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# Condition Assessment Technologies for Water Transmission and Distribution Systems

SCIENCE

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**Condition Assessment Technologies for**
**Water Transmission and Distribution Systems**

by

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## DISCLAIMER

# ABSTRACT

As part of the U.S. Environmental Protection Agency's (EPA's) Aging Water Infrastructure Research Program, this research was conducted to identify and characterize the state of the technology for structural condition assessment of drinking water transmission and distribution systems. The broad definition of structural condition assessment of water mains encompasses physical modeling of the pipe in the soil, understanding of pipe failure modes, empirical/statistical modeling of historical failures, inspection of a pipe to discern distress indicators, interpretation of distress indicators into pipe condition rating and modeling deterioration to forecast future failures and pipe residual life.

Any asset management program must start with a thorough review of available historical data about pipe performance and failure. Once the necessary data is gathered, deterioration models can go a long way in providing insight into the condition of these assets. A well-defined and cost-effective inspection program that complements the historic data can then be used to fill in gaps that remain. This report provides a comprehensive inventory of both condition assessment technologies and decision support systems applied to water mains and identifies capability gaps that need to be addressed. A comprehensive list is provided of existing non-destructive evaluation technologies and techniques that are currently used for buried pipes or that have the potential of being adapted to pipe inspection. Scientific principles, advantages, and limitations of each technique are described. A review is also provided of physical models, statistical/empirical models, and decision support software tools available to facilitate water main renewal decisions.

To date, there has been a substantial amount of work and effort that has been invested in developing approaches and tools for the condition assessment of water mains. However, there are still a number of technology gaps and research needs including: the need for live internal insertion and retrieval of inspection tools; the need to assess joint condition in metallic pipes; the need to develop technologies for asbestos cement and plastic pipes with few options currently available; and the need for low cost inspection methods to conduct screening for high risk locations in all pipe types for further assessment. To overcome the barriers and challenges identified in this research, field demonstrations and further research efforts are warranted in order to test promising technologies that could fill these gaps against well defined performance criteria and to identify the critical performance, cost, and/or value added attributes of emerging and innovative technologies for water main inspection.

## EXECUTIVE SUMMARY

The aging of water mains, coupled with the continuous stress placed on these systems by operational and environmental conditions, has led to their deterioration. This deterioration can be classified into two categories: (1) structural deterioration, which diminishes the structural resiliency of the pipes and their ability to withstand various types of stress, and (2) deterioration of pipe inner surfaces, resulting in diminished hydraulic capacity, degradation of water quality and even diminishing structural resiliency in cases of severe internal corrosion. This deterioration manifests itself in the following ways:

- Increased rate of pipe breakage due to deterioration in pipe structural integrity. This, in turn, causes increased operation and maintenance (O&M) costs, increased loss of (treated) water and social costs such as property damage, loss of service, disruption of traffic, disruption of business and industrial processes, disruption of residential life, public safety hazard, and loss of landscape vegetation. In addition, pipe breakage events increase the risk of water quality failure through intrusion of contaminants into the system.

- Decreased hydraulic capacity of pipes in the systems, which results in increased energy consumption and disrupts the quality of service to the public. This includes drinking water as well as fire extinguishing needs.

- Deterioration of water quality in the distribution system due to the condition of inner surfaces of pipes, which may result in taste, odor, and aesthetic problems in the supply water and even public health problems in extreme cases.

The structural deterioration of water mains and their subsequent failure are complex processes, which are affected by many factors, both static (e.g., pipe material, size, soil type) and dynamic (e.g., age, climate, cathodic protection, pressure zone changes). The physical mechanisms that lead to pipe breakage are often very complex and not completely understood. The facts that most pipes are buried, and that relatively little data are available about their breakage modes also contribute to this incomplete knowledge.

It appears that while physical modeling of the structural deterioration of water mains may be scientifically more robust, it is, to date, limited by existing knowledge and available data. Some of the data that are required for the physical models can be obtained albeit at significant costs. These costs may currently be justified only for major transmission water mains, where the consequences of failure are significant. In contrast, statistically-derived empirical models can be applied with various levels of input data and may therefore be useful for small diameter water mains for which low cost of failure does not justify expensive data acquisition campaigns. The statistical analysis of breakage patterns of water mains has thus been a cost effective way to model this deterioration, particularly when available data are scarce. However, this effectiveness is higher at high-level planning (i.e., regional or network level) and diminishes to a certain degree when applied to individual water mains. Information on the current structural condition of the individual water main, combined with good understanding of failure modes and deterioration models, will greatly enhance the ability of water utilities to manage these assets in a cost-effective manner.

Task Order 0062 (TO 0062) of the Environmental Protection Agency (EPA) contract addresses the condition assessment of installed drinking water transmission and distribution mains. This report was prepared under Task 2.2 of TO 0062, which focused on the assessment of structural condition (not hydraulic capacity and water quality aspects) of pipes. The definition can vary to encompass different elements. The broad definition of structural condition assessment of water mains encompasses physical modeling of the pipe in the soil, understanding of pipe failure modes, empirical/statistical modeling of historical failures, inspection of pipe to discern distress indicators, interpretation of distress indicators into pipe condition rating and modeling deterioration to forecast future failures and pipe residual life. This report focuses on direct and indirect inspection of pipes to discern their structural condition, interpretation of distress indicators into condition rating and modeling structural deterioration to forecast future failures and decision making about pipe renewal. The report covers extensively cast and ductile iron pipes, pre-stressed concrete cylinder pipes (PCCP), asbestos cement (AC) and polyvinyl chloride (PVC) pipes. However, some of the described technologies apply also to welded steel (WS), glass-fiber reinforced polyester (GRP), concrete pressure pipe (CPP), un-plasticized polyvinyl chloride (uPVC), and polyethylene (PE) pipes.

