ultrascan WM: GE Oil & Gas	Force mains, gravity	Wall loss	
Ultrasonic Inspection Robot Inspector Systems	Force mains 12 -20 in.	Wall loss (measures wall thickness)	Incorporates high-resolution CCTV
Wavemaker: Guided Ultrasonics	Force mains, gravity ≥2 in.	Wall loss	Uses guided waves (Lamb wave), mounted to outer surface of pipe.

4.3 Electrical and Electromagnetic Methods

Several sewer evaluation techniques utilize electrical or electromagnetic currents. The electrical leak location method is used to detect leaks in surcharged non-ferrous pipes. Eddy current testing (ECT) and remote field eddy current (RFEC) technology identify defects in ferrous pipes. Magnetic flux leakage (MFL) inspection is widely used in the oil and gas industry to measure metal loss and detect cracks in ferrous pipelines. Table 4-10 summarizes these technologies.

Table 4-10: Electrical and Electromagnetic Methods Summary

SUMMARY	ELECTRICAL LEAK LOCATION	ECT/RFEC	MFL
Sewer type	Force main, gravity sewers, service laterals	Force main, gravity sewers, service laterals	Force main, gravity sewers, service laterals
Material	Non-ferrous	Ferrous	Ferrous
Pipe size	$\geq$3-in.	$\geq$2-in.	2-in. to 56-in.
Defects detected	Cracks, leaks	Metal loss, cracks, leaks, broken wire, graphitization, wall thickness	Metal loss, circumferential and longitudinal cracks
Original application	Leak potential in geomembrane liners	Inspection of piping and tubing including boilers, heat exchangers, cast iron pipes, and gas pipelines.	Petrochemical industry
Status	Commercially available for wastewater pipes	Commercially available for wastewater pipes	Commercially available, limited use in wastewater applications
Advantages	Available for service laterals	Can be used on pipes of most diameters, can be used to locate a variety of defects.	Extensive experience with method in the oil and gas sector
Disadvantages	Gravity pipes must be filled prior to inspection	Limited to ferrous pipes, typically requires post-processing of data by vendor.	Has not been extensively used for assessment of sewer pipes.

4.3.1 Electrical Leak Location Method

The Electrical Leak Location Method was first developed in 1981 for the inspection of geomembrane liners. The method became commercially available in 1985, and is one of the most widely used techniques for detecting leaks in geomembrane liners. The technique involves placing an electrode on either side of the material being tested, and connecting voltage to each electrode. Because the material being tested is an electrical insulator, voltage only flows through holes in the material. The area of defects in the material has high current density, which can be detected by measuring electrical potential in the survey area. Although primarily used for geomembrane liner inspection, the technique is also applicable to pipe inspection.

As this technology relies on the pipe material being an electrical insulator, it can only be used on non-ferrous pipes. The technology is useful for inspecting force mains, service laterals, and smaller gravity lines. While it is possible to inspect larger diameter gravity lines, since the technology requires gravity lines to be surcharged, the time and effort required to fill larger pipes might make this inspection method infeasible.

Although there are more than twenty commercial providers of electrical leak location services for integrity monitoring of geomembrane liners, the Focused Electrode Leak Location (FELL) is the only application developed specifically for detecting leaks in pipelines. FELL, also referred to as Electro-Scan technology, and was developed in Germany by Seba Dynatronic in 1999. GRW Engineers, Inc. has introduced the FELL system in the US. The FELL system identifies leak potential in non-conductive (i.e. non-ferrous) sanitary sewer mains, gravity lines, and service laterals using electrical continuity technology. The original application, FELL-41, was designed for use in force mains. A technique has been devised to allow for the inspection of gravity sewers by this method as well. The corporation later developed FELL-21 for inspection of service laterals. As of 2004, there were three electro-scan devices located in the United States, two of which are owned by GRW Engineering in Louisville, KY.

FELL 41– Seba Dynatronic/Metrotech

FELL, or Electro-Scan, inspection is accomplished by feeding a mobile electrode, called a sonde, through the pipe of interest. Simultaneously, a fixed surface electrode, usually a metal stake, is placed in the ground. Electrical current is generated by the sonde and flows through the water within the pipe, through the pipe wall and earth surrounding the pipe, and to the surface electrode. As water, earth, and the connecting cables have a low electrical resistance and the pipe material has a high electrical resistance, very little current flows between the two electrodes. However, if a leak exists in the pipe, the electrical current passes through it easily; the larger the defect, the greater the current that flows through. The electrical current flowing between the two electrodes is measured by the sonde; this data is then transmitted to a laptop computer, which records data and displays graphically the current flowing through the pipe.

The technique only detects defects in surcharged portions of a pipe; to inspect the entire circumference of pipes that are typically not surcharged, such as gravity sewers, the pipe must first be prepared by completely filling it with water. Two techniques are used to fill pipes in preparation for FELL-41 investigation. The first involves plugging the downstream manhole and then filling the pipe with enough water that the pipe is covered at the upstream manhole; this method can be quite time-consuming and may result in back-up of service laterals. The alternative method involves the use of a sliding pipe plug. The sonde is attached to the upstream side of the plug, which is manually pulled a short distance down the pipe. The upstream portion of the pipe is filled so that the sonde is submerged, and then the plug and attached sonde is pulled through the pipe, so that the entire pipe wall can be assessed.

FELL-41 is suitable for inspecting force mains ranging from 6-in. to 60-in. in diameter. The system only works on non-conductive pipes and lined metallic pipes, and can only detect defects below the water line. Although gravity sewers can be manually filled to allow for a complete inspection; the process of surcharging large diameter pipes requires extensive time and preparation. The product can be used to detect leaks caused by radial and longitudinal cracks, as well as faulty joints.

FELL 21 – Seba Dynatronic/Metrotech

The FELL-21works on the same principle as FELL-41, but is designed for use in 3-in. to 6-in. diameter service laterals. Rather than being deployed through the pipeline via a haul line, this device is inserted via a cleanout and moved through the pipe with a push rod. Like FELL-41, the device can only be used for the inspection of non-conductive pipes or non-ferrous pipes. FELL-21 detects leaks caused by radial and longitudinal cracks, as well as faulty joints.

4.3.2 Eddy Current Testing and Remote Field Eddy Current Technology

ECT and RFEC technology involve the generation of electric currents and magnetic fields to investigate the condition of ferrous material. ECT pipe inspection involves the use of an alternating current magnetic coil to induce an electric current in conductive pipes. In turn, the electric current generates small magnetic fields or eddy currents in opposition to the coil's magnetic field, which results in a change in the impedance of the coil. As the magnetic coil transverses the pipeline, the change in impedance is measured, allowing for the identification of defects. The effectiveness of ECT for pipeline inspection is limited by an electromagnetic phenomenon termed "skin effect". The density of eddy currents decreases exponentially with depth. This limits the detection of defects to those located on the surface of the pipe nearest the magnetic coil, because defects located deeper within the pipeline cannot be measured.

