Developing a Framework for Selecting Condition Assessment Technologies for Water and Wastewater Pipes

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ABSTRACT

Beneath North America's roads lie 1.6 million miles of pipeline that provides users with potable water and carry away wastewater. These buried infrastructure systems have been functioning for duration longer than their intended design life, often with little or no repair. Asset management of pipeline systems pose a major challenge for most municipalities due to budgetary constraints, demand for quality service, and need to preserve existing pipeline infrastructure. The first step in developing and implementing a comprehensive asset management plan is to perform a condition assessment.

There is a gamut of inspection and monitoring technologies available to enable the condition assessment of pipelines. All of these have advantages and limitations, which determine the performance quality and effectiveness of an individual technology for particular utility assets. Unfortunately, utilities choose technologies not suitable for their specific assets and collect data that is not useful for understanding the condition of their system.

The objective of this thesis is to develop a framework for the effective selection of condition assessment technologies for water and wastewater utilities. A Microsoft-Excel based framework is developed to help the utility managers in selecting condition assessment technologies for their water and wastewater pipeline assets.

The recommended tool selection approach uses a multi-step exclusion protocol in which the tools are excluded on the basis of their applicability relating to technical feasibility and technical suitability for a particular situation. Usable tools are then compared against a performance and cost database to determine performance and cost in a given project/ utility condition.

This thesis provides a brief description and review of 24 non-destructive commercialized condition assessment technologies, including the principal and implementation considerations. A framework for decision system tool was developed to facilitate utilities in selecting appropriate

condition assessment technologies. This framework could facilitate the selection of usable technologies by excluding the options, which are not technically feasible and suitable. The user can then further explore the usable tools and determine the most suitable technologies for their assets.

The data considered in the research is provided by technology providers, thus it may lack complete understanding of the capabilities and limitations of technology. This thesis also presents a case study which highlights the existing gap between the understanding of capabilities and limitations of various technologies.

A program is developed as a part of this thesis, Condition Assessment Selection Tool (CAST), which consists of performance and economic database, a graphical user interface to facilitate user input, and the results of the comparison of each usable technology in the database to the project information provided by the user for their assets. The results are presented as performance indices and economic indices indicating the performance and technology cost of usable technologies. A data reliability index was also developed to provide a scale for comparing the reliability of the existing data in the database.

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Chapter 1 – Introduction

1.1 Pipe Infrastructure

Beneath North America's roads lie 1.6 million miles of pipelines that provide users with potable water and carry away the wastewater (sewage and storm water). Aging wastewater management systems discharge billions of gallons of untreated sewage into U.S. surface waters each year. The Environmental Protection Agency (EPA) estimates that the nation must invest $390 billion over the next 20 years to replace existing systems and build new ones to meet increasing demands (USEPA, 2005). These buried infrastructure systems have been functioning longer than their intended design life with little or no repair. They are aging and in a progressive state of deterioration.

Maintenance and rehabilitation of pipeline systems pose a major challenge for most municipalities in North America given their budgetary constraints, demand for quality service, and the need to preserve existing pipeline infrastructure. Neglecting regular maintenance and rehabilitation (M&R) of these buried pipelines adds to life-cycle costs and liabilities, and in extreme cases, it can cause stoppage or reduction of vital services. An example of a sign of aging US infrastructure can be seen by the recent water-main break in Bethesda, Maryland in late December 2008.

Unsurprisingly, the American Society of Civil Engineers (ASCE) 2009 Report Card for America's Infrastructure gave a grade of "*D -*" to water/wastewater infrastructure. It has been estimated that upwards of 40% of underground infrastructure in the US will have failed or will be on the brink of failure within 20 years, unless efforts are initiated to renew it (WIN, 2000).

According to an April 2000 report by the Water Infrastructure Network (WIN) Agency, America's water and wastewater systems face an estimated funding gap of $23 billion per year between current investments in infrastructure and the investments that will be needed annually over the next 20 years to replace aging and failing pipes and to meet mandates of the "Clean Water Act and Safe Drinking Water Act" (WIN, 2000). The ASCE report also showed that in

Virginia only, an investment of $2.87 billion will be required in the drinking water infrastructure and $4.74 billion worth in wastewater infrastructure over the next 20 years.

1.2 Asset Management

The goal of asset management is to meet a required level of service in the most cost-effective way through the creation, acquisition, maintenance, operation, rehabilitation, and disposal of assets to provide for present and future customers (IPWEA, 2006). Condition assessment process involve the assessment of the current operating performance of the system and continued monitoring of the performance in order to either manage the associated risk or take remedial action where necessary. There are a number of definitions for the practice of asset management as follows

According to Vanier and Rahman:
"Asset Management is a business process and decision support framework that: (1) covers the extended service life of an asset, (2) draws from engineering as well as economics, and (3) considers a diverse range of assets."

According to USEPA:
"Asset management is a continuous process that guides the acquisition, use and disposal of infrastructure assets to optimize service delivery and minimize costs over the asset's entire life."

For utilities, the adoption of a formal asset management plan has generally lagged behind the construction of new assets. In the past decade or so, however, asset management has commonly evolved and developed around the existing utility in light of existing assets (WERF, 2007). Utilities starting to carry out a formal asset management plan generally face a lack of knowledge about their assets. A fundamental requirement for the success of any asset management plan is comprehensive information on the assets, so utilities in this position must therefore address the following fundamental questions (Vanier, 2000 & 2001).

- What assets are owned?
- What are they worth?
- What is the deferred maintenance?
- What is the current condition of assets?

- What is the remaining service life of the assets?
- What should be fixed first?

Various tools and approaches are required to answer these questions, but condition and performance are the key elements in answering most of these questions. There are various asset management philosophies, which are being adopted in different countries (WERF, 2007). These philosophies are categorized based on the driving force as follows:

- Condition-based asset management
- Performance-based asset management
- Service-based asset management
- Risk-based asset management

There are a number of factors driving utilities to improve asset management including, but not limited to:

- A clear understanding of the condition and performance of the assets;
- Regulatory compliances;
- Optimization of the life cycle cost of assets; and
- New inspection technologies are providing better tools for the asset owners to better assess the condition of their assets and optimize the overall asset management.

Utilities need to have a clear understanding regarding performance and condition of their assets, as all management decisions regarding maintenance revolve around these aspects. A limited understanding about an asset may lead to its premature failure or premature replacement (AWWARF, 2004).

1.3 Condition Assessment

Condition assessment is the procedure that allows utility managers to identify the condition of their infrastructure assets. It is a process of understanding the level of asset deterioration and the impact it has on the probability of failure (AWWARF, 2004). The various technologies implemented in order to enable this process are known as condition assessment technologies (CAT). As mentioned before, an accurate assessment of pipeline condition is essential to develop an effective and efficient asset management plan. The benefits of condition assessment within the overall asset management process are enlisted in order of preference as

- Rehabilitation decision-making;
- Future failure protection;
- Leakage reduction;
- Risk management;
- Asset valuation; and
- Reduction in operation expenditure costs.

The cost benefit analysis of asset management can be justified using various business and technical aspects as follows:

1. **Deferral of capital expenditure:** Condition assessment of the entire section would identify whether the entire length of a pipe actually needs to be replaced now, or whether a localized section could just be repaired to prevent future failures. This would significantly reduce premature spending.
2. **Reduction of capital expenditure:** Condition assessment can significantly help in targeting only the areas that need replacement rather than replacing an entire length of pipeline. This saves time, staffing requirement and money.
3. **Leakage reduction:** The cost of the lost water due to the leakage could be used to justify the investment required on the condition assessment and subsequent repairs.
4. **Benefits of proactive repairs:** The primary benefit of assessing the condition and thus predicting failure is to reduce the number of unplanned outages and prevent overall disruption of supply.
5. **Reduction of consequential damage:** There are significant amounts of direct costs involved with the failure of the pipe including, but not limited to, cost of lost water, excavation, staffing requirement, clean-up, mobilization and damages caused due to flooding etc. Condition assessment and asset management can prevent these costs.
6. **Extended service life:** Condition assessment can help in increasing the longevity of the pipe assets significantly. Figure 1 illustrates the impact of condition assessment on the service life of the asset. The Curve ‘S’ represents the asset deterioration curve without any condition assessment while the curve ‘S’’ represents the asset deterioration curve

with condition assessment. It is visible from the curve that condition assessment has a direct impact on increasing the service life of the assets.

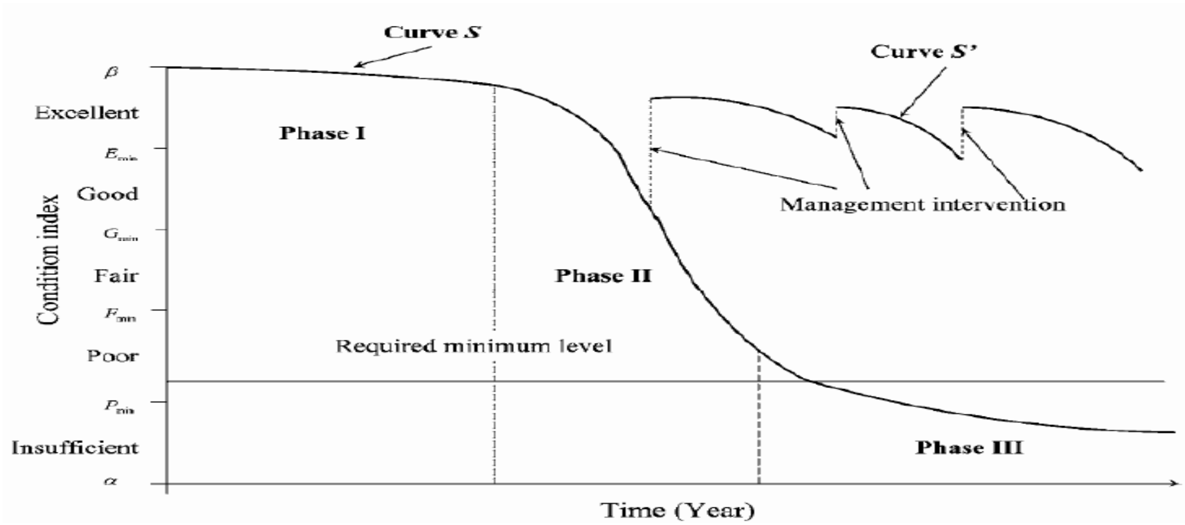

Figure 1: Deterioration Curves with and without Asset Management (Sinha, 2009)

7. **Improved utility image and staff morale:** With improved condition and performance assessment, staff members have a higher level of confidence in the cost efficiencies and service delivery of their program.
8. **Improved level of service:** A better understanding of the condition/performance of assets leads to the implementation of appropriate measures to promote higher reliability of operation.
9. **Improved financial transparency:** More precise and transparent asset evaluations are possible with improved data on asset conditions and the actual historical life of assets.

A generic 10 step approach for designing a condition assessment program was developed by American Water Works Association Research Foundation (AWWARF) in 2007 which takes into account various protocols. This approach is in line with the best practices prevalent in the industry. Figure 2 illustrates the 10 step approach for designing the asset management program.

Figure 2: A 10-Step Approach to Specify a Condition Assessment Program

This research builds on this approach and concentrates on the **Step 6: Select Inspection/ Assessment Techniques**. The decision has to be made by excluding the technologies based on technical feasibility and suitability for a particular utility. This is discussed in detail in later chapters.

1.4 Motivation

1.4.1 Previous Work

The condition assessment of water and wastewater pipelines has been researched to some extent in the past and a discussion of projects with direct relevance to this research follows:

WRc Sewer Rehabilitation Manual: This tool works only for wastewater systems and focuses on cost-effective management of assets by identifying the service problems in drainage areas. The limitation of this tool is that it is just a framework and is very generic in nature (WERF, 2007).

WRc Trunk Main Structural Condition Assessment: This tool works only for water assets and focuses on identifying the current condition and remaining service-life water transmission pipes. The limitation of this tool is that it is just a framework and is generic in nature (WERF, 2007).

Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets: The key goal of this research was to provide a framework that would assist the utilities in the selection and use of condition assessment tools. It developed a table-based tool and is based on the specifications and capabilities of the technologies. The framework developed is perfectly valid but this is still a framework and the performance and cost information are broadly, rather than specifically, defined (WERF, 2007).

International Infrastructure Management Manual: This presents an approach to the selection of condition monitoring techniques that involves a process where the utility 1) evaluates the condition and performance assessment techniques being used already, and 2) develops an understanding of shortfalls. This gap analysis then drives the selection of a new approach. While this approach is perfectly valid, it assumes that condition monitoring already plays a central role in the asset management approach, and that utility simply wants to assess whether better approaches are available to those already in use (IPWEA, 2006).

Non-Destructive Testing of Water Mains for Physical Integrity: This study analyzes the condition assessment technologies for a variety of materials. This study further recommends the need for technical improvements to optimize the performance of current condition assessment technologies. The report gives a detailed analysis of the performance of technologies but lacks the development of a framework for selecting the condition assessment technologies (AWWARF, 1992). Since this report has been published, a lot of development has been done on the technological frontier, invalidating some of the work already done in the area.

Electromagnetic Inspection of Pre-stressed Concrete Pressure Pipes: This study presents the capability of remote field eddy current- transformer coupled (RFEC/TC) technology. The limitation of this study is the fact that it has been based on limited samples (AWWARF, 2001).

Nondestructive, Noninvasive Assessment of Underground Pipelines: This study presents the technologies capable of assessing ductile iron pipes. It is specific to a very small set of materials and lacks general acceptability (AWWARF, 2002).

Techniques for Monitoring Structural Behavior of Piping Systems: This study evaluates the performance and economic parameters of various technologies like leak detection and ultrasonic technologies, but it does not develop a protocol for identifying appropriate condition assessment technologies (AWWARF, 2003).

Testing and Condition Assessment of Joints in Water Distribution Pipelines: This research presents investigative techniques for testing and condition assessment of joints in water distribution pipelines. This study also evaluates the performance of existing and emerging techniques for water and wastewater pipelines. It does not develop a protocol for condition assessment technologies (AWWARF, 2004).

Workshop on condition assessment for water transmission mains: The aim of this study was to conduct a state-of-the-art literature review of non-invasive condition assessment technologies for transmission mains. This study also reviews the business needs and drivers as well as the research needs (AWWARF, 2004).

Installation, Condition Assessment, and Reliability of Service Lines: This research focuses on residential service lines 2 inches in diameter and smaller. This study goes on to develop a Service Line Information Tool (SLIT), which provides information regarding service line maintenance. The tool deals only with service lines and lacks a wider approach (AWWARF, 2007).

Assessment and Renewal of Water Distribution System: This report is a synthesis of the knowledge and suggestions of the utilities and other professionals about renewing distribution systems. This research identifies and evaluates the performance of various non-destructive technologies (AWWARF, 2004).

Condition Assessment of Wastewater Collection System: This study identifies and classifies condition assessment technologies for wastewater collection systems. This research evaluates these technologies and develops protocols, metrics and site selection criteria for field demonstration of selected innovative condition assessment technologies and decision support systems. It provides a generic framework specifically for wastewater systems (USEPA, 2007).

Leakage Management Technologies: This research aims to 1) review proactive leakage monitoring technologies, 2) assess the applicability of these technologies in North American water utilities, and 3) provide guidance on how to apply the technologies in North America in a cost-efficient manner. The research is perfectly valid and useful but gives an insight about leakage only (AWWARF, 2008).

Inspection Guidelines for Ferrous Mains: This research identifies and evaluates the condition assessment technologies specific to ferrous transmission pipes. It provides a generic framework for selecting the technologies but lacks a standardized approach to selecting appropriate condition assessment technologies (WERF, 2007).

Sewer Cataloging, Retrieval and Prioritization System (SCRAPS): This expert system targets the inspection of critical areas of the sewer network. This tool can assist small to medium-sized utilities develop a strategy to gather information about their systems by prioritizing their inspection process. The research is valid for prioritizing but lacks the framework to select appropriate condition asset monitoring technologies (WERF, 2000).

Draft Selection Procedures for Condition Assessment Inspection of Transmission Mains: This study develops a detailed framework for water transmission mains taking into account various performance and economic parameters. Though this research is valid and applicable for transmission mains, it lacks applicability for pipes of other function. In addition, this report develops a framework but is not a tool that can be readily used by the utility managers (PII Group Limited, 2002).

Table 1 illustrates the summary of relevant previous works on condition assessment technologies for water and wastewater technologies. The first column in the table illustrates the name of the previous work, the second column refers to the commercial availability of this work, the third and fourth column refers to the type of the pipe (water or wastewater), that the work focuses on some work focuses on a specific pipe function like transmission, distribution etc. The fifth column refers to the materials of pipe, which the report focuses on. The column six, seven, eight, and nine refers to the nature of the previous work like literature review, evaluation of technology, framework or protocol for selection of condition assessment technology, and software tool for selection of condition assessment technology respectively.

Table 1: Summary of Previous Relevant Works on Condition Assessment Technologies for Water and Wastewater Technologies

Name of Previous Work	Commercialization	Water	Waste water	Material	Report/ Literature Review	Evaluation of Technologies	Frame Work	Software Tool
WRc SRM Program	YES	NO	YES	ALL	YES	NO	NO	NO
WRc Trunk Main Structural condition assessment approach	YES	TRANSMISSION	FORCE	ALL	YES	YES	YES	NO
Condition Assessment Strategies and Protocols for water and wastewater utility assets (AWWARF 2007)	YES	YES	YES	ALL	YES	YES	YES	NO
International Infrastructure Management Manual (IPWEA, 2006)	YES	YES	YES	ALL	YES	YES	YES	NO
Non Destructive Testing of water mains for physical integrity (AWWARF)	YES	TRANSMISSION	NO	ALL	YES	NO	NO	NO
Electromagnetic Inspection of Pre-stressed Concrete Pressure Pipes (AWWARF)	YES	YES	YES	PCCP	YES	NO	NO	NO
Non-destructive, Noninvasive assessment of underground pipelines (AWWARF)	YES	YES	YES	DUCTILE IRON	YES	NO	NO	NO
Techniques for monitoring structure behavior of piping systems (AWWARF)	YES	YES	YES	ALL	YES	YES	NO	NO
Testing and condition assessment of joints in water distribution pipelines (AWWARF)	YES	DISTRIBUTION	NO	ALL/ (JOINTS ONLY)	YES	NO	NO	NO
Workshop on condition assessment for water transmission mains (AWWARF)	YES	TRANSMISSION	NO	ALL	YES	YES	NO	NO

Installation, condition assessment, and reliability of service lines (AWWARF)	YES	SERVICE	NO	ALL	YES	NO	YES	NO
Assessment and Renewal of water distribution system (AWWARF)	YES	DISTRIBUTION	NO	ALL	YES	YES	NO	NO
Leakage management technologies (AWWARF)	YES	YES	YES	ALL/ (LEAK ONLY)	YES	NO	NO	NO
Condition Assessment of wastewater collection system (USEPA)	YES	NO	YES	ALL	YES	YES	YES	NO
Inspection Guidelines for Ferrous and Non-Ferrous mains (WERF)	YES	TRANSMISSION	NO	ALL	YES	YES	NO	NO
SCRAPS (WERF)	YES	YES	YES	ALL	YES	NO	NO	NO
Draft selection procedures for condition assessment inspection of transmission mains (PII Group Limited, 2002)	YES	TRANSMISSION	NO	ALL	YES	YES	YES	NO

1.4.2 Lack of Condition Assessment Protocols

Based on a survey of 24 North American 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.

1.4.3 Lack of Understanding about Capabilities and Limitations of Technologies

There is a gamut of technologies available for assessing the condition of water and wastewater pipelines, but more than often utility managers are ill informed about their capabilities and limitations. The lack of knowledge with technology providers about their technologies also adds to the gap in knowledge. e.g., in case of acoustic fiber optic sensors, technology providers claim that the technology is capable of detecting and identifying all type of acoustic signals near pipes. But, more than often, false alarms are experienced by utility managers. In order to address this issue a case study was developed to investigate the existing gap in knowledge. The case study is presented in Chapter 5, which identifies the need of advanced signal processing to better understand the capabilities and limitations of acoustic fiber optic technology. This case study thus proves the lack of understanding about the capabilities and limitation of condition assessment technologies at present.

1.5 Problem Statement

At present very few technologies like Closed Circuit Tele-Vision (CCTV) survey, Ultrasonic Inspection, etc. have been successful in finding much acceptance in the industry. The reason is that the utilities depend on consultants for technical advice regarding technologies for carrying out inspections. Moreover, lack of awareness about the performance and economic parameters of all the commercially available technologies acts as a major drawback in the use of these technologies. As discussed in the previous section, there is also a definite lack of protocols to aid in selection of the most appropriate condition assessment technologies for water and wastewater pipelines. There is also a lack of knowledge about the evaluation parameters for assessment technologies. It is often observed that even after using the condition assessment technologies the utilities are not able to collect data relevant to their assets; this is because not all the technologies are applicable in all the situations. Thus, there is a need to develop a protocol/tool to assist utilities in selecting appropriate condition assessment technologies for water and wastewater pipelines.

1.6 Objective and Scope

Most of the world's pipeline utilities work in an information vacuum. The major reason for this is a lack of awareness about the latest technologies available to provide better information regarding the structural and operational condition of the pipes. This lack of awareness leads the utilities to implement less effective technologies, which result in unreliable data. The primary objective of this research is to develop a framework for decision support system to assist utilities in selecting appropriate condition assessment technologies for assessing the condition of their pipeline assets. The objectives of the research project specifically are to:

- Develop a state-of-the-art literature review for non-destructive and commercialized condition assessment technologies available for water and wastewater pipes.
- Determine the parameters, which contribute to the performance and economic analysis.
- Develop a simple way to compare these technologies.
- Collect the data for various technologies from available literature and evaluate the collected data from the technology providers.
- Centralize the data for each technology so it could be readily available to anyone.
- Develop a decision support system to assist the utility manager in selecting the condition assessment technologies for water and wastewater pipelines.
- Ensure that the tools could be adapted as more technologies are developed or used as part of the asset management process.

The framework for decision support system needs to be based on the facts while also taking into account the proven results from use of the technologies. Thus a performance and economic evaluation of the technologies was developed considering various factors including but not limited to:

- The surrounding characteristics;
- The utility characteristics;
- The ease of setup;
- The ease of data analysis and processing; and
- The performance specifications like mobility rate and range.

This project assumes that **Step 5** of the 10-step condition assessment design process, as shown in Figure 2, has been completed which means that the need to assess the condition of pipes has already been established and the assets to be inspected are already determined. The various technologies considered for this tool are discussed and listed in Chapter 3.

1.7 Thesis Organization

This section explains the organization of this thesis. The purpose of this section is to enhance the level of understanding and readability of this thesis.

Chapter 2 presents a literature review of the state of the condition assessment technologies for water and wastewater pipelines. This chapter provides a brief description of each technology followed by working principles and the science behind the application and data analysis of the technology.

Chapter 3 presents the parameters selected for evaluating the feasibility, performance and economic indices. This chapter also explains the underlying rationale for selecting these parameters and their significance in calculating the indices.

Chapter 4 presents an overview of the CAST. It begins with a brief background regarding the software requirement and layout of CAST. It then introduces a graphical user interface which gathers the project specific information regarding various parameters. The chapter also explains the master-list or database of all the technologies that are accounted for in this research. Next, it explains the rationale of these parameters in calculating the various indices. Last, the chapter explains the process for calculating performance and economic indices on the basis of the information collected from the users of CAST.

Chapter 5 presents a case study on Acoustic Fiber Optic Sensor Systems (FOSS). It begins with a brief overview of Prestressed Concrete Cylinder Pipelines (PCCP), modes of failure and mechanisms and FOSS technology. It then briefly introduces a concept of acoustic emission based condition assessment technologies, signal features and signal processing methods. Next, it reviews the data collection and analysis of these signals to identify the underlying, unexplored potential of FOSS to monitor the structural performance of the pipes. This chapter highlights the existing knowledge gap regarding the capabilities and limitations of the technology.

Chapter 6 presents a summary of the research, advantages and limitation of CAST. It also provides suggestions for future research.

Chapter 2- Literature Review

There is a gamut of technologies available for assessing the condition of water and wastewater pipes. This section describes the technologies that are already commercialized and substantial data regarding performance and economics are available. The information about these technologies are collected through various sources like research reports, case studies, technology providers and research papers etc. The descriptions below are not a critical review of the technology's capability, but merely a summary of how the technology works and a brief explanation of science behind them. The description of the condition assessment technologies provided below are in no specific order. The condition assessment technologies can be broadly classified on the basis of type of failures being assessed by the technology. Figure 3 illustrates the classification of the condition assessment technologies

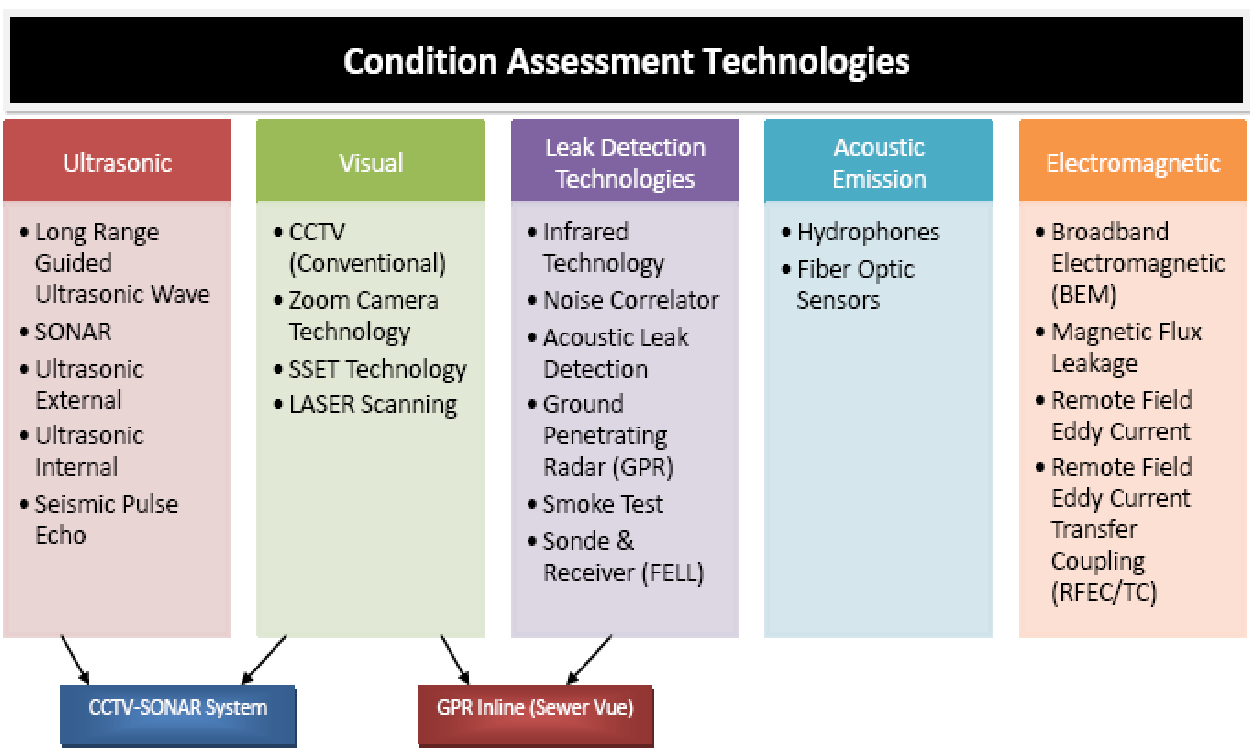

Figure 3: Classification of Condition Assessment Technologies

The classes of condition assessment technology as shown in Figure 3 are defined as follows:

Ultrasonic: These are the technologies, which are based on a transducer and receiver mechanism. The transducers produce ultrasonic signals, which are then reflected from the deformities or surfaces caused by structural or corrosion failure. The time between sending and receiving the signal is analyzed to understand the thickness of the pipe or other deformities.

Visual: These technologies capture visual images of pipes internally using a camera. These visual images are then analyzed for determining the structural condition of the pipe.

Leak Detection Technologies: These are the technologies, which are specifically designed to locate and identify leakages in pipes. The technologies categorized in this class are based on various operating principles.

Acoustic Emission (AE): These are the technologies which are designed to identify and locate wire-break events in PCCP.

Electromagnetic: These are the technologies which are designed to determine structural or corrosion related failure. These technologies also operates or transducer and receiver mechanism.

2.1 Acoustic Leak Detection- Inline

It is a type of non-destructive technology in which acoustic sensors are passed along the pipeline while in service. These sensors detect the sound emanated by the leakages in pressurized water pipes.

The most widely used leak detection system is noise correlator, but at any significant distance from location of leakage, the leak noise signal is swamped by background noise. This led to the invention of inline Acoustic leak detection equipments; they can be either tethered or free-swimming (Najafi and Gokhale, 2004). This technology can be used to detect and precisely locate the leaks in the pressurized pipes without rendering them out of service. This can be used for both water mains and force sewer pipes greater than 10 inch in diameter (Mergelas et. al., 2007). Leaks are often a precursor to larger problems. Thus, if a leak is detected and mitigated before it becomes critical, a large problem or catastrophic failure can be prevented (Holley, M. Personal Communication, 2009). The rate of data collection is rapid and the equipments have shown excellent applicability in detecting:

- Leaking joints.
- Weld leaks.
- Pinhole leaks as small as 0.005gal/min.
- Condition assessment as well as evaluation.

- Map the pipes.
- The tethered system is also capable of video inspection.

The amplitude and frequency of noise depends on a variety of factors vis-à-vis the pipe material and internal pressure. Leaks generally make three sounds, a medium frequency sound, 500-800Hz associated with water passing through orifices, and two low frequencies in range 20-300Hz, associated with the water stream impacting soil and circulating outside the pipe (Najafi and Gokhale, 2004). The proprietary software is capable of automatically plotting the signals using the spectral energy and amplitude.

2.2 Acoustic Leak Detection- Noise Correlator

It is a type of leak-detection technology, using computer based devices (acoustic sensors) which measure sound or vibration at two points on a pipe, on either side of a suspected leak. The acoustic sensors are generally attached to the pipe contact point (normally fire hydrants). Signals detected by the sensors are wirelessly transmitted to the correlator which pin points the location of the leak signal measured from the two adjacent sensors, on the basis of time-lag and sensor-to-sensor spacing (Hunaidi, 2000). These sensors detect the noise emanated by the leakages in the pressurized water pipes.

These sensors can also be attached for a long duration; certain equipments available in industry are capable of recording and transmitting data up to 10 years. The principle of this technology is similar to other acoustic leak detection technologies except for the fact that the signals are picked up by the acoustic sensor attached to the pipes; these signals are transmitted to a nice correlator, which than correlates signals from the various sensors using Fast Fourier Transform or other methods of spectral analysis to pinpoint the location of the leakage.