The report describes a comprehensive inventory of technologies, techniques, and methods that are actually or potentially employed in the field of condition assessment of water mains, as follows:

- Section 1 describes the objective and scope of the task, as well as provides some background information.

- Section 2 provides a primer on general issues related to the deterioration of buried pipes, including distress indicators, known modes of failure and a general introduction to the classes of nondestructive evaluation (NDE) technologies and methods to discern distress indicators leading to failure.

- Section 3 provides a comprehensive list of existing NDE technologies/techniques that are currently being used for buried pipes or that have the potential of being adapted to pipe inspection. Each technology/technique is provided with a description of scientific principles, advantages, and limitations. Where available, data on the breadth and manner of usage of the inspection technologies are presented.

- Section 4 provides a comprehensive description of computational methods used to translate inspection data (or discerned distress indicators) into pipe condition rating.

- Section 5 provides a comprehensive compilation of mathematical models that have been proposed in the literature to model the deterioration of buried water mains. These include both physical/mechanistic models and statistical/empirical models.

- Section 6 provides a comprehensive compilation of mathematical models intended to support decisions related to the renewal planning of water mains. This includes theoretical models from the literature as well as brief descriptions of currently available decision support software tools.

- Section 7 identifies current technological gaps requiring further research between desired and available capabilities of inspection techniques.

- Section 8 provides a summary and concluding remarks.

- Section 9 presents the references cited throughout the document.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 3D | three-dimensional |
| AC | asbestos cement |
| AE | acoustic emission |
| AFO | acoustic fiber optic |
| AMI | advanced metering infrastructure |
| AR | augmented reality |
| ARP | Annual Rehabilitation Project |
| AWWA | American Water Works Association |
| BEM | broadband electromagnetic |
| BPA | basic probability assignment |
| CARE-W | Computer Aided Rehabilitation of Water Networks |
| CCTV | closed circuit television |
| CCD | charge-coupled device |
| CI | cast iron |
| CMOS | complementary metal oxide semiconductor |
| CP | cathodic protection |
| CPP | concrete pressure pipe |
| CSIRO | Commonwealth Scientific and Industrial Research Organization |
| DBP | disinfection byproduct |
| DC | direct current |
| DCVG | direct current voltage gradient |
| DFT | discrete Fourier transform |
| DI | ductile iron |
| D-S | Dempster-Shafer |
| DS | decision support (tool or software) |
| ECP | embedded cylinder pipe |
| EIS | electrochemical impedance spectroscopy |
| EMAT | electromagnetic acoustic transducer |
| EPA | U.S. Environmental Protection Agency |
| EPR | evolutionary polynomial regression |
| ER | electrical resistance |
| FCP | fuzzy composite programming |
| FOX-TEK | Fiber Optic Systems Technology, Inc. |
| FSE | fuzzy synthetic evaluation |
| FUT | flexible ultrasonic transducer |
| GA | genetic algorithm |
| GIS | geographic information system |
| GPIR | ground penetrating imaging radar |
| GPR | ground penetrating radar |
| GRP | glass-fiber reinforced polyester |
| GTI | Gas Technology Institute |

| | |
|---|---|
| HER | hierarchical evidential reasoning |
| IWA | International Water Association |
| KARO | Kanalroboter |
| KURT | Kanal-Untersuchungs-Roboter-testplatform |
| LCP | lined cylinder pipe |
| LEYP | linearly extended yule process |
| LPR | linear polarization resistance |
| LTP | long-term planning |
| LVVWD | Las Vegas Valley Water District |
| LWC | Louisville Water Company |
| MAKRO | Multi-segmented autonomous sewer robot |
| MBS | microwave back-scattering |
| MEMS | microelectromechanical system |
| MFL | magnetic flux leakage |
| MIC | microbial induced corrosion |
| MLP | multilayer perceptron |
| MsS | magnetostrictive sensor |
| NASSCO | National Association of Sewer Service Companies |
| NDE | nondestructive evaluation |
| NDT | nondestructive testing |
| NRC | National Research Council of Canada |
| O&M | operation and maintenance |
| OP | operating pressure |
| PARMS | Pipeline Asset and Risk Management System |
| PCCP | prestressed concrete cylinder pipe |
| PCM | pipeline current mapper |
| PE | polyethylene |
| PI | performance indicator |
| PIRAT | Pipe Inspection Real-Time Assessment Technique |
| PHM | proportional hazard method |
| PoD | probability of detection |
| PPIC | Pressure Pipe Inspection Company |
| PRF | pulse repetition frequency |
| psi | pounds per square inch |
| PV | present value |
| PVC | polyvinyl chloride |
| PWD | Philadelphia Water Department |
| RFEC | remote field eddy current |
| RFEC/TC | remote field eddy current/transformer coupling |
| RPV | replacement priority value |
| SCADA | supervisory control and data acquisition |
| SI | saturation index |

| | |
|---|---|
| SPU | Seattle Public Utilities |
| SSET | side scanning evaluation technology |
| | |
| TC | transformer coupling |
| TDR | time domain reflectometry |
| TO | task order |
| | |
| UMP | Utility Master Plan |
| UT | ultrasonic testing |
| UWB | ultra-wideband |
| | |
| WARP | Water Main Rehabilitation Planner |
| WRc | Water Research Centre |
| WRF | Water Research Foundation |
| WS | welded steel |
| WSN | wireless sensor network |
| WSSC | Washington Suburban Sanitary Commission |