The RFEC method was developed to surmount the limitations of standard eddy current testing. This method can detect both internal and external defects in pipelines. RFEC involves the deployment of a probe consisting of multiple magnetic coils, an exciter coil and one or more detector coils, through the pipeline. As in standard eddy current testing, eddy currents are induced in the pipe wall. These direct currents quickly attenuate as they flow along the pipe wall towards the detector coil that is typically located approximately two pipe-diameters apart from the exciter. 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. This remote field attenuates very slowly along the outer pipe wall, and is therefore much stronger then the direct field when it reaches the detector. Pipeline defects and pipe wall thickness affect the propagation of the magnetic fields along the pipe walls, thereby altering the signal received by the detector. This allows for the identification of pipeline defects.

ECT and RFEC testing are primarily used to detect defects in ferrous pipe walls, such as pitting, corrosion, leaks and cracks. These testing methods can be used for the inspection of small-diameter pipes, in some cases as small as two inches in diameter, as well as very large diameter pipelines. ECT/RFEC can be used in empty, full, and partially full pipelines. Devices utilizing ECT and RFEC technology can be used to inspect force mains and gravity sewers. However, since most gravity sewers are not constructed of ferrous materials, the technology has limited use for this application.

ECT and RFEC testing services for ferrous structures are available from a variety of vendors. Several commercial applications are specifically designed for the investigation of gas, water, and sewer pipelines. The following are descriptions of some of these applications; as these technologies use the same basic principal, the summaries focus primarily on the differences between the various applications.

Broadband Electromagnetic Methodology (BEM) – Rock Solid Proprietary Limited (Pty. Ltd), Australia

BEM was originally developed by Rock Solid Pty. Ltd for use in the Australian mineral exploration industry. The technology has since been modified for use in pipeline inspection, and has been used for this purpose in both the United States and Europe. Unlike other RFEC applications, BEM is frequency independent, allowing operation of the device to be modified based on the material being investigated and site conditions. This reduces the likelihood that the device will be affected by electromagnetic noise, which can occur with the use of other ECT/RFEC applications.

BEM has primarily been used for condition assessment of water mains. The technology can only be used on ferrous pipes, but does work through thick coatings and linings. This technology can be used to detect a variety of pipe defects including cracks and anomalies in the pipe wall. Thomson et al. (2004) conducted field demonstrations of this method, and they state it is able to detect metal loss to 0.04 inch (1mm). BEM can also be used to measure wall thickness, quantify graphitization, and locate broken wires in PCCP.

BEM pipeline inspection can either be accomplished internally or externally. Internal pipeline inspection generally requires the pipeline to be taken out of service and emptied prior to deployment of the BEM device. As an alternative, the BEM device can be waterproofed. Internal inspection of pipelines can be accomplished in large diameter pipes by either pulling or pushing the device through the pipeline. A robotic version of the application is available for smaller pipelines (less than 36-in. in diameter). Results of pipeline inspections using BEM cannot be analyzed on-site; rather, results must be post processed. Special software is used to create a topographic map of the pipeline which can then be analyzed to detect pipe defects.

Hydroscope – Hydroscope, Inc.

The Hydroscope was developed as a collaborative effort between Hydroscope, Canada and EPCOR Water Services (Edmonton, Canada's privatized water utility). The application was first used in 1995 in Canada and became commercially available in the United States in 1996. However, the U.S. licensee for Hydroscope is currently in bankruptcy. Therefore, the technology may not be available in the U.S.

Originally developed for inspection of waterlines, the technology has since been used for the inspection of sewer mains.

The Hydroscope consists of a series of stainless steel modules embedded with circuitry, creating a flexible probe which can travel through pipelines. The probe is connected to a computer in a service vehicle by a tether and data cable. Data cannot be analyzed in the field; rather, data are analyzed at the Hydroscope Analysis Center with a proprietary software package called HYDA or the more advanced HYREL.

Like all ECT/RFEC-based pipeline inspection applications, the Hydroscope can only be used in pipes composed of ferrous material. One advantage of the Hydroscope system is that it functions in both dry and submerged conditions. Probes are available for pipe diameters in the range of 6-in. to 15-in. The technology can detect pitting, corrosion, graphitization and wall thinning in pipes.

See Snake Tool – Russell NDE Systems, Inc.

Russell NDE System's, Inc.'s See Snake is a small, flexible device which uses RFEC technology to detect corrosion and pitting in pipelines and to measure wall thickness and surface area. The tool can also detect areas of pipe under external stress such as movement of soil, poor support, rippling, bridging and denting. This technology is primarily intended for inspection of pipes before purchase or after construction to ensure pipeline integrity, and after a pipeline failure to determine if there are additional defects in the vicinity of the break.

Unlike most RFEC devices, which pass signals through a data cable, signals from the See Snake are detected from above ground. This allows for tracking the tool as it passes through the pipeline. Another distinguishing feature of the See Snake is that data analysis can be performed on site during the inspection, unlike other technologies which require off-site analysis.

The See Snake is primarily used in the oil and gas industry. Currently, the tool is only available for small pipes, ranging in size from 2-in. to 8-in. in diameter. Given the small size of the device, and its ability to be pushed through pipelines by liquid, the See Snake is potentially viable for inspection of force mains.

P-Wave® - Pure Technologies

Pure Technologies' P-Wave[3] system generates an electromagnetic field and detects changes induced in the field by broken wires in PCCP. Results of P-Wave inspection include an estimate of the number of broken wires, as well as their location. The technology allows for the evaluation of a pipe's current condition and the identification of distressed areas. The system is available for use in sewer pipes; however, the pipe must be empty to use the product. P-Wave inspection is often followed up with the use of an acoustic monitoring technology, such as Soundprint®, also available from Pure Technologies.

Remote Field Eddy Current/Transformer Coupling (RFEC/TC) – Pressure Pipe Inspection Company

Pressure Pipe Inspection Company's patented RFEC/TC is specifically designed for use in pre-stressed concrete pipe, including embedded Concrete Pipe, lined cylinder pipe, and bar-wrapped pipe. Rather than detecting defects such as corrosion, pitting, and leaks, this technology is primarily used to detect and quantify broken wires within the concrete pipe to determine whether pipe segments need further monitoring, repair, or replacement. In this application, the electromagnetic field generated by the exciter is amplified by the pre-stressed wires within the pipe. Signals generated by broken wires can be differentiated from those generated by intact wires.

RFEC/TC is effective for inspecting pipes 25-in. in diameter and larger. The largest pipe inspected to date is 252-in. In addition to broken wires, RFEC/TC can detect manholes, blow-offs, short pipe lengths,

[3] P-Wave stands for Polar Wave

cylinder thickness, cylinder composition, wire pitch, diameter and wraps (Pressure Pipe Inspection Company, n.d.). RFEC/TC can be used for the investigation of both force mains and gravity sewers.