2.3 Acoustic Emission Testing

It is a type of non-destructive technology in which acoustic sensors are placed along the pipeline, and the energy that is released when a pre-stressing wire breaks or slips is recorded and the origin location is calculated. Wire breaks and slips both indicate the presence of distress and loss of strength in compression and are referred to as wire related events (WRE). This technology helps in locating which of the PCCP that are actively deteriorating, if any, is a key step in determining the condition of the main (Mergelas et. al., 2007).

The available, commercialized systems monitor the pipe using accelerometers or hydrophone arrays or advanced fiber optic sensors. Following an acoustic event, the recorded signals are analyzed and compared to an existing database to determine the nature of the event. Monitoring PCCP by means of AE may not be very accurate because the method is restricted to detecting ongoing wire breaks, and cannot detect already broken wires (Wardany, 2008).

PCCP is reinforced by spirally wrapping high strength steel wire around a concrete cylinder. This wire is critical for the structural integrity of PCCP as it maintains the cylinder in compression. Often, these wire starts to fail, which translates to imminent failure of a pipe. When this wire-break fails the stored energy is released in the form of sound energy - this energy travels through the pipe core into the water column within the pipe. If the deterioration persists, the wire keeps slipping and breaking, releasing more energy in a series of discrete events that can be detected by the acoustic sensors or accelerometers. The origin of the acoustic event is located through the precise identification of the arrival times of these signals at a series of sensors. Sound travels through water at a known and constant speed of approximately 4850 feet per second. The time it takes to reach the sensors is dependent directly on this speed (Galleher, 2007). In case of fiber optic sensors, the origin of the acoustic event is located through the precise identification of the arrival times of these signals at the optical cable.

The basic principle of FOS is Optical Time Domain Reflectometry (OTDR). It is defined as the process in which a pulsed pump light that is launched at one end of an optical fiber counter propagates with a probe light launched at the other end. The probe light is amplified by the pump light through the Brillouin Scattering Process and the distributed strain along the optical fiber is obtained from Time Domain Analysis of the probe light. The spatial resolution can be improved by using the correlation between pump and probe lights modulated both in frequency and phase.

2.4 Broadband Electromagnetic (BEM)

It is a type of non-destructive technology to inspect ferrous pipes. This technology uses Electromagnetic or Eddy current to detect corrosion and provide information on thickness (Black & Veatch, 2010). The technology is independent of frequency and thus immune to any type of electromagnetic interference (USEPA, 2009). It can detect both the internal and external defects. The technology works only for ferrous pipes and thus has limited applications in sewer pipes.

This technology was developed by Rock Solid Pty Limited for use in Australian mineral exploration industry. The technology has been modified to be used in pipeline inspection, and has been used in US and Europe. The technology is an electromagnetic technology, but it differs from eddy current technology (ECT) as it is frequency independent, thus rendering much flexibility to the system.

BEM works by generating a pulsed eddy current (an induced electric current that flows in a circular path containing a continuum of frequencies) that propagates through the metal and is detected by a receiving probe adjacent to the exciting probe. Apart from measuring wall thickness, BEM can also detect cracks and other anomalies (Stubblefield et. al., 2008). It differs from other electromagnetic inspection by being independent of frequency. Instead of providing point readings, this technology scans the entire exposed surface and averages readings over two inches square. Since the readings are averaged, only estimation of wall-thinning can be reported (Ratliff et. al., 2009).

Typically, the operator establishes a rectangular grid and moves the antenna around, taking successive readings which are stored on the computer. The signals require intensive post-processing using proprietary software which generates contour maps, which is then interpreted to provide data on apparent wall thickness, evidence of corrosion and other parameters.

2.5 Ground Penetrating Radar (GPR)

It is a non-destructive geophysical method that produces a cross-sectional profile or record of sub-surface features. The system operates by transmitting the pulses of ultra high frequency radio waves down into the ground through a transducer. The transmitted energy is reflected from various buried objects or distinct contacts between various materials. The conventional GPR systems are generally operated from the surface, but the new systems can be used inside the pipe to determine the surrounding soil condition, the soil-pipe interaction and the structure of the pipe respectively (Costello et. al., 2007). The time lag between transmitted and reflected waves corresponds to the depth or the distance of the reflecting object. For leakage, the GPR is used from the surface and it looks for the voids around the pipe created due to saturation of leaking water (Misiunas, 2005). For the external defects of the pipe like corrosion or delamination in concrete pipes, the inline GPR detects the reflected signals from the targets of different dielectric properties.

The GPR is moved across the ground surface above the pipe or inside the pipe to create a 2D profile of the area. The profile can then be analyzed by the operator to identify features of importance. GPR uses high frequency electromagnetic (EM) wave to acquire subsurface information. EM wave travels at a specific velocity that is determined primarily by the electrical permittivity of the material. The velocity is different between materials with different electrical properties, and a signal passed through two different materials of different permittivities over the same distance will arrive at different times. As the antennas are moved along a survey line, a series of traces or scans are collected at discrete points along the line (USEPA, 2000). The depth of penetration is dependent on soil type and on the wavelength of the EM wave. There is a compromise in the depth of penetration and the resolution of the data (Makar, 1999). The amplitude of each pulse received by the GPR unit is recorded on a time scale giving a vertical plot for each pulse (trace). A series of these traces are taken and colors or Grey scale are allocated to the amplitude of each. The colored traces are then placed along a distance scale and a 2D profile is created (Chen, 2010).

The detection of void or leakages in the GPR survey is based on the hypothesis that the variable moisture content of soil is a major contributing factor to dielectric variation. GPR operates by emitting EM radio impulses into a medium at a high repetition rate, from an antenna array moved along the surface of the pipe inside the pipe. Reflection occurs at interfaces of the materials with different electrical characteristics. An experienced operator is necessary to interpret this data to determine the significance of the collected data.

2.6 Infrared Thermography (IR)

It is a type of non-destructive technology for defects like leaks and voids. This technology involves the use of an infrared camera to measure the temperature difference across an object. Infrared Thermography is also a remote sensing (no contact) technology and has proved to be an effective, economical and efficient method for detection of leaks and other anomalies in pipelines. The technology is one of the several technologies recognized by the American Society of Non Destructive Testing (ASNT) (Amirrato, 1999). The technology was developed in Germany, and is currently used in US, Europe, and Canada; the technology was developed for manufacturing plants.

This technology can be used to determine the location of leaks from cracks and joints qualitatively; the results from this method needs to be evaluated and confirmed using other methods. This can be used for any type of pipe and for all diameters. The technology is based on the energy transfer theory, which states that energy transfers from warmer to cooler areas. The technology is completely non invasive and remote sensing in nature. Thus, it is not affected by any parameters related to pipe or soil conditions. An infrared scanner, sensitive to infrared wavelengths is used to measure variations in temperature, which in turn are converted into thermographic images in which objects are represented by their thermal rather than optical values (Costello et. al., 2007). Caution must be taken as IR cannot determine the comprehensive structural condition of the pipe. Caution must also be taken to ensure the flow of energy from pipe to earth or vice versa (Weil, 1994). The IR scanner can be mounted on the top of a van or an aircraft, depending on the project-specific need (Weil, 1994).

The IR Technology is based on detection of the flow of energy. The thermal images taken with an IR camera measure the temperature distribution at the surface of the object at the time of the test. The water has different thermal characteristics than the pipe material and surrounding soil. The leaking water will affect the thermal characteristics of the surrounding soil, i.e., make it a more effective heat sink than the dry soil (Misinuas, 2005).

2.7 Internal Visual Technologies

It is a type of non-destructive technology which determines the internal condition of pipes. Examining the interior surface of the pipe wall is a standard practice for sewer inspection. Many technologies are available to determine the internal damage to the pipe walls like deformation, cracking, delamination, etc. (Rajni, 2004). The most popular of these technologies is CCTV surveys which use a camera mounted on a remote-controlled tractor arrangement. There are number of variations of CCTV which are cost-effective or enhance the performance of the system. Various authors have studied and compared these technologies in past like (Makar, 1999) and (Iyer, 2007). The variants of this technology are as follows:

CCTV

There are two basic types of CCTV system; each uses a camera, source of illumination, video monitor and other recording devices. In one case the camera is mounted on a mobile, robotic arrangement (Conventional CCTV) and in other case the inspection is performed using a stationary camera mounted at manhole (Zoom Camera). Both the technologies are vulnerable to miss out defects like slight deformation, and defects hidden due to obstruction. These types of technologies are also vulnerable to operator/inference errors. The CCTV mobile system is the most widely used inspection tool used for sewer inspection. The cameras are transported through pipes using self-propelled crawlers. The camera is movable and has the mobility to zoom, pan and tilt. This system relies on a camera operator to concentrate in critical areas for further review. The images captured by the camera are stored for further investigation by operator or specialized automated software. Zoom-Camera inspection is generally much faster in operation as it uses a single operator to lower down the camera inside the manhole which uses the zoom characteristics to inspect the pipe. This technology is generally used to screen and prioritize the pipes which need detailed inspection using other variants of CCTV method; this method doesn't provide detailed evaluation of CCTV but it doesn't require cleaning of the pipes either. It can be used only to inspect pipes which have manholes like gravity sewer.

Laser Profiling

This technology creates a ring of laser around the pipe wall. This technology is generally used in conjunction with CCTV cameras and uses the reflection of laser from different surfaces to determine the change in pipe shape due to deformation, sedimentation etc. This method can be used only in the dry areas. Figure 3 illustrates the Laser Profile Scanning equipment. Laser profiling is used in conjunction with CCTV and it uses a ring of laser to assess the shape of the pipe wall or any change caused by deformation, sedimentation and corrosion etc. This can also be used to create a 3D model of the pipeline. This technology can be only used in a dry portion of a pipe and thus requires complete dewatering before inspection.

SSET (Sewer Scanner and Evaluation Technology)

It is the latest variant of this technology, provides the engineer with the capability to see the total internal surface of the pipe, along the length of the pipe with use of optical scanners and gyroscopes. Unlike CCTV inspection, SSET doesn't have to stop to allow closer inspection of the defect. SSET systems are similar to CCTV system but they only have one or two high-resolution cameras with wide-angle lenses in front, or front and rear. The hemispherical images scanned are put together to form a 360 degree image. The major advantage is that it is possible for data to be assessed independently of the real-time sewer inspection. The SSET develops a complete digital image of the pipe segment, which allows the reviewer to control the direction of pan, zoom and tilt while analysis. The inner pipe surface can be unfolded providing a complete review of the surface area of the pipe wall. This permits use of CAD based software to measure the defects and objects.

2.8 Magnetic Flux Leakage (MFL)

It is a type of non-destructive technology to inspect ferrous pipes (conductive CI and Steel). This technology was developed specifically for oil and gas pipelines. The technology can work mainly on the external surface of the pipes in water and wastewater industry as most of the pipes have tuberculation, debris or lining, while this technology requires close contact with the surface. MFL depends on the ferromagnetic nature of the object being inspected.

This technology can be used to determine the corrosion or wall-thickness of both water and wastewater pipelines. This can be used for any ferrous pipes and for all diameters 2 to 56 inches (USEPA, 2009). The technology is non-invasive therefore, this can be performed without disrupting the supply. The technology cannot be used as a pig in case of water and wastewater pipes as it requires close contact with the surface of the pipe wall which is not feasible due to presence of tuberculation/ lining or debris. The exact location, size and shape of the defect can be determined.

MFL relies on active magnetization in which the pipe wall is magnetized to near saturation by using strong permanent magnets. These magnets induce a direct current (DC) magnetic field into the pipe wall so that the field travels the same direction as pipe axis. Wherever a corrosion pit is present, a small amount of magnetic strength will leak into the ground and causes a local perturbation of the magnetic field distribution. These leakages can then be detected by the magnetic sensors on the equipment (Makar, 1999).

2.9 Remote Field Eddy Current (RFEC)

It is a type of non-destructive technology to inspect ferrous pipes (CI/DI/Steel). This technology was developed to surmount the limitation of Eddy current technology that limits its detection of defects to those on the surface of pipe nearest to the magnetic coil. RFEC can detect both the internal and external defects. RFEC involves the deployment of a probe consisting of multiple magnetic coils, an exciter coil and a detector coil. This technology uses low-frequency alternating current (AC) and through-wall transmission for inspection of pipes.
This technology can be used to determine the internal and external condition of both water and wastewater pipelines.

This can be used for any ferrous pipes and for all diameters 2 to 20 inches (Russell, 1997). Depressurization and dewatering is required to enable the use of this technology. The cleaning of the pipe is also required to some extent, the equipment is inserted though fire hydrants. The technology is capable to work in both wet and dry conditions. The technology can work in presence of lining unlike MFL and ECT. The technology is in form of probe having the magnetic coils exciter and detector sensors. The equipment is generally tethered. The process of data collection is relatively slow, but is compensated by high accuracy in presence of liners and other depositions up to 1 inch. In this technology, the probe is placed inside the pipe so that the axis of pipe and axis of coil are parallel (Makar, 1999).

RFEC method in its simplest form has a circular emitter coil that is placed inside the pipe. A detector signal is also put inside the pipe at a distance approximately two times the diameter of the pipe. Passing an AC through the coil produces a magnetic field that can reach the detector sensor coil by two paths. The first is inside the pipe through the water column, while the second is through the pipe wall near the emitter, outside the pipe and then back through the pipe wall. In the first case the attenuation of signal is very rapid as compared to the latter case (Makar, 1999).

The attenuation of the signal through outside of the pipe depends on the thickness of the pipe wall and thus the signature of these changes enables the determination of pipe wall thickness (Rajani and Kleiner, 2004). This property allows corrosion pit, wall thinning and some forms of cracks etc. The commercially available equipments have various options to collect data. The first option is that the RFEC equipment is connected to the base station using a cable and the data is collected in the real-time. The other method is in which the data is collected and recorded by the equipment of a memory device which is downloaded to a computer using USB or Bluetooth technology.

2.10 Remote Field Eddy Current- Transformer Coupled (RFEC/ TC)

It is a type of non-destructive technology to inspect PCCP. This technology is a mobile electromagnetic method that identifies and quantifies the broken pre-stress wires within the concrete pipe to determine whether pipe segment need further monitoring, repair or replacement (EPA, 2009). Locating and quantifying the distress of the PCCP pipes is a key step in determining the condition of the main.

The RFEC/TC can be compared to a radio transmitter and receiver system. The pre-stressing wires act as an antenna, boosting the signal. If the wires are broken, the received signal will be distorted. By measuring and calibrating the signal distortion the number of wire-breaks can be accurately determined (Catalano, 2009).

This technology establishes the baseline condition of PCCP. RFEC/TC provides the information about the location, distribution and number of wire-breaks to the water and wastewater system. This can be used for all diameters greater than 16 inches (AWWARF, 2004). Depressurization and dewatering is required to enable the use of this technology. The RFEC/TC mobile equipment comes with various options like walker, rider and ranger depending on the diameter of the pipe. The process of data collection is rapid; the rate of data collection can be 3 feet per second. If manned, the inspection team monitors the data quality as the inspection progresses. Calibration is a very important process as it enables the precise quantification of wire-breaks in a pipe. Though the wire-breaks can be identified instantaneously, detailed report and precise analysis requires 2-4 weeks (Elliot and Mergelas, 2002). The technology can be used for long-term strategic inspection to monitor the rate of increase of wire-break. This rate of increase of wire-breaks can be used to assess the frequency of inspection on the basis of assumptions regarding the operating condition of pipe it is possible to predict the maximum permissible number of wire-breaks before the pipe enters a high priority class (Mergelas et. al., 2001).

RFEC is a 'through-wall transmission method'; of the two coupling paths between the exciter and detector, the most significant path is the 'indirect path' that passes through the pipe wall. The direct path is attenuated by circumferential eddy currents induced in the pipe's wall. The field of the 'indirect path' diffuses from the exciter through the wall of the pipe and is attenuated and phase shifted in the process. It then travels along the outside of the pipe wall with reduced attenuation and diffuses back in. This area where the field from outside the pipe is greater than the field inside the pipe is named the "remote field region". Anomalies above the exciter or detector will create changes in the received signal (Mergelas et. al., 2001).

Fortunately, the prestressing windings around the steel cylinder of a concrete pipe have a transformer coupling (TC) effect. This effect can be understood as an interaction between the indirect transmission path and the external winding of the prestressing wire in PCCP. When the external windings are excited by the AC signal, the windings behave as a solenoid coupling flux between the exciter and detector. Thus, the signal received in a RFEC/TC system has two components; the first involves the steel liner and the second involves the prestressing wires. The remote field component will show a phase shift and attenuation consistent with the double through wall transmission of the field through the thin steel cylinder and is relatively small. The larger transformer component will dominate the response as a result of the solenoid coupling flux caused by the pre-stressing wires. This component is reduced in the presence of broken prestressing wires which allow the broken wires to be identified, recorded, and located along the pipe's longitudinal axis. The pre-stressing winding acts as a closed coil, linking the detector and exciter inductively. A broken wire disrupts the electrical continuity of electromagnetic fields created by the RFEC effect and the TC effect. The RFEC and TC effects combine and a broken wire acts as a clear disruption in the continuity of the overall electromagnetic field. This result in the distortion of the signal received at detector, which is a clear indication of broken wires. The calibration of signals ensures precise quantification of broken wires (Galleher et. al., 2008).

2.11 Remote Field Eddy Current- Transformer Coupled (RFEC/TC) Inline/In-service

This technology can be used to determine the baseline condition of PCCP, without disrupting the service. This can be used for any type of PCCP 24-48 inches. This free-swimming RFTC equipment can be inserted into a live pipeline via 1) a hot tap connection and insertion sleeve, 2) an existing access, or 3) a submerged tank or reservoir. The movement of the equipment and location is monitored from the checkpoints on the surface. The process of data collection is rapid; the rate of data collection can be 3 feet per second, and the range is as large as 22 miles.

Calibration is a very important process as it enables the precise quantification of wire-breaks in pipe. Though the wire-breaks can be identified instantaneously, detailed reporting and precise analysis requires 2-4 weeks (Elliot and Mergelas, 2002).

The technology can be used for long-term strategic inspection to monitor the rate of increase of wire-breaks. This rate of increase of wire-breaks can be used to assess the frequency of inspection on the basis of assumptions regarding the operating condition of pipe it is possible to predict the maximum permissible number of wire-breaks before the pipe enters a high priority class (Mergelas et. al., 2001).

Upon completion of an inspection, the data is immediately downloaded and its integrity is validated. On site analysis is also possible but the typical analysis process includes two highly trained experts for complete analysis. The distorted signals are matched to an extensive signal library to ensure accuracy in analysis. The end-user receives a report summarizing the condition of the pipeline which pipes have distressed wires, the location of distress and quantification of broken wires. The calibration is thus an important procedure for ensuring bet quantification results. The principle and basis of the application of this technology are same as that of RFEC technology.

2.12 Smoke test

This technology was developed in 1961 as a way to locate sewer faults at a low-cost. It has proven to be an extremely effective method for pin-pointing sources of inflow and other sewer line problems in both existing and new collection systems. In Smoke Test two sections of line (600-800 ft.) are tested simultaneously, with the smoke being introduced through a centrally located manhole. Blocking the far side of the upstream and downstream manholes is only necessary when isolating a section of the line. The smoke under pressure will quickly fill the main plus all connected lines, and follow the path of least resistance. It will flow through all openings to the surface, revealing the location of the faults. Invariably, the fault will be found at the site or within a few feet of it. Only enough pressure to sufficiently overcome atmospheric pressure is required (Misinuas, 2005).

Smoke tests are effective regardless of surface, type of soil, or depth, provided openings exist for the smoke to follow. For example, it is not uncommon to see smoke exiting from cracks in paved surfaces, showing points of surface water entry. The blower should not be started over the manhole because of the possibility of igniting flammable vapors in the line. The blower should be started first and then placed over the manhole. In less than a minute, smoke will be issuing from the roof vents of buildings connected to the line. If plugs are being used, do not tighten them before the smoke has fully penetrated the line, otherwise trapped air may prevent complete penetration (Najafi, 2005).

The crew should check buildings, grounds and streets for telltale signs of smoke. Smoke immediately backing up into the blower indicates a line blockage. If this should occur, testing should be discontinued until the line has been cleared. Smoke issuing from the ground, pavement, yards, roof-drains, etc., shows sources of inflow. Smoke from either smoke bombs or a liquid smoke system is forced into the system at manholes using specially designed fans. The smoke escapes from the system at house vent pipes, illegal connections, and leakages allowing them to be identified (Costello, 2007).

2.13 Sonde & Receiver or Focused Electrode Leak Location (FELL)

Sonde & Receiver is a type of non-destructive technology to inspect and quantify leaks in non-ferrous pipes. This technology measures the flow of electric current between a probe that travels in the pipe (Sonde) and a surface electrode (receiver). Pipe defects related to I/I cause a spike in the electric signal. The technology is performed inside the pipe but don't require putting the pipe of surface as this technology can only perform in surcharged situations (Moy, 2006).

This technology can be used to determine the location of leaks from cracks and joints as well as the quantification. This can be only used for non-ferrous pipes and for all diameters 3 to 60 inches. The technology needs the Sonde to be submerged. Thus, it works well for sewer mains but not for gravity as it requires the sewer pipe to be surcharged. The technology can work in presence of lining. The Sonde is in the form of a special electrode that creates an electric field in a radially outwards direction. The receiver is a metallic stake that is inserted in the ground at the surface. Sewer-electro scanning locates pipe defects by measuring the electrical resistance of the pipe wall. Most sewer pipe materials such as clay, plastic, concrete, reinforced concrete and brick are electrical insulators that have high resistance to electrical current. A defect in the pipe that leaks water will also leak electrical current, whether or not water infiltration is occurring at the time of the test (Harris, 2004 & 2006).

A fixed electric voltage is applied between an electrode in the pipe, called a Sonde, and an electrode on the surface, which is usually a metal stake driven into the ground. It is needed to keep the pipe is full at the Sonde location. The electrical resistance of the current path between the Sonde and the surface electrode is very low except for through the pipe wall. The high electrical resistance of the pipe wall prevents electric current from flowing between the two electrodes unless there is a defect in the pipe, such as a crack, defective joint or faulty service connection (Harris, 2004 & 2006).

2.14 Ultrasonic Inspection Technologies (Continuous)

Ultrasonic Inspection is a type of Non Destructive Technology with different variations for inspecting ferrous pipes and non-ferrous pipes. This technology is conducted by sending high frequency acoustic waves into an asset and evaluating any echoes. Variations of this method have been used widely for thickness measurement, corrosion monitoring, delamination, sedimentation or debris, and flaw detection (WERF, 2006). The detection of flaw is based on the reflection of the wave from the interface between materials of different properties. The acoustic waves get attenuated very fast in air. Thus, it’s very important that the transducer is in close contact with the pipe or there is another medium like water in which the attenuation is relatively low.

This technology can be used to determine the internal and external corrosion of pipelines. Depressurization and dewatering is not required to enable the use of this technology as this is a non-invasive technology. The cleaning of the pipe is also very critical as the probe requires close contact with the surface of the pipe (Birchall, 2007).

In general, UI equipment has an oscillator circuit that sends electrical pulses to a probe. The transducer in the probe produces ultrasonic vibrations when it receives the electrical pulse. A range of vibration frequencies can be chosen between 100 KHz and 15 MHz depending on the specific application. For example, typical frequencies used in weld examination are between 2 MHz and 5 MHz; a small amount of the energy is reflected back to the probe, where it vibrates the piezoelectric crystal, generating an electric current. This current returns to the flaw detector, where it is amplified, rectified, filtered and displayed. The ultrasonic pulse can be generated by a variety of sources like piezoelectric exciters, transducers etc. In the case of Long Range Guided Ultrasonic Waves (LRGUW), waves in the frequency range of a few hundred Hz are used. The range of LRGUW is typically 100 feet in an ideal situation. The technology works well for steel pipes.

Guided waves refer to mechanical (or elastic) waves in ultrasonic and sonic frequencies that propagate in a bounded medium (such as a pipe, plate, rod, etc.) parallel to the plane of its boundary. The wave is termed "guided" because it travels along the medium guided by the geometric boundaries of the medium. Since the wave is guided by the geometric boundaries of the medium, the geometry has a strong influence on the behavior of the wave. In contrast to ultrasonic waves used in conventional ultrasonic inspections that propagate with a constant velocity, the velocity of the guided waves varies significantly with the wave frequency and the geometry of the medium (Lowe, 1998). In addition, at a given wave frequency, the guided waves can propagate in different wave modes and orders. The long-range guided wave inspection involves: (1) installing a guided wave probe or sensor on the structure under inspection, (2) generating a short pulse of guided waves in the structure, and (3) detecting waves that are reflected from defects in the structure as the generated guided waves propagate along the length of the structure. From the occurrence time of the defect signal and the signal amplitude, the axial location and severity of the defects are determined (Lowe, 1998).

2.15 Ultrasonic Inspection (Discrete)

This technology can be used to determine the internal and external condition of both water and wastewater pipelines. The variations of this technology can be used for any type of material and any diameter (USEPA, 2009). Depressurization and dewatering is not required to enable the use of this technology as any air gap in between the surface and probe attenuate the signal. The equipment can be used either from inside (Sonar, Pulse Echo, Seismic Pulse Echo) or outside (Pulse Echo) (Birchall, 2007).

In general, UI equipment has an oscillator circuit that sends electrical pulses to a probe. The transducer in the probe produces ultrasonic vibrations when it receives the electrical pulse. A range of vibration frequencies can be chosen between 1 MHz and 15 MHz depending on the specific application. For example, typical frequencies used in weld examination are between 2 MHz and 5 MHz; a small amount of the energy is reflected back to the probe, where it vibrates the piezoelectric crystal, generating an electric current. This current returns to the flaw detector, where it is amplified, rectified, filtered and displayed. The inspection is done in real-time and the data is collected on a hard drive (Stubblefield, 2008).

The time interval between the first echo (front wall) and second echo (back wall) is the measure of wall thickness. As the mirror rotates, the probe takes 360 readings circumferentially. The probe can perform inspection at the rate of 6 feet per min.

Another variation of this technology requires the probe to be in close contact with the pipe wall to induce the pulse wave. This method requires cleaning of the pipe very carefully in order to get precise information about the pipe wall thickness. One more variation of this technology is seismic pulse echo which is only applicable for PCCP and requires man entry into the pipe. In this method, the impact from a metal sphere is used to generate acoustic waves which are collected by an array of sensors. Currently, the technology can work only for pipes greater than 54 inches and can inspect at a rate of 3feet per minute through clean pipe. This can detect the base line for PCCP wire breaks, delamination and cracks.

Proprietary software is utilized to do the analysis of the data collected. The software is capable of giving the complete information regarding the thickness measurements of the wall. The signal received is similar to the A-scan, where the horizontal axis represents distance and vertical axis represents amplitude, which is indicative of the severity of the corrosion.

Chapter 3- Parameters for Technology Evaluation and Data Collection

3.1 Background

In order to develop a framework for decision support system to assist utilities in selecting most appropriate condition assessment technologies for assessing their pipeline assets it is necessary to collect and compile data pertaining to the performance and economics of CAT. To enable the process of data collection it is vital to understand the parameters that are critical for evaluating the feasibility, performance and cost of CAT. This chapter discusses various parameters that have been selected for evaluating CAT and explains their relevance to the overall framework of the decision support system. As explained in section 1.4.1, a protocol developed by WERF Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets is identified as an excellent framework for selecting CAT for their assets. Figure 4, illustrates the classification of parameters for evaluation of CAT. This section also discusses the method of data collection for this study.

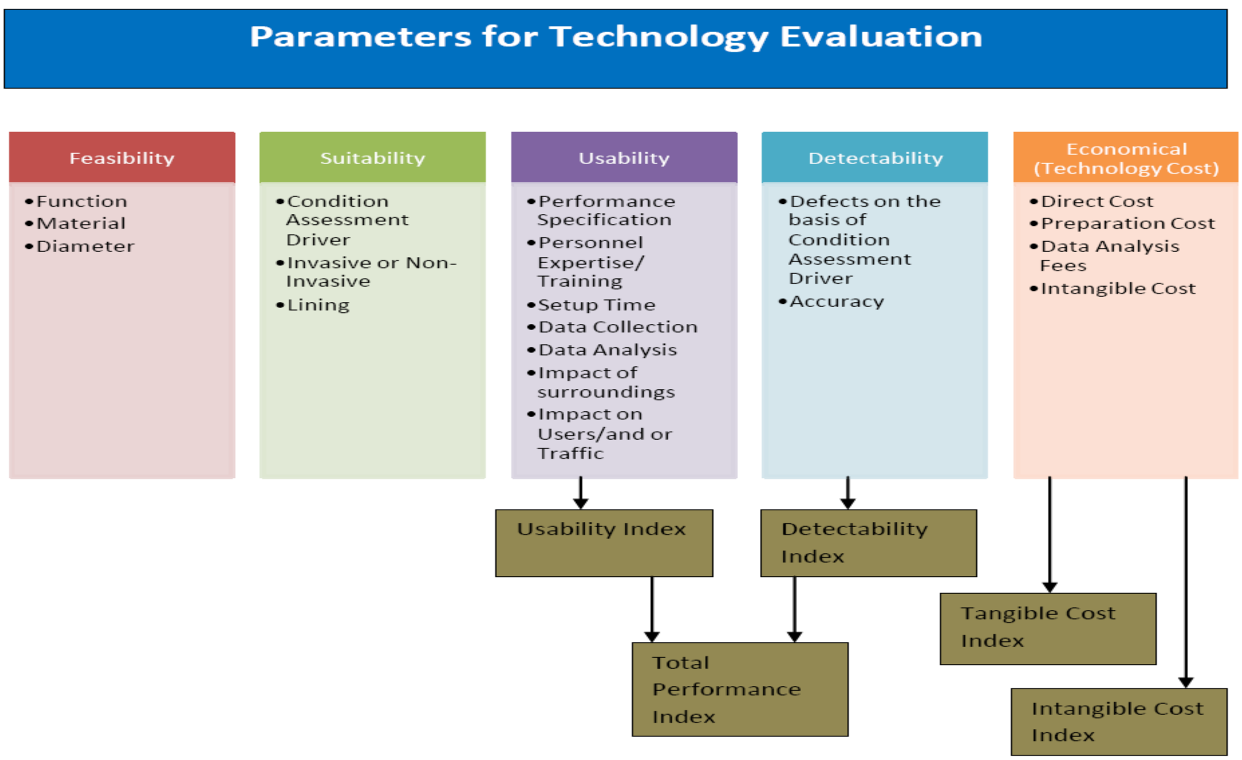

Figure 4: Classification of Parameters for Technology Evaluation

3.2 Feasibility Parameters

These are the parameters that determine the viability of a technology for the asset(s) in question. The various parameters considered for this purpose are listed below

3.2.1 Function

Most of the technologies are specifically designed to work for water supply system or wastewater collection system. The systems are defined as follows:

3.2.1.1 Water Supply System

The purpose of water supply system is to deliver water from the source or treatment facility to the customer (Misinuas, 2005). The size and complexity of this may vary. The objective is to provide safe and potable water for domestic use, and sufficient pressure for fire protection and industry etc. The water supply system can be divided into three major parts:

Transmission

It consists of components that are designed to convey large amounts of water over great distances. Water transmission pipelines usually have diameters above 12 inches. The length of the pipe can vary significantly. Pumps may be used to transport water from one facility to another. Individual customers are not served directly through transmission mains (Misinuas, 2005).