# 1.0: INTRODUCTION

As part of the U.S. Environmental Protection Agency's (EPA's) Aging Water Infrastructure Research Program, which supports the Sustainable Infrastructure Initiative, scientific and engineering research is being conducted to evaluate and improve promising innovative technologies that can reduce costs and improve the effectiveness of operation, maintenance, and replacement of aging and failing drinking water distribution and wastewater conveyance systems (EPA, 2007). This research was conducted under Task 2.2 of Task Order (TO) 0062 (EPA STREAMS Contract No. EP-C-05-057), which is being conducted by Battelle, in collaboration with National Research Council of Canada (NRC), to identify and characterize the state of the technology for condition assessment of drinking water transmission and distribution systems.

## 1.1 Objective, Scope, and Background

The objective of Task 2.2 is to compile a comprehensive inventory of condition assessment technologies and decision support systems applied to water transmission and distribution mains and identify gaps that need to be addressed by the research and development community.

EPA (2007) defines pipe condition assessment as "the collection of data and information through direct and/or indirect methods, followed by analysis of the data and information, to make a determination of the current and/or future structural, water quality, and hydraulic status of the pipeline." This task focuses on the structural aspect of condition assessment. Pipe condition assessment may be undertaken by water utilities with specific objectives, which include, but are not limited to:

- Monitoring and detecting critical indicators to prevent or mitigate catastrophic failures
- Implementing appropriate and timely repair/rehabilitation measures
- Early detection of accelerated deterioration for timely implementation of preventive measures (e.g., retrofit cathodic protection [CP]) and for anticipation (and, where possible, mitigation) of spikes in failure rate during extreme conditions (e.g., abnormally cold winters or drought)
- Setting inspection schedules and frequencies
- Screening and prioritizing assets to focus detailed, expensive inspections on critical sections
- Estimating remaining service life for pipe cohorts for mid- or long-term financial planning and rate setting
- Detecting and reducing leakage to reduce water losses and water main breaks
- Determining whether structural vs. non-structural rehabilitation is suitable
- Providing insight into new pipe selection decisions – this could come from break histories, forensic evaluations, screening inspections, or detailed inspections

The aging of water mains, coupled with the continuous stress placed on these systems by operational and environmental conditions, has led to their deterioration, which has structural, hydraulic and water quality manifestation, as implied in the EPA definition above. More specifically:

- Structural deterioration diminishes the structural resiliency of pipes and their ability to withstand various types of stress, resulting in an increased rate of breakage. This, in turn, causes increases in operation and maintenance (O&M) costs, loss of (treated) water, and social costs such as loss of service, disruption of traffic, disruption of business and industrial processes, disruption of residential life and loss of landscape vegetation. In addition, pipe breakage events increase the risk of water quality failure through intrusion of contaminants into the system.

- The deterioration of pipe inner surfaces decreases the hydraulic capacity of pipes, which results in increased energy consumption and disrupts the quality of service to the public. This includes drinking water as well as fire extinguishing needs.
- The deterioration of pipe inner surfaces also causes deterioration of water quality. This deterioration of water quality may manifest itself in taste, odor, and aesthetic problems in the supply water and sometimes even in public health problems, such as higher risk of disinfection byproduct (DBP) formation due to a higher need for chlorination.

The structural deterioration of water mains and their subsequent failure are complex processes, which are affected by many factors, both static (e.g., pipe material, size, age, soil type) and dynamic (e.g., climate, CP, pressure zone changes). The physical mechanisms that lead to pipe breakage are often very complex and not completely understood. The facts that most pipes are buried, and that relatively little data are available about their breakage modes (due to historical lack of awareness at water utilities of the importance of collecting such data, as well as the time and cost involved in collecting and analyzing these data) also contribute to this incomplete knowledge. It appears that while physical modeling of the structural deterioration of water mains may be scientifically more robust, it is, to date, limited by existing knowledge and available data.

Information on the current structural condition of individual water mains, combined with a good understanding of failure modes and deterioration models, can greatly enhance the ability of water utilities to manage their assets in a cost-effective manner. Some of the data required for physical models (e.g., detailed soil properties and detailed pipe material properties, data obtained by inspection of the pipe current condition) can be obtained albeit at significant costs. These costs may currently be justified only for major transmission water mains, where the consequences of failure are significant. In contrast, statistically derived empirical models can be applied with various levels of input data and may therefore be useful for small diameter water mains for which the low cost of failure does not justify expensive data acquisition campaigns. The statistical analysis of breakage patterns of water mains has thus become a cost-effective way to model this deterioration, particularly when available aforementioned data are scarce. However, this effectiveness is higher at high-level planning (e.g., regional or network level) and diminishes to a certain degree when applied to individual water mains.

The assessment of the structural condition of water mains and decision making on pipe renewal include several elements:

(1) Physical modeling of the pipe in the soil.