Emerging Technology

Due to the versatility of RFEC testing for the inspection of pipelines, several institutions are working on the development of new applications. The Gas Technology Institute is currently developing a tool for the inspection of gas pipelines of a variety of diameters, including ones with valve and bore restrictions and tight bends. The Southwest Research Institute has recently developed an inspection technology for 6-in. to 8-in. diameter gas pipelines that couples an RFEC system to a robotic transport tool, the Explorer II, developed by Carnegie Mellon University's Robotics Engineering Consortium. Monash University in Australia has developed a RFEC tool called TESTAU. This instrument provides an improvement to the quality of visual data over other RFEC tools.

4.3.3 Magnetic Flux Leakage Detection

MFL is a widely used inspection technique for oil and gas pipelines. The MFL technique was first developed in the 1920s and 30s for materials testing. The Tuboscope, which became commercially available in 1965, was the first tool specifically developed for pipeline inspection.

MFL detection involves the placement of one or more magnets near a pipe wall, leading to the inducement of a direct current magnetic field in the pipe wall. The strength and direction of magnetic fields are represented by flux lines. When a magnet is near a conductive pipe wall, the majority of flux lines pass through the pipe wall. However, in areas of metal loss, less flux can be carried than the intact, full wall sections of pipe. This leads to leakage of flux from pipe areas which have undergone metal loss, as well as a change in the shape of the induced magnetic field. Flux leakage is detected by sensors; computer software is then used to determine the type and size of anomalies detected by the sensor.

MFL devices consist of several systems packaged into a single tool. At a minimum, an MFL tool contains a magnetizing element, sensor, data recording, and power systems. MFL tools are usually categorized as single piece or segmented. Single piece MFL tools contain all system components in a single rigid tool while segmented tools consist of multiple pieces joined to one another with flexible connectors.

Inspection of pipelines via MFL detection involves the deployment of an MFL device through the pipeline. As the device moves through the pipeline, usually pushed by the product flowing through the pipeline, the tool detects and records changes in magnetic flux. Traditional MFL devices, also called axial MFL, produce a magnetic field oriented along the axis of the pipe. More recently, circumferential MFL has been developed whereby the magnetic field is oriented around the pipe, allowing for better detection of axial defects such as cracks, seam weld defects, and groove corrosion.

MFL inspection only works on conductive cast iron or steel pipelines. Most MFL applications are large, and therefore only suited to larger diameter pipelines; however, some commercial applications have been developed for use in smaller diameter pipelines. Although MFL is most commonly used to detect metal loss, the technique can detect a variety of pipeline anomalies, including circumferential and longitudinal cracks. Newer, advanced MFL tools are additionally capable of producing accurate measurements of pipe defects.

Given the widespread use of MFL technology in the oil and gas industry, there are a variety of commercial MFL products available. However, the technology has yet to gain acceptance in condition assessment for wastewater collection systems. The majority of MFL tools operate on the basic principles outlined in the previous section. The primary distinction between them is whether they use axial or circumferential MFL, and the applicable diameter range. Table 4-11 provides basic specifications on available MFL tools.

Table 4-11: MFL Product Comparison

DEVICE	VENDOR	TYPE	PIPE SIZE	NOTE
AES 19	Advanced Engineering Services	Circumferential	3-in. to 12-in.	
AES ECAT	Advanced Engineering Services	Axial	>12-in.	Works externally
Axial Flaw Detection (AFD) Tool	Rosen Inspection	Circumferential	6-in. to 56-in.	
Corrosion Detection Pig (CDP)	Rosen Inspection	Axial	6-in. to 56-in.	
CPIG	Baker Hughes	Axial	4-in. to 48-in.	
LINSCAN	Lin Scan	Axial	6-in. to 56-in.	
MagneScan	GE Energy	Axial	6-in. to 56-in.	
MAGPIE	TDW Services, Inc.	Axial	4-in. to 42-in.	
MFL Inspection Tool	NGKS	Axial	8-in. to 56-in.	
Pipesurvey MFL	Pipesurvey International	Axial		Bidirectional
TranScan	GE Energy	Circumferential	12-in. to 36-in.	
VECTRA	BJ Services Company	Circumferential		Inertial navigation
Vertiline /V-Line*	Baker Hughes	Axial	2-in. to 36-in.	Bidirectional

*According to Baker Hughes, the Vertiline/V-line system is applicable for use in sewer lines.

4.4 Laser Profiling

Laser profiling generates a profile of a pipe's interior wall. The technique involves using a laser to create a line of light around the pipe wall. For this reason, it is also called the lightline method. The laser light highlights the shape of the sewer, allowing for the detection of changes to the pipe's shape, which may be caused by deformation, corrosion, or siltation. Laser inspection can only be used to inspect dry portions of a pipe. To assess the entire internal surface of a pipeline requires the pipe to be taken out of service. Lasers are often used in combination with other inspection methods, most commonly CCTV and/or sonar. Table 4-12 provides a summary description of the laser profiling technology.

Table 4-12: Laser Profiling Summary

SUMMARY	
Sewer type	Gravity sewers, force mains.
Material	Any
Pipe size	Product dependent
Defects detected	Deformations, siltation, corrosion,
Original application	Earlier use in large diameter tunnels and caverns
Status	Commercially available
Advantages	Provides better data quality then CCTV alone, can be used to create 3D models of pipelines.
Disadvantages	Can only detect defects above the water line.

Specific examples of laser profiling technologies are presented in the following section.

__Active 3D Laser Scanning – Redzone Robotics__

RedZone Robotics offers the Active 3D Laser Scanning Attachment for its Responder Robotic platform. This attachment creates a three dimensional model of the pipe, which allows for visualization of features not visible by CCTV inspection. The attachment can be used to assess pipes ranging from 48-in. to 100-in. in diameter, and requires a minimum 24-in. diameter manhole for deployment. Inspections up to 5,500-ft. are standard while specialized configurations enable custom inspections of up to 14,000-ft.

__Coolvision – Sima Environmental__

Coolvision is an attachment for traditional CCTV systems. The laser system results in reports which detail pipe grade and deflection. The system allows for the detection and measurement of cracks, as well as the measurement of sediment, water depth, and service locations.

__Laser Profiler – CUES__

CUES offers the Laser Profiler as an attachment to the CUES CCTV system. The attachment easily snaps on to the system, and allows for the creation of reports which include measurements of sewer defects. The attachment works by projecting a ring of light on the pipe's surface. The light is recorded by the CCTV camera as the inspection is conducted. Software is used to analyze the laser ring and create a 3D digital profile of the pipe. This can be done either from live or recorded video. The profiler can be used to detect and measure pipe size, ovality and capacity, laterals, water levels, and off-set joints, as well as to collect survey data. The CUES laser attachment can be used to inspect pipes ranging from 6-in. to 72-in. in diameter.