Distribution System

The water transported in transmission pipelines to the residential areas is distributed through the water distribution system. Generally, a distribution system has a complex topology and contains a large number of elements. Typically, distribution mains follow the general topology and alignment of the city streets. Pipes can be connected by junctions and form loops. Generally, every single branch in the distribution network has a stop valve at each end. Valves are installed for the purpose of isolation in case of a failure event or during maintenance work. They can also be used to reroute flows in the network, in some cases, the valves are closed permanently to establish pressure zones within the network or to form district metering areas (DMAs) (Misinuas, 2005).

Services Lines

They are the smallest pipes in the supply system and transmit the water from the distribution mains to the customers. Usually, service pipes have smaller diameter than distribution mains and run from the street to the property. Households, businesses and industries have their own internal plumbing systems to transport water to sinks, washing machines, and so forth (Misinuas, 2005).

3.2.1.2 Wastewater Collection System

It is defined as the network of pipes and plumbing systems used to convey sanitary flow to a wastewater treatment facility for treatment before discharge to the environment. The wastewater collection system can be divided into three major parts:

Force or Force Main

It is a pressure line used to convey pumped sewage. A survey conducted by WERF indicated that force main comprises, on average 7.5% of a collection system. The most common pipe material for force mains are Cast Iron and Ductile Iron (EPA, 2009).

Gravity or Gravity Sewer

It 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. The minimum diameter of a gravity line is typically 8 inches. However, large interceptors can have diameters in excess of 12 feet. Older systems may contain 6 inch gravity lines (EPA, 2009).

Laterals or Service Lateral

These are the gravity lines that convey wastewater from a building 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 (EPA, 2009).

Appendix A summarizes the feasibility of CAT for various functions of pipelines.

3.2.2 Material

As mentioned in the previous chapter, there is a gamut of technologies available to assess the condition of pipelines. The different principles, upon which the technologies are based, render some technologies applicable for some of the materials and some for all the materials (Costello et. al., 2007). The material varies with the types of pipe which are listed as below:

3.2.2.1 Water Supply System

For large transmission pipelines steel or PCCP are typically used. Older water distribution mains are typically made of Cast Iron or Asbestos Cement, while the newer distribution pipelines are made of Ductile Iron or PVC (Misinuas, 2005). The service lines are steel, plastic and copper (AWWARF, 2009). Table 2 lists the material used for water pipelines used in this project.

3.2.2.2 Wastewater Collection System

Force mains are generally made up of ferrous materials, PVC, and PCCP for large diameter (>24 inches) pipes (WERF, 2007). Other materials that are used for gravity and lateral in addition to the materials stated above are vitrified clay, reinforced concrete pipe and bricks. Table 2 lists the material used to make the wastewater pipelines used in this project.

Table 2: List of Materials for Water and Wastewater Pipes

Water Supply System	Wastewater Collection System
Cast Iron	Cast Iron
Ductile Iron	Ductile Iron
PCCP	Steel
Steel	PCCP
Copper	Reinforced Concrete Pipe
PVC	Brick
Polyethylene	Vitrified Clay
Asbestos Cement	PVC

Appendix B summarizes the feasibility of CAT for the different pipe materials.

3.2.3 Diameter

The technologies as mentioned in Chapter 2 are designed to perform in a particular diameter range and don't work for pipelines of other diameters. The diameter ranges are thus classified according to the technology capability. Appendix C presents a complete list of technologies with the respective diameter ranges in which it can work.

3.3 Technical Suitability

The factors that determine the suitability of a condition assessment technology related to the specific needs of utility manager for their asset(s) in question. The three major factors that are taken into the consideration for determining the technical suitability of a technology are as follows:

3.3.1 Condition Assessment Driver

This is the parameter that is based on the objective or purpose of condition assessment established by utility managers for their asset(s) in question. This parameter tends to include the objectives that a utility manager wants to achieve using the condition assessment program. The objectives of a condition assessment program are classified on the basis of pipeline deterioration mechanism as most of the utilities are interested in assessing the condition of their asset(s) to identify a particular type of failure. The objectives of condition assessment are:

3.3.1.1 Structural Failure

The structural failures depend on the size of defect, soil type, corrosion, and loading etc. In most pipes, the structural failure often starts with minor defects like cracks or holes which lead to leakage and eventually corrosion of soil is initiated. The final result of structure failure is collapsing of pipe which is related to the cause of the deterioration. The various defects related to the structural failure are cracks, holes, fractures, and breaks etc.

3.3.1.2 Hydraulic Failure

The hydraulic failures are caused by Inflow/Infiltration (I/I) problems. These I/I problems reduce the planned hydraulic capacity of pipes, increasing the potential for collapse (Najafi and Gokhale

2004). The various defects related to Hydraulic failure are delamination, cracks, deformation, and breaks etc.

3.3.1.3 Operation and Maintenance Failure

These are the failures caused by the various defects like obstruction, delamination, corrosion, leakages, and exfiltration etc. These are the failures which created problems in daily operations and result in complaints from users due to turbidity, loss of pressure, and sewer backflow etc.

3.3.1.4 Leakage Failure

These are the failures which lead to loss of water due to leakages causes by break, cracks, holes, joint displacement, and fractures etc. This is a very important driver as most of the water utilities want to improve their performance on basis of reducing the leakages in their water pipes.

3.3.1.5 Corrosion Failure

Corrosion is the most important deterioration mechanism for ferrous pipes. Most of the defects start with corrosion or wall-thinning. For some utilities detecting the corrosion is the main objective of their assessment program (Najafi and Gokhale 2004).

3.3.1.6 Service or Quality Issues

These are the objectives which are guided by the experience of the users of the pipelines. This is considered separately because some utilities are driven towards condition assessment if the end users are facing some service or quality related issues like turbidity and loss of pressure, etc. For the purpose of this project, technologies for assessment of these factors are not considered.

3.3.2 Invasive/ non- Invasive

This parameter determines the suitability of a technology in functioning with or without interrupting the supply or function of pipelines. It depends on a variety of factors like availability of redundancy in a system, critical users e.g. hospital, security and schools and down time etc. Thus it depends on the utility owners to determine their preference for invasive (interruptive) or non-invasive (non-interruptive) technology. Appendix E illustrates the list of technologies and their behavior regarding interruption to supply/ function of pipe.

3.3.3 Lining Performance

This parameter determines suitability of a technology to perform with the liner inside the pipes, as some technologies can work with a liner and other require the liners to be removed in order to perform efficiently and effectively. This parameter also depends on utility owners to determine their preference for the technologies that require removal of liners or not. Appendix E illustrates the performance of various technologies with liners.

3.4 Usability

These are the parameters that help in determining the performance of technology regarding the operation, and the effects if any of the surrounding environment or structures. These parameters are further divided into seven sections as outlined below

3.4.1 Performance Specification

These parameters are intrinsic to technologies and are specified by manufactures and experiences in real world settings. These parameters include range and rate etc. A higher value of range means longer sections of the pipe can be inspected, while higher rate means lesser down time and faster inspection, the lower data analysis time refers to faster reporting of findings of inspection. Appendix F summarizes the performance specification of various technologies.

3.4.2 Personnel Requirement

These are the parameters that determine expertise level and training time required for performing inspection and/or analysis of the collected data. The lesser expertise level and training time required indicates ease in application of a technology by the user. Appendix G summarizes the personnel requirement for various technologies.

3.4.3 Set-up

These are the parameters that determine the ease in setting up a technology. These parameters include preparation level (mobilization, excavation, depressurization and cleaning etc.), preparation time required for a particular technology. The ease in setting up a technology makes a technology more efficient in comparison to other technologies. For the purpose of this project, only the set-up time is being considered. Lower setup time indicates easier use of technology. Appendix H summarizes the set-up time for all the technologies.

3.4.4 Data Collection

These are the parameters related to the data collection process. For the purpose of this project, only data collection time is considered. Lower data collection time indicates easier use of technology.

3.4.5 Data Analysis

These are the parameters related to the data analysis process. For the purpose of this project, only data analysis time is considered. Lower data analysis time indicates easier use of technology.

3.4.6 Impact of Surroundings

These are the parameters which determine the effect of surroundings like soil type, metallic structures, non-metallic structure, noise, surrounding utilities and ground water on the performance of a technology. Low or negligible effect indicates better usability of a technology because it means that the technology is relatively more immune to the surrounding properties and structures.

The soil classification has been adapted from Unified Soil Classification (ASTM D 2487). All the technologies except GPR have no effect of soil characteristics on their performance. The GPR cannot perform effectively in the soil like silt and clay (Hutchins 2010). Some of the technologies like noise correlator are affected by the presence of noise in the vicinity. The location of the pipe under the road is a major factor as it becomes difficult to access the technology if the pipe is under the road. Impact of the surrounding features on the technologies is summarized in Appendix I. The values provided are on the basis of inspection of 3000 feet of pipe in an ideal situation. The higher impact of surroundings on the performance of technology makes it less usable.

3.4.7 Impact on User and Traffic

Some technologies affect users relatively higher than other technologies, while some technologies affect traffic relatively more than other technologies. The higher impact on users or traffic suggest that the technology will lead to increased cost due to revenue loss, detouring, loss of service and other intangible factors. This factor is very important in determining social impact of a technology. For the purpose of this study the weighed impacts on the user are based on the population served by the asset(s) in question which are categorized as Small (3,300-49,999), Medium (50,000-99,999) and Large (more than 100,000).

The weighed impact on the traffic is based on the nature of the roads which are classified as Urban and Rural which are further classified as arterial (principal & minor), collector, and local (Highway Functional Classification System 2003). The summary of impact of technologies is available in Appendix J. The values provided are purely qualitative in nature, they are based on service disruption time and access methods required to assess a pipe.

3.5 Detectability

These are the parameters that help in determining performance of technology regarding detection of defects pertaining to the objectives of condition assessment specified by the utility manager. These parameters are further divided into two sections as outlined below

3.5.1 Defects on Basis of Condition Assessment Drivers:

This parameter determines the capability of a technology in identifying the defects that are inherent to a particular objective as specified by a utility manager for their pipeline asset(s). Table 3 illustrates various defects related to a particular type of condition assessment objective/ driver.

Table 3: Defects Related to Condition Assessment Objectives/ Drivers

S.No.	Condition Assessment Objective/ Driver	Defects
1	Structural Failure	Break, Missing Brick, Crack, Fracture, Holes, Lining Failure, Joint Failure, Pulled Joint, Wire-Beak events
2	Hydraulic Failure	Deformed, Delamination, Exfiltration, Obstructions, Cracks, Fracture, Holes, Breaks
3	Operation and Maintenance Failure	Delamination, Fracture, Break, Cracks, Holes, Joint leakages, Leakages, Lining failure, Obstructions
4	Leakage Failure	Leakage, Joint Leakage
5	Corrosion Failure	Corrosion, Wall-Thinning
6	Service or Quality Issues	Turbidity, Loss of Pressure and Sewer Back-up etc.

3.5.2 Accuracy

This parameter determines the accuracy of a technology in identifying these defects (Derr 2008). The accuracy of the technologies is a combined result of various factors which depend on utility characteristics. Further site investigations are needed to determine the exact accuracy or effectiveness of technologies in identifying a defect. For the purpose of this research the data regarding accuracy is collected from the technology providers and consultants (personal communication with Kelly Derr and technology providers).

3.6 Economic Assessment

The parameters that determine the economic assessment of the technology are costs (including tangible and intangible). This is a very important parameter as it comes down to the cost of the technology to inspect the pipes. The cost is highly variable depending on the function, diameter, material, and other utility characteristics. The unit cost is collected from the information provided by the technology providers and previous research conducted by (Kola 2009), (WERF 2004 & 2007), (Rizzo 2010) etc.

For the purpose of this project, only technology cost (Direct cost, data analysis fees, and preparation cost are considered). In this thesis the unit prices that were found and included are a unit cost/ ft to operate the technology and all associated appurtenances for inspecting the pipe on the basis of the technology cost incurred for inspecting 3000 ft of pipe in an ideal situation. It was found that unit price is typically dependent on time and most companies have a minimum daily charge. It is very difficult to quantify the exact amount of time that will be required to inspect a length of pipe due to high amount of uncertainty involved in most projects. The users of this thesis and CAST should take these technology costs only for indicative purposes only and need to undergo a detailed cost analysis before using the technologies that have high performance for their pipeline assets. The various types of costs considered in this thesis are explained as follows:

3.6.1 Direct Cost

This cost includes a variety of costs like mobilization cost, operation cost, and equipment cost etc. Appendix K provides a summary of direct costs for various technologies which is presented as unit price ($/ft).

3.6.2 Preparation Cost

This cost includes the preparation cost if specified by the technology provider specifically. Appendix K provides a summary of preparation costs for various technologies which is presented as unit price ($/ft).

3.6.3 Data Analysis Cost

This cost includes the cost of data analysis if it is not included in the direct cost and provided specifically by the technology provider. Appendix K provides a summary of data analysis costs for various technologies which is presented as unit price ($/ft).

3.6.4 Intangible Cost

The intangible cost includes impact on user and traffic. The exact amount for this is very difficult to quantify due to the dynamics and number of factors involved. For the purpose of this research the figures are qualitative in nature and just representative of relative cost impacts of various technologies in a similar situation. These values should be used only for comparative purposes only.

3.7 Data Collection and Compilation

Extensive literature has been done in order to collect the data regarding various parameters of technologies. In order to evaluate this data, the collected data for the various technologies were sent to the respective technology providers. Appendix L provides the technology data sheets for various technologies. Since data for different technologies were collected from different sources, a data reliability index was developed to provide a scale for the reliability of data available for a particular technology.

3.7.1 Data Reliability Index

The Data Reliability Index (DRI) gives the users an idea about the reliability of the data available for a technology in this thesis. The sources of the data have been categorized into 3 classes:

a. Case Study: The reporting of use of the technology in a real-world situation. These provide a lot of practical information about the advantages, and application limitations of the technology
b. Available Literature: This includes all other literature including but not limited to journal papers, conference papers, research reports, websites, and personal communications.
c. Cost Information: This is classified separately as it is a very important parameter in technology selection.

All these classes are rated from 1 to 3 depending upon:

Case Studies

(1) refers to 1-2 case study
(2) refers to 2-4 case study
(3) refers to >4 case study

Available literature

(1) refers to < 5 articles
(2) refers to 5-10 articles
(3) refers to >10 articles

Cost Information

(1) refers to information available only for direct cost

(2) refers to information available for direct, preparation, and data analysis cost

(3) refers to information available for total project cost

The **Data Reliability Index (DRI)** is the sum of all the three factors. The technologies are further categorized as

Low Reliability Index if DRI=5

Medium Reliability Index if DRI= 6&7

High Reliability Index if DRI= 8

Very High Reliability Index DRI =9

Appendix M provides a summary of the **Data Reliability Index (DRI)** for various technologies. The data reliability of a technology can improve with time by incorporation of more information.

Chapter 4- Development of a framework for Decision Support Tool- Condition Assessment Selection Tool (CAST)

4.1 Introduction

The main objective of this thesis was development of a framework for decision support tool, CAST. Once the data was collected on condition assessment technologies a means of comparing them was needed. Several different formats and programs were considered including MS Access, MS Excel and MS Visio method. After careful review of all methods, MS Excel based method was selected because of the following features:

- Wide usage is possible due to universal acceptance and availability of MS Excel
- The revision and addition of new technologies is much easier
- It doesn't require any special training

Both MS Excel and MS Access based tools have the capability of comparing the technologies and storing the data within themselves. Excel was chosen over Access because of the ease at which the new information can be input allowing the databases to be expanded as new technologies are added. This along with the ability to copy formulas used to compare the multiple technologies in the database to produce the graphs as part of the results was deemed a perfect fit for developing the CAST.

4.2 Assumptions

In order to develop CAST, there is a basic assumption that has to be made, which is as follows:

4.2.1 Identification of assets to be inspected

It is assumed that the step 5 of the 10 step condition assessment program as discussed in section 1.3 has already been completed before using the tool. The use of CAST requires the users to have basic information about the pipelines assets and surrounding parameters they need to inspect. The basic information about the assets and surrounding characteristics that are required by the users of CAST are explained in section 4.4.

4.3 Framework

As mentioned before, there is a gamut of technologies for assessing the condition of pipelines available in the market. It is desirable to help utilities in to undertake their own selection of technologies given their asset(s) specific needs for assessment, the objective of assessment and other project specific information. The framework developed for CAST is shown in Figure 5.

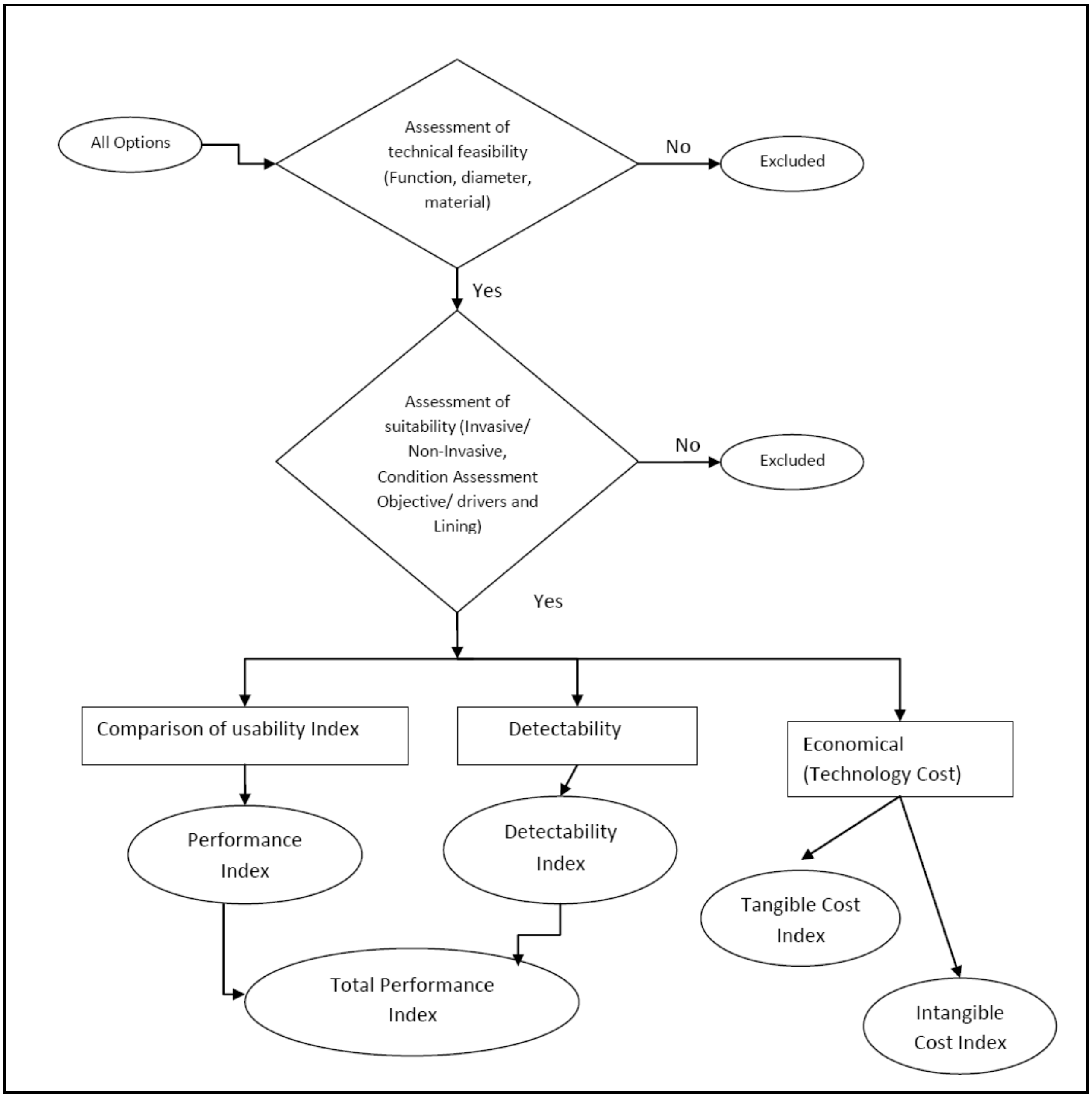

Figure 5: Basic Framework of CAST

The parameters used in this framework are already explained in chapter 3.

4.4 Layout

The layout of the workbook consists of eight individual worksheets with the following purposes:

4.4.1 Instruction

This worksheet provides a general overview of CAST program and resources for the further development of the workbook.

4.4.2 Start

This worksheet contains a button that will launch a Graphical User Interface (GUI), which allows the users of CAST to input their asset(s) specific information. The users need to be cautious for enabling the macros for proper function of CAST. Figure 6, illustrates the START worksheet.

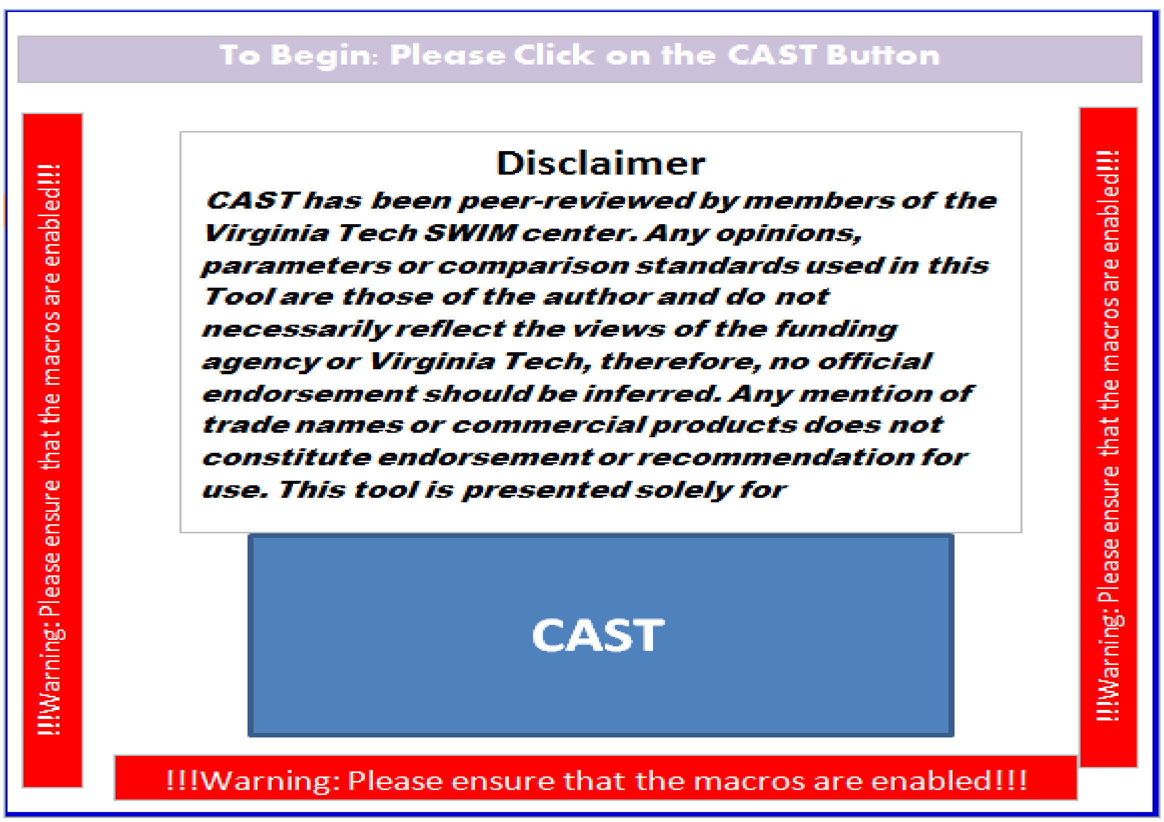

Figure 6: Start Worksheet to Enable the Graphical User Interface

As soon as the user clicks on the "CAST", a GUI pops up with the variety of questions which are classified into four categories:

Start form:

This category/ form consists of two questions that determines the type of pipes a utility manager wants to assess (water and wastewater) and the condition assessment drivers/ objectives. The values that populate the in-cell drop lists are identical to that explained in chapter 3. Figure 7 illustrates an example of Start form. The second question also has the option to choose service and water quality issues, but this option will yield an error message as technology for this option has not been included in the database.

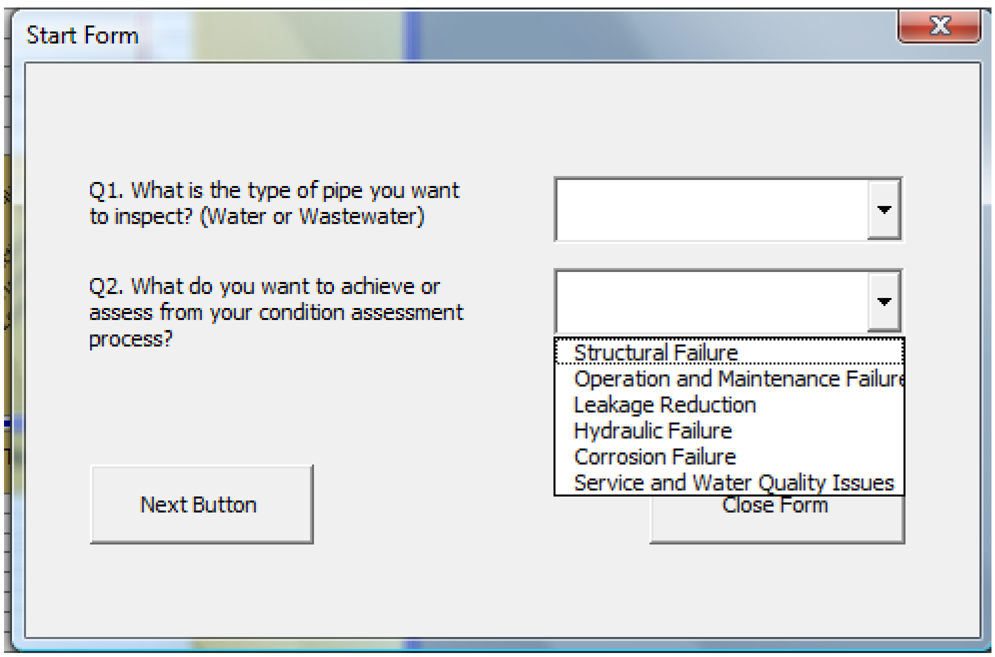

Figure 7: GUI Form to Select Type and Condition Assessment Drivers

Feasibility Parameters:

This category/ form consist of three questions that help to determine the characteristics of the assets which are critical for feasibility of the technologies like function, material and diameter. The input is limited to a dropdown list. The values that populate the in-cell drop down lists are identical to the options that are explained in the chapter 3. Figure 8, illustrates an example of Feasibility parameters for water pipelines. Similar form wastewater pipelines will appear on the basis of selection made in the Start Form.

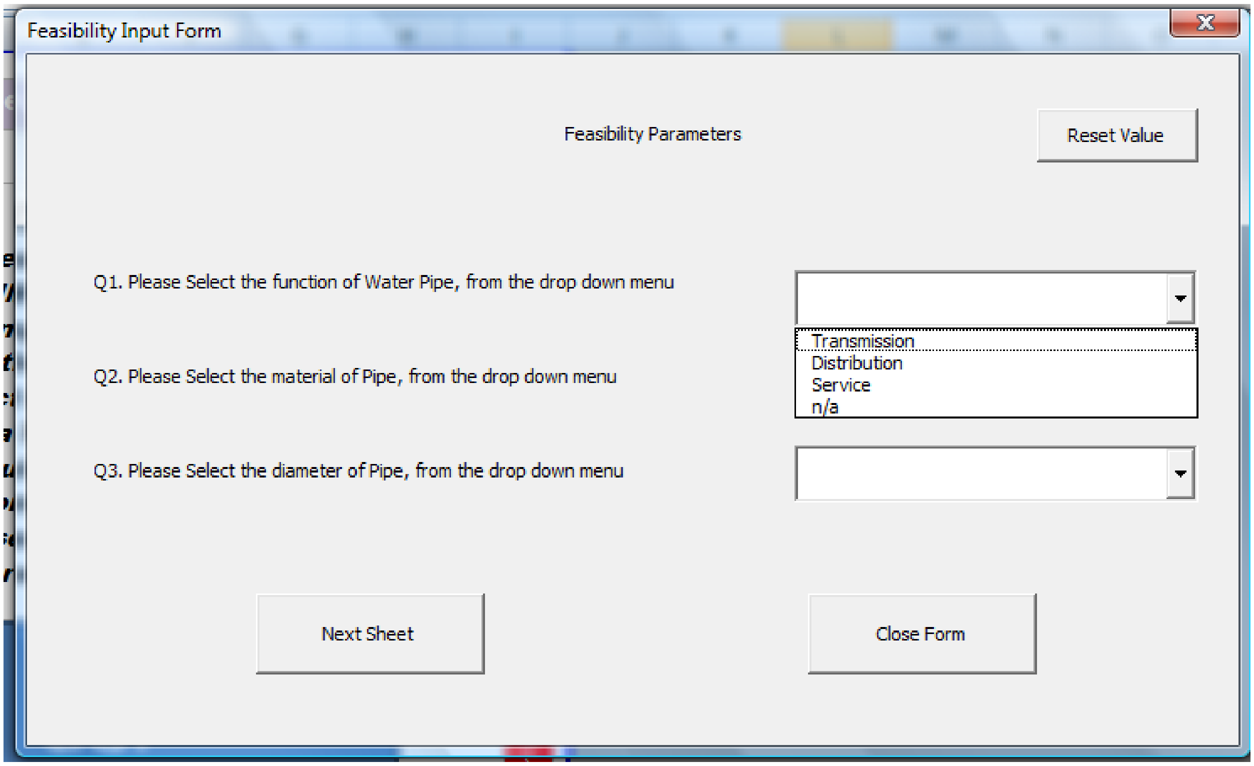

Figure 8: GUI Form to Select Function, Material, and Diameter Specific to a Project

Surrounding Characteristics:

This category/ form consist of eight questions that help to determine the surrounding characteristics of the pipeline assets. The questions are designed to collect information specific to the parameters like presence of structures, ground water, surrounding utilities, highway, and nature of road, soil type and source of noise. The values that populate the in-cell drop down list are "Yes" and "No" for all the questions except for nature of road and soil type. The options of nature of road and soil type are in line with generally acceptable standards for Highway functional classification and soil classification respectively, the values for nature of road have been adapted from Highway Functional Classification System (HFCS) and the values of soil classification system have been adapted from the Unified soil classification system, as described by ASTM D 2487. Figure 9, illustrates an example of surrounding characteristics user input form.