(2) Understanding of pipe failure modes and their associated frequencies, including observable or measurable signs (or distress indicators) that point to these modes, as well as inferential indicators that point to potential existence of deterioration mechanisms.

(3) Inspection of the pipe to discern distress indicators.

(4) Interpretation of distress indicators to determine pipe condition.

(5) Empirical/statistical modeling of historical failures (mainly in small diameter distribution mains).

(6) Modeling deterioration to forecast future failure rates and pipe residual life.

(7) Assessment of failure consequences (direct, indirect and social costs).

(8) Scheduling pipe renewal so as to minimize life-cycle costs while meeting or exceeding functional objectives of water distribution (quantity, quality, reliability, etc.)

Rajani and Kleiner (2004) described these elements schematically (Figure 1-1). Note that the determination of pipe condition should not rely on distress indicators alone. Relevant information, such as soil properties, environmental loads (climate, groundwater, overburden, etc.), operational practices (CP, leak detection), sensor monitoring data, and pipe geometry, could also augment the understanding of pipe condition.

In this report, all of the elements listed above (except item 7) will be discussed, but the main focus is on elements 3 and 4, as well as elements 5, 6 and 8, in the context of making decisions about pipe renewal. The American Water Works Association (AWWA) estimated, based on a survey of 337 water utilities, that in the U.S. about two thirds (66%) of water mains are metallic (about 40% cast iron [CI], 22% ductile iron [DI] and 4% steel), about 16% are asbestos cement (AC), 13% polyvinyl chloride (PVC) and 3% various concrete pipes (Lillie et al., 2004). Rajani and McDonald (1995), in a survey encompassing 21 Canadian cities (about 11% of the population of Canada), revealed a similar distribution of pipe material types. Consequently, pipe materials covered in this report include CI and DI, prestressed pressure cylinder pipes (PCCP), AC, and PVC.

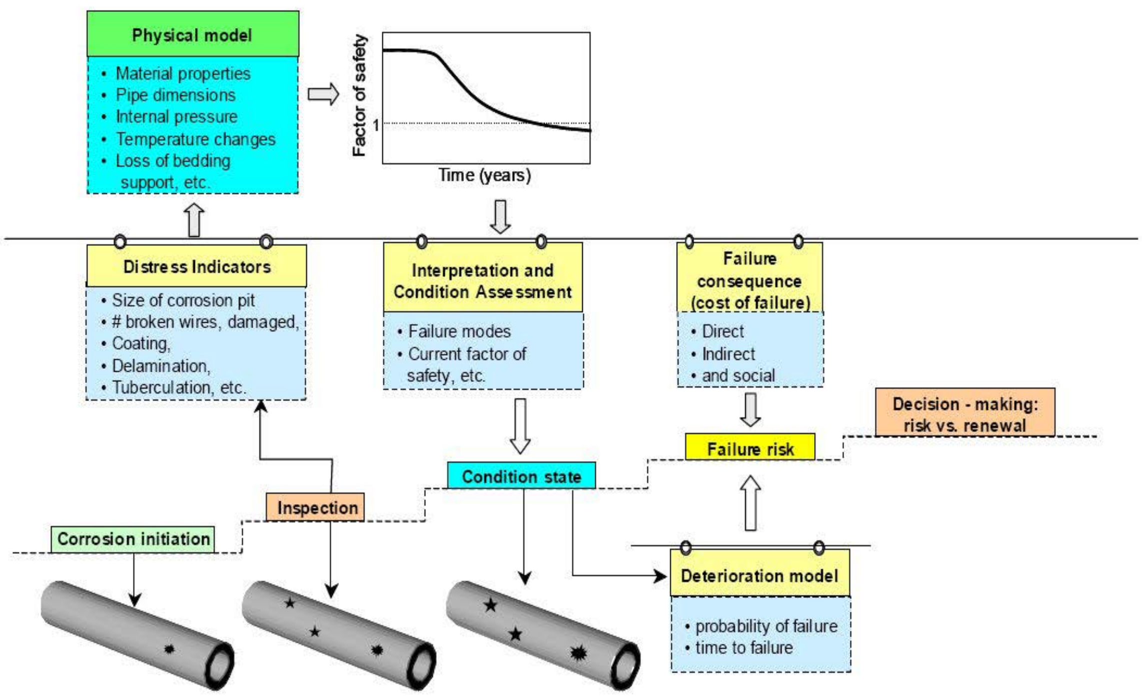



**Figure 1-1. Schematic for Inspection, Condition Assessment, and Failure Risk Evaluation of Pipes (Rajani and Kleiner, 2004)**

## 1.2 Organization of this Report

The objective, scope and background information is presented in Section 1. Section 2 provides a primer on general issues related to the deterioration of buried pipes, including distress indicators, known modes of failure and a general introduction to the classes of nondestructive evaluation (NDE) technologies and methods to discern distress indicators leading to failure. Section 3 provides a comprehensive list of existing NDE technologies/techniques that are currently used for buried pipes or that have the potential of being adapted to pipe inspection. Scientific principles, advantages, and limitations of each technique are described. Data about the extent of usage of many of these technologies cannot be easily obtained. Some information is provided on usage, including the results of a limited survey conducted for this research. Section 4 provides a comprehensive description of computation methods used to translate the inspection data (or discerned distress indicators) into pipe condition rating. Section 5 provides a comprehensive compilation of mathematical models that have been proposed in the literature to model the deterioration of buried water mains. These include both physical models and statistical/empirical models. Section 6 provides a comprehensive compilation of mathematical models intended to support decisions related to the renewal planning of water mains. This includes theoretical models from the literature as well as brief descriptions of currently available decision support software tools. Section 7 identifies current technological gaps that require further research. Section 8 provides summary and concluding remarks. Section 9 presents the references cited throughout the report.