__Laser Profiling Tool - Envirosight__

Envirosight provides a laser profiling tool which can be used with either the ROVVER or SuperVision crawlers and a CCTV camera. The device can detect corrosion, cracks, debris, pipe deformation, and incorrect installation of liner. The tool can be used individually, or in combination with a sonar profiler to inspect the pipe surface below the flow line. The tool can be used in pipes ranging from 4-in. to 160-in. in diameter. The tool is used with machine vision software, which uses data gathered from the CCTV video to create a variety of reports, statistical analyses, and 2D or 3D models of the pipe.

__Laser Profiler – R&R Visual__

R&R Visual offers the Laser Profiler for inspection of dry gravity sewers. The tool works on pipes ranging in sizes from 6-in. to 160-in. in diameter. The device allows for accurate pipeline measurement, measurement of sediment depth and volume. R&R Visual suggests utilizing this technology to assist in soliciting accurate price quotes for pipeline cleaning in order to create cost savings for the utility owner. The system works with R&R Visual proprietary software and Clearline software for 3D modeling.

4.5 Flow Meters

Flow meters (area-velocity meters) typically operate by direct measurement of depth and velocity. Flow is then calculated based on the continuity equation. Metering devices referred to as "depth-only" or "primary" metering devices calculate flow using weirs or flumes based on flow discharge relationship equations. These metering devices are limited for pipe reaches that do not surcharge. Other "velocity-only" metering devices function by measuring velocity in pipe sections that continually operate under full flow conditions.

Communication with a flow meter can be achieved in the following manners: direct connection by laptop in the field, telephone land lines, wireless digital telephone or internet technology, or radio frequency networks. This includes communication through such technologies as general packet radio service/enhanced data rates for global evolution (GPRS/EDGE); code division multiple access (CDMA); mobile digital radio technology, including CDMA-1XRTT and CDMA-EVDO (evolution data optimized). Although most meter data are collected with laptops in the field, wireless communication is becoming the most popular method for new meters. Most wireless communication uses internet technology. A major distinction between the communication approaches is whether each meter is assigned a fixed internet protocol (IP) address or a floating IP address. The floating IP address is the easiest and least costly to deploy, but it also allows only one-way communication from the meter to the host. Communication with a fixed IP address occurs only when initiated by the meter. Fixed IP addresses allow the user to communicate with the meter for altering set up features, changing alarm setup features and downloading new software. Many wireless carriers do not offer fixed IP addresses.

Real time communication is a very popular concept and is becoming widely used in wastewater treatment plants. Implementing real time communication in sewers is more difficult for two reasons. Most meters operate by battery and frequent communication uses more energy than data collection does. Energy use for communication is high both for operating a modem with land lines and operating the radio frequency equipment for wireless communication. Additionally, the term “real-time” in sewers is actually “near time”, because most meter measurements are in 5-minute or 15-minute collection frequencies, as many operators prefer lower collection frequencies to achieve longer battery life. Most metering technologies relying on wireless communication operate in a one-way mode from the meter to the host. This strategy is dictated primarily by the energy cost to “stay awake” for incoming communication.

The traditional view of real time data is from a Supervisory Control and Data Acquisition (SCADA) perspective in which data are collected at a high frequency from many “dumb” sensors and a central computer sorts and archives the data. This approach works well for process control. An operator is alerted to problems by the use of “set points”, such as a drop in dissolved oxygen level below a specified concentration. This may trigger an alarm condition requiring an operator response. Real time data in sewers have less value because there rarely are controllable processes in sewers, except for pump stations and perhaps diversion gates.

Software for collecting and reporting flow monitoring data has evolved along with improvements in communication protocols. Desk-top programs for analyzing flow data, performance monitoring, and project reporting are being replaced with web-based applications, which connect wirelessly to flow monitors. These software applications automate time-consuming tasks; making them more reliable and cost-effective than traditional software programs. Additionally, some of the programs incorporate GIS functionality, allowing users to integrate flow data with GIS models of the sewer system.

4.6 Innovative Technologies

Besides the range of commercially available technologies for evaluation of wastewater systems and other underground pipes, several other innovative technologies are currently under development. While the following technologies are not currently commercially available for condition assessment of wastewater systems, they may be feasible methods of sewer assessment in the future.

4.6.1 Gamma-Gamma Logging

Gamma-gamma logging is a technique used primarily to evaluate cast-in-place concrete pilings and for vertical borehole investigation in the mining and oil and gas industries. The technique involves the use of a gamma-gamma probe, which consists of a source of gamma radiation such as cesium-137 and one or more gamma detectors. The detectors are shielded from direct radiation by a heavy metal such as lead. The gamma-gamma probe emits photons which react to surrounding material based on density. The photons are backscattered by the surrounding material, and data are recorded as a density log. Inspection using this technique is accomplished by raising and lowering the probe within a PVC inspection tube that is inserted into the concrete piling or borehole. Results of the inspection yield information on the average bulk density of the concrete. Properly constructed structures will have a consistent density. The technique can also be used to locate voids.

To date, gamma-gamma logging has not been used in pipeline inspection. However, researchers at Karlsruhe University in Germany performed laboratory tests that indicated a gamma-gamma probe could be used to locate lateral connections and locate and measure the size of cavities in the bedding surrounding a pipe. The technology may be applicable for evaluating the overall condition of concrete pipe or for detecting voids in bedding surrounding pipes. However, significant application issues would exist in terms of training requirements and the tracking of the nuclear materials. These issues are faced by the users of nuclear density gauges for soil compaction control.

4.6.2 Ground Penetrating Radar

The U.S. military originally developed ground penetrating radar (GPR) to locate underground tunnels and mines. GPR operates on the same principle as radar. A transmitting antenna emits high-frequency radio waves into the ground. The waves travel through the ground until they reach a material which has a different conductivity and dielectric constant than the earth. The signal is reflected and recorded by a separate receiving antenna. The amount of time it takes for the electromagnetic radio waves to be reflected by subsurface materials can be analyzed to determine the position and depth of features below the earth's surface.

There are a number of commercially available GPR systems. While some are designed to be used to locate underground utilities, none is significantly used at present for pipeline inspection. GPR systems that have been used to date in North America for internal pipe inspection could be considered more in the prototype stage than in commercial use. However, since GPR can detect underground voids, it is potentially useful for examination of pipe bedding. GPR can also potentially be used to locate leaks, since saturated soil slows radio waves, resulting in a GPR profile showing a pipe deeper then would be expected. Research into using GPR for sewer and bedding condition inspections is ongoing. Research has already been conducted on its use for small diameter sewer lines and brick sewers.