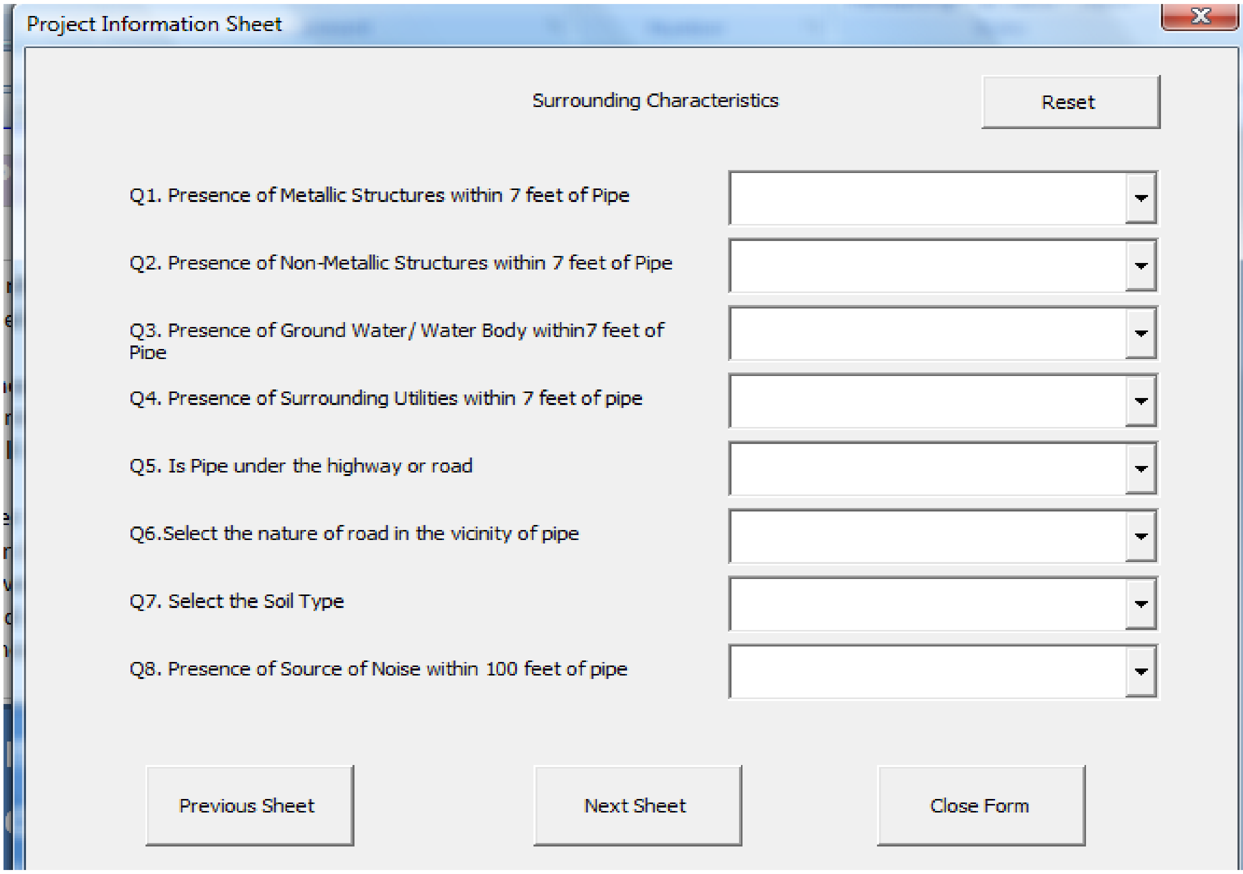

Figure 9: GUI Form to Select the Surrounding Characteristics Specific to a Project

The distances of 7 feet have been taken because of the existing spatial resolution of the Subsurface Utility Engineering (SUE) equipments applied to locate the pipes, which is 2 feet and 3 feet of gap required for trench box if the pipe requires to be excavated to inspect or monitor.

Utility Characteristics:

This category/ form consist of three questions, which are designed to determine the utility characteristics on the basis of the knowledge and experience of the users about the assets they need to inspect. Presence of redundancy in the system, size of utility, critical defects on the basis if user's experience and knowledge, preference for invasive or non-invasive technology and presence of liner. In this form also, the values can be selected from in-cell dropdown lists. Figure 10 illustrates an example of utility characteristics user input form. The values that populate the in-cell dropdown list are explained as follows:

Population served

There are 3 values for the above question Small (3,300-49,999), Medium (50,000 -99,999), and Large (>100,000). The user needs to choose the appropriate option.

Can the section of the pipe be taken offline for inspection?

The options available for the above questions are Invasive and non-Invasive. The user needs to choose the appropriate option on the basis of their assets and site conditions.

If Liner present, can the liner be removed?

There are 3 values available for the above question Yes, No, “n/a”. The user needs to choose “n/a” if liner is not present, “Yes” if a liner is present and can be removed and “No” if a liner is present and cannot be removed.

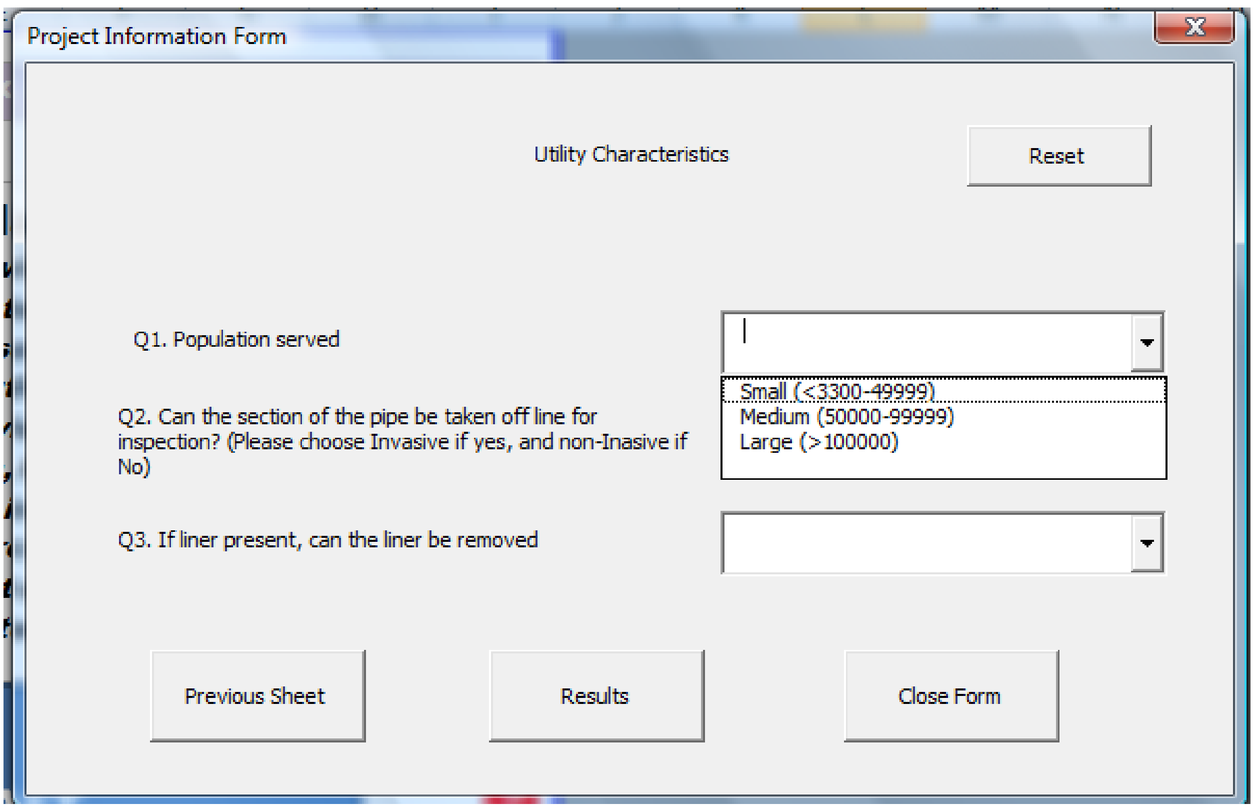

Figure 10: GUI to Select the Utility Characteristics Specific to a Project

Results:

This section just reminds user about reviewing the entered data, and directs them to the worksheets in the workbook where performance and economic indices can be analyzed. Figure 11, gives an example of the result message box.

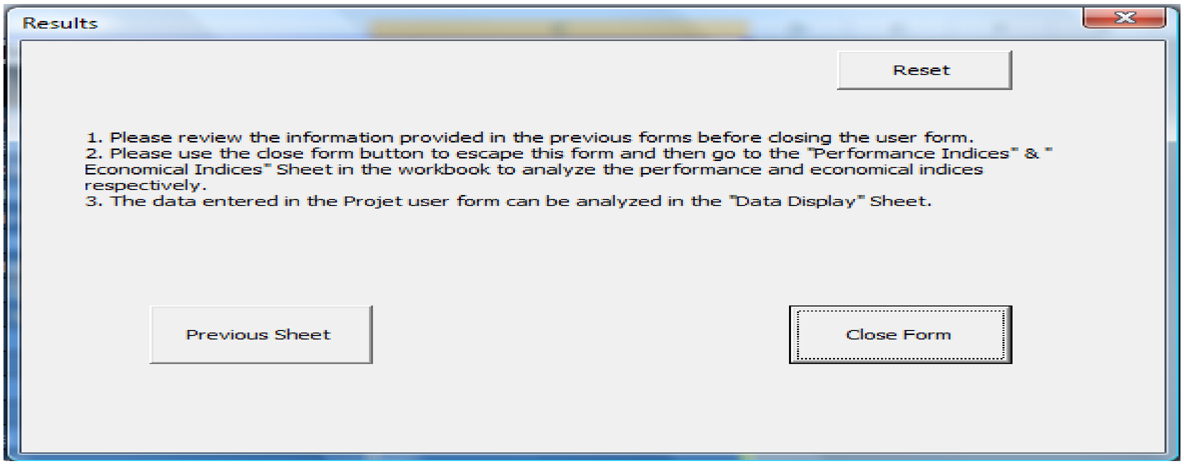

Figure 11: Result Message Box

In all these forms, there is a provision of navigating the previous filled form at any time and change them. There is also a provision for resetting the project information form, which will delete all the previously entered values and start the tool from beginning. The user needs to use the "Next Sheet" button to go to the next sheet. Table 4 illustrates all the option available for the various questions.

Table 4: Summary of all the Questions and Options in the GUI

SNo.	Questions	Options
	Start Form	
1	What is the type you want to inspect?	Water Wastewater
2	What do you want to achieve or assess from your condition assessment process?	Structural Failure Hydraulic Failure Operation & Maintenance Failure Leakage Failure Corrosion Failure Service and Quality issues

	Feasibility Parameters	
1	Please Select the function of Water Pipe, from the drop down menu (appears only when water is selected in the Start Form)	Transmission Distribution Service
1	Please Select the function of Wastewater Pipe, from the drop down menu (appears only when wastewater is selected in the Start Form)	Force Gravity Lateral
2	Please Select the material of Pipe, from the drop down menu	Concrete Reinforced Concrete Pipe Vitrified Clay Asbestos Cement Brick PVC Polyethylene PCCP Steel Ductile Iron Cast Iron Steel
3	Please Select the diameter of Pipe, from the drop down menu	<2 in 2-3 in 3-4 in 4-8 in 8-12 in 12-16 in 16-18 in 18-24 in 24-30 in 30-36 in 36-48 in 48-56 in >56 in
	Surrounding Characteristics	
1	Presence of Metallic Structures within 7 feet of Pipe	Yes No
2	Presence of Non-Metallic Structures within 7 feet of Pipe	Yes No
3	Presence of Ground Water/ Water Body within 7 feet of Pipe	Yes No
4	Presence of Surrounding Utilities within 7 feet of pipe	Yes No
5	Is Pipe under the highway or road	Yes

		No
6	Select the nature of road in the vicinity of pipe	Arterial-Principal (Urban) Arterial- Minor (Urban) Collectors (Urban) Local (Urban) Arterial-Principal (Rural) Arterial- Minor (Rural) Collectors (Rural) Local (Rural)
7	Select the Soil Type	Clay Silt Sand Gravel Organics loam/ loess Rock Weathered Intact Rock
8	Presence of Source of Noise in 100 feet of pipe	Yes No
	Utility Characteristics	
1	Population Served	Small (3,300-49,999) Medium (50,000 - 99,999) Large (>100,000)
2	Can the section of the pipe be taken offline for inspection? (Please choose Invasive if yes, and non-Invasive if No)	Invasive Non-Invasive
3	If liner present, can the liner be removed	Yes No n/a

4.4.3 Data Display

The data entered in the GUI is displayed in this worksheet; it can help in the review of information provided and can also be used to take a print-out.

4.4.4 Master List

This is the database for performance and economic evaluation of all the technologies. This worksheet is visible during the normal use of CAST but is restricted so that data cannot be edited.

4.4.5 Feasibility & Suitability

Once the data is input in the forms the data is transferred to this sheet to calculate the feasibility and suitability of the technologies by comparing the information provided by the user and data available in the Master List. The various parameters used for this calculation are already explained in Chapter 3. The parameters are again enlisted as follows:

- Feasibility
  - Function
  - Material
  - Diameter
- Suitability
  - Condition assessment objectives/ drivers
  - Lining Performance
  - Invasive/ non-Invasive

In order to compare the input data and data stored in master list, Formulas as illustrated in Equation 1 are used to compare the data. The calculated values (0 or 1) are stored in the sheet itself.

$$
\begin{aligned}
= IF(AND(\$B\$5 = \text{"}Transmission\text{"}, \text{'}Master\ List\text{'}!\,D6 \\
&= 1), 1, IF(AND(\text{'}Feasibility\ \&\ Suitability\text{'}!\,\$B\$5 \\
&= \text{"}Distribution\text{"}, \text{'}Master\ List\text{'}!\,D7 \\
&= 1), 1, IF(AND(\text{'}Feasibility\ \&\ Suitability\text{'}!\,\$B\$5 \\
&= \text{"}Service\text{"}, \text{'}Master\ List\text{'}!\,D8 = 1), 1, 0)))
\end{aligned}
$$

Equation 1: Comparing Input data and Master list

Once the calculations are done for all the feasibility and suitability parameters are completed, the feasibility of an individual technology is calculated using the formulas as illustrated in Equation 2. The values calculated in this formula are 1(Feasible) or 0 (Not feasible).

$$= IF(AND(OR('Feasibility\ \&\ Suitability'!C5 = 1, 'Feasibility\ \&\ Suitability'!C6 = 1), 'Feasibility\ \&\ Suitability'!C7 = 1, 'Feasibility\ \&\ Suitability'!C8 = 1, 'Feasibility\ \&\ Suitability'!C9 = 1, 'Feasibility\ \&\ Suitability'!C10 = 1, 'Feasibility\ \&\ Suitability'!C11 = 1), 1, 0)$$

Equation 2: Feasibility Calculation

4.4.6 Calculation

Once the feasibility of technologies is determined, the performance and economic indices for feasible technologies are calculated in this sheet, described as follows:

4.4.6.1 Calculation of Performance Indices

The means of comparing the technically feasible and suitable technologies are to develop performance indices, the definition of the indices are as follows:

Performance Indices: It consists of 3 indices namely Usability Index, Detectability Index and Total Performance Index

Usability Index: This is the Index which determines, the ease in using a particular technology to inspect the assets in question, the index value is determined in percentage, higher percentage means that the technology is easier to use.

Detectability Index: This is the index which determines the capability of technology to assess the defect of the assets in question, the value is determined in percentage; higher percentage means that the technology is better capable of determining the defects.

Total Performance Index: This is the index which determines the combined performance of a technology in terms of usability and detectability, this index is also determined in terms of percentage, higher percentage means that the technology is better performing.

Once the feasibility is calculated the input data regarding performance is compared with the master-list data to calculate performance indices, the parameters required to calculate the performance indices have already been explained in chapter 3. The three indices calculated are Usability, Defect identification and total performance. The weights for the various parameters have already been explained in Chapter 3. The weights for all the parameters are kept same except for impact on users and traffic, defect and surrounding characteristics, which depends on the nature of road, size of utility, critical defect and material, and presence of the surrounding characteristics respectively. The weight for impact on traffic and user is calculated using the following Equation 3 and Equation 4, respectively.

$$
\begin{aligned}
&= IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$13, 20, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$14, 17.5, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$15, 15, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$16, 12.5, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$17, 17.5, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$18, 15, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$19, 12.5, IF('Feasibility \,\&\, Suitability'!\$B\$23 \\
&\quad = Projinf!\$J\$20, 10, 0))))))))
\end{aligned}
$$

Equation 3: Calculation for Weights of Impact on Traffic

$$
\begin{aligned}
&= IF(Projinf!\$C\$19 = Projinf!\$G\$14,10, IF(Projinf!\$C\$19 \\
&\quad = Projinf!\$G\$15, 15, IF(Projinf!\$C\$19 = Projinf!\$G\$16, 20, 0)))
\end{aligned}
$$

Equation 4: Calculation for Weights of Impact on User

All the defects, associated with the material as described in section 3.2.2.3 are assigned equal weights except for the defect chosen as the critical defect, which is assigned a value twice of the normal value in order to highlight the criticality of that defect. Equation 5, illustrates an example of calculation of weights for a defect.

$$= IF('Feasibility \,\&\, Suitability'!\$B\$24 = 'Master\ List'!\$C\$56,10,0)$$

Equation 5: Calculation of Defect Weights

The weights for surrounding characteristics are also kept same and depend on the presence of surrounding characteristics for the asset(s) for which CAST is being used. The following Equation 6 is used to calculate the weight for surrounding characteristics.

$$= IF(Projinf!C15 = "Yes", 10, 0)$$

Equation 6: Calculation of Surrounding Characteristics Weight

Once the weights for all the parameters are calculated, total weight and values are calculated for all the technologies.

*Defect Identification Index= (Defect Performance Total/ Total defect weight of technologies)*100*

The defect performance total is calculated on the basis of the sum of the products of the defects value, defect weight and accuracy. The total weight is calculated as the sum of the products of defect weight and maximum accuracy.

*Usability Index = (Usability performance total/ total usability weight)*100*

The usability performance total is the sum of the product or division of performance weights and performance value depending whether the options are 2 (Yes or No) or multi-option respectively. In case the performance value is "n/a" the performance weight is also assigned 0 as the parameter has no significance for the technology.

*Total performance index = (Defect Performance Total+ Usability Performance Total/ Total defect weight of technologies+ Total usability weight)*100*

The performance indices are percentage values.

4.4.6.2 Calculation of Economic Indices

The economic indices are the secondary indices as cost of using the technology is highly variable. There are two indices for economic factors tangible and intangible cost indices. The parameters behind these parameters are already explained in chapter 3. The definitions of these indices are reiterated here as follows:

Tangible Cost Index: This is the Index which determines, the tentative cost to perform the assessment using this technology in ($/ft). The values taken in this index can vary significantly on the basis of the particular site condition.

Intangible Cost Index: This is the Index which determines the cost of impact on traffic and user due to assessment of pipe using a technology, the index is determined as a comparative value, which means higher value suggests that the technology has higher impact on users and traffic. The weights of the impact on traffic and user are given by the same formulas in Equation 3 and Equation 4 respectively. The Intangible cost index are the comparative values and gives a general idea about which technology will impact more on users and traffic under the same circumstances.

For the purpose of this project, this sheet remains hidden and protected during normal use of CAST

4.4.7 Performance Indices

The performance indices of the technically feasible and suitable technologies are displayed in this worksheet in form of graphs. The source of data is the calculation work sheet where the values of all the indices are calculated. The index values of the technologies are then classified into 4 categories according to their Data reliability Index as discussed in section 3.6.1. The formula used to classify these values is illustrated in Equation 7.

$$= IF(D11 = 5, D4, NA())$$

Equation 7: Formula to Classify the Values According to DRI

A verbal translation of formula would reach such as:

"If DRI value is equal to 5 then classify as Low Reliability else blank."

Figure 12, Figure 13, and Figure 14 represents the graphs for usability index, detectability index and total performance index respectively. The graphs have the list of condition assessment technologies on the X-axis; the Y-axis illustrates the percentage values the bars are colored in accordance to the DRI value of the technologies. The legend on the right side illustrates the color coding for the bars.

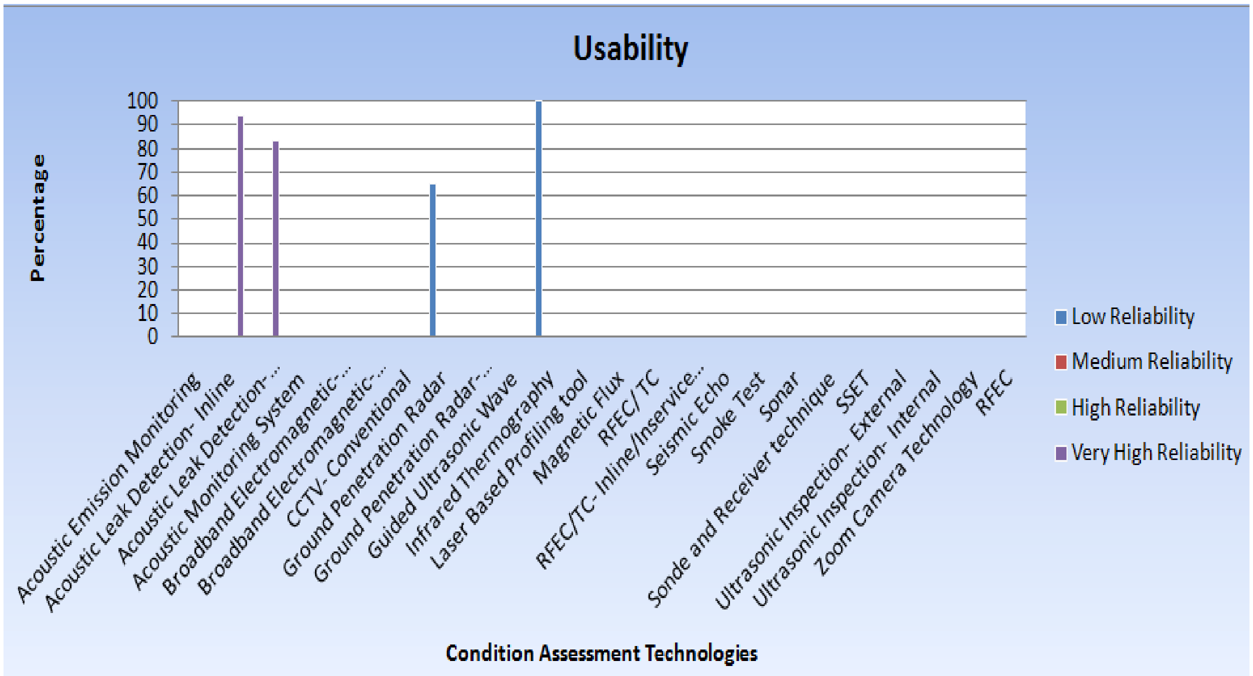

Figure 12: Usability Index

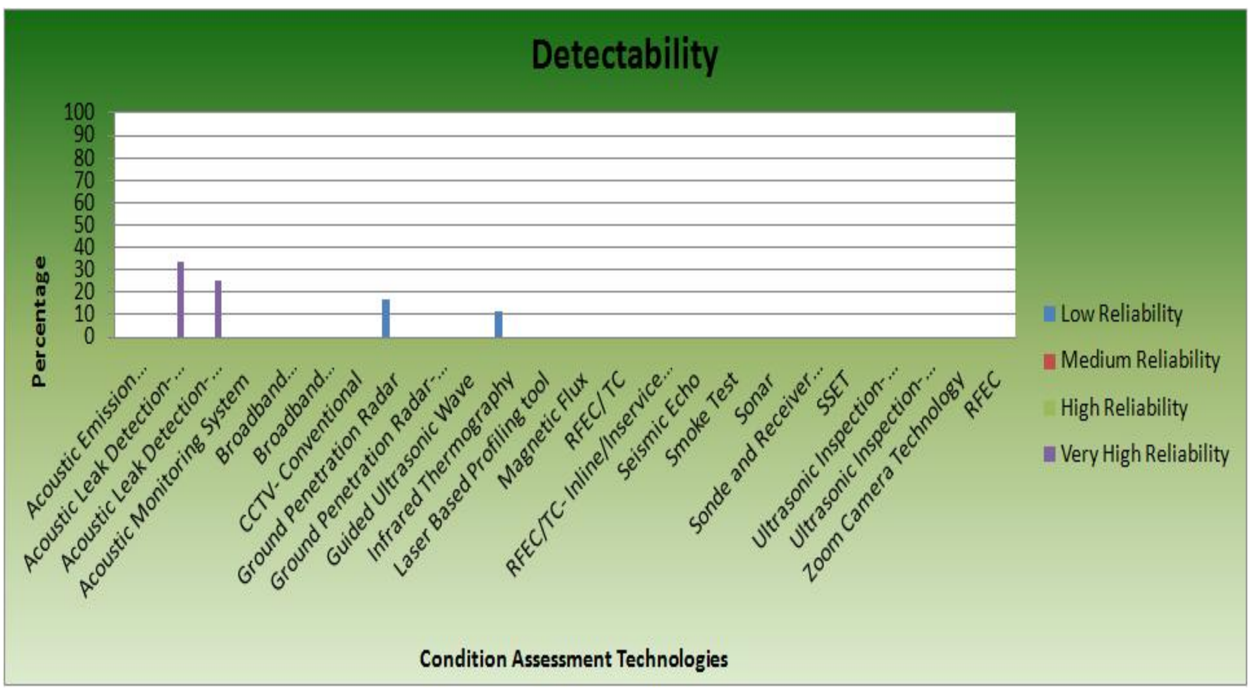

Figure 13: Detectability Index

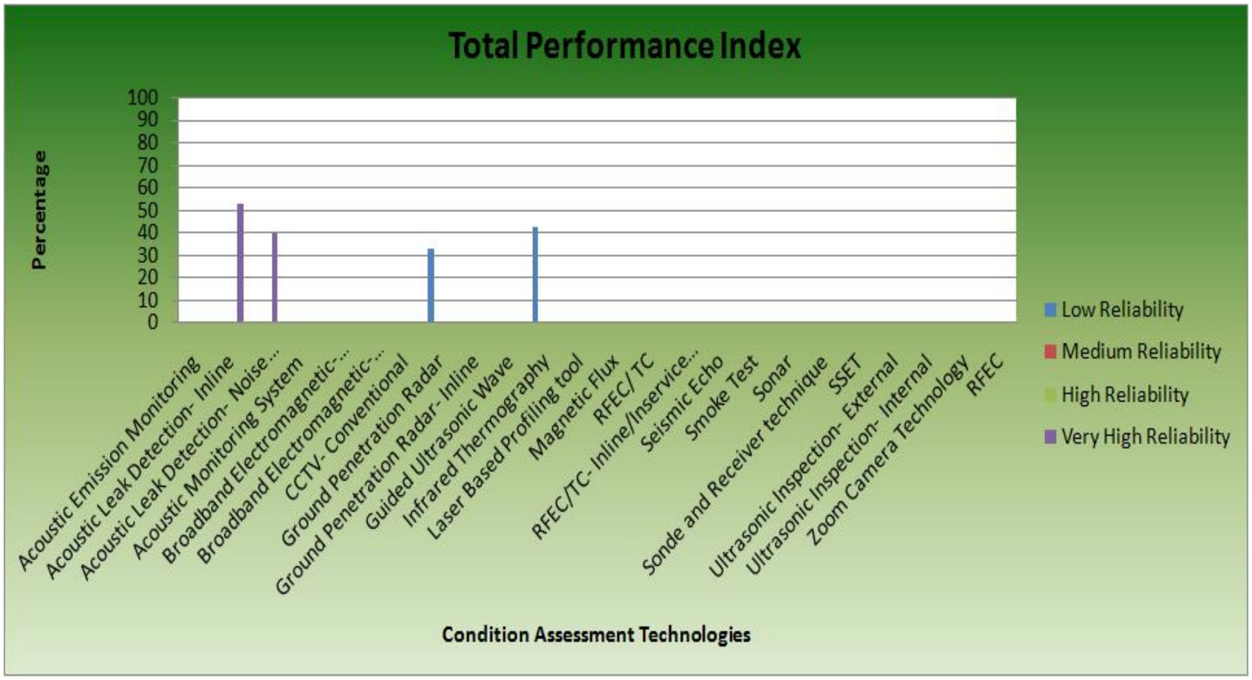

Figure 14: Total Performance Index

4.4.8 Economic Indices

The economical indices of various technologies are displayed in this worksheet in form of graphs. Figure 15 and Figure 16 illustrates the tangible cost index and intangible cost index respectively. The tangible cost index gives the $ per ft value of implementing a condition assessment technology. The intangible cost index gives a comparative value of combined impacts on user and traffic due to implementation of a condition assessment technology.