## 2.0: PIPE DETERIORATION, DISTRESS INDICATORS AND FAILURE MODES

### 2.1 Overview of Distress Indicators and Failure Modes

Pipe condition is the cumulative effect of many factors acting on the pipe. Al-Barqawi and Zayed (2006) classified these factors into three categories: physical, environmental, and operational, as depicted in Figure 2-1. The factors in the first two classes can be further divided into static and dynamic (or time-dependent). Static factors include pipe material, pipe geometry, and soil type, while dynamic factors include pipe age, climate, and seismic activity. Operational factors are inherently dynamic.

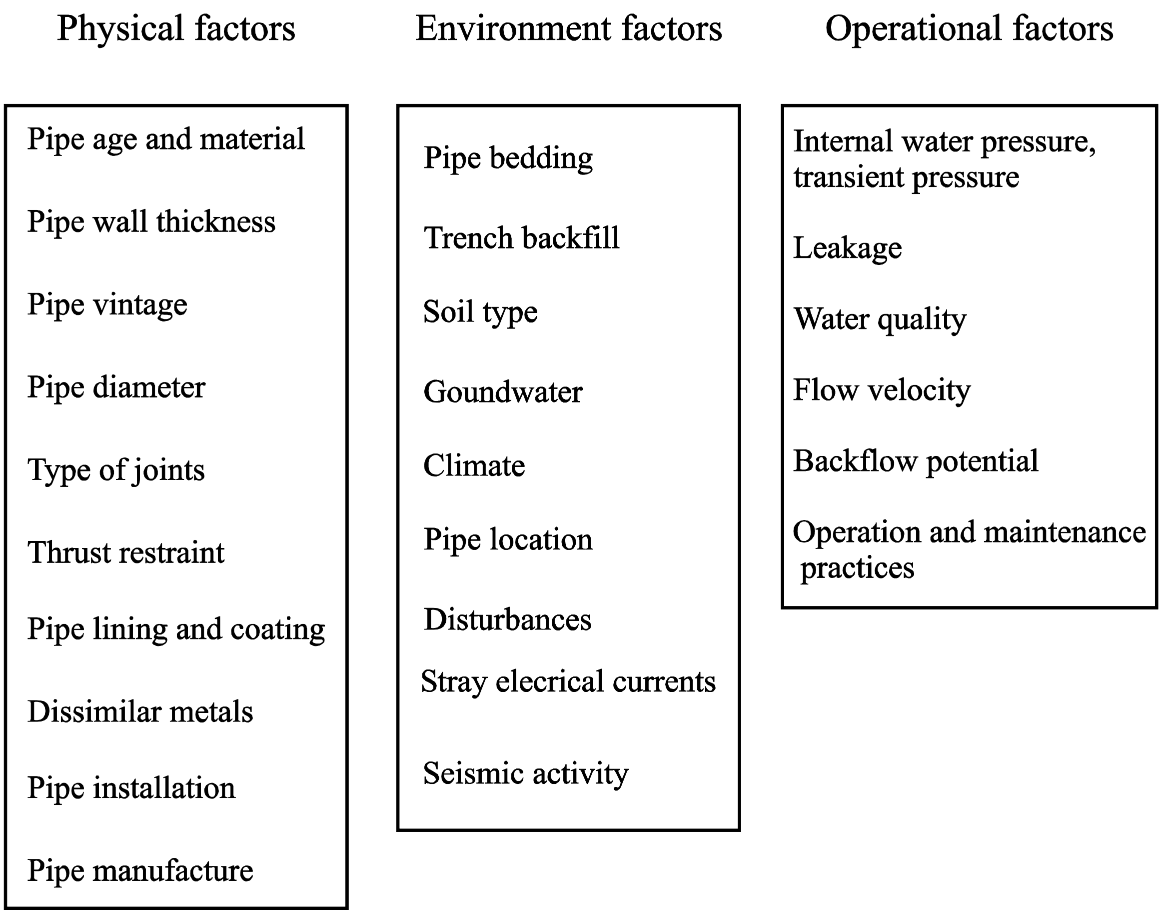



**Figure 2-1. Factors Contributing to Water System Deterioration**

**(Al-Barqawi and Zayed, 2006)**

Many of the factors listed in Figure 2-1 are not readily measurable or quantifiable. Moreover, the quantitative relationships between these factors and pipe failure are often not completely understood. Consequently, contemporary practices of pipe condition assessment use two types of indicators, namely distress indicators and inferential indicators.

## 2.2 Distress Indicators for Major Pipe Types

Rajani et al. (2006) defined distress indicators as the observable/measurable physical manifestations of the aging and deterioration process. Distress indicators are a result of some or all of the factors listed above. Each distress indicator provides partial evidence for the condition of specific pipe components. It is practical to refer to distress indicators by the respective pipe material, as provided in Tables 2-1 through 2-4, for CI and DI pipes, PCCP, AC, and PVC pipes, respectively. It is noted that leakage could also be considered as a universal distress indicator regardless of pipe type (although the presence of a leak often indicates that failure has already occurred). Leakage out of pressurized water mains is not an acceptable public health risk and short-term pressure surges may pull contaminants into the pipe.