4.6.3 Infrared Thermography

Infrared thermography (IRT) involves the use of an infrared camera to measure the temperature differential across the surface of an object. Software can then be used to create an image displaying different temperatures as different colors. This allows for the detection of the surface expression of thermal conditions beneath the surface. In this regard, it is a potential method of detecting sewer defects such as leaks and voids, both of which can result in surface temperature variations when a sufficient internal/external temperature difference exists.

Two basic methods of IRT are generally employed: passive IRT, which requires no external heat source; and active IRT, which requires the use of a heat source such as an infrared tube light. Research into the use of passive IRT to detect defects in and around subsurface pipelines has been conducted. The method has been demonstrated to be capable of detecting subsurface defects such as leaks, voids, and deteriorated insulation. Because the process is carried out from the surface, and the equipment used can scan a large area quickly, the technology can be an efficient method for detecting pipe defects. Active IRT has been proposed as a method for pipeline assessment, but has not yet been evaluated.

4.6.4 Micro-Deflection

Micro-deflection is a nondestructive technology used to evaluate brick, concrete, and clay structures. The method involves the use of a load to create slight deformation, termed a micro-deflection, in the test material. The change in position of the structure is measured, and a graph of load versus deflection is created. Structurally sound test materials would be expected to have a consistent load versus deflection graph, while deteriorated sections of the material would have a different value on the graph.

Although not a widespread method of evaluating wastewater pipes, micro-deflection has been used to evaluate brick sewers. However, the usefulness of micro-deflection is limited, because the process can only give a general understanding of pipe condition, such as the integrity of joints, rather than identifying individual defects. In addition, plastics such as PVC and HDPE cannot be inspected using this method.

4.6.5 Impact Echo/Spectral Analysis of Surface Waves (SASW)

Impact Echo and SASW are two related techniques for evaluation of concrete and masonry. Both work by subjecting a pipe to an elastic impact, produced by a device such as a pneumatic hammer, which then propagates through the pipe. The waves are reflected by internal flaws, as well as the surface of the material, and the reflected waves are detected by an acoustic transducer such as a geophone located on the exterior of the pipe. The technique can locate and measure cracks, delaminations, voids, and honeycombing.

Impact Echo testing services are provided by several companies and its applicability for pipelines has been researched. The Acoustic Impact Hammer, developed by the University of Karlsruhe in Germany, uses a hammer to tap the inner surface of a pipe; laboratory trials resulted in the detection of cracks and cavities around the pipe. A German technology which uses lasers to scan the response to impacts and analyze them via SASW is available for tunnels and large pipes; however, this system requires entry into the pipe and is therefore only suitable for very large pipes.

4.6.6 Ultrasonic Testing Systems

Several new ultrasonic-based testing systems are currently under development. Researchers at King's College in London are developing a multi-sensor system termed the Ultrasonic-Based Inspection System that can be integrated into existing CCTV inspection systems. This system automatically classifies data based on an artificial neural network, and can detect very small cracks in the millimeter range. Research into use of ultrasonic pulse velocity for the evaluation of concrete is being carried out at the University of Waterloo in Canada. Researchers at Pennsylvania State University are working to develop a sensor using No-Contact Ultrasonic technology, which would be deployed into pipelines on a wheeled carriage.

5.0 Technology Forum Summary

5.1 Background

A technology forum was held on September 11 and 12, 2008 in Edison, New Jersey to discuss the state of the science for condition assessment of wastewater collection systems and to identify critical gaps in current knowledge. The white paper was distributed to participants in advance of the meeting and served as a basis for forum discussions. The objective of the forum was to present the findings of the research and obtain direction for additional research and further evaluation during the field demonstration tasks. Figure 5-1 lists the presenters and attendees at the Technology Forum.

WERF and other research institutions expressed interest in collaboration and sharing of research findings. WERF has completed twelve research projects related to condition assessment and rehabilitation of wastewater infrastructure in the last ten years; these research reports can be found at www.werf.org. WERF's Condition Assessment Protocols project, completed in 2007, provides guidance on developing and implementing a condition assessment program, and includes an inventory of condition assessment tools and techniques. On-going WERF research includes development of decision support tools and implementation guidance for risk analysis, cost-benefit, and estimation of residual life. Virginia Tech is working on a WERF project to create the National Database for Sustainable Water Infrastructure Management, with the objective of creating a web-based model that can be used by utilities to determine information requirements for asset management decisions and support the formal specification of data requirements.

5.2 General Discussion

The primary components of any asset management program include the identification, location and condition of assets; the determination of their useful life, and their valuation. Condition assessment provides the critical information needed to determine the condition of each pipe within the system and its estimated time to failure or remaining useful life. Critical gaps in the use of condition assessment as an asset management tool include lack of consistent, standard condition assessment protocols; methods for the systematic collection of data; and formal risk assessment methods to prioritize resources for maintenance and or/rehabilitation activities.

Data needs for conducting condition assessment and making asset management decisions were discussed at the Forum. It is important to define data needs so resources are spent wisely. The level of data needed for day-to-day management is different than what is needed for making decisions on major rehabilitation. Some meeting participants suggested that simple rules of thumb are adequate for making rehabilitation decisions (i.e., three or more major defects per 250-300 foot pipe segment triggers rehab or replacement). It was agreed by the participants that very detailed information is needed for CMOM. Better data including historical information are required for modeling. There is a concern that creating large databases for condition assessment data would be overwhelming to utilities. There is added value from gathering extra data. Information from a variety of inspection tools should be used to make better decisions; CCTV is only one aspect of assessment and should not be used in isolation.

Flow monitoring is an important tool in asset management. In one case, pipes were going to be replaced at tremendous cost, but flow monitoring data showed a restriction at a stream crossing was causing a backup; the restriction was fixed, and overflows were reduced dramatically at a much lower cost. Flow assessment data can be used to assess sewer condition and long-term system performance and to help calibrate models. Flow metering data is traditionally used to generate hydrographs which provide information about water upstream of the meter. Scattergraphs (displays of paired depth and velocity readings that look like a pipe curve under normal flow conditions), can reveal both upstream and downstream conditions, and can be used as verification of other inspection data. Flow metering data may not be useful for predicting pipe failure.

The development and implementation of condition assessment programs was a topic of discussion. Most condition assessment programs are currently focused on identifying and correcting I/I problems. A question was raised as to whether condition assessment should focus on other sewer defects in the future. Some utilities focus on coding defects, but may not spend enough time on identifying and correcting problems. The condition assessment program should have a system-wide focus and not be limited to one aspect of the collection system such as laterals or manholes.