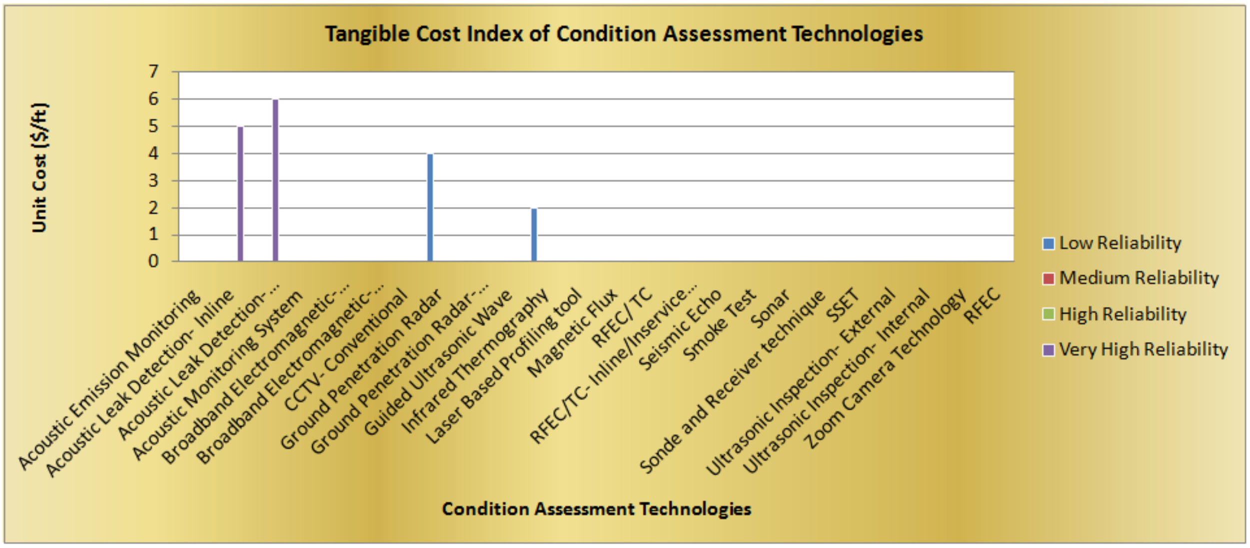

Figure 15: Tangible Cost Index

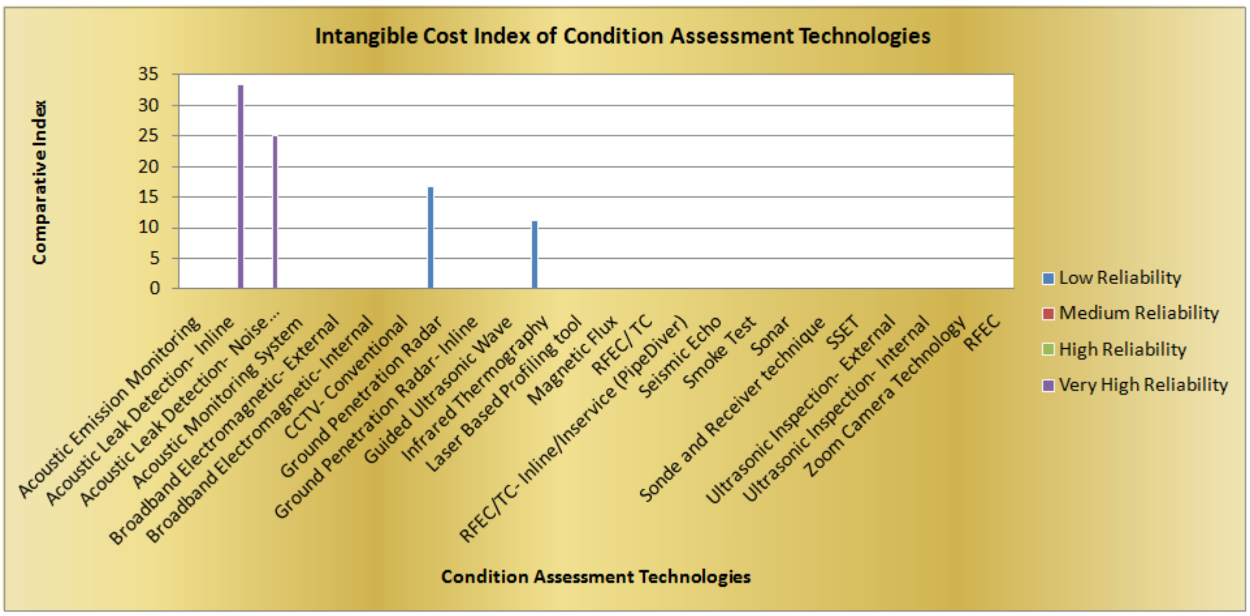

Figure 16: Intangible Cost Index

Chapter 5- A Case-Study on Acoustic Fiber Optic Sensors Systems

5.1 Introduction

The purpose of this case study is to highlight the existing knowledge gap about the capabilities and limitations of condition assessment technologies for water and wastewater pipelines. This study is done on acoustic fiber optic sensing systems which are commercially available. The technology providers claim that the technology is capable of detecting and identifying any acoustic signals in the near vicinity of the pipe. But, often the utilities complain about a significant amount of false signals.

In order to establish the existing gap in knowledge, the signals were collected from a test site using a commercially available system. They were then subjected to advanced signal processing using various statistical methods. The details about the PCCP, failure of PCCP, description of technology, methodology of research, and conclusion are provided in following sections.

5.2 PCCP

PCCP is a composite material of concrete and steel. The primary structural component of the pipe is high strength steel wires which are helically wound around the cylindrical shape. There are two basic types of PCCPL Lined Cylinder pipe (LCP) and Embedded Cylinder pipe (ECP). For LCP the high strength wire is wrapped on the thin steel cylinder. For ECP, the high strength concrete core is on the outside of the thin steel cylinder and the high strength steel wire is wrapped on over the concrete cylinder. In either case the intent of the high strength wire is to maintain the concrete core in compression and the wires receive a mortar coating for protection from physical damage and, hopefully, corrosion. Generally, LCP is smaller in diameter compared to ECP, but both designs are typically intended for high pressure water conveyance situations (AWWARF, 2008) and (Kola, 2010).

5.3 Modes of Failure and Mechanisms

The strength and function of PCCP is dependent on a set of prestressed wires that are wound around a concrete core. These wires are subjected to failure due to corrosion and embrittlement. If these wires snap or break, then the pressure-capacity of the pipe is compromised. Thus, the performance and structural health condition of PCCP ultimately comes down to assessing the condition and performance of the high strength steel wires and the presence or lack of compression in concrete core. The sequence of PCCP failure is illustrated in Figure 17.The fact that PCCP prematurely fails structurally after decades of service implies that either the applied loads are unexpectedly beyond the original design capacity or that the structural capacity of pipe has changed over time. Surge events have been reported as preceding several catastrophic failures of PCCP (Romer et. al., 2007). Long term causes of the deterioration of PCCP are numerous and include high chloride environment, the quality of the mortar including lack of complete envelopment of the prestressing wires within the cement mortar coating, the reinforcing wires, corrosive soils, inadequate thrust restraint, construction damage, cracks in the cylinder welds, and delamination of the coating (Romer et. al., 2007) and (Padewski et. al., 2007). However, catastrophic PCCP failures are generally due to loss of structural integrity due to accumulation of damaged prestressing wires which leads to loss of compression in the concrete core. One the compression is compromised, the structure failure is imminent (Price, 1990), (Price, 1998) and (Galleher, 1998). Figure 18 represents the modes of failure and mechanism of PCCP.

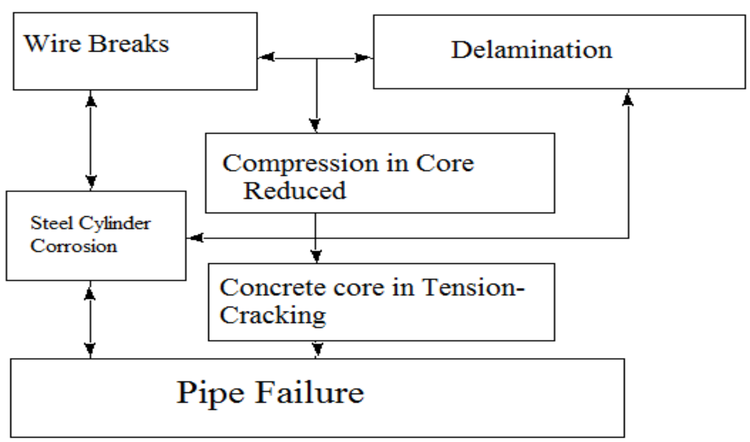

Figure 17: Generic Failure Sequence for PCCP (Romer, 2001)

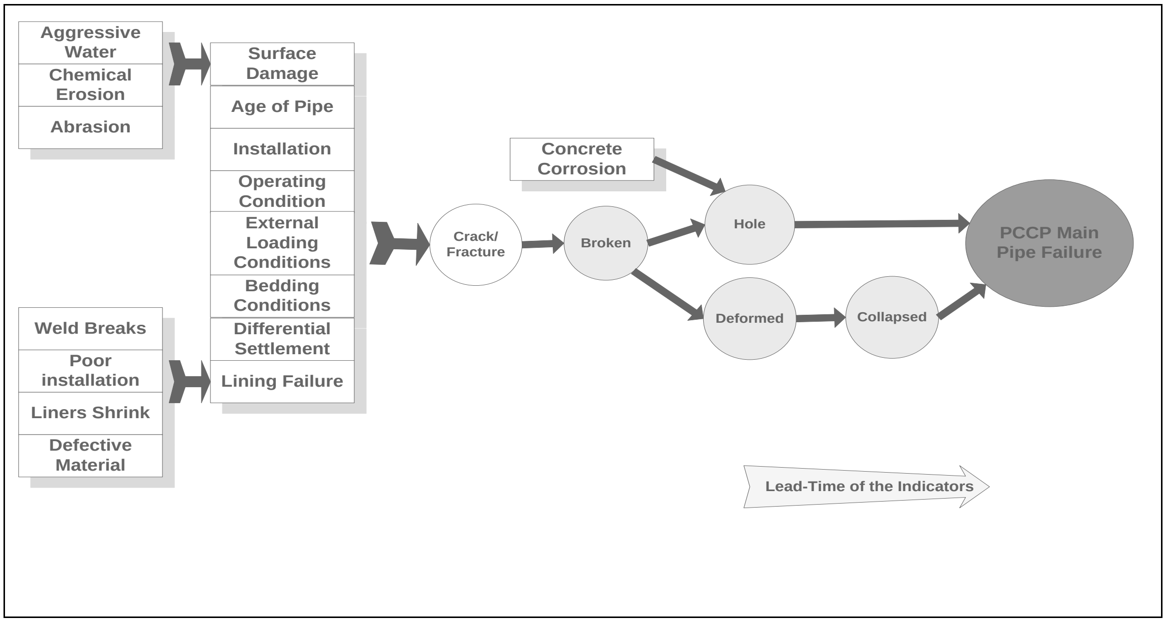

Figure 18: Modes of Failure and Mechanisms for PCCP (Kola, 2010)

5.4 Consequence of Failure of PCCP

Unfortunately, due to their diameter and pressure, PCCP failures result in spectacular visual displays. Estimates of equivalent stored energy range from 0 to 200 pounds of dynamite per 20 ft pipe section (AWWARF, 2008). For PCCP the owners, PCCP failures result in expensive emergency repair costs, in some cases in the several millions of dollar, and the specter of even more expensive pipeline rehabilitation or replacement projects in the hundreds of millions and even billions of dollars (Galleher, 2008) and (Essamin, 2005). These costs do not include the political and societal costs that go along with being the featured story on national news. All of these factors combine to make the owners of PCCP interested in the performance and in assessing the monitoring the condition and the risk of the PCCP in their system (Romer and Bell, 2005), (Romer et al., 2008), (Bell et al., 2001), (Marshall et al., 2005), (Parks et al., 2001) and (Zhargamee et al., 1998).

5.5 Current Condition Assessment Practices for PCCP

Fundamentally, all PCCP assessment or monitoring methods try to measure wire-breaks or assess concrete core compression using various methods and techniques of excitation, measurement of a response and analysis of the excitation/ response to accepted norms or patterns (calibrations) (Alghumery et al., 2005), (Mergelas et al., 2005), (Mergelas et al., 2001a, 2001b & 2001c) and (AWWARF, 1992). The various condition assessment technologies that are used for assessing the condition of PCCP can be classified into following categories:

- Electromagnetic Technology
- Acoustic Monitoring Technology
- Ultrasonic Technology

The background of these technologies is described in Chapter 2. For the purpose of this case study the acoustic monitoring system or acoustic fiber optic sensor systems is considered because of the fact that the technology is relatively new and is designed to identify the wire breaks of PCCP in real-time. The purpose of this case study is to assess the performance of these technologies in the real-world scenario against the claims that are being made by the technology providers.

5.5.1 Comparison of Acoustic Monitoring System with other NDT

Acoustic Emission is unlike most other nondestructive testing techniques in two regards. The first difference pertains to the origin of the signal. Instead of supplying energy to the object under examination, AET simply listens for the energy released by the object. AE tests are often performed on structures while in operation, as this provides adequate loading for propagating defects and triggering acoustic emissions.

The second difference is that AET deals with dynamic processes, or changes, in a material. This is particularly meaningful because only active features (e.g. crack growth) are highlighted. The ability to discern between developing and stagnant defects is significant. However, it is possible for flaws to go undetected altogether if the loading is not high enough to cause an acoustic event. Furthermore, AE testing usually provides an immediate indication relating to the strength or risk of failure of a component. Other advantages of AET include fast and complete volumetric inspection using multiple sensors, permanent sensor mounting for process control, and no need to disassemble and clean a specimen.

5.5.2 Advantages of Acoustic Fiber Optic Sensor Technology

Acoustic Fiber Optic Sensors have been successful in getting some acceptance from the industry because of the various reasons listed as follows:

- High level of acceptance in other infrastructure systems like Oil & Gas.
- Dual capability of sensing and transmitting simultaneously.
- Real-time and Continuous Monitoring
- Practically no power requirement
- Immunity to extreme environments and Electromagnetic Induction (EMI)
- High Spatial Resolution, Spatial Accuracy, Strain and temperature resolution
- Minimum attenuation of signal as fiber is always at a distance less than diameter of pipe from AE event.
- Single Data Acquisition System (DAQ) is capable of monitoring 50 miles.

FOS based system has already been commercialized by various companies and being implemented in the industry to assess the condition of the pipes (Galleher, 2005).

5.5.3 Limitations of Acoustic Fiber Optic Sensor Technology

Unfortunately, these systems can only qualitatively gauge how much damage is contained in a structure. In order to obtain quantitative results about size, depth, and overall acceptability of a part, other NDT methods (often ultrasonic testing) are necessary. Another drawback of these system stems from loud service environments which contribute extraneous noise to the signals. For successful applications, signal discrimination and noise reduction are crucial.

However, assessment or estimates of the number of wire break events in a given time period does not provide information as to the condition of the pipe or the probability/ likelihood of the failure for that section of pipe (AWWARF, 2004), (AWWARF, 2008), (Romer and Bell, 2005). In order to avoid failure, PCCP owners need reliable and actionable information and not simply data on broken wires. One of the primary concerns with current assessment technologies is the reports of false-positives and false-negative results (Bambei et al., 2005). This problem is compounded by the fact that even if suspect pipes are excavated and inspected, damage is generally not visible without removal of the mortar coating.

5.6 Collection of Signals

The data that is required to be collected to calculate this research is the acoustic emission signals emanating from the wire breaks in PCCP. Figure 19 illustrate a typical AE signal emanating from wire break. For the purpose of this research the experimental data will be collected from the field set up of a manufacturer of Acoustic Fiber Optic Sensor System. The significant features of the signals are as follows:

1. The signals are collected and received in *wav form.
2. The duration of each signal is 150 milliseconds.
3. The frequency of the signal is 44.1 KHz, which means 6615 data points in each signal.
4. The signals are distinctly audible and preprocessed for de-noising operation.
5. For the purpose of this research 173 experimental AE signals have been collected.

For the purpose of this research 173 signals have been collected from an experimental setup.

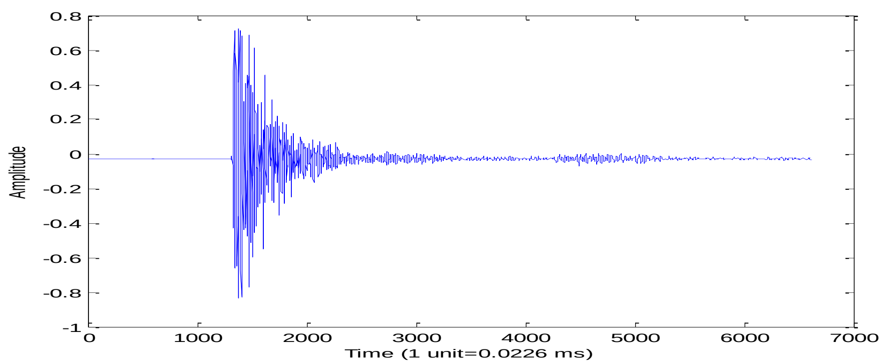

Figure 19: Typical AE Signal Emanating from Wire-break

5.7 AE Signal Features

Once the AE data is collected, various parameters like amplitude, counts, measured areas under the rectified signal envelope (MARSE) and duration etc. are extracted for each signal. These parameters are known as features which play a critical role in determining the difference between two signals and the condition associated with a particular signal, Figure 20 illustrates the various AE features. The various features used for the purpose of this research are as follows:

Amplitude, A, is the greatest measured voltage in a waveform and is measured in decibel (dB). This is an important parameter in acoustic emission inspection because it determines the detectability of the signal. Signals with amplitudes below the operator-defined, minimum threshold will not be recorded.

Rise time, R, is the time interval between the first threshold crossing and the signal peak. This parameter is related to the propagation of the wave between the source of the acoustic emission event and the sensor. Therefore, rise time is used for qualification of signals and as a criterion for noise filter.

Duration, D, is the time difference between the first and last threshold crossings. Duration can be used to identify different types of sources and to filter out noise. Like counts (N), this parameter relies upon the magnitude of the signal and the acoustics of the material.

Counts, N, refers to the number of pulses emitted by the measurement circuitry if the signal amplitude is greater than the threshold. Depending on the magnitude of the AE event and the characteristics of the material, one hit may produce one or many counts. While this is a relatively simple parameter to collect, it usually needs to be combined with amplitude and/or duration measurements to provide quality information about the shape of a signal. Some other features critical for determining the characteristics of the signals will also be explored.

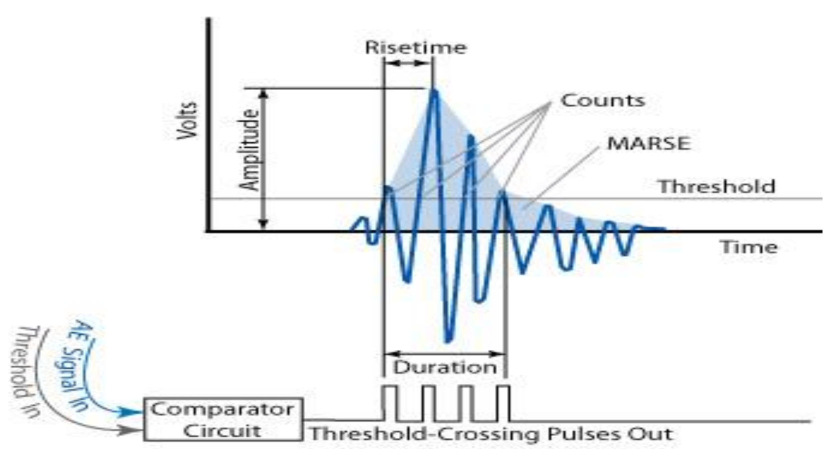

Figure 20: AE Features/ Parameters. Source: www.ndt-ed.org, (accessed February 2010) Fair use determination attached

5.8 Feature Matrix

The feature matrix is a matrix representing all the statistical features that have been selecting to analyze the acoustic signals emanating from the wire-break events in PCCP. Table 5 represents an example of feature matrix showing the seven main statistical values selected for analyzing the collected signals.

Table 5: An Example of Feature Matrix Showing Various Statistical Values of Signals Collected

S.No.	Maximum	Minimum	Mean	Ceptrum RMS Value	Standard Deviation	Median	RMS Value
1	0.61	-0.84	-0.03	2.29	0.08	-0.03	5.60
2	0.73	-0.72	-0.03	1.49	0.07	-0.03	6.64
3	0.11	-0.19	-0.03	2.71	0.06	-0.03	2.41
4	0.61	-0.79	-0.03	2.29	0.07	-0.03	5.60
5	1.00	-1.00	-0.03	1.70	0.15	-0.03	12.38

5.9 Tools and Methods for Signal Analysis

For the purpose of this study, MATLAB has been used to analyze the signals. Various toolboxes like signal processing, neural network and wavelet have been used to analyze and empirically classify the signals.

5.10 Analysis

As for the analysis, once the feature matrix has been developed, various features are plotted on a 2D and 3D plane so as to understand the behavior of these features depending on the various signals. These plots also help in understanding a clear relation and distinguishing feature in the signals depending on the structural condition of the pipe from which they emanated. Figure 21, Figure 22, Figure 23, and Figure 24 represent some of these plots which clearly illustrate difference in the signals. On the basis of the heuristic knowledge we know that these signals originated from wire-breaks in PCCP with different structural conditions. But, due to the limited information about the source of this data we cannot classify the signals exactly to structural condition that produced them from within in the pipe.

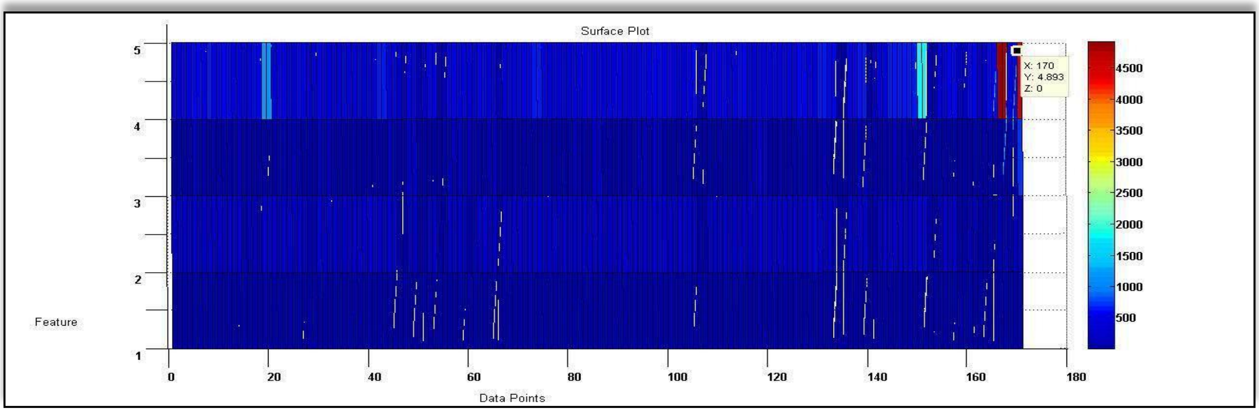

Figure 21: Surface Plot of Feature Matrix of Collected Signals

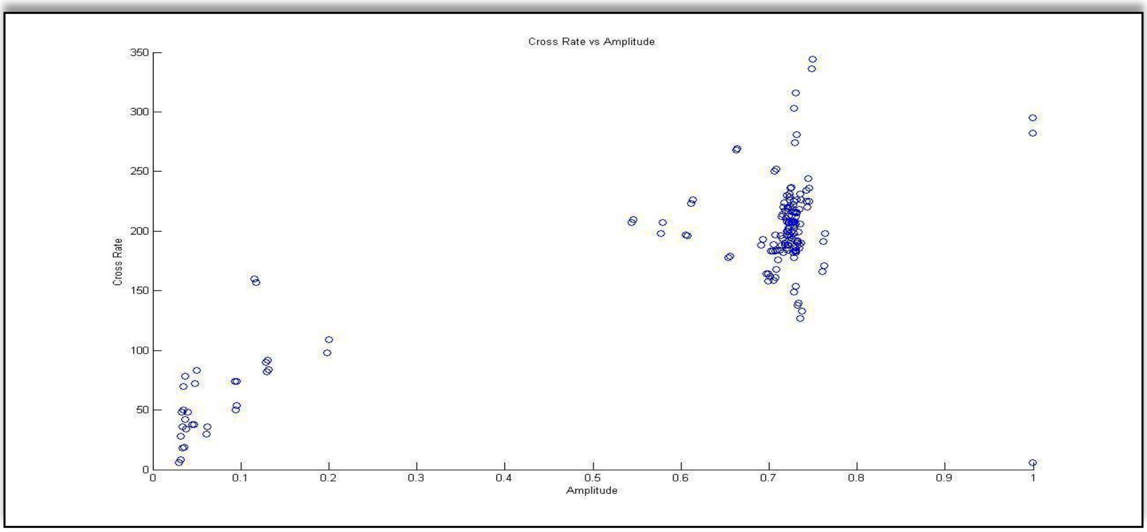

Figure 22: Cross Rate vs. Amplitude of Collected Signals

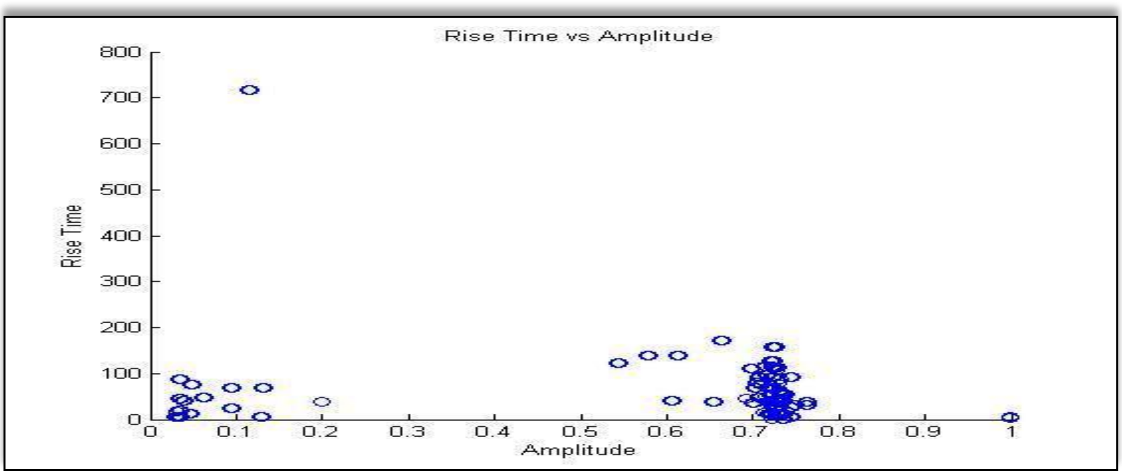

Figure 23: Rise Time vs. Amplitude of Collected Signals

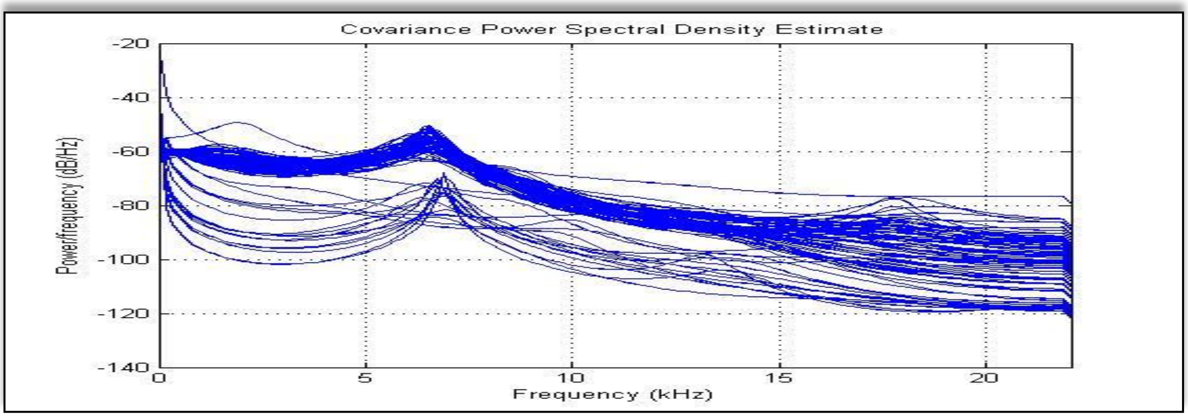

Figure 24: Power Spectral Density Plot of Collected Signals

5.11 Conclusion

As mentioned above, this case study clearly demonstrates the existence of knowledge gap between claims made by technology providers and actual capabilities or limitations of acoustic fiber optic technology. This case study thus successfully highlights the existence of gap in complete understanding of the advantages and capabilities of condition assessment technologies. These gaps need to be fixed by further investigation by field investigations or advanced signal processing. As the information included in CAST has been collected from technology providers, thus caution must be taken in using CAST as the data may lack actual performance data.

Chapter 6- Conclusion

This thesis developed a framework for CAST which could assist utility managers in making informed decisions for selecting appropriate condition assessment technologies. This decision support system provides a user-friendly means of organizing information about condition assessment technologies. This Excel-based program, when integrated into a formal asset management program, could add value to a project by decreasing the amount of money spent on incorrect or inappropriate amounts of utility data. The performance and economic evaluation also serves to standardize the criteria used to evaluate such technologies. The process of using this tool will not increase the cost of condition assessment program or associated processes and can be used to evaluate an entire project or multiple parts of a single project.

6.1 Feedback and Evaluation

Utilities of various sizes like Washington Suburban Sanitary Commission (WSSC) and Western Virginia Water Authority have been contacted for evaluating CAST. The feedback is very encouraging as they explained the framework as very user-friendly, robust, and an excellent starting point. The utility managers also wanted to know more about the potential use and how they can use it. This was as a good sign that people in the utility engineering field have an interest in learning about the program after seeing it for the first time.

6.2 Dissemination

The research work is protected under U.S. Copyright Law but is intended for public use by anyone working in a role that could benefit from its use. CAST will be rendered online to provide a central place to access it, and this thesis, technology description, and a manual for using CAST. This will help in getting more feedbacks from users and thus make it more robust.

6.3 Advantages of CAST

The various advantages of CAST are as follows:

- CAST will be a web-based tool that any utility can use for selecting CAT
- The excel-based system makes it very user-friendly
- As new technologies are developed and commercialized, the tool can be updated

- As new performance evaluation parameters are identified, the tool will be updated
- As more sources of information are included DRI can be improved
- CAST is very comprehensible and compatible with any platform
- It uses the basic information readily available with the users
- Use of CAST will not have any effect on the cost of the project.