**Table 2-1. Distress Indicators that Influence Pipe Condition for Cast and Ductile Iron Pipes**

| Category | Distress Indicator | Comments |
|---|---|---|
| External coating (poly wrap/ tar/ zinc) | Crack/tear/holiday | State of external coating will dictate how external corrosion is likely to encourage damage to the pipe. |
| External pipe barrel/bell | Remaining wall thickness | Remaining pipe wall thickness is usually obtained from NDE tests or from spot exhumations and sand blasting samples. Casting defects (voids or inclusions) can be of significant size in CI pipes. |
| | Graphitization (pit) areal extent | Areal extent as percentage of pipe diameter times unit length indicates the size of affected area. Severe graphitization may not always mean the pipe should have failed. In practice, graphitized area can still provide some resistance – it acts as a form of sticky plaster. In CI, graphitization is typically in the form of graphite flakes, while in DI it is in the form of nodules. |
| | Crack (pit)† type | A pit is a manifestation of an electro-chemical process, while a crack is a mechanical response to stress. Circumferential cracks indicate some type of longitudinal movement, loss of bedding support, or increase in vertical load (frost) has taken place. Longitudinal cracks occur due to low hoop resistance, typically coupled with high internal pressure. |
| | Crack (pit)† width | Crack width is another indicator of corrosion. A wide crack together with a deep pit will be more detrimental to the pipe than a narrow, but shallow crack. |
| Inner lining/ surface | Cement lining (epoxy) spalling (blistering) | Inner lining deterioration is often due to incompatible water chemistry or abrasion due to the presence of high water velocities and sediments. |
| | Remaining wall thickness | Occasionally, closed circuit television (CCTV) scans can give estimates of internal corrosion pits when NDE tests are not done to get an overall picture of the pipe wall status. |
| | Tuberculation | Heavy tuberculation (blockage) can significantly reduce water delivery and produce red water condition. |
| Joint | Change in alignment | Changes in joint alignment (rotation) indicate pipe susceptible to ground movement. Large changes can lead to leakage and eventually joint failure. |
| | Joint displacement | Joints can displace without undergoing joint misalignment and hence is also an indicator of other forces at play. |

(Rajani et al., 2006)

† Cracks and pits are common in CI pipes, while DI pipes usually only have pits. Small diameter CI pipes may also be susceptible to ring fractures in shrink/swell soil conditions.

**Table 2-2. Distress Indicators that Influence Pipe Condition for PCCP Water Mains**

| Category | Distress Indicator | Comments |
|---|---|---|
| Mortar coating | Spalling | Spalling is often a first indicator of corrosion. Large spalling area may indicate that corrosion is taking place over a significant surface area of the pipe exterior. |
| | Crack type | Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur due to low hoop resistance. |
| | Crack width | Crack width is another indicator of severity of spalling. Large widths mean that spalling is imminent. |
| | Crack density (frequency) | Closer crack spacing usually means the pipe is under higher stress. |
| | Coloration | Signs of color/stains on concrete exterior indicate that corrosion is taking place. Often stains are precursors to spalling, i.e., corrosion products have built up. |
| Prestressed wire | Wire breaks | As the number of wire breaks increase, the factor of safety decreases and eventually leads to pipe failure. |
| Concrete core | Delamination | Delamination occurs when there is poor bonding between concrete/wire or steel/steel cylinder. This can also occur when prestressing is lost due to wire breaks. |
| | Crack type | Circumferential cracks indicate some type of longitudinal movement has taken place. Longitudinal cracks occur when prestressing is lost due to wire breaks. |
| | Crack width | Crack width is another indicator of severity of delamination. Large width means that delamination is imminent. |
| | Crack density (frequency) | Closer crack spacing usually means the pipe is under higher stress. |
| | Hammer tapping sound | Hammer tapping sounds can indicate delamination. It can be as simple as tapping a hammer or using the pulse echo method. |
| | Hollow area | Areal extent of hollow sound can give an idea of the seriousness of the delamination (in comparison to pipe surface area). |
| Pipe geometry | Out of roundness | Out-of-roundness is another indicator of wire loss that may not be evident from concrete spalling or presence of corrosion products, etc. |
| Joint | Change in alignment | Changes in joint alignment (rotation) indicate pipe susceptible to ground movement. Eventually it can lead to weld failures and joint failure. |
| | Joint (internal) displacement | Joints can displace without undergoing joint misalignment and hence are also an indicator of other forces at play. |
| | Joint diaper crack size | Crack of external diaper can give an idea of joint quality. |
| | Joint ring degradation | Joint failure due to microbial degradation of the natural rubber joint rings. |

(Kleiner et al., 2006a)