An understanding of pipe failure mechanisms is needed to tailor a condition assessment program to the utility's high priority needs and also to improve use of predictive models. The United Kingdom has developed a comprehensive database on wastewater utility assets and pipe failures that can be used to study pipe failure mechanisms. Pipe failure is dependent on many factors including the system design, installation, operation, maintenance and inspection. For example, system operating conditions (i.e. hydraulics, I/I) together with poor maintenance practices may cause accumulation of sediment and other debris, resulting in sewage blockages, overflows, increased hydrogen sulfide production and/or increased corrosion. The main cause of failure in ferrous force mains is internal corrosion whereas PCCP fails most often due to external corrosion. Rehabilitated pipe may fail at an accelerated rate depending on contractor experience, selection of rehab technology and the understanding of baseline conditions. Many failures can be traced to human error.

There are many tools and risk assessment models for decision making related to asset management, ranging from simple to complex. A question was raised as to whether utilities should use simple vs. complex tools. A one-size fits all approach does not seem appropriate. One tool that is needed is a branched decision-making tree based on defect coding that can help prioritize areas for inspection. Decision making models are used to assess the probability of failure and the consequences of failure. With accurate assessments of the probability of failure and the consequences of failure, cost-effective decisions can be made on risk mitigation. While the physical science is good, the decision sciences are lagging. Utilities often lack the input data for pipe failure prediction models. There is a need for better decision making, and to improve on the general rules-of-thumb to make decision making more cost effective.

A number of models related to risk-based pipe performance and condition assessment were presented and discussed at the Forum:

- An on-going WERF project is developing a web-based model that can be used by utilities to determine information requirements for asset management decisions and support the formal specification of data requirements. The project is developing protocols and methods for predicting the remaining economic life of water and wastewater pipes, and developing a condition/performance index.
- Fuzzy logic can be used for modeling pipe deterioration and to help make decisions on pipe renewal. Fuzzy mathematics provides an alternative in cases where pipe condition data are lacking. It analyzes possibilities rather than probabilities of failure. The method was applied to large water transmission mains as part of an AwwaRF project. Prototype software T-WARP is available on AwwaRF's website (AwwaRF Project No. 2883).
- CARE-S, funded by the European Union, was designed as a proactive approach to develop methods and software that support efficient rehabilitation decisions. Failure codes developed as part of this project have been adopted by six European countries to date. CARE-S can be used for failure forecasting, assessments of hydraulic performance and environmental impacts, and selection of rehabilitation technologies.
- A simple approach for condition assessment presented at the Forum taps into the utility's extensive knowledge of the piping network rather than a comprehensive database of pipe information. The approach uses the utility's "beliefs" or observations about pipe condition to develop a criticality rating of likelihood and consequences of failure. The approach is user friendly and does not require expert input. It can be applied using a simple computer program by utilities and their consultants. The approach was developed by a WERF-funded project, SCRAPS.

5.3 Critical Gaps Identified in State of the Science

Critical gaps in our knowledge of inspection technologies, and our ability to diagnose and predict infrastructure failures were identified at the Technology Forum and are summarized below.

1. Research is needed to further define the costs and benefits of pipe inspection and rehabilitation as part of a utility's condition assessment program. Methods of determining the impact of deteriorating collection systems on municipal budgets are needed.

2. Inspection technologies need to be identified for the following applications:
    a. Reduce use of confined space entry during sewer system inspections and investigations.
    b. Affordable inspection technology that utilizes multi-sensor devices on a small transportable package.
    c. Inspecting pipes below the waterline.
    d. Inspecting force mains that are in service.
    e. Inspecting laterals.
3. Data management methods and models are available but a lack of standardization makes it difficult to compare historical data collected with different inspection technologies that have proprietary data structures.
4. Research is needed to improve how asset condition is tracked over time. Geospatial information (with a high degree of accuracy) needs to be collected along with pipe condition data in order to link historical inspection data with an exact physical location.
5. Information transfer to practitioners was identified as a critical industry need. Practitioners need training on topics such as infrastructure failure mechanisms; using historical inspection data for condition assessment applications; applying the PACP coding system to characterize pipe defects; developing a condition assessment program; and preparing accurate record drawings for new and rehabilitated pipe. Practitioners need simple condition assessment tools (i.e. scattergraphs for analyzing flow data, decision trees, and rules of thumb).

5.4 Recommended Next Steps

Based on the Technology Forum discussions and findings, the project team has identified the following technologies for possible inclusion in the project's field demonstrations:

1. Focused Electrode Leak Location System FELLS 41.
2. Ultra-wide band (UWB).
3. Laser (2D/3D).
4. Autonomous crawler technology.
5. Zoom Camera.
6. Digital scanning vs. CCTV.
7. Flow metering analysis as input to decision making tools to prioritize need for inspection.
8. Embedded sensors to monitor deflection, corrosion potential, and pressure.

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Robert A. Villee – WEF Collection System Committee

ADDITIONAL ATTENDEES

Wendy Condit – Battelle
George Kurz - Barge Waggoner Sumner & Cannon
Robert Pennington - Camp Dresser & McKee Inc.
Lily Wang - Battelle
Dan Watts - New Jersey Institute of Technology

Technology Forum Presenter

Figure 5-1: Technology Forum Attendees

6.0 References

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Appendix A

Technology Vendors

Camera Technologies

Digital Camera Inspection

Product(s)	Vendor/Address	Phone/Fax/Email/URL
DigiSewer	Envirosight 111 Canfield Ave. Randolph, NJ 07869	Tel: (866) 936-8476 Fax: (973) 252-1176 Email: through website URL: http://www.envirosight.com
Panoramo	Rapidview-IBAK USA 1828 West Olson Road Rochester, IN 46975	Tel: (800) 656-4225 Fax: (574) 224-5426 Email: info@rapidview.com URL: http://www.rapidview.com
Sewer Scanning Evaluation Technology (SSET)	Hydromax USA, LLC 1766 Brent Drive Newburgh, IN 47630	Tel: (812) 925-3930 Fax: (812) 925-3911 Email: info@hydromaxusa.com URL: http://www.hydromaxusa.com

Zoom Cameras

Product	Vendor/Address	Phone/Fax/Email/URL
AquaZoom	Aquadata, Inc. 95 5th Avenue Pincourt, Quebec Canada J7V 5K8	Tel: (800) 567-9003 Fax: (514) 425-3506 Email: info@aquadata.com URL: http://www.aquadata.com
Aries HC3000 Zoom Pole Camera	Aries Industries 550 Elizabeth St. Waukesha, WI 53186	Tel: (800) 234-7205 Fax: (262) 896-7099 Email: through website URL: http://www.ariesind.com
Ca-Zoom PTZ Quickview	GE Sensing & Inspection Technologies 721 Visions Drive Skaneateles, NY 13152	Tel: (888) 332-3848 Fax: (866) 899-4184 Email: through website URL: http://www.geinspectiontechnologies.com
CUES IMX Truck Mounted Zoom Camera	CUES IMX Corporate Office 3600 Rio Vista Ave. Orlando, FL 32805	Tel: (800) 327-7791 Fax: (407) 425-1569 Email: salesinfo@cuesinc.com URL: http://www.cuesinc.com