6.4 Limitations of CAST

The limitations of CAST are as follows:

- The parameters that are taken are limited by the availability of data
- The data is provided by technology providers and lacks long-term performance data
- CAST doesn't take into the account the drivers or philosophies of condition assessment
- CAST doesn't work on a system level
- CAST assumes that the assets to be monitored/ inspected are identified
- The intangible index gives a comparative value only which is just an indicator of impact on traffic and user
- The cost is tentative, thus it provides only an indication of the cost that may be incurred.
- The effect on surrounding characteristics data is also qualitative in nature and may vary from project to project

6.5 Future Work

Further development of this tool will require modification of some settings or features based on the needs of the utility managers. Future work will require industry feedback and new, innovative ideas as to how to address utility conflicts on heavy civil projects. The most important works that are required to enhance the value of this framework as described as follows

First, expansion of the performance and economic databases by collecting data from utilities and relevant case studies is required. This would also be the start of a potential national storage space and clearing house for condition assessment technologies. This will also help in improving the Data Reliability Index. Also, further research needs to be done to better understand social impacts of various condition assessment technologies. Second, it is very important to populate the database with more innovative technologies. It is also very important to create awareness amongst utility managers about the availability of CAST, potentially by integrating it with an online workspace. The future work required to enhance the applicability and robustness of CAST are enlisted as follows:

- More parameters need to be included
- Long term performance data and field data needs to be collected and included
- The drivers and philosophies of Asset Management Plan needs to be included
- A web-based system needs to be created to enable enhanced dissemination
- Cost data needs to be captured on the based on the actual field data in different scenario
- More technologies as they are commercialized needs to be included
- The weights based on the heuristic knowledge for intangible cost and impact on users and traffic

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Appendix A- Feasibility of technologies for various function of pipelines

Technology	Force	Gravity	Lateral	Transmission	Distribution	Service
Acoustic Emission Monitoring	1	0	0	1	1	1
Acoustic Leak Detection- Inline	1	0	0	1	1	1
Acoustic Leak Detection- Noise Correlator	1	0	0	1	1	1
Acoustic Monitoring System	1	0	0	1	1	1
Broadband Electromagnetic- External	1	1	1	1	1	1
Broadband Electromagnetic- Internal	1	1	1	1	1	1
CCTV- Conventional	1	1	1	1	1	1
Ground Penetration Radar	1	1	1	1	1	1
Ground Penetration Radar- Inline	1	1	1	1	1	1
Guided Ultrasonic Wave	1	1	1	1	1	1
Infrared Thermography	1	1	1	1	1	1
Laser Based Profiling tool	1	1	1	1	1	1
Magnetic Flux	1	1	1	1	1	1
RFEC/ TC	1	1	1	1	1	1
RFEC/TC- Inline/In-service	1	0	0	1	1	1
Seismic Echo	1	1	0	1	1	0
Smoke Test	0	1	1	0	0	0
Sonar	1	1	1	0	0	0
Sonde and Receiver technique	1	1	1	0	0	0
SSET	1	1	1	1	1	1
Ultrasonic Inspection- External	1	1	1	1	1	1
Ultrasonic Inspection- Internal	1	1	1	1	1	1
Zoom Camera Technology	0	1	0	1	0	0
RFEC	1	1	1	1	1	1

1= Can Perform, 0=Cannot Perform

Appendix B- Feasibility of technologies for various materials

Technology	Concrete	RCP	VC	AC	Brick	PVC	PE	PCCP	Steel	DI	CI	Copper
Acoustic Emission Monitoring	0	0	0	0	0	0	0	1	0	0	0	0
Acoustic Leak Detection- Inline	1	1	1	1	1	1	1	1	1	1	1	1
Acoustic Leak Detection- Noise Correlator	1	1	1	1	1	1	1	1	1	1	1	1
Acoustic Monitoring System	0	0	0	0	0	0	0	1	0	0	0	0
Broadband Electromagnetic- External	0	0	0	0	0	0	0	0	1	1	1	0
Broadband Electromagnetic- Internal	0	0	0	0	0	0	0	0	1	1	1	0
CCTV- Conventional	1	1	1	1	1	1	1	1	1	1	1	1
Ground Penetration Radar	1	1	1	1	1	1	1	1	1	1	1	1
Ground Penetration Radar- Inline	1	1	1	1	1	1	1	1	0	0	0	0
Guided Ultrasonic Wave	0	0	0	0	0	0	0	0	1	0	0	0
Infrared Thermography	1	1	1	1	1	1	1	1	1	1	1	1
Laser Based Profiling tool	1	1	1	1	1	1	1	1	1	1	1	1
Magnetic Flux	0	0	0	0	0	0	0	0	1	1	1	0
RFEC/ TC	0	0	0	0	0	0	0	1	0	0	0	0
RFEC/TC- Inline/In-service	0	0	0	0	0	0	0	1	0	0	0	0
Seismic Echo	0	0	0	0	0	0	0	1	0	0	0	0
Smoke Test	1	1	1	1	1	1	1	1	1	1	1	1
Sonar	1	1	1	1	1	1	1	1	1	1	1	1
Sonde and Receiver technique	1	1	1	1	1	1	1	0	0	0	0	0
SSET	1	1	1	1	1	1	1	1	1	1	1	1
Ultrasonic Inspection- External	0	0	0	0	0	0	0	0	1	1	1	0
Ultrasonic Inspection- Internal	0	0	0	0	0	0	0	0	1	1	1	0
Zoom Camera Technology	1	1	1	1	1	1	1	1	1	1	1	0
RFEC	0	0	0	0	0	0	0	0	1	1	1	0

1= Can Perform, 0=Cannot Perform

Appendix C- Feasibility of technologies for various diameter ranges

Technology	< 2"	2-3"	3-4"	4-8"	8-12"	12-16"	16-18"	18-24"	24-30"	30-36"	36-48"	48-56"	>56"
Acoustic Emission Monitoring	0	0	0	0	0	0	1	1	1	1	1	1	1
Acoustic Leak Detection- Inline	0	0	0	0	0	1	1	1	1	1	1	1	1
Acoustic Leak Detection- Noise Correlator	1	1	1	1	1	1	1	1	1	1	1	1	1
Acoustic Monitoring System	0	0	0	0	0	0	0	0	0	0	1	1	1
Broadband Electromagnetic- External	0	0	1	1	1	1	1	1	1	1	1	1	1
Broadband Electromagnetic- Internal	0	0	1	1	1	1	1	1	1	1	0	0	0
CCTV- Conventional	0	0	0	1	1	1	1	1	1	1	1	1	1
Ground Penetration Radar	1	1	1	1	1	1	1	1	1	1	1	1	1
Ground Penetration Radar- Inline	0	0	0	0	0	0	0	1	1	0	0	0	0
Guided Ultrasonic Wave	0	1	1	1	1	1	1	1	1	1	1	0	0
Infrared Thermography	1	1	1	1	1	1	1	1	1	1	1	1	1
Laser Based Profiling tool	0	0	0	1	1	1	1	1	1	1	1	1	1
Magnetic Flux	0	1	1	1	1	1	1	1	1	1	1	1	0
RFEC/ TC	0	0	0	0	0	0	1	1	1	1	1	1	1
RFEC/TC- Inline/In-service	0	0	0	0	0	0	0	0	1	1	1	0	0
Seismic Echo	0	0	0	0	0	0	0	0	0	0	0	0	1
Smoke Test	1	1	1	1	1	1	1	1	1	1	1	1	1
Sonar	0	0	0	0	1	1	1	1	1	1	1	1	1
Sonde and Receiver technique	0	0	1	1	1	1	1	1	1	1	1	1	0
SSET	0	0	0	0	1	1	1	1	1	1	1	1	0
Ultrasonic Inspection- External	1	1	1	1	1	1	1	1	1	1	1	1	1
Ultrasonic Inspection- Internal	1	1	1	1	1	1	1	1	1	1	1	1	1
Zoom Camera Technology	0	0	0	0	1	1	1	1	1	1	1	1	1
RFEC	0	1	1	1	1	1	1	0	0	0	0	0	0

1= Can Perform, 0=Cannot Perform

Appendix D- Defect Identification Capability of technologies

Technology	Break	Corrosio n	Crack	Deforme d	Ex- filtration	Fracture	Holes	Joint Leakage	Leakage
Acoustic Emission Monitoring	0	0	0	0	0	0	0	0	0
Acoustic Leak Detection- Inline	0	0	0	0	0	0	0	1	1
Acoustic Leak Detection- Noise Correlator	0	0	0	0	0	0	0	1	1
Acoustic Monitoring System	0	0	0	0	0	0	0	0	0
Broadband Electromagnetic- External	0	1	1	0	0	0	0	0	0
Broadband Electromagnetic- Internal	0	1	1	0	0	0	0	0	0
CCTV- Conventional	1	0	1	0	0	1	1	0	0
Ground Penetration Radar	0	0	0	0	0	0	0	1	1
Ground Penetration Radar- Inline	1	1	1	0	1	1	1	1	1
Guided Ultrasonic Wave	0	1	0	0	0	0	0	0	0
Infrared Thermography	0	0	0	0	0	0	0	0	1
Laser Based Profiling tool	1	0	1	1	0	1	0	0	0
Magnetic Flux	0	1	0	0	0	0	0	0	0
RFEC/ TC	0	0	0	0	0	0	0	0	0
RFEC/TC- Inline/In-service	0	0	0	0	0	0	0	0	0
Seismic Echo	1	0	1	0	0	1	1	0	0
Smoke Test	0	0	0	0	1	0	0	0	1
Sonar	1	1	1	1	1	1	1	0	0
Sonde and Receiver technique	1	0	1	0	1	1	1	1	1
SSET	1	0	1	1	0	1	1	0	0
Ultrasonic Inspection- External	0	1	0	0	0	0	0	0	0
Ultrasonic Inspection- Internal	0	1	0	0	0	0	0	0	0
Zoom Camera Technology	1	1	1	0	0	1	1	0	0
RFEC	0	1	1	0	0	1	1	0	0

Technology	Lining Failure	Obstructions	Pulled Joint	WRE Base-line	WRE Real Time
Acoustic Emission Monitoring	0	0	0	0	1
Acoustic Leak Detection- Inline	0	0	0	0	0
Acoustic Leak Detection- Noise Correlator	0	0	0	0	0
Acoustic Monitoring System	0	0	0	0	1
Broadband Electromagnetic- External	0	0	0	0	0
Broadband Electromagnetic- Internal	0	0	0	0	0
CCTV- Conventional	1	1	0	0	0
Ground Penetration Radar	0	0	0	0	0
Ground Penetration Radar- Inline	1	1	1	0	0
Guided Ultrasonic Wave	0	0	0	0	0
Infrared Thermography	0	0	0	0	0
Laser Based Profiling tool	1	1	0	0	0
Magnetic Flux	0	0	0	0	0
RFEC/ TC	0	0	0	1	0
RFEC/TC- Inline/In-service	0	0	0	1	0
Seismic Echo	0	0	0	1	0
Smoke Test	0	0	0	0	0
Sonar	1	1	1	0	0
Sonde and Receiver technique	0	0	0	0	0
SSET	1	1	0	0	0
Ultrasonic Inspection- External	0	0	0	0	0
Ultrasonic Inspection- Internal	0	0	0	0	0
Zoom Camera Technology	1	1	0	0	0
RFEC	0	0	0	0	0

1= Can Perform, 0=Cannot Perform

WRE= Wire Related Event

Appendix E- Interruptive behavior of technologies

Technologies	Invasive	Non-Invasive	Lining or External coating
Acoustic Emission Monitoring	0	1	1
Acoustic Leak Detection- Inline	0	1	1
Acoustic Leak Detection- Noise Correlator	0	1	1
Acoustic Monitoring System	1	1	1
Broadband Electromagnetic- External	0	1	1
Broadband Electromagnetic- Internal	1	0	1
CCTV- Conventional	1	0	1
Ground Penetration Radar	0	1	1
Ground Penetration Radar- Inline	1	0	1
Guided Ultrasonic Wave	0	1	0
Infrared Thermography	0	1	1
Laser Based Profiling tool	1	0	1
Magnetic Flux	0	1	0
RFEC/ TC	1	0	1
RFEC/TC- Inline/In-service	0	1	1
Seismic Echo	1	0	0
Smoke Test	1	0	1
Sonar	1	0	1
Sonde and Receiver technique	0	1	1
SSET	1	0	1
Ultrasonic Inspection- External	0	1	0
Ultrasonic Inspection- Internal	1	0	0
Zoom Camera Technology	0	1	1
RFEC	1	0	1

1= Can Perform, 0=Cannot Perform

Appendix F- Performance Specification of Technologies

Technologies	Rate	Range	Analysis Time
Acoustic Emission Monitoring	0	3	1
Acoustic Leak Detection- Inline	3	4	1
Acoustic Leak Detection- Noise Correlator	0	3	1
Acoustic Monitoring System	0	4	2
Broadband Electromagnetic- External	1	3	4
Broadband Electromagnetic- Internal	1	3	4
CCTV- Conventional	2	3	3
Ground Penetration Radar	3	0	3
Ground Penetration Radar- Inline	1	3	3
Guided Ultrasonic Wave	0	2	1
Infrared Thermography	3	4	1
Laser Based Profiling tool	2	3	3
Magnetic Flux	0	0	3
RFEC/ TC	3	4	4
RFEC/TC- Inline/In-service	3	4	4
Seismic Echo	2	0	1
Smoke Test	0	0	1
Sonar	2	4	2
Sonde and Receiver technique	3	4	1
SSET	3	3	3
Ultrasonic Inspection- External	0	0	1
Ultrasonic Inspection- Internal	0	0	1
Zoom Camera Technology	3	2	2
RFEC	3	3	2

Rate *0=N/A; 1=less than 5ft/min; 2=5-10ft/min 3=more than 10ft/ min*
Range *0=N/A 1=<100 ft 2= 100-500 ft 3=500-3000ft 4=>4000ft*
Analysis Time *1= < 1day 2=1-3days, 3=3-10days 4=10days or more*

Appendix G- Personnel requirement for various technologies

Technologies	Skill Level	Training Time
Acoustic Emission Monitoring	3	0
Acoustic Leak Detection- Inline	2	0
Acoustic Leak Detection- Noise Correlator	2	0
Acoustic Monitoring System	3	0
Broadband Electromagnetic- External	3	0
Broadband Electromagnetic- Internal	3	0
CCTV- Conventional	3	3
Ground Penetration Radar	3	3
Ground Penetration Radar- Inline	3	3
Guided Ultrasonic Wave	1	1
Infrared Thermography	1	0
Laser Based Profiling tool	2	3
Magnetic Flux	4	0
RFEC/ TC	3	0
RFEC/TC- Inline/In-service	2	0
Seismic Echo	2	1
Smoke Test	1	1
Sonar	1	1
Sonde and Receiver technique	1	0
SSET	2	3
Ultrasonic Inspection- External	1	1
Ultrasonic Inspection- Internal	1	1
Zoom Camera Technology	3	3
RFEC	3	0

Skill Level *1= Skilled workers/operators 2= Technicians with experience 3= Engineers with experience 4=Technical Experts*

Training Fees *0=N/A 1= less than 1 day 2= 1-3 day 3= 3-7day 4=more than 7 day*

Appendix H- Set-up Time for various technologies

Technologies	Set-up Time
Acoustic Emission Monitoring	1
Acoustic Leak Detection- Inline	1
Acoustic Leak Detection- Noise Correlator	1
Acoustic Monitoring System	3
Broadband Electromagnetic- External	3
Broadband Electromagnetic- Internal	1
CCTV- Conventional	1
Ground Penetration Radar	1
Ground Penetration Radar- Inline	1
Guided Ultrasonic Wave	2
Infrared Thermography	1
Laser Based Profiling tool	1
Magnetic Flux	3
RFEC/ TC	1
RFEC/TC- Inline/In-service	1
Seismic Echo	3
Smoke Test	1
Sonar	1
Sonde and Receiver technique	1
SSET	1
Ultrasonic Inspection- External	3
Ultrasonic Inspection- Internal	3
Zoom Camera Technology	1
RFEC	1

Time *1= < 1day 2= 1-3days, 3= > 3days*

Appendix I- Effect of surroundings on various technologies

Technologies	Groundwater/ Water Body	Structures Non Metallic	Structures Metallic	Under Road	Other Utilities	Noise	Soil type
Acoustic Emission Monitoring	1	0	0	1	0	1	0
Acoustic Leak Detection- Inline	0	0	0	0	0	0	0
Acoustic Leak Detection- Noise Correlator	0	0	0	0	0	2	0
Acoustic Monitoring System	0	0	0	0	0	1	0
Broadband Electromagnetic- External	0	0	0	2	0	0	0
Broadband Electromagnetic- Internal	0	0	0	0	0	0	0
CCTV- Conventional	0	0	0	0	0	0	0
Ground Penetration Radar	2	2	3	3	2	0	1
Ground Penetration Radar- Inline	1	0	1	0	1	0	0
Guided Ultrasonic Wave	0	0	0	0	0	0	0
Infrared Thermography	0	0	0	0	0	0	0
Laser Based Profiling tool	0	0	0	0	0	0	0
Magnetic Flux	0	0	0	3	0	0	0
RFEC/ TC	0	0	0	0	0	0	0
RFEC/TC- Inline/In-service	0	0	0	0	0	0	0
Seismic Echo	0	0	0	0	0	0	0
Smoke Test	0	0	0	0	0	0	0
Sonar	0	0	0	0	0	0	0
Sonde and Receiver technique	0	0	0	0	1	0	0
SSET	0	0	0	0	0	0	0
Ultrasonic Inspection- External	0	0	0	2	0	0	0
Ultrasonic Inspection- Internal	0	0	0	0	0	0	0
Zoom Camera Technology	0	0	0	0	0	0	0
RFEC	0	0	0	0	0	0	0

Groundwater, Structure, Under Road, Other utilities, Noise: *0= No Impact, 1=Impact contained with cost less than US$10,000 for entire project, 2=Impact contained with cost more than $10,000 for entire project, 3= Impact Cannot be contained*

Soil Type: *1= Can Perform, 0=Cannot Perform*

Appendix J- Impact on user and traffic for various technologies

Technologies	Traffic	Users
Acoustic Emission Monitoring	1	0
Acoustic Leak Detection- Inline	0	0
Acoustic Leak Detection- Noise Correlator	0	0
Acoustic Monitoring System	0	1
Broadband Electromagnetic- External	3	0
Broadband Electromagnetic- Internal	0	3
CCTV- Conventional	0	2
Ground Penetration Radar	0	0
Ground Penetration Radar- Inline	0	3
Guided Ultrasonic Wave	2	0
Infrared Thermography	1	0
Laser Based Profiling tool	0	2
Magnetic Flux	3	0
RFEC/ TC	0	2
RFEC/TC- Inline/In-service	0	0
Seismic Echo	0	3
Smoke Test	0	2
Sonar	0	3
Sonde and Receiver technique	0	0
SSET	0	1
Ultrasonic Inspection- External	3	0
Ultrasonic Inspection- Internal	0	3
Zoom Camera Technology	0	0
RFEC	0	2

0=No 1=Low 2=Medium 3=High; qualitative values for comparative purposes only

Appendix K- Economic Parameters for various technologies

Technologies	Direct Cost ($/ft)	Preparation Cost ($/ft)	Data Analysis fees ($/ft)	User Disruption (Qualitative values on scale of 1 to3 for comparative purposes only)	Traffic Disruption (Qualitative values on scale of 1 to3 for comparative purposes only)
Acoustic Emission Monitoring	6	1	2.5	0	1
Acoustic Leak Detection- Inline	4	1	0	0	0
Acoustic Leak Detection- Noise Correlator	6	0	0	0	0
Acoustic Monitoring System	8	1	2.5	2	0
Broadband Electromagnetic- External	45	30	0	0	3
Broadband Electromagnetic- Internal	40	10	0	3	0
CCTV- Conventional	2	0	0	2	0
Ground Penetration Radar	1	1	2	0	0
Ground Penetration Radar- Inline	7	2	2	3	0
Guided Ultrasonic Wave	8	1	0	0	2
Infrared Thermography	1	1	0	0	1
Laser Based Profiling tool	3	0	0	2	0
Magnetic Flux	50	0	0	0	3
RFEC/ TC	8	2	0	2	0
RFEC/TC- Inline/In-service (PipeDiver)	8	2	0	0	0
Seismic Echo	2	3	0.4	3	0
Smoke Test	0.1	0	0	2	0
Sonar	6	1	0	3	0
Sonde and Receiver technique	1	0.5	0	0	0
SSET	4	0	1	1	0
Ultrasonic Inspection- External	2.6	3	0.4	0	3
Ultrasonic Inspection- Internal	2.6	3	0.4	3	0
Zoom Camera Technology	1	0	0	0	0
RFEC	9	0	0	2	0

Appendix L- Technology Data Sheets

I. Technology Background	
Technology/Method	Acoustic Leak Detection- Inline
Utilization Rates	Actively being used in US and other countries. Available commercial products are: 1. Sahara (PPIC), developed by WRc, Tethered 2. Smart-Ball (Pure Technologies), developed by Pure Technologies, Free Flowing
Description of Main Features	Acoustic Leak Detection- Inline is a type of Non Destructive Technology in which acoustic sensors are passed along the pipeline while in service. These sensors detect the noise emanated by the leakages in the pressurized water pipes. The amplitude and frequency of noise depends on variety of factors vis-à-vis pipe material, internal pressure. The most widely used leak detection system is the noise correlator, but at any significant distance from the leak points the leak noise signal is swamped by background noise. This led to the invention of inline Acoustic leak detection equipments; they can be either tethered or free-swimming. The two commercially available equipments are Sahara and SmartBall.
Advantages	• As an in-pipe technique, factors like pipe material and diameter do not influence the detection of leaks, as they do in on-pipe techniques. • Tethered hydrophone technology can be used to accurately pinpoint leaks. • Non-tethered systems can survey a large length of pipe than tethered systems in each use. • No Disruption to Pipe Service. • Tethered control ensures no lost sensor. • Sensitivity to leak as small as 0.005gal/min. • Spatial Accuracy of 18”
Limitations	• The Sahara technology is relatively expensive, so other techniques and equipment should be used to target and prioritize area to identify where it would be most useful. • Tethered hydrophones can become fouled in valves and have limited range, and require a minimum flow rate to pull them along the main. • There is a risk of losing free swimming hydrophones.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	>10”

Depth	No impact
Lining	No Impact
III. Soil Characteristics	
Soil Type	No impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive but performs in service
Set Up Time	<1 day
Expertise	Technician with experience
Training Time	N/A as Manufacturer or service provide performs inspection itself
V. Data Interpretation	
Time Required	<1day
Expertise	Technician with experience
Software Requirement	N/A as Manufacturer or service provider do the analysis
Training	N/A as Manufacturer or service provider do the analysis
VI. Technology Specifications	
Defects	Leakages
Range	N/A, 4800 ft in Tethered system
Rate	3 ft/sec
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$4/ ft
Effect of Density	No Impact
Payment Options	Inspected and Analyzed by manufacturer or service provider
Training Fees	N/A
Data Analysis Fees	Included
User Disruption	N/A
Traffic Disruption	N/A
Installation Fees	$1/ft
IX. Data Sources	
References	• Heart, S. and Urquhart, H. (2007). “WERF Condition Assessment Protocols (CAP) Project.” • Mergelas, B., Balliew, J, Larsen, M and Roy, D. (2007). “How EL PASO water utilities optimizes transmission pipeline remediation expenditure.” • Rizzo, P. (2009). “Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review.” Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). “Condition Assessment of Wastewater Collection

	Systems." State of Technology Review Report. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Mergelas, B.J. and Henrich, G. (2005). "Leak Locating Methods for Pre-commissioned Transmission Pipelines: North America Case Studies." Leakage 2005, pp 1-6. • Derr, K. (2008). "In-service Inspection of Wastewater Force Mains." GAWP. • **http://www.ppic.com/services/sahara.shtml** • **http://www.ppic.com/case_studies/index.shtml** • **http://www.puretechnologiesltd.com/html/smartball_water.php** • **http://www.puretechnologiesltd.com/html/smartball_water_case_studies.php** • **http://www.ssis.co.za/services2.htm**
X. Previous Projects	
El Paso	Water Mains, Sahara®
Philadelphia Water Department	Water Mains, Sahara®
San Francisco Public Utilities Commission	Water Mains, Sahara®
Dallas Water utilities	Water Mains, Sahara®
Toho Water Authority	Water Mains, SmartBall®
City of Allentown	Water Mains, SmartBall®
City of Grand Forks	Water Mains, SmartBall®
Hampton Roads Sanitation District	Forcement, Sahara® and SmartBall®

I. Technology Background	
Technology/Method	Acoustic Leak Detection- Noise Correlator
Utilization Rates	Actively being used in US and other countries. Available commercial products are: 3. Echologics Inc, 4. Fluid Conservation Systems. 5. Many other
Description of Main Features	Acoustic Leak Detection- Noise Correlator is a type of Leak Detection Technology, in which a computer based devices (acoustic sensors) which are used to measure sound or vibration at two points on a pipe, on either side of suspected leak. The acoustic sensors are generally attached to the pipe contact point (normally fire hydrant). Signals detected by the sensors are wirelessly transmitted to the correlator which pin points the location of the leak signal measured from the two adjacent sensors, on the basis of time-lag and sensor to sensor spacing.
Advantages	• System offers leak detection from surface of pipeline features • No user and traffic disruption • Easy to use and highly portable
Limitations	• Multiple leaks within a given monitored area often yield an un-localized signal. • Leak signal strength dissipates rapidly within large diameter pipelines - pipelines over 12" in diameter - inferring that the acoustic signal of the leak may not be practically detectable by correlator in large diameter pipe.- This limitation has been limited to considerable level. • Multiple diameter mains may lead to inaccurate identification of leak location. • The leak signal is lost within pipelines that contain air pockets. • Non-metallic mains (HDPE, PVC, asbestos cement or concrete) do not conduct the leak signal effectively. The leak noise is attenuated very rapidly as it travels away from the source in these types of pipe, inferring that correlator may have difficulty in practically identifying leaks in non-metallic mains. Some recent advances in the technology based on low frequency equipments have dealt successfully with this limitation. • At any significant distance from the leak point background noise can corrupt the leak noise signal
Applicability (Underline those that apply)	<u>Force Main</u> Gravity Sewer Laterals <u>Water Main</u> <u>Distribution</u>
II. Pipe Characteristics	
Material	All
Diameter	All
Depth	No impact

Lining	No Impact
III. Soil Characteristics	
Soil Type	No impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non Invasive
Set Up Time	<1 day
Expertise	Technician with experience
Training Time	< 1 day
V. Data Interpretation	
Time Required	< 1 day
Expertise	Technician with experience
Software Requirement	Principle component of system, Included
Training time	< 1 day
VI. Technology Specifications	
Defects	Leakages
Range	1600 ft
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact, can cause extraneous noise
Noise	Can be contained within $10000-$30000
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$6/ ft
Effect of Density	No Impact
Payment Options	Inspected and Analyzed by owner or 3rd party
Training Fees	No additional fees
Data Analysis Fees	No additional fees
User Disruption	N/A
Traffic Disruption	N/A
Installation Fees	No additional fees
IX. Data Sources	
References	• Heart, S. and Urquhart, H. (2007). "WERF Condition Assessment Protocols (CAP) Project." • Mergelas, B., Balliew, J, Larsen, M and Roy, D. (2007). "How EL PASO water utilities optimizes transmission pipeline remediation expenditure." • Mergelas, B.J. and Henrich, G. (2005). "Leak Locating Methods for Pre-commissioned Transmission Pipelines: North America Case Studies." Leakage 2005, pp 1-6. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil

	Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Derr, K. (2008). "In-service Inspection of Wastewater Force Mains." GAWP. • Hunaidi, O. and Wang, A. (2000). "LeakFinder- New Pipeline Leak Detection System." 15th World Conference on Non Destructive Testing. • **http://www.fluidconservation.com/microCorr7.htm** • **http://www.ppic.com/home/deteccionpresen.html** • **http://www.echologics.com/leakfinder_overview.html** • **http://www.echologics.com/leakfinder/pdf/factsheet.pdf**
X. Previous Projects	
Amman	Water main
Many other	Water Distribution successful

I. Technology Background	
Technology/Method	Acoustic Emission Technology
Utilization Rates	Actively being used in US and other countries, developed & commercialized by Pressure Pipe Inspection Company for water and waste water industry
Description of Main Features	Acoustic Emissions Testing (AET) is a type of Non Destructive Technology in which acoustic sensors are placed along the pipeline and the energy that is released when a prestressing wire breaks or slips is recorded and the origin location is calculated. Wire breaks and slips both indicate the presence of distress and loss of prestressed and are referred to as wire related events (WRE). Locating which of the PCCP pipes, if any, that are actively deteriorating is a key step in determining the condition of the main.
Advantages	• In-service inspection- The ability to evaluate the structural integrity of a pipe in-line, under the operating condition it experiences while in use. This valuable information, about the structural performance of the pipe and degradation of the pipe, can help in identifying when and where detailed inspection inspections are needed to be performed. This technology can help in providing advanced warning to the impending failure. • Long Range- The entire length of the pipe can be tested with a relatively small number of sensors, if the sensor's area of coverage is carefully determined. • Prioritize capital expenditures by enacting a selective repair and replacement programs that is based on current condition level. • A long term monitoring capability enables the operator to establish the rate of deterioration. • Non-invasive- This capability of this technology enables uninterrupted supply to the users.
Limitations	• Baseline measurement- This technology lacks capability of identifying the baseline condition of the pipeline assets. • Need to assess the pipe surface in order to install accelerometers, and can be a reason for digging a pothole in case the pipe is passing under a highway.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	PCCP
Diameter	>16"
Depth	No impact, except for increased cost of installation
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact, except for variable cost of installation
IV. Installation Characteristics	

Invasive/ Non-Invasive	Non-Invasive
Set Up Time	Half a day/ monitoring site
Expertise	Engineers with experience
Training	N/A as Manufacturer installed the system itself
V. Data Interpretation	
Time Required	2hrs to 1 day
Expertise	Technical Experts
Software Requirement	N/A as Manufacturer do the analysis
Training	N/A as Manufacturer do the analysis
VI. Technology Specifications	
Defects	Wire Related Events (WRE), Wire-Breaks
Range	500-3000 ft
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact as sensors are enclosed in a water-proof housing
Surrounding Structure	Can result in increased noise
Noise	May cause an increase in false positives
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$6/ft
Effect of Density	No Impact
Payment Options	Installed and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	$2.5/ft
User Disruption	N/A
Traffic Disruption	Minimal dependent on the project
Installation Fees	$1/ft
IX. Data Sources	
References	• Vahaviolos, S.J. (1999). "Acoustic Emission Standard and Technology Update." P50-100. • Wardany, R. A. (2008). "Condition assessment of prestressed concrete cylindrical water pipes," *Proceedings of the 60th Annual WCWWA Conference and Trade Show*, Regina, Canada. • Mergelas, B., Stubblefield, N., Craig, M., Morrison, R. and White, C. (2007). "Turn-key Condition Assessment and Rehabilitation/ Replacement solution for an effluent force main." Advances and Experiences with Trenchless Pipeline projects, ASCE. • Mergelas, B., Balliew, J, Larsen, M and Roy, D. (2007). "How EL PASO water utilities optimizes transmission pipeline remediation expenditure." • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil

	Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • **http://www.ppic.com/services/aet.shtml** • **http://www.pipepressure.com/pdfs/Acoustic%20Emisssion%20Testing%20-%20PPIC.pdf** • **http://www.ndt-ed.org/EducationResources/CommunityCollege/Other%20Methods/AE/AE_Index.htm**
X. Previous Projects	
EL PASO	Water Mains
City of West Palm Beach	Force Sewer
Other	Query sent to the manufacturer

I. Technology Background	
Technology/Method	Acoustic Fiber Optics
Utilization Rates	Actively being used in US and other countries, developed & commercialized by Pure Technologies Ltd. & Pressure Pipe Inspection Company for water and waste water industry
Description of Main Features	Acoustic Emissions Testing (AET) is a type of Non Destructive Technology in which acoustic sensors (Optical fibers in this case) are placed along the pipeline and the energy that is released when a prestressing wire breaks or slips is recorded and the origin location is calculated. Wire breaks and slips both indicate the presence of distress and loss of prestressed and are referred to as wire related events (WRE). Locating which of the PCCP pipes, if any, that are actively deteriorating is a key step in determining the condition of the main.
Advantages	• In-service inspection- The ability to evaluate the structural integrity of a pipe in-line, under the operating condition it experiences while in use. This valuable information, about the structural performance of the pipe and degradation of the pipe, can help in identifying when and where detailed inspection inspections are needed to be performed. This technology can help in providing advanced warning to the impending failure. • Long Range- 25 mile of pipe can be monitored with a single DAQ. • Prioritize capital expenditures by enacting a selective repair and replacement programs that is based on current condition level. • A long term monitoring capability enables the operator to establish the rate of deterioration. • Non-invasive- This capability of this technology enables uninterrupted supply to the users except for the period of installation. • The fiber optic sensor is always at a distance maximum to the diameter of pipe from the WRE, which results in much lesser attenuation of the signals. • The optical fibers are immune to the extreme environment, temperature, EM Interference. • The spatial and spectral resolution is very high. • The entire length of optical fiber works as a sensor, thus the data collection is actually continuous. • The fibers have dual capabilities of sensing and data transmission.
Limitations	• Baseline measurement- This technology lacks capability of identifying the baseline condition of the pipeline assets. • The condition to place the DAQ should not be very hot and humid. • The technology is very sensitive to the extraneous noise, which translates to higher false positives and negatives. • The sensor can be spliced for a limited number of times, after the particular number of splicing the entire optical fiber has to be changed.

Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	PCCP
Diameter	>36”
Depth	No impact,
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive
Set Up	1-2 weeks
Personnel	Engineers with experience
Training	N/A
V. Data Interpretation	
Time Required	2hrs to 1 day
Expertise	Technical Experts
Software Requirement	N/A as Manufacturer do the analysis
Training	N/A as Manufacturer do the analysis
VI. Technology Specifications	
Defects	Wire Related Events (WRE), Wire-Breaks
Mobility	N/A
Range	25 miles
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No Impact
Surrounding Structure	No Impact
Noise	Can be contained within <$10000
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$300,000 per DAQ
Effect of Density	No Impact
Payment Options	Installed and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	$100,000/year
User Disruption	Moderate (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Medium(Quantitative value not available)
IX. Data Sources	
References	• Vahaviolos, S.J. (1999). “Acoustic Emission Standard and Technology Update.” P50-100.

	• Wardany, R. A. (2008). "Condition assessment of prestressed concrete cylindrical water pipes," *Proceedings of the 60th Annual WCWWA Conference and Trade Show*, Regina, Canada. • Mergelas, B., Stubblefield, N., Craig, M., Morrison, R. and White, C. (2007). "Turn-key Condition Assessment and Rehabilitation/ Replacement solution for an effluent force main." Advances and Experiences with Trenchless Pipeline projects, ASCE. • Mergelas, B., Balliew, J, Larsen, M and Roy, D. (2007). "How EL PASO water utilities optimizes transmission pipeline remediation expenditure." • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Higging, M.S. and Paulson, P.O. (2006). "Fiber Optic Sensors for Acoustic Monitoring of PCCP." ASCE Pipelines. • Kurtz, D.W. (2007). "Case Studies for a Free-Swimming Acoustic Leak Detection System used in Large Diameter Pipelines." ASCE Pipelines • Lenghi, A., Essamin, O., Elgalbati, K. and Wrigglesworth, W. (2009). "Assessing 380Km of PCCP using Acoustic Monitoring- A comparison of Technologies." ASCE Pipelines • Higgins, M.S., Gadoury, P.J., LePage, P., Razza, R., Keaney, J. and Mead, I. (2007). "Technologies to assess and manage of providence water's 102" Pipe Aqueduct." ASCE Pipelines. • Galleher, J.J., Holley, M., Shenkiryk, M. and Eaton, G. (2007). "Snap, Crack, Pop- Recording of PCCP Failure." ASCE Pipelines. • Lyori, V. (2007). "Structural Monitoring With Fibre-Optic Sensors Using The Pulsed Time-Of flight Method And Other Measurement Techniques." Doctoral Dissertation, Oulu. • **http://www.puretechnologiesltd.com/html/soundprintafo_water_and_wastewater.php** • **http://www.ppic.com/services/fiber_optic_monitoring.shtml**
X. Previous Projects	
WSSC	Water Transmission
San Diego	Water Transmission
Great Manmade River Project, Libya	Water Transmission
STA Aqueduct	Water Transmission

Baltimore	Water Transmission
Providence water supply board.	Water Transmission

I. Technology Background	
Technology/Method	Broadband Electromagnetic- External
Utilization Rates	Actively being used in US, UK, Canada and other countries, developed by Rock Solid Group (RSG).
Description of Main Features	BEM is a type of Non Destructive Technology to inspect ferrous pipes (CI/DI/Steel). This technology uses Electromagnetic or Eddy current to detect corrosion and provide information on thickness (Black & Veatch, 2010). The technology is independent of frequency thus immune to any type of electromagnetic interference (USEPA 2009). It can detect both the internal and external defects. The technology works only for ferrous pipes thus have limited applications in sewer pipes.
Advantages	• Able to survey through external coating and internal linings. • No upper limit on pipe diameter in case of external • Used across the world on various projects • Immune to EM Interference • Metal loss to 1 mm can be detected using this technology
Limitations	• The technology is not continuous thus takes longer inspection time. • The technology is effective on straight pipes but not on sharp bends or siphons. • The pipe needs to be completely exposed which is an arduous task. • The internal equipment can inspect the pipelines up to 36”. • Since the results are averaged out, thus isolated pits or scratches Cannot be identified. • The rate of inspection is very slow and cost is very high.
Applicability (Underline those that apply)	<u>Force Main</u> <u>Gravity Sewer</u> <u>Laterals</u> <u>Water Main</u> <u>Distribution</u>
II. Pipe Characteristics	
Material	CI, DI, Steel
Diameter	3”-36”
Depth	No impact
Lining or coating	No Impact up to 2”
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive
Set Up Time	<1 day
Expertise	Engineer with experience
Training Time	N/A as Manufacturer or 3rd party performs inspection themselves
V. Data Interpretation	
Time Required	7-10 days
Expertise	Technical Experts
Software	N/A as Manufacturer or 3rd party do the analysis

Requirement	
Training	N/A as Manufacturer or 3rd party do the analysis
VI. Technology Specifications	
Defects	Crack, Corrosion and Graphitization
Range	3000ft
Rate	<5ft/min
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$45/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or 3rd party
Training Fees	N/A
Data Analysis Fees	Included in Direct Cost
User Disruption	High (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	$30 /ft
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). “Workshop on Condition Assessment Inspection Devices for Water Transmission Mains.” Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). “Non Destructive, Noninvasive assessment of underground pipelines.” Pg 25-27. • Grigg, N.S. (2004). “Assessment and Renewal of water distribution system.” pg 49. • USEPA (2008). “White Paper: Condition Assessment of Wastewater Collection System.” • Rajani, B. and Kleiner, Y. (2004). “Non-Destructive Inspection techniques to determine structural distress indicators in water mains.” Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). “Water and Wastewater Pipe Nondestructive Evaluation and Health Monitoring: A Review.” Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). “Condition Assessment of Wastewater Collection Systems.” State of Technology Review Report. • Black & Veatch. (2010). “Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement.” • Ratliff, A., Russo, M., Frechette, E. and Fox, S. (2009). “Phased and focused approach for water pipeline corrosion assessment.” ASCE Pipelines.

	• Stubblefield, N.D., Glaus, H., White, C., Morrison, W. and Shields, B. (2008). "Pipe Vision: Condition Based Assessment of a South Florida Sewage Force Main." ASCE Pipelines. • Hazelden, G., Ragula, G. and Roubal, M. "The use of BEM for integrity inspection of a 760mm CI and Steel." • **www.inframetrix.com** • **www.rocksolidgroup.com.au** • **www.gastechnology.org**
X. Previous Projects	
Palm Beach County Water Utility	Water Mains
Las Vegas	Water Mains
Seattle	Force Main
Louisville	Force Main
Lake worth	Force Main

I. Technology Background	
Technology/Method	Broadband Electromagnetic- Internal
Utilization Rates	Actively being used in US, UK, Canada and other countries, developed by Rock Solid Group (RSG).
Description of Main Features	BEM is a type of Non Destructive Technology to inspect ferrous pipes (CI/DI/Steel). This technology uses Electromagnetic or Eddy current to detect corrosion and provide information on thickness (Black & Veatch, 2010). The technology is independent of frequency thus immune to any type of electromagnetic interference (USEPA 2009). It can detect both the internal and external defects. The technology works only for ferrous pipes thus have limited applications in sewer pipes.
Advantages	• Able to survey through external coating and internal linings. • No upper limit on pipe diameter in case of external • Used across the world on various projects • Immune to EM Interference • Metal loss to 1 mm can be detected using this technology
Limitations	• The technology is not continuous thus takes longer inspection time. • The technology is effective on straight pipes but not on sharp bends or siphons. • The pipe needs to be completely exposed which is an arduous task. • The internal equipment can inspect the pipelines up to 36". • Since the results are averaged out, thus isolated pits or scratches Cannot be identified. • The rate of inspection is very slow and cost is very high.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	CI, DI, Steel
Diameter	>3"
Depth	No impact
Lining or coating	No Impact up to 2"
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non-Invasive
Set Up Time	>3day
Personnel	Engineer with experience
Training	N/A as Manufacturer or 3rd party performs inspection themselves
V. Data Interpretation	
Time Required	7-10 day
Expertise	Technical Experts
Software	N/A as Manufacturer or 3rd party do the analysis

Requirement	
Training	N/A as Manufacturer or 3rd party do the analysis
VI. Technology Specifications	
Defects	Crack, Corrosion and Graphitization
Range	3000ft
Rate	<5ft/ min
Energy Requirement	Not Available
Accuracy	Not Available
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$40/ ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or 3rd party
Training Fees	N/A
Data Analysis Fees	Included in direct cost
User Disruption	N/A
Traffic Disruption	High (Quantitative value not available)
Installation Fees	$10/ft
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water and Wastewater Pipe Nondestructive Evaluation and Health Monitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Black & Veatch. (2010). "Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement." • Ratliff, A., Russo, M., Frechette, E. and Fox, S. (2009). "Phased and

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X. Previous Projects	
Palm Beach County Water Utility	Water Mains
Las Vegas	Water Mains
Seattle	Force Main
Louisville	Force Main
Lake worth	Force Main

I. Technology Background	
Technology/Method	Acoustic Emission Technology
Utilization Rates	Actively being used in US, Europe, South Africa and Australia, GPR equipment is manufactured and commercialized by many companies but only Sewer Vue has commercialized an In-Pipe GPR Euipment.
Description of Main Features	Ground Penetrating Radar or GPR is a nondestructive geophysical method that produces a cross-sectional profile or record of sub-surface features. The system operates by transmitting the pulses of ultra high frequency radio waves down into the ground through a transducer. The transmitted energy is reflected from various buried objects or distinct contacts between various materials. Although the conventional GPR systems are operated from the surface, but the new systems can be used inside the pipe to determine the surrounding soil condition, the soil-pipe interaction and the structure of the pipe respectively (Costello et. al., 2007). The time lag between transmitted and reflected waves corresponds to the depth or the distance of the reflecting object. For, leakage the GPR is used from the surface and it looks for the voids around the pipe created due to saturation of leaking water (Misiunas, 2005). For the external defects of the pipe like corrosion, delamination in concrete pipes the inline GPR detects the reflected signals from the targets of different dielectric properties (www.sewervue.com).
Advantages	• GPR is quick and gives immediate results • Can determine the ground conditions external to the pipe. • Can be used as invasive as well as non-invasive method (Costello et.al., 2007). • In-line systems have visual (CCTV) capabilities also, thus the system negates the limitations of both the technologies. • Cleaning is not required for In-pipe system.
Limitations	• Penetration into soils with high conductivity like clays can be limited to less than 1 meter. (Marlow et. al., 2006). • The equipment can be difficult to move in steep slopes and uneven ground. • The inline equipment is very slow (3.2ft/min) (www.sewervue.com). • Skilled operator is necessary for accurate of interpretation of data. • The depth of the pipe is a major limitation
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	All (surface), Non-Metallic (In-Pipe)
Diameter	All (Surface), 18"-30"(In-Pipe)
Lining	N/A
III. Soil Characteristics	
Soil Type	Quantitative values not available
IV. Installation Characteristics	
Invasive/ Non-	Non-Invasive(Surface), Invasive (In-Pipe)

Invasive	
Set Up Time	< 1 day
Expertise	Operator with experience
Training Time	>3 day
V. Data Interpretation	
Time Required	3-5 Days
Expertise	Operator with experience
Software Requirement	N/A comes with package
Training Time	3-7 days
VI. Technology Specifications	
Defects	Leakage (Surface) and Cracks, Bedding Condition, Holes, Breaks, Delamination, Corrosion etc. (In-Pipe)
Range	N/A (Surface) and 1000ft (In-pipe)
Rate	20 mph (surface) and 192 ft/hr (In-pipe)
VII. Environmental Characteristics	
Water Bodies/ Ground Water	Can be contained within $10000-$30000 (surface) and Can be contained within <$10000(in-pipe)
Surrounding Structure	Can be contained within $10000-$30000 (surface)
Noise	Can be contained within <$10000
Surrounding Utilities	Can be contained within $10000-$30000
VIII. Economical Parameters	
Direct Cost	Depends on length to be monitored, Sensor spacing and time to be monitored. ($ Value needs to be confirmed)
Effect of Density	Can be contained within $10000-$30000
Payment Options	Installed and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	N/A
User Disruption	N/A (Surface) and Can be contained within $10000-$30000 (In-pipe)
Traffic Disruption	N/A
Installation Fees	N/A
IX. Data Sources	
References	• Heart, S. and Urquhart, H. (2007). “WERF Condition Assessment Protocols (CAP) Project.” • Rizzo, P. (2009). “Water and Wastewater Pipe Nondestructive Evaluation and Health Monitoring: A Review.” Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). “Condition Assessment of Wastewater Collection Systems.” State of Technology Review Report. • USEPA (2008). “White Paper: Condition Assessment of Wastewater Collection System.” • Lillie, K., Reed, C. and Rodger, M. (2004). “Workshop on Condition Assessment Inspection Devices for Water Transmission Mains.” Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). “Non Destructive,

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X. Previous Projects	
Europe, Australia, S. Africa	Surface GPR
Phoenix, AZ	In-Pipe

I. Technology Background	
Technology/Method	Infrared (IR) Technology
Utilization Rates	Actively being used in US, Europe, South Africa and Australia, GPR equipment is manufactured in Germany for inspection of manufacturing plants.
Description of Main Features	Infrared Thermography is a type of Non Destructive Technology to defects like leaks and voids. This technology involves the use of an infrared camera to measure the temperature difference across an object. Infrared Thermography is also a remote sensing (no contact) technology and has proved to be an effective, economical and efficient method for detection of leaks and other anomalies in pipelines. The technology is one of the several technologies recognized by American Society of Non Destructive Testing (ASNT).
Advantages	• Non Invasive, no contact technology • Economical • Very High rate • Not affected by various factors or parameters related to the pipes • This technology can also detect void in the soil.
Limitations	• The structural condition Cannot be determined. • The quantification of leakage is not possible. • The performance of technology is heavily dependent on the environmental factors which are beyond the control. • If the considerations like shadow and superstructures are not considered properly than it may result in faulty data.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	All
Depth	All
Lining	N/A
III. Soil Characteristics	
Soil Type	All
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non Invasive, Non Contact
Set Up Time	<1day
Expertise	N/A
Training Time	N/A
V. Data Interpretation	
Time Required	<1 Day
Expertise	N/A
Software Requirement	N/A part of the system

Training Time	N/A
VI. Technology Specifications	
Defects	Leakage and Voids in bed
Range	100 miles/ day
Rate	3-100 miles/ day
VII. Environmental Characteristics	
Water Bodies/ Ground Water	N/A
Surrounding Structure	N/A
Noise	N/A
Surrounding Utilities	N/A
VIII. Economical Parameters	
Direct Cost	$1/ft
Effect of Density	N/A
Payment Options	Installed and Monitored by manufacturer or service provider
Training Fees	N/A
Data Analysis Fees	N/A
User Disruption	N/A
Traffic Disruption	Low to Medium (Quantitative value not available)
Installation Fees	$1/ft
IX. Data Sources	
References	• Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). "Failure Monitoring and Asset Condition Assessment in water supply systems." Doctoral dissertation, Lund University, Lund, Sweden. • Heart, S. and Urquhart, H. (2007). "WERF Condition Assessment Protocols (CAP) Project." • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Amirrato, F. and Zayicek, P (1999). "Infrared Thermography Field Application Guide." EPRI • Weil, G.J. and Graf, R.J. (1994). "Infrared Thermography based pipeline detection system." SPIE Thermosense XIII, 1467, 18-33. • **http://www.entechworld.com** • **http://www.aerotecusa.com** • **http://www.rjn.com/Projects/MSD/stlouis_study.htm**
X. Previous Projects	
Metropolitan St.	Water Mains

Louis District, Missouri	
• New Hampshire Airport, NH	Water Distribution

<table>
<tr><th colspan="2">I. Technology Background</th></tr>
<tr><td>Technology/Method</td><td>Magnetic Flux Leakage</td></tr>
<tr><td>Utilization Rates</td><td>The technology has been in existence since 1965, but it has been developed oil and gas pipelines which are clear and unlined. The application in water main is still being explored and limited to clear and unlined pipes. The external method requires the pipe to be completely exposed and cleared to maintain a close contact.</td></tr>
<tr><td>Description of Main Features</td><td>MFL is a type of Non Destructive Technology to inspect ferrous pipes (conductive CI and Steel). This technology was developed specifically for oil and gas pipelines. The technology can work mainly on the external surface of the pipes in water and wastewater industry as most of the pipes have tuberculation, debris or lining, while this technology requires close contact with the surface. MFL depends on the ferromagnetic nature of the object being inspected. Figure 1 illustrates MFL equipment being used on a ferrous pipe.</td></tr>
<tr><td>Advantages</td><td>• No Interruption to Supply, non intrusive technique</td></tr>
<tr><td>Limitations</td><td>• Can only be used where pipe is exposed or by digging excess pits.
• MFL response to anomalies depending primarily upon the magnetic properties of pipeline material.
• In steel pipes mechanical damage due to plastic deformation can also be detected as defect.
• Very High level of expertise is needed to interpret the data as imperfect detection and measuring capabilities of MFL (Rizzo 2010).
• The Equipment is most likely to miss smaller and shallow defects.</td></tr>
<tr><td>Applicability (Underline those that apply)</td><td>Force Main Gravity Sewer Laterals Water Main Distribution</td></tr>
<tr><th colspan="2">II. Pipe Characteristics</th></tr>
<tr><td>Material</td><td>CI and Steel</td></tr>
<tr><td>Diameter</td><td>2” to 56”</td></tr>
<tr><td>Depth</td><td>No impact</td></tr>
<tr><td>Lining</td><td>No Impact</td></tr>
<tr><th colspan="2">III. Soil Characteristics</th></tr>
<tr><td>Soil Type</td><td>No Noticeable impact</td></tr>
<tr><th colspan="2">IV. Installation Characteristics</th></tr>
<tr><td>Invasive/ Non-Invasive</td><td>Non-Invasive</td></tr>
<tr><td>Set Up time</td><td>>3 day</td></tr>
<tr><td>Personnel</td><td>Technical Experts</td></tr>
<tr><td>Training Time</td><td>N/A as Manufacturer or 3rd party performs inspection themselves</td></tr>
<tr><th colspan="2">V. Data Interpretation</th></tr>
<tr><td>Time Required</td><td>3-7 days</td></tr>
<tr><td>Expertise</td><td>Technical Experts</td></tr>
</table>

Software Requirement	N/A
Training	N/A as Manufacturer or 3rd party do the analysis
VI. Technology Specifications	
Defects	Wall Thickness or Corrosion
Range	N/A
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$50/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or 3rd party
Training Fees	N/A
Data Analysis Fees	Included in direct cost
User Disruption	N/A
Traffic Disruption	High (Quantitative value not available)
Installation Fees	N/A
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Chen, C. (2007). "Ultrasonic and Advanced Method for Non Destructive Testing and Material Characterization." • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542.

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X. Previous Projects	
No Literature could be found for this purpose	

I. Technology Background	
Technology/Method	Remote Field Eddy Current
Utilization Rates	Actively being used in US, UK, Canada and other countries, developed by Applied Magnetics Group at Queens University & commercialized by Russell NDE Systems Inc., Canada
Description of Main Features	RFEC is a type of Non Destructive Technology to inspect ferrous pipes (CI/DI/Steel). This technology was developed to surmount the limitation of Eddy current technology that limits its detection of defects to those located on the surface of pipe nearest to the magnetic coil. RFEC can detect both the internal and external defects. RFEC involves the deployment of a probe consisting of multiple magnetic coils, an exciter coil and a detector coil. This technology uses low frequency alternating current (AC) and through-wall transmission for inspection of pipes.
Advantages	• RFEC tools are available to suit a range of pipe sizes 2” and up. • The probes can be used in wet or dry condition • The probe can be inserted through fire hydrant • Close contact between the exciter and detector coils and pipe wall is not essential and thus thorough cleaning is not required. • The technology works in lined as well as unlined pipes. • Equally sensitive to internal and external wall loss • Detection of wall loss, pitting and corrosion is possible • Over 50000+ pipes tested with more than 80% accuracy
Limitations	• The method is only suitable for ferrous pipes. • The pipe requires cleaning before inspection to ensure that the equipment travels freely through the pipe without encountering encumbrances. • Scrubbing-off the tuberculation can enhance the likelihood of water main leak. • RFEC technique is not likely to detect the small pits • Unable to negotiate sharp bends • The rate of inspection is rather slow. • Very high spectral and spatial resolution • The inherent stresses from the manufacture of the pipes can also be detected.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	CI, DI, Steel
Diameter	2” to 18”
Depth	No impact
Lining	No Impact up to 1 inch
III. Soil Characteristics	
Soil Type	No Noticeable impact

IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive
Set Up Time	>3 day
Expertise	Engineer with experience
Training	N/A as Manufacturer or 3rd party performs inspection themselves
V. Data Interpretation	
Time Required	<1 day
Expertise	Engineer with experience
Software Requirement	N/A as Manufacturer or 3rd party do the analysis
Training	N/A as Manufacturer or 3rd party do the analysis
VI. Technology Specifications	
Defects	Crack, Holes, Corrosion and Graphitization
Range	3000 ft
Rate	12 ft/ min
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$9/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	Included
User Disruption	High (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Not available
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20.

	• Rizzo, P. (2009). “Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review.” Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). “Condition Assessment of Wastewater Collection Systems.” State of Technology Review Report. • Black & Veatch. (2010). “Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement.” • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). “Underground asset location and condition assessment technologies.” Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). “Failure Monitoring and Asset Condition Assessment in water supply systems.” Doctoral dissertation, Lund University, Lund, Sweden. • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). “Protocols for Assessing Condition and Performance of Water and Wastewater Assets.” WERF. • Skabo, R.R. (1991). “Nondestructive Testing of Water Mains for Physical Integrity.” AWWA • Teitsma, A. and Maupin, J. (2006). “Reduced Mandated Inspection by RFEC Inspection of Unpiggable Pipelines.” Gas Technology Institute. • Ferguson, P., Heathcote, M., Moore, G. and Russell, D. (1996). “Condition Assessment of Water Mains Using RFEC.” • Russell, D. (1997). “Condition Evaluation of Iron Water Mains-NDT for Water Industry.” UCT. • Makar, J. and Chagnon, N. (1999). “Inspection Systems for leaks, pits and corrosion.” AWWA, 91(7), pp 36-46. • **http://www.physics.queensu.ca/~amg/applied_magnetics.html** • **http://www.russelltech.com/PipelineProducts/SeeSnakeTool/SeeSnakeTool.html**
X. Previous Projects	
EPCOR Water utility	Force Main
Denver Water Board	Force Main
City of Edmonton	Force Main
City of Sydney and Adelaide	Force Main
Five cities in province of Quebec	Force Main

Five Cities in UK	Force Main

I. Technology Background	
Technology/Method	Remote Field Eddy Current- Transformer Coupled
Utilization Rates	Actively being used in US and other countries, developed by Applied Magnetics Group at Queens University & commercialized by Pressure Pipe Inspection Company for water and waste water industry similar equipment called P-wave technology is also available by Pure Technologies Ltd.
Description of Main Features	RFEC/TC is a type of Non Destructive Technology to inspect PCCP. This technology is a mobile electromagnetic method that identifies and quantifies the broken pre-stress wires within the concrete pipe to determine whether pipe segment need further monitoring, repair or replacement (EPA 2009). Locating and quantifying the distress of the PCCP pipes, is a key step in determining the condition of the main. The RFEC/TC can be compared to a radio transmitter and receiver system. The pre-stressing wires act as an antenna, boosting the signal. If the wires are broken, the received signal will be distorted, by measuring and calibrating the signal distortion the number of wire-breaks can be accurately determined.

Advantages	• Detects single or multiple pre-stressing wires.
	• Multiple Platforms for virtually any type of inspection situation.
	• Well established technology
	  o Over 2000 miles of pipes inspected
	  o Detect wire breaks in all type of PCCP
	  o Can detect spot wire-breaks in pipes with or without shorting straps.

Limitations	• Dewatering- Required • Human Entry- Required • Results are interpretative, thus calibration is a major requirement, and in some cases the validity of data is not established. • The accuracy is relatively for lesser number of breaks. • RFTC doesn’t work on fully welded joints. • The system is not able to determine the location of wire-break around the circumference of the pipe. • RFTC doesn’t provide real time analysis
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	PCCP
Diameter	>16”
Depth	No impact
Lining	N/A
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	

Invasive/ Non-Invasive	Invasive
Set Up Time	<1 day
Expertise	Operator with experience
Training Time	N/A as Manufacturer performs inspection itself
V. Data Interpretation	
Time Required	2-4 weeks
Expertise	Specialist with Experience
Software Requirement	N/A as Manufacturer do the analysis
Training	N/A as Manufacturer do the analysis
VI. Technology Specifications	
Defects	Broken Wires
Mobility	n/a
Range	N/A, 4000 ft in some cases
Rate	3 ft/sec
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$8/ft (including data analysis)
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	Included
User Disruption	Low as compared to other invasive technologies because of the relatively high rate of inspection (3ft/ sec)
Traffic Disruption	N/A
Installation Fees	Varies with site conditions
IX. Data Sources	
References	• Najafi, M. and Gokhale, S. (2004). "Trenchless Technology." Pg 73-76 • Wardany, R. A. (2008). "Condition assessment of prestressed concrete cylindrical water pipes," *Proceedings of the 60th Annual WCWWA Conference and Trade Show*, Regina, Canada. • Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). " Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Mergelas, B., Balliew, J, Larsen, M and Roy, D. (2007). "How EL PASO water utilities optimizes transmission pipeline remediation

	expenditure." • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • Romer, A.E., Bell, G.E.C., Duranceau, S.J. and Forman, S. (2004). "External corrosion and corrosion control of buried water mains." Pg 20-23. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Elliot, C.L., Mergelas, B.J., Sutherland, J. and Athertopn, D.L. (2002). "Inspection of 36" and 48" LCP for the city of Montreal using RFEC/TC." • Catalano, L.F., Parks, R. and Vidmar, T. (2009). "Continuity Testing of Rampart and Homestake Pipelines." ASCE Pipelines: Infrastructure Hidden Assets, pp 30-44. • Mergelas, B.J., Atherton, D. and Kong, X. (2001). "Risk Management: A case study in operating PCCP." • Mergelas, B.J., Atherton, D. and Kong, X. (2001). "RFEC/ TC Inspection of PCCP with no shorting straps at the San Francisco public utilities commission." ASCE Pipeline 2006. • Galleher, J.J., Stift, M.T., Mergelas, B. and Stine, G.P. (2008). "Detecting Damaged PCCP using RFEC/ TC." ASCE Pipelines. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • **http://www.ppic.com/services/rftc.shtml** • **http://www.ppic.com/case_studies/index.shtml** • **http://www.physics.queensu.ca/~amg/applied_magnetics.html**
X. Previous Projects	
EL PASO	Water Mains
Tarrant Regional Water District, Texas	Water Mains
Metropolitan Water District of South California (MWD)	Water Mains
Dallas Water Utility	Water Mains
El Paso	Water Mains
Great Manmade River (GMRA) Libya	Water Mains

Denver Water Authority	Water Mains

<table>
<tr><th colspan="2">I. Technology Background</th></tr>
<tr><td>Technology/Method</td><td>Remote Field Eddy Current- Transformer Coupled- Free Swimming</td></tr>
<tr><td>Utilization Rates</td><td>Actively being used in US and other countries, developed by Applied Magnetics Group at Queens University & commercialized by Pressure Pipe Inspection Company for water and waste water industry</td></tr>
<tr><td>Description of Main Features</td><td>RFEC/TC is a type of Non Destructive Technology to inspect PCCP. This technology is a mobile electromagnetic method that identifies and quantifies the broken pre-stress wires within the concrete pipe to determine whether pipe segment need further monitoring, repair or replacement (EPA 2009). Locating and quantifying the distress of the PCCP pipes, is a key step in determining the condition of the main. This Free-swimming system ensures no service outage for inspection.
The RFEC/TC can be compared to a radio transmitter and receiver system. The pre-stressing wires act as an antenna, boosting the signal. If the wires are broken, the received signal will be distorted, by measuring and calibrating the signal distortion the number of wire-breaks can be accurately determined.</td></tr>
<tr><td>Advantages</td><td>• Pipeline can be kept in service during inspection which greatly reduces overall inspection cost.
• Long Inspection distance (up to 22 miles) reducing linear ft cost of inspection.
• Once the access point is established, the re-inspection process is very simple enabling the long term asset management of pipelines.
• In absence of redundancy in system, this technology can be used to develop a predictable and repeatable inspection program as the line remain in service.
• No clean up fees</td></tr>
<tr><td>Limitations</td><td>• Results are interpretative, thus calibration is a major requirement, and in some cases the validity of data is not established.
• The accuracy is relatively for lesser number of breaks.
• RFTC doesn’t work on fully welded joints.
• The system is not able to determine the location of wire-break around the circumference of the pipe.
• RFTC doesn’t provide real time analysis</td></tr>
<tr><td>Applicability (Underline those that apply)</td><td><u>Force Main</u> Gravity Sewer Laterals <u>Water Main</u> Distribution</td></tr>
<tr><th colspan="2">II. Pipe Characteristics</th></tr>
<tr><td>Material</td><td>PCCP</td></tr>
<tr><td>Diameter</td><td>24”- 48”</td></tr>
<tr><td>Depth</td><td>No impact</td></tr>
<tr><td>Lining</td><td>No impact</td></tr>
<tr><th colspan="2">III. Soil Characteristics</th></tr>
<tr><td>Soil Type</td><td>No impact</td></tr>
<tr><th colspan="2">IV. Installation Characteristics</th></tr>
</table>