**Table 2-3. Distress Indicators that Influence Pipe Condition for AC Pipes**

| Category | Distress Indicator | Comment |
|---|---|---|
| External coating (tar or bitumen) | Holiday | State of external coating will indicate how external soil properties encourage damage to the pipe. |
| External pipe barrel | Remaining wall thickness | Remaining pipe wall thickness (includes both external and internal walls) is usually obtained from spot test samples and performing phenolphthalein test (to measure cement softening) or on-site measurements using the georadar technique. |
| | Corrosion[†] areal extent | Areal extent as percentage of pipe diameter times pipe segment length indicates the size of affected area. Severe corrosion may not always mean the pipe should have failed. |
| | Crack type | Circumferential cracks indicate bending or significant longitudinal movement has taken place. Longitudinal cracks occur due to exceedance of hoop resistance, due to occurrence of very high operational loads or due to low remaining wall thickness as a result of sulfate attack. |
| | Crack width | Crack width is another indicator of corrosion. Wide crack together with a deep softening of asbestos cement matrix will be more detrimental to the pipe than a narrow but shallow crack. |
| Internal pipe surface | Remaining wall thickness | See above for external pipe barrel category. |
| | Corrosion areal extent | See above for external pipe barrel category. |
| Joint | Change in alignment | Changes in joint alignment (rotation) indicate pipe is susceptible to ground movement. Large changes can lead to leakage and eventually joint failure. |
| | Joint displacement | Joints can displace without undergoing joint misalignment (axial movement) and hence are also an indicator of other forces at play. |
| | Joint ring degradation | Joint failure due to microbial degradation of the natural rubber joint rings. |

[†]Corrosion is meant to indicate leaching/depletion of cement within the AC matrix due to some chemical mechanism.

**Table 2-4. Distress Indicators that Influence Pipe Condition for PVC Pipes**

| Category | Distress Indicator | Comment |
|---|---|---|
| External pipe barrel surface | Remaining wall thickness | Cavities or unfilled air bubbles introduced during manufacturing (and not detected upon installation) can be of significant size in PVC pipes. |
| | Scratch type | Longitudinal scratches are formed due to improper or rough handling. Circumferential scratches can form if lifted or handled using rough slings (e.g., chains). Also sharp scratches have more detrimental effects than blunt scratches. Longitudinal scratches can eventually lead to longitudinal split failures. |
| | Scratch depth | Fatigue failure becomes an important consideration for deeper scratches, especially when they exceed 10% of pipe wall thickness. |
| Service connection | Split at tap | Inadequate tapping procedure or thin pipe wall can lead to a split in the PVC mains, usually on the pipe inside. This type of failure is commonly referred to as a fitting failure. |
| Joint | Change in alignment | Changes in joint alignment (rotation) indicate pipe is susceptible to ground movement. Large changes can lead to leakage. |
| | Joint displacement | Joints can displace without undergoing joint misalignment and hence are also an indicator of other forces at play. |

## 2.3 Inferential Indicators for Major Pipe Materials

Inferential indicators point to the potential existence of a pipe deterioration mechanism without actual knowledge if this potential has actually been realized. Many of the environmental indicators are inferential in nature, such as soil type, groundwater fluctuations, etc. It is important to note that inferential indicators do not provide direct evidence about pipe deterioration, but rather indicate the potential thereof. However, these indicators are usually easier and cheaper to discern since they can be obtained by nondestructive and nonintrusive methods, and are often used to pre-screen pipes for more expensive direct inspection or to obtain supplemental information in conjunction with distress indicators. Pipe age could, in some context, be viewed as a universal inferential indicator. However, the age of the pipe is only a measure of the pipe exposure to its surrounding environment and operating conditions (i.e., to other inferential indicators), therefore it does not appear as an explicit indicator in the following tables.

Tables 2-5 through 2-8 present the inferential indicators for CI and DI pipes, PCCP, AC, and PVC pipes, respectively.

Some distress indicators can be discerned by direct observation, while others require the application of more elaborate technologies. In either case, discerned distress indicators usually require interpretation, aggregation and/or some other type of techniques (methods) to fuse data (data fusion) from different sources to obtain the condition rating of the pipe. In this context, pipe condition rating is understood to mean a grade or a score (or a rating) on some consistent ordinal scale (e.g., good, fair, poor) that enables the condition rating of pipes relative to each other as well as to “quantify” and track the amount of deterioration over time in a given pipe.