PortaZoom	CTZoom Technologies 2500 Boul. Des Enteprises #104 Terrebonne (Quebec) Canada J6X 4J8	Tel: (888) 965-8987 Fax: (450) 965-8987 Email: info@ctzoom.com URL: http://www.ctzoom.com

Push Cameras

Product(s)	Address	Phone/Fax/Email/URL
Insight Vision Push Camera	Insight Vision 600 Dekora Woods Boulevard Saukville, WI 53080	Tel: (800) 488-8177 Fax: (262) 268-9952 URL: http://insightvisioncameras.com
CrystalCam Push Camera	Inuktun Services Ltd. 2569 Kenworth Road, Ste. C Nanaimo, BC Canada, V9T 3M4	Tel: (877) 468-5886 Fax: (250) 729-8080 Email: sales@inuktun.com URL: http://www.inuktun.com/head-office.htm
Flexiprobe	Pearpoint/RADIODETECTION 154 Portland Road Bridgton, ME 04000	Tel: (877) 247-3797 Fax: (207) 647-9495 Email: rd.sales.us@spx.com URL: http://www.pearpoint.com
Hydrus, Orion, Orion L	Rapidview-IBAK USA 1828 West Olson Road Rochester, IN 46975	Tel: (800) 656-4225 Fax: (574) 224-5426 Email: info@rapidview.com URL: http://www.rapidview.com

Lateral Launchers

Product(s)	Vendor/Address	Phone/Fax/Email/URL
LAMP	CUES IMX Corporate Office 3600 Rio Vista Ave. Orlando, FL 32805	Tel: (800) 327-7791 Fax: (407) 425-1569 Email: salesinfo@cuesinc.com URL: www.cuesinc.com
Lateral Evaluation Television System	Aries Industries 550 Elizabeth St. Waukesha, WI 53186	Tel: (800) 234-7205 Fax: (262) 896-7099 URL: http://www.ariesind.com
Lateral Inspection System	RS Technical Services 1327 Clegg St. Petaluma, CA 94954	Tel: (800) 767-1974 Fax: (707) 778-1974 URL: http://www.rstechserv.com

IBAK LISY 150-M	Rapidview-IBAK USA 1828 West Olson Road Rochester, IN 46975	Tel: (800) 656-4225 Fax: (574) 224-5426 Email: info@rapidview.com URL: http://www.rapidview.com

Small Diameter Tractors

Product(s)	Address	Phone/Fax/Email/URL
ELKT100 Mini	Pearpoint/RADIODETECTION 154 Portland Road Bridgton, ME 04000	Tel: (877) 247-3797 Fax: (207) 647-9495 Email: rd.sales.us@spx.com URL: http://www.pearpoint.com
KRA 65	Rapidview-IBAK USA 1828 West Olson Road Rochester, IN 46975	Tel: (800) 656-4225 Fax: (574) 224-5426 Email: info@rapidview.com URL: http://www.rapidview.com
Mighty Mini Transporter	RS Technical Services 1327 Clegg St. Petaluma, CA 94954	Tel: (800) 767-1974 Fax: (707) 778-1974 URL: http://www.rstechserv.com
Rovver 100	Envirosight 111 Canfield Ave. Randolph, NJ 07869	Tel: (866) 936-8476 Fax: (973) 252-1176 Email: through website URL: http://www.envirosight.com
Versatrax 100	Inuktun Services Ltd. 2569 Kenworth Road, Ste. C Nanaimo, BC Canada, V9T 3M4	Tel: (877) 468-5886 Fax: (250) 729-8080 Email: sales@inuktun.com URL: http://www.inuktun.com/head-office.htm
Xpress Silver-Bullet Crawler	Insight Vision 600 Dekora Woods Boulevard Saukville, WI 53080	Tel: (800) 488-8177 Fax: (262) 268-9952 URL: http://insightvisioncameras.com

Long Range Tractors

Product	Vendor/Address	Phone/Fax/Email/URL
Versatrax 300 VLR	Inuktun Services Ltd. 2569 Kenworth Road, Ste. C Nanaimo, BC Canada, V9T 3M4	Tel: (877) 468-5886 Fax: (250) 729-8080 Email: sales@inuktun.com URL: http://www.inuktun.com/head-office.htm

Responder	Redzone Robotics 91 43rd St., Ste.250 Pittsburgh, PA 15201	Fax: (412) 476-8981 Email: through website URL: http://www.redzone.com

Acoustic Technologies

In-Line Leak Detectors

Product	Address	Phone/Fax/Email/URL
LxSentry	LxSix Photonics 520 McCaffrey St. St-Laurent, Quebec Canada H4T 1N1	Tel: (514) 599-5714 Fax: (514) 599-5729 Email: info@lxsix.com URL: http://www.lxsix.com
Sahara	Pressure Pipe Inspection Company 1930 West Qual Avenue, Suite A Phenix, AZ 85027	Tel: (866)-990-2466 Email: info@ppic.com URL: http://www.ppic.com
Smartball	Pure Technologies Suite A, 9130 Red Branch Road Columbia, Maryland 21045	Tel:1-800-537-2806 Fax: (443) 766-7877 Email: through website URL: http://www.puretechnologiesltd.com

Acoustic Monitoring Systems

Product	Address	Phone/Fax/Email/URL
AET	Pressure Pipe Inspection Company 1930 West Qual Avenue, Suite A Phenix, AZ 85027	Tel: (866)-990-2466 Email: info@ppic.com URL: http://www.ppic.com
Soundprint AFO	Pure Technologies Suite A, 9130 Red Branch Road Columbia, Maryland 21045	Tel:1-800-537-2806 Fax: (443) 766-7877 Email: through website URL: http://www.puretechnologiesltd.com

Sonar/Ultrasonic

Product	Address	Phone/Fax/Email/URL
Amtec Sonar TISCIT	Amtec Surveying Inc. 3355 Lenox Rd. Ste. 750 Atlanta, GA 30326	Tel: (404) 504-7044 Fax: (404) 504-7004 Email: info@amtecsurveying.com URL: http://www.amtecsurveying.com