Invasive/ Non-Invasive	Invasive but No service outage Required
Set Up Time	Not Available
Expertise	Operator with experience
Training Time	Not available
V. Data Interpretation	
Time Required	2-4 weeks
Expertise	Technical Experts
Software Requirement	N/A as Manufacturer do the analysis
Training	N/A as Manufacturer do the analysis
VI. Technology Specifications	
Defects	Broken Wires
Range	22 Miles
Rate	3 ft/sec
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$8/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	Include in direct cost
User Disruption	N/A
Traffic Disruption	N/A
Installation Fees	$2 /ft
IX. Data Sources	
References	• Najafi, M. and Gokhale, S. (2004). "Trenchless Technology." Pg 73-76 • Wardany, R. A. (2008). "Condition assessment of prestressed concrete cylindrical water pipes," *Proceedings of the 60th Annual WCWWA Conference and Trade Show*, Regina, Canada. • Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). " Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Mergelas, B., Balliew, J, Larsen, M and Roy, D. (2007). "How EL PASO water utilities optimizes transmission pipeline remediation expenditure." • Grigg, N.S. (2004). "Assessment and Renewal of water distribution

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X. Previous Projects	
Halifax	Water Mains

I. Technology Background	
Technology/Method	Smoke Test
Utilization Rates	Actively being used in US and other countries
Description of Main Features	Smoke Testing Technique was developed in 1961 as a way to locate sewer faults at a low cost. It has proven to be an extremely effective method of pin-pointing sources of inflow and other sewer line problems in both existing and new collection systems
Advantages	• Very quick method, up to 10000ft of pipe can be inspected/ day • Very economical about 10cents/ft • Leakages can be qualitatively determined
Limitations	• The results need to be validated using other technologies. • Only helpful for reconnaissance level inspection.
Applicability (Underline those that apply)	Force Main <u>Gravity Sewer</u> <u>Laterals</u> Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	All
Depth	No impact
Lining	No Impact up to 1 inch
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non-Invasive
Set Up	<1 Day
Expertise	Technician
Training	< 1 day
V. Data Interpretation	
Time Required	<1 day
Expertise	Technician
Software Requirement	N/A
Training	N/A
VI. Technology Specifications	
Defects	Leakages and Ex-filtration
Range	N/A
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact

VIII. Economical Parameters	
Direct Cost	0.10 $/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or service provider or in-house
Training Fees	N/A
Data Analysis Fees	N/A
User Disruption	Medium (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	N/A
IX. Data Sources	
References	• USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). "Failure Monitoring and Asset Condition Assessment in water supply systems." Doctoral dissertation, Lund University, Lund, Sweden. • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for Assessing Condition and Performance of Water and Wastewater Assets." WERF. • http://www.superiorsignal.com/sewerpdf.pdf
X. Previous Projects	
Many Utilities	

I. Technology Background	
Technology/Method	Sonde & Receiver or Focused Electrode Leak Location (FELL)
Utilization Rates	Actively being used in US, Europe and Canada, developed by Metrotech in Germany
Description of Main Features	Sonde & Receiver is a type of Non Destructive Technology to inspect and quantifiably determine leaks in non-ferrous pipes. This technology measures the electric current flow between a probe that travels in the pipe (Sonde) and a surface electrode (receiver). Pipe defects related to I/I cause a spike in the electric signal. The technology is performed inside the pipe but don’t require putting the pipe of surface as this technology can only perform in surcharged situation.
Advantages	• Very cost effective method for force main pipes and gravity pipes up to 24”. • Very accurate (within inches). • No effect of ground water or soil condition. • Results are reproducible. • No operator interpretation or expertise required. • Very portable and mobile equipment. • The data can be collected at a very fast rate (30ft/min) • Give a better assessment of Joint condition
Limitations	• Not recommended for gravity pipes above 24”. • Not recommended for steep slopes. • Need Access to the pipe.
Applicability (Underline those that apply)	<u>Force Main</u> <u>Gravity Sewer</u> <u>Laterals</u> Water Main Distribution
II. Pipe Characteristics	
Material	Non Ferrous
Diameter	3”-60”
Depth	No impact,
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non-invasive
Set Up Time	<1 day
Expertise	Technician
Training Time	< 1 day
V. Data Interpretation	
Time Required	<1 day
Expertise	Technician
Software Requirement	Part of the system

Training Time	< 1 day
VI. Technology Specifications	
Defects	Leakage, Joint leakage
Range	More than 4000 ft/ day
Rate	30ft/ min
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No Impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	Can be contained within <$10000
VIII. Economical Parameters	
Direct Cost	$1/ft
Effect of Density	Can be contained within <$10000
Payment Options	Leased and self performed
Training Fees	N/A user manual is sufficient
Data Analysis Fees	N/A
User Disruption	N/A
Traffic Disruption	N/A
Installation Fees	Not available
IX. Data Sources	
References	• USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Najafi, M. and Gokhale, S.B. (2004). "Trenchless Technology: pipeline and utility design, construction and renewal." • Moy, T., Coleman, G. and Wilmut, C. (2006). "Field Application of Sewer Electro-Scan in Large Pipe Condition Assessment." ASCE Pipelines. • Harris, R.J. and Tasello, J. (2004). "Sewer Leak Detection- Electro-Scan adds a New Dimension Case Study: City of Redding, California." ASCE Pipelines. • Harris, R.J. and Dobson, C. (2006). "Sewer Pipe Infiltration Assessment: Comparison of Electro-Scan, Joint Pressure Test and CCTV." ASCE Pipelines • **http://www.fell41.com/Home.html**
X. Previous Projects	
City of Redding, CA	Force Main
Athens Clark County, GA	Gravity
Montreal Quebec	Force Main

I. Technology Background	
Technology/Method	Long Range Guided Ultrasonic Wave (LRGUW)
Utilization Rates	Actively being used in US, UK, Canada and other countries
Description of Main Features	Ultrasonic Inspection is a type of Non Destructive Technology with different variations for inspecting ferrous pipes (CI/DI/Steel) and non-ferrous pipes. This technology is conducted by sending high frequency acoustic waves into an asset and evaluating any echoes. The variations of this method have been used widely for thickness measurement, corrosion monitoring, delamination, sedimentation or debris and flaw detection (WERF 2006). The detection of flaw is based on the reflection of the wave from the interface between materials of different properties. The acoustic waves get attenuated very fast in air thus it's very important that the transducer is in close contact with the pipe or there is another medium like water in which the attenuation is relatively low.
Advantages	• No interruption to supply, non- intrusive technique. • Local Access to the pipe surface is required.
Limitations	• Only successfully performed in steel pipes • Could miss a critical defect • Range of inspection is limited by a lot of factors like scale and coatings • Equally sensitive to internal and external corrosion it Cannot distinguish between them • The present systems are capable of inspecting pipe in range of 2”-48” and thickness up to 1.6”
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	Steel
Diameter	2” to 48”
Wall Thickness	<1.6”
Depth	No impact
Lining/ Coating	Cannot perform
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non-Invasive
Set Up Time	1-3 day
Expertise	Technician
Training Time	<1 day
V. Data Interpretation	
Time Required	< 1 day

Expertise	Technician
Software Requirement	Purchase/ lease the software
Training Time	Not required as the software is comprehensive
VI. Technology Specifications	
Defects	Corrosion
Range	100 ft
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$7-$20/ ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer
Training Fees	N/A
Data Analysis Fees	Included in direct cost
User Disruption	High(Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Rate not available
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water and Wastewater Pipe Nondestructive Evaluation and Health Monitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Black & Veatch. (2010). "Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement." • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N.

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X. Previous Projects	
Milwaukee	Force Main

I. Technology Background	
Technology/Method	Sonar
Utilization Rates	Actively being used in US, UK, Canada and other countries
Description of Main Features	Ultrasonic Inspection is a type of Non Destructive Technology with different variations for inspecting ferrous pipes (CI/DI/Steel) and non-ferrous pipes. This technology is conducted by sending high frequency acoustic waves into an asset and evaluating any echoes. The variations of this method have been used widely for thickness measurement, corrosion monitoring, delamination, sedimentation or debris and flaw detection (WERF 2006). The detection of flaw is based on the reflection of the wave from the interface between materials of different properties. The acoustic waves get attenuated very fast in air thus it's very important that the transducer is in close contact with the pipe or there is another medium like water in which the attenuation is relatively low.
Advantages	• Sonar provides a convenient way to measure the cross-sectional area of a sewer. • Sonar can be used to inspect and assess the structural condition of otherwise inaccessible or flooded sections of large diameter sewers • Sonar allows inspection of the portion of the sewer below the flow line. When combined with CCTV, sonar allows an inspection of the entire sewer, with sonar providing images below the flow line
Limitations	• The Sonar technique requires specially trained personal to undertake the inspection and interpret the results.
Applicability (Underline those that apply)	<u>Force Main</u> <u>Gravity Sewer</u> <u>Laterals</u> Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	>8"
Wall Thickness	N/A
Depth	No impact
Lining/ Coating	Can perform
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive
Set Up Time	<1 day
Expertise	1-3 day
Training Time	1-3 day
V. Data Interpretation	
Time Required	<1 day
Expertise	Operator with experience

Software Requirement	Purchase/ lease the software
Training	1-3 day
VI. Technology Specifications	
Defects	Corrosion, Cracks, Deformation, Delamination, Obstruction
Range	8000 ft
Rate	6 ft/min
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$7/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or can be rented and used
Training Fees	Rate not available
Data Analysis Fees	N/A
User Disruption	N/A
Traffic Disruption	N/A
Installation Fees	Rate not available
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Black & Veatch. (2010). "Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement." • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for

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X. Previous Projects	
South Florida	Force Main

I. Technology Background	
Technology/Method	Ultrasonic Inspection-External
Utilization Rates	Actively being used in US, UK, Canada and other countries
Description of Main Features	Ultrasonic Inspection is a type of Non Destructive Technology with different variations for inspecting ferrous pipes (CI/DI/Steel) and non-ferrous pipes. This technology is conducted by sending high frequency acoustic waves into an asset and evaluating any echoes. The variations of this method have been used widely for thickness measurement, corrosion monitoring, delamination, sedimentation or debris and flaw detection (WERF 2006). The detection of flaw is based on the reflection of the wave from the interface between materials of different properties. The acoustic waves get attenuated very fast in air thus it's very important that the transducer is in close contact with the pipe or there is another medium like water in which the attenuation is relatively low.
Advantages	• Probes are availability in wide a range of sizes, measurement accuracies and costs. • Simple to use. User manuals supplied with instruments sufficient for operator training • The external units can be used without supply interruption. • Wall thickness reductions detected with a reasonable degree of accuracy
Limitations	• For other variations, inspection requires pipe cleaning prior to inspection to remove material, which would affect the readings. For internal inspection, the pipe has to be off-line and dry as inspection units are generally not waterproof • Access required which means digging up the pipe and cleaning the surface
Applicability (Underline those that apply)	<u>Force Main</u> <u>Gravity Sewer</u> <u>Laterals</u> <u>Water Main</u> <u>Distribution</u>
II. Pipe Characteristics	
Material	CI/DI/Steel
Diameter	All
Wall Thickness	N/A
Depth	No impact
Lining/ Coating	Cannot perform
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Non-Invasive
Set Up Time	>3 day
Expertise	Technician

Training Time	<1 day
V. Data Interpretation	
Time Required	<1 day
Expertise	Technician
Software Requirement	Purchase/ lease the software
Training Time	<1 day
VI. Technology Specifications	
Defects	Wall thickness
Range	N/A
Rate	3ft/min
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$3/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or can be rented and used
Training Fees	Rate not available
Data Analysis Fees	N/A
User Disruption	High(Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Rate not available
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). “Workshop on Condition Assessment Inspection Devices for Water Transmission Mains.” Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). “Non Destructive, Noninvasive assessment of underground pipelines.” Pg 25-27. • Grigg, N.S. (2004). “Assessment and Renewal of water distribution system.” pg 49. • USEPA (2008). “White Paper: Condition Assessment of Wastewater Collection System.” • Rajani, B. and Kleiner, Y. (2004). “Non-Destructive Inspection techniques to determine structural distress indicators in water mains.” Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). “Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review.” Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). “Condition Assessment of Wastewater Collection Systems.” State of Technology Review Report.

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X. Previous Projects	
WSSC	Water Mains

I. Technology Background	
Technology/Method	Ultrasonic Inspection-Internal
Utilization Rates	Actively being used in US, UK, Canada and other countries
Description of Main Features	Ultrasonic Inspection is a type of Non Destructive Technology with different variations for inspecting ferrous pipes (CI/DI/Steel) and non-ferrous pipes. This technology is conducted by sending high frequency acoustic waves into an asset and evaluating any echoes. The variations of this method have been used widely for thickness measurement, corrosion monitoring, delamination, sedimentation or debris and flaw detection (WERF 2006). The detection of flaw is based on the reflection of the wave from the interface between materials of different properties. The acoustic waves get attenuated very fast in air thus it's very important that the transducer is in close contact with the pipe or there is another medium like water in which the attenuation is relatively low.
Advantages	• Probes are availability in wide a range of sizes, measurement accuracies and costs. • Simple to use. User manuals supplied with instruments sufficient for operator training • The external units can be used without supply interruption. • Wall thickness reductions detected with a reasonable degree of accuracy
Limitations	• For other variations, inspection requires pipe cleaning prior to inspection to remove material, which would affect the readings. For internal inspection, the pipe has to be off-line and dry as inspection units are generally not waterproof
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	CI/DI/Steel
Diameter	All
Wall Thickness	N/A
Depth	No impact
Lining/ Coating	Can perform
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive
Set Up Time	1-3 days
Expertise	Technician
Training Time	<1 day
V. Data Interpretation	

Time Required	<1 day
Expertise	Technician
Software Requirement	Purchase/ lease the software
Training Time	<1 day
VI. Technology Specifications	
Defects	Wall thickness
Range	N/A
Rate	N/A
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$2/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or can be rented and used
Training Fees	Rate not available
Data Analysis Fees	N/A
User Disruption	High (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Rate not available
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water and Wastewater Pipe Nondestructive Evaluation and Health Monitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Black & Veatch. (2010). "Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement."

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X. Previous Projects	
Many Projects	All Types

I. Technology Background	
Technology/Method	Ultrasonic Inspection-Seismic Pulse Echo
Utilization Rates	Actively being used in US, UK, Canada and other countries
Description of Main Features	Ultrasonic Inspection is a type of Non Destructive Technology with different variations for inspecting ferrous pipes (CI/DI/Steel) and non-ferrous pipes. This technology is conducted by sending high frequency acoustic waves into an asset and evaluating any echoes. The variations of this method have been used widely for thickness measurement, corrosion monitoring, delamination, sedimentation or debris and flaw detection (WERF 2006). The detection of flaw is based on the reflection of the wave from the interface between materials of different properties. The acoustic waves get attenuated very fast in air thus it's very important that the transducer is in close contact with the pipe or there is another medium like water in which the attenuation is relatively low. This is similar to impact echo test.
Advantages	• Successfully identifies defect in PCCP. • Can be used to determine the baseline of wire-break events
Limitations	• Requires Dewatering and Manentry • Its Invasive • Only for PCCP >54"
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	PCCP
Diameter	>54"
Wall Thickness	N/A
Depth	No impact
Lining/ Coating	Cannot perform
III. Soil Characteristics	
Soil Type	No Noticeable impact
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive
Set Up time	>3 day
Expertise	Operator
Training Time	<1 day
V. Data Interpretation	
Time Required	< 1 day
Expertise	Operator
Software Requirement	Purchase/ lease the software
Training Time	<1 day
VI. Technology Specifications	

Defects	Wire-Break Baseline, delamination and cracks
Mobility	N/A
Range	N/A
Rate	N/A
Energy Requirement	Low
VII. Environmental Characteristics	
Water Bodies/ Ground Water	No impact
Surrounding Structure	No Impact
Noise	No Impact
Surrounding Utilities	No Impact
VIII. Economical Parameters	
Direct Cost	$2/ft
Effect of Density	No Impact
Payment Options	Inspected and Monitored by manufacturer or can be rented and used
Training Fees	N/A
Data Analysis Fees	N/A
User Disruption	High (Quantitative values not available)
Traffic Disruption	N/A
Installation Fees	High (Quantitative values not available)
IX. Data Sources	
References	• Lillie, K., Reed, C. and Rodger, M. (2004). "Workshop on Condition Assessment Inspection Devices for Water Transmission Mains." Pg 40-56 and 111-116. • Dingus, M., Haven, J. and Austin, R. (2002). "Non Destructive, Noninvasive assessment of underground pipelines." Pg 25-27. • Grigg, N.S. (2004). "Assessment and Renewal of water distribution system." pg 49. • USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Black & Veatch. (2010). "Milwaukee Metropolitan Sewerage district, Underwood Creek Force Main Improvement." • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for Assessing Condition and Performance of Water and Wastewater Assets." WERF.

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X. Previous Projects	
Many Projects	All Types

I. Technology Background	
Technology/Method	CCTV Mobile
Utilization Rates	Actively being used in US and other countries
Description of Main Features	Visual Inspection is a type of Non Destructive Technology which determines the internal condition of the sewer pipes. Examining the interior surface of the pipe wall is a standard practice for sewer inspection. Many technologies are available to determine the internal damage to the pipe walls like deformation, cracking and delamination etc. (WRc, 1995). The most popular of these technologies is CCTV Survey which uses a camera mounted on a remote-controlled tractor arrangement. There are number of variations of CCTV which are cost effective or enhance the performance of the system.
Advantages	• CCTV can detect visible internal damage, lining deterioration, and partial blockages
Limitations	• CCTV cameras can only give qualitative information about the condition of the pipe. • CCTV cameras are dependent on the operator expertise and concentration for performance.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	>4”
Depth	No impact, except for increased cost of installation
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact, except for variable cost of installation
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive (Needs to be dewatered)
Set Up Time	<1 day
Expertise	Engineer or Operator with experience
Training Time	>3 day
V. Data Interpretation	
Time Required	Depends on Length inspected
Expertise	Engineer or Operator with experience
Software Requirement	N/A
Training Time	3-7 days
VI. Technology Specifications	
Defects	Visible defects from inside (crack, sedimentation, Root intrusion, Joint alignment)
Range	1300 ft
Rate	Depends on condition of pipe (3.3 ft/min)

VII. Environmental Characteristics	
Water Bodies/ Ground Water	N/A
Surrounding Structure	N/A
Noise	N/A
Surrounding Utilities	N/A
VIII. Economical Parameters	
Direct Cost	Varies but in ideal situation $1/ft
Effect of Density	No Impact
Payment Options	Inspect and analyzed by service provider or in-house
Training Fees	High(Quantitative value not available)
Data Analysis Fees	N/A
User Disruption	Moderate(Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Moderate (Optimal if dewatered and flushed before inspection) rate not available
IX. Data Sources	
References	• USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). "Failure Monitoring and Asset Condition Assessment in water supply systems." Doctoral dissertation, Lund University, Lund, Sweden. • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for Assessing Condition and Performance of Water and Wastewater Assets." WERF. • Skabo, R.R. (1991). "Nondestructive Testing of Water Mains for Physical Integrity." AWWA • Makar, J.M. (1999). "Diagnostic Technique for sewer system." J of Infra. Sys., 5(2), pp 69-78. • Iyer, S. (2007). "MULTI-SENSOR BASED CONDITION ASSESSMENT SYSTEM FOR BURIED CONCRETE PIPE."

	Doctoral Dissertation, Pennsylvania State University, Pennsylvania, US • **http://www.nassco.org/index.html**
X. Previous Projects	
Various Projects	All over use majorly for sewer and storm water

I. Technology Background	
Technology/Method	Laser Profile
Utilization Rates	Actively being used in US and other countries
Description of Main Features	Visual Inspection is a type of Non Destructive Technology which determines the internal condition of the sewer pipes. Examining the interior surface of the pipe wall is a standard practice for sewer inspection. Many technologies are available to determine the internal damage to the pipe walls like deformation, cracking and delamination etc. (WRc, 1995). This technology creates a ring of laser around the pipe wall. This technology is generally used in conjunction with CCTV camera and uses the reflection of laser from different surfaces to determine the change in pipe shape due to deformation, sedimentation etc. This method can be used only in the dry areas.
Advantages	• Laser Technology can be used to make a 3D model and give a better QA/QC than CCTV • Information from the lasers is readily recorded and analyzed in the computer, reducing operator errors.
Limitations	• Visual technologies can only give information about the condition of the pipe that is visible from inside. • Laser technologies can detect defects above water line
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	>4”
Depth	No impact, except for increased cost of installation
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact, except for variable cost of installation
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive (Needs to be dewatered)
Set Up Time	1-3 day
Expertise	Operator with experience
Training Time	>3day
V. Data Interpretation	
Time Required	Depends on Length inspected
Expertise	Operator with experience
Software Requirement	N/A
Training time	3-7 day
VI. Technology Specifications	
Defects	Visible defects from inside (crack, sedimentation, Root intrusion, Joint alignment), better deformation characteristics

Range	1300 ft
Rate	Depends on condition of pipe (3.3 ft/min)
VII. Environmental Characteristics	
Water Bodies/ Ground Water	N/A
Surrounding Structure	N/A
Noise	N/A
Surrounding Utilities	N/A
VIII. Economical Parameters	
Direct Cost	Varies but in ideal situation $2/ft
Effect of Density	No Impact
Payment Options	Inspect and analyzed by service provider or in-house
Training Fees	High(Quantitative value not available)
Data Analysis Fees	N/A
User Disruption	Moderate (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Moderate (Optimal if dewatered and flushed before inspection) (Quantitative value not available)
IX. Data Sources	
References	• USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). "Failure Monitoring and Asset Condition Assessment in water supply systems." Doctoral dissertation, Lund University, Lund, Sweden. • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for Assessing Condition and Performance of Water and Wastewater Assets." WERF. • Skabo, R.R. (1991). "Nondestructive Testing of Water Mains for Physical Integrity." AWWA • Makar, J.M. (1999). "Diagnostic Technique for sewer system." J of Infra. Sys., 5(2), pp 69-78.

	• Iyer, S. (2007). "MULTI-SENSOR BASED CONDITION ASSESSMENT SYSTEM FOR BURIED CONCRETE PIPE." Doctoral Dissertation, Pennsylvania State University, Pennsylvania, US • **http://www.nassco.org/index.html**
X. Previous Projects	
City of Portland	Inspection of CIPP Liner
Loisville, KY	Ovality verification
Tarunga City Council, NZ	Corrosion
Many other	

I. Technology Background	
Technology/Method	Sewer Scanning and Evaluation Technology (SSET)
Utilization Rates	Actively being used in US and other countries
Description of Main Features	Visual Inspection is a type of Non Destructive Technology which determines the internal condition of the sewer pipes. Examining the interior surface of the pipe wall is a standard practice for sewer inspection. Many technologies are available to determine the internal damage to the pipe walls like deformation, cracking and delamination etc. (WRc, 1995). This technology creates a ring of laser around the pipe wall. SSET is a latest variant of this technology provides the engineer with the capability to see the total internal surface of the pipe, along the length of the pipe with use of optical scanner and gyroscope. Unlike CCTV inspection, SSET doesn't have to stop to allow closer inspection of the defects.
Advantages	• SSET has Increased QA/QC control, additional project personnel able to review/control data imagery, able to make digital measurements of defects. • Much faster than conventional CCTV system
Limitations	• Visual technologies can only give information about the condition of the pipe that is visible from inside. • SSET is more costly than CCTV, lower production rate compared to traditional CCTV, only works below waterline.
Applicability (Underline those that apply)	<u>Force Main</u> <u>Gravity Sewer</u> <u>Laterals</u> <u>Water Main</u> <u>Distribution</u>
II. Pipe Characteristics	
Material	All
Diameter	6"-56"
Depth	No impact, except for increased cost of installation
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact, except for variable cost of installation
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive (Needs to be dewatered)
Set Up	1-3 day
Expertise	Operator with experience
Training Time	1-3 day
V. Data Interpretation	
Time Required	3-7 day
Expertise	Operator with experience
Software Requirement	N/A
Training Time	>3day
VI. Technology Specifications	

Defects	Visible defects from inside (crack, sedimentation, Root intrusion, Joint alignment), better deformation characteristics
Range	3000 ft
Rate	Depends on condition of pipe (30 ft/min)
VII. Environmental Characteristics	
Water Bodies/ Ground Water	N/A
Surrounding Structure	N/A
Noise	N/A
Surrounding Utilities	N/A
VIII. Economical Parameters	
Direct Cost	Varies but in ideal situation $3/ft
Effect of Density	No Impact
Payment Options	Inspect and analyzed by service provider or in-house
Training Fees	High (Quantitative value not available)
Data Analysis Fees	N/A
User Disruption	Moderate (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Moderate (Optimal if dewatered and flushed before inspection) (Quantitative value not available)
IX. Data Sources	
References	• USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). "Failure Monitoring and Asset Condition Assessment in water supply systems." Doctoral dissertation, Lund University, Lund, Sweden. • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for Assessing Condition and Performance of Water and Wastewater Assets." WERF. • Skabo, R.R. (1991). "Nondestructive Testing of Water Mains for Physical Integrity." AWWA

	• Makar, J.M. (1999). "Diagnostic Technique for sewer system." J of Infra. Sys., 5(2), pp 69-78. • Iyer, S. (2007). "MULTI-SENSOR BASED CONDITION ASSESSMENT SYSTEM FOR BURIED CONCRETE PIPE." Doctoral Dissertation, Pennsylvania State University, Pennsylvania, US • **http://www.nassco.org/index.html**
X. Previous Projects	
Virginia Beach	Inspection of Sewer
List can be accessed for Rapid view	Inspection of Sewer

I. Technology Background	
Technology/Method	Zoom Camera
Utilization Rates	Actively being used in US and other countries
Description of Main Features	Visual Inspection is a type of Non Destructive Technology which determines the internal condition of the sewer pipes. Examining the interior surface of the pipe wall is a standard practice for sewer inspection. Many technologies are available to determine the internal damage to the pipe walls like deformation, cracking and delamination etc. (WRc, 1995). The most popular of these technologies is CCTV Survey which uses a camera mounted on a remote-controlled tractor arrangement. Zoom-camera system is a variant of CCTV in which the camera is stationary and suspended from manhole to inspect the pipe
Advantages	• The Zoom-camera technology is very economical and fast in collecting the data and analyzing
Limitations	• CCTV cameras can only give qualitative information about the condition of the pipe. • CCTV cameras are dependent on the operator expertise and concentration for performance. • Zoom-Camera gives only a partial assessment of the system and can only be used for prioritization purpose. • Visual technologies can only give information about the condition of the pipe that is visible from inside.
Applicability (Underline those that apply)	Force Main Gravity Sewer Laterals Water Main Distribution
II. Pipe Characteristics	
Material	All
Diameter	>6”
Depth	No impact, except for increased cost of installation
Lining	N/A
III. Soil Characteristics	
Soil Type	No impact, except for variable cost of installation
IV. Installation Characteristics	
Invasive/ Non-Invasive	Invasive (Needs to be dewatered)
Set Up Time	<1 day
Expertise	Operator with experience
Training Time	>3day
V. Data Interpretation	
Time Required	< 1day
Expertise	Operator with experience
Software Requirement	N/A
Training Time	>3 day
VI. Technology Specifications	

Defects	Visible defects from inside (crack, sedimentation, Root intrusion, Joint alignment)
Range	100-300 ft
Rate	40-50 manholes/day (10-30ft/min)
VII. Environmental Characteristics	
Water Bodies/ Ground Water	N/A
Surrounding Structure	N/A
Noise	N/A
Surrounding Utilities	N/A
VIII. Economical Parameters	
Direct Cost	Varies but in ideal situation $ .25/ft
Effect of Density	No Impact
Payment Options	Inspect and analyzed by service provider or in-house
Training Fees	High(Quantitative value not available)
Data Analysis Fees	N/A
User Disruption	Moderate (Quantitative value not available)
Traffic Disruption	N/A
Installation Fees	Not available
IX. Data Sources	
References	• USEPA (2008). "White Paper: Condition Assessment of Wastewater Collection System." • Rajani, B. and Kleiner, Y. (2004). "Non-Destructive Inspection techniques to determine structural distress indicators in water mains." Evaluation and Control of Water Loss in Urban Water Networks, Spain, pp. 1-20. • Rizzo, P. (2009). "Water andWastewater Pipe Nondestructive Evaluation and HealthMonitoring: A Review." Advances in Civil Engineering, 2010, 13 pages. • USEPA (2009). "Condition Assessment of Wastewater Collection Systems." State of Technology Review Report. • Costello, S.B., Chapman, D.N., Rogers, C.D.F. and Metje, N. (2007). "Underground asset location and condition assessment technologies." Tunneling and Underground Space Technology, 22, pp 524-542. • Misiunas, D. (2005). "Failure Monitoring and Asset Condition Assessment in water supply systems." Doctoral dissertation, Lund University, Lund, Sweden. • Marlow, D., Heart, S., Burn, S., Urquhart, A., Gould, S., Anderson, M., Cook, S., Watson, T. and Ambrose, M. (2006). "Protocols for Assessing Condition and Performance of Water and Wastewater Assets." WERF. • Skabo, R.R. (1991). "Nondestructive Testing of Water Mains for Physical Integrity." AWWA • Makar, J.M. (1999). "Diagnostic Technique for sewer system." J of

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X. Previous Projects	
Various Projects	All over use majorly for sewer and storm water

Appendix M- Data Reliability Index

Technologies	Case Studies	Available Literature	Cost Information	Data Reliability Index
Acoustic Emission Monitoring	2	2	1	5
Acoustic Leak Detection- Inline	3	3	2	8
Acoustic Leak Detection- Noise Correlator	3	3	2	8
Acoustic Monitoring System	3	3	2	8
Broadband Electromagnetic- External	3	3	2	8
Broadband Electromagnetic- Internal	3	3	2	8
CCTV- Conventional	3	3	2	8
Ground Penetration Radar	2	2	1	5
Ground Penetration Radar- Inline	2	2	1	5
Guided Ultrasonic Wave	2	2	1	5
Infrared Thermography	1	2	2	5
Laser Based Profiling tool	2	2	2	6
Magnetic Flux	1	2	2	5
RFEC/ TC	3	3	2	8
RFEC/TC- Inline/In-service	2	2	1	5
Seismic Echo	3	2	1	6
Smoke Test	3	3	2	8
Sonar	2	3	2	7
Sonde and Receiver technique	2	2	2	6
SSET	3	3	2	8
Ultrasonic Inspection- External	3	3	2	8
Ultrasonic Inspection- Internal	3	3	2	8
Zoom Camera Technology	2	2	2	6
RFEC	3	3	2	8

Case Studies

(1) refers to 1-2 case study
(2) refers to 2-4 case study
(3) refers to >4 case study

Available literature

(1) refers to < 5 articles
(2) refers to 5-10 articles
(3) refers to >10 articles

Cost Information

(1) refers to information available for direct cost
(2) refers to information available for direct and indirect cost
(3) refers to information available for direct, indirect and intangible cost

Data Reliability Index (DRI) is sum of all the three factors categorized into 4 classes

Low for DRI=5
Medium for DRI= 6&7
High for DRI= 8
Very High for DRI =9