A-SIS AquaCoustic	AquaCoustic Remote Technologies, Inc. 3339 West 8th Ave. Vancouver, BC V6R 1Y3 Canada	Tel: (888) 3749-7601 Fax: (604) 730-8771 Email: Info@AquaCoustic.com URL: http://www.aquacoustic.com
Envirosight	Envirosight 111 Canfield Ave. Randolph, NJ 07869	Tel: (866) 936-8476 Fax: (973) 252-1176 Email: through website URL: http://www.envirosight.com
PipeEye	PipeEye International Unit 28 – 6275 Harrison Dr., Park 2000 Las Vegas, NV 89120	Tel: (888) 756-2033 Fax: (250) 753-2642 Email: info@pipeeyeinternational.com URL: http://pipe-eye-int.com
RVS2	R&R Visual, Inc. 1828 West Olson Rd. Rochester, In 46975	Tel: (800) 776-5653 Fax: (574)-223-7953 Email: support@seepipe.com URL: http://www.expipeinspection.com
Sonar Profiler System (submerged/semi-submerged)	CUES Corporate Office 3600 Rio Vista Ave. Orlando, FL 32805	Tel: (800) 327-7791 Fax: (407) 425-1569 Email: salesinfo@cuesinc.com URL: www.cuesinc.com
Sonar Sewer Profiling Attachment Sonar Sweep Attachment	Redzone Robotics 91 43rd St., Ste.250 Pittsburgh, PA 15201	Fax: (412) 476-8981 Email – through website URL: http://www.redzone.com
Ultrascan CD Ultrascan DUO Ultrascan WM	GE Inspection Technologies 50 Industrial Park Road Lewistown, PA 17044	Tel: (866) 243-2638 Fax: (717) 242-2606 URL: http://www.geinspectiontecnologies.com
Inspector Systems Ultrasonic Inspection Robot	Aqua Drill International Inc. 1300 FM 545 East Dickinson, TX 77539	Tel: (281) 337-0900 Fax: (281) 337-7270 URL: http://www.inspector-systtems.com
Wavemaker	Guided Ultrasonics Ltd. 30 Saville Road Chiswick, London W4 5HG United Kingdom	Tel: +44 (0) 20 8991 3771 Fax: +44 (0) 20 8987 0558 Email: info@guided-ultrasonics.com URL: http://www.guided-ultrasonics.com

Electrical and Electromagnetic Products

Electrical Leak Location Method

Product	Address	Phone/Fax/Email/URL
FELL-21 FELL-41	Metrotech Corporation 3251 Olcott St. Santa Clara, CA 95054	Tel: (800) 446-3392 Fax: (408) 734-1415 Email: sales@metrotech.com URL: http://www.fell21.com

Eddy Current and Remote Field Eddy Current

Product	Vendor/Address	Phone/Fax/Email/URL
BEM	Rock Solid Pty, Ltd. 11 Evans Str. Burwood Vic 3124 Australia	Tel: (+613) 9335-6122 Fax: (613) 9335-6733 Email: info@rocksolidgroup.com.au URL: http://www.rocksolidgroup.com.au
Hydroscope	Hydroscope Canada, Inc 8170 50 St. NW Suite 260 Edmonton, AB, T6B 1E6	Tel: (780)-450-6224 Fax: (780) 450-6224 Email: info@hydroscope.com URL: http://www.hydroscope.com
See Snake Tool	CHECK IF VENDOR Russel NDE Systems, Inc. 4909 75th Avenue Edmonton, AB, Canada T6B 2S3	Tel: (780) 468-6800 Fax: (780) 462-9378 Email: info@russelltech.com URL: http://www.russeltech.com
P-Wave	Pure Technologies Suite A, 9130 Red Branch Road Columbia, Maryland 21045	Tel:1-800-537-2806 Fax: (443) 766-7877 Email: through website URL: http://www.puretechnologiesltd.com
RFEC/TC	Pressure Pipe Investigation Company	info@ppic.com http://www.ppic.com/home/index.asp

Magnetic Flux Leakage

Product	Address	Phone/Fax/Email/URL
AES 19 AES ECAT	Advanced Engineering Solutions, LTD South Nelson Road South Nelson Industrial Estate Cramlington, Northumberland NE23 1WF United Kingdom	Tel: +41 41 618 0 300 Fax: +41 41 618 0 319 Email: info@roseninspection.net URL: http://www.aesengs.co.uk
Axial Flaw Detection (AFD) Corrosion Detection Pig (CDP)	Rosen Inspection Obere Spichermatt 14 6370 Stans Switzerland	Tel: +41 41 618 0 300 Fax: +41 41 618 0 319 Email: info@roseninspection.net URL: www.RosenInspection.net
CPIG Vertiline/V-line, CPIG	Baker Hughes 12645 West Airport Blvd. Sugar Land, TX 77478	Tel: (281) 276-5400 Email: BPC_ebiz_USA@bakerpetrolite.com URL: http://www.bakerhughesdirect.com
LINSCAN	LIN SCAN 205/206 Al Zahra Shopping Complex U.A.E.	Tel: +9716-7473600 Fax: : +9716-7473800 Email: Marketing@linscan.biz, URL: http://www.linscan.biz
MagneScan TranScan	GE Energy	URL: http://www.gepower.com/contact/index.htm
MAGPIE	TDW Services, Inc 4220 World Houston Pkwy, Ste. 100 Houston, Texas 77032	Tel: (832) 448-7221 Email: Chuck.Harris@tdwilliamson.com URL: http://www.magpiesystems.com
MFL Inspection Tool	NGKS 7, Guilyarovsky St. Moscow, Russia 129090	Tel: + 7 495 937 86 36/26 Fax: + 7 495 937 86 35/31 Email: khafizov@ngksint.com URL: http://www.ngksint.com

Pipesurvey MFL	Pipesurvey International Schrijnwerkersstraat 13 3334 KH Zwijndrecht P.O. BOX 117 3330 AC Zwijndrecht the Netherlands	Tel + 31 78 610 1428 Fax + 31 78 610 2128 Email: info@pipesurveyinternational.com URL: http://www.pipesurveyinternational.com
VECTRA	BJ Services Company 414 Pinckney Houston, TX 77009	Tel: (713) 224-1105 Fax: (713) 229-0541 URL: http://www.bjservices.com/

Laser Products

Product	Address	Phone/Fax/Email/URL
Active 3D Laser Scanning	Redzone Robotics 91 43rd St., Ste.250 Pittsburgh, PA 15201	Fax: (412) 476-8981 Email: through website URL: http://www.redzone.com
Coolvision	Sima Environmental 1153 E Ogden, # 705-135 Naperville, IL 60563	Phone: (630) 327-8503 Email: sima@wideopenwest.com URL: http://www.simaenvironmental.com
Laser Profiler	CUES IMX Corporate Office 3600 Rio Vista Ave. Orlando, FL 32805	Tel: (800) 327-7791 Fax: (407) 425-1569 Email: salesinfo@cuesinc.com URL: http://www.cuesinc.com
Laser Profiling Tool	Envirosight 111 Canfield Ave. Randolph, NJ 07869	Tel: (866) 936-8476 Fax: (973) 252-1176 Email: through website URL: http://www.envirosight.com
Laser Profiler	R&R Visual, Inc. 1828 West Olson Rd. Rochester, In 46975	Tel: (800) 776-5653 Fax: (574)-223-7953 Email: support@seepipe.com URL: http://www.expipeinspection.com