## Table 2-5. Inferential Indicators for Cast and Ductile Iron Pipes

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| Pipe vintage | Material type, historic standards, and installation practices | Pipes of specific vintages can experience a higher breakage rate. This can be a manifestation of manufacturing processes and standards (e.g., pit vs. spun cast, pipe wall thickness, etc.), or installation practices (e.g., internal lining, polywrap on DI pipes, etc.). Knowledge of the installer could also help to identify poor vs. adequate installation practices. |
| Pipe joint | Joint type | Historically, three main joint types: (1) rigid, e.g., bored bell and turned spigot; flanged; (2) semi-rigid, e.g., lead-yarn; and (3) flexible, e.g., rubber-gasket push in joint. Pre-mid 1930s, most joints were semi-rigid type (lead-yarn combination). "Leadite" (brand name for sulfur based compounds - mixture of iron, sulfur, slag, and salt) also was used in North America between early 1900s and late 1940s, however, lead was often the jointing material of choice in North America and in the UK. Rubber gasket push-on or roll-on joints introduced in mid 1950s. Anecdotal reports indicate that leadite joints have performed poorly over the years. |
| Water quality | Water pH | Water with low pH can leach the internal cement lining or pipe wall itself if lining is absent. |
| Water pressure | Operating pressure (OP) | High pressure subjects pipe to high stress and hence higher propensity to failure. |
| | Pressure change amplitude (% OP) | Large pressure changes (% of OP) can induce higher stresses than expected by design. |
| | Pressure change frequency | Either slow or fast fatigue mechanism can induce early failure. |
| Location | Pipe embedment | Pipes exposed to wet/dry conditions have higher failure rate than pipes totally below water table or pipes totally exposed to atmosphere. |
| | Surface loads - traffic type | Heavy surface loads will subject the pipe to high stresses and hence faster deterioration in the long term. |
| | Wet/dry cycle(s) | Changing environment can promote corrosion. |
| | Water table level | Water table position will indicate if wet/dry cycle is likely to occur. |
| Soil | Soil type / backfill | Non-draining backfill leads to moisture retention and promotes corrosion; also, poor backfill can lead to development of out-of-roundness condition as soil side (springline) support is not available as required by design of DI pipes. |
| | Soil resistivity | Low resistivity soil leads to higher corrosion rates. Soil chlorides (e.g., from de-icing salts) reduce soil resistivity. |
| | Soil pH | Low pH (< 4) means soil is acidic and likely to promote corrosion; high alkaline conditions (pH > 8) can also lead to high corrosion. |
| | Redox potential | High availability of oxygen promotes microbial induced corrosion (MIC) in the presence of sulfates and sulfides. |
| | Soil chloride | Low chloride levels in high pH (> 11.5) environments can lead to serious corrosion. |
| | Soil sulfate | Accounts for MIC and possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings. |
| | Soil sulfide | Sulfate reducing bacteria give off sulfides that are excellent electrolytes. |

**Table 2-5. Inferential Indicators for Cast and Ductile Iron Pipes (Continued)**

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| | Frost susceptibility (load) | CI and DI pipes are not designed for frost loads. If conditions exist to develop significant frost loads, then pipe will be subjected to additional stresses (annual) and lead to pipe failure if already significantly corroded. These conditions are: high water table; thermal gradient; right soil type to develop suction (i.e., silt or clayey silt). |
| Corrosion | Cathodic protection | Cathodic protection (galvanic as well as impressed current) is likely to reduce corrosion. |
| | Stray current | Stray current is known to accelerate corrosion unless adequate measures have been taken. |

(Kleiner et al., 2005)

**Table 2-6. Inferential Indicators for PCCP**

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| Pipe vintage | Material type, historic standards, and installation practices | Some early vintage PCCP suffered from inadequate design and manufacture and has a record of failure and increased wire breakage rates. This can be a manifestation of manufacturing processes and standards or installation practices. Knowledge of the installer could also help to identify poor vs. adequate installation practices. |
| Water quality | Water pH | Water with low pH can leach the internal cement/concrete lining. |
| Water pressure | Operating pressure (OP) | High pressure subjects pipe to high stress and hence higher propensity to failure. |
| | OP change amplitude (% OP) | Large pressure changes (% of OP) can induce higher stresses than expected by design. |
| | OP change frequency | Either slow or fast fatigue mechanism can induce early failure. |
| Location | Pipe embedment | Pipes exposed to wet/dry conditions have higher failure rate than pipes totally below water table or pipes totally exposed to atmosphere. |
| | Surface loads - traffic type | Heavy surface loads will subject the pipe to high stresses and hence to faster deterioration in the long term. |
| | Wet/dry cycle(s) | Changing environment promotes corrosion of wires if chloride concentration exceeds 140 mg/kg (140 ppm). |
| | Water table level | Water table position will indicate if wet/dry cycle is likely to occur. |
| Soil | Soil type / backfill | Non-draining backfill leads to moisture retention and hence promotes corrosion; also, poor backfill can lead to development of out-of-roundness condition as soil side (spring line) support is not available as required by design. |
| | Soil resistivity | Low resistivity soils lead to higher corrosion rates of prestressing wire and steel cylinder. Soil chlorides (e.g., from de-icing salts) reduce soil resistivity. |
| | Soil pH | Low pH (< 4) means soil is acidic and likely to promote corrosion; high alkaline conditions (pH > 8) can also lead to high corrosion of prestressing wire and steel cylinder. |
| | Soil chloride | Mortar coating usually creates a pH environment of >12.4. Low chloride levels in high pH (> 11.5) environments can lead to serious corrosion as noted by Bianchetti (1993). |

**Table 2-6. Inferential Indicator for PCCP (Continued)**

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| | Soil sulfate | Accounts for MIC and possible food source for sulfate reducing bacteria in anaerobic conditions under loose coatings. |
| | Soil sulfide | Sulfate reducing bacteria giving off sulfides, which are excellent electrolytes. |
| | Frost susceptibility (load) | PCCP pipes are not designed for frost loads. If conditions exist to develop significant frost loads, then pipe will be subjected to additional stresses (annual) and prematurely lead to development of cracks. These conditions are: high water table; thermal gradient; right soil type to develop suction (i.e., silt or clayey silt). |
| External coating | Coating type | Cast coating was applied prior to the mid 1960s which is prone to spalling. After 1970, this coating has since been superseded by mortar coating, which cracks but does not spall. |
| | Concrete chloride concentration | Chloride levels higher than 1,000 ppm promote corrosion. |
| | Absorption capacity | Mortar absorption greater than 8% leads to higher corrosion rates. |
| Prestressed wire | Wire class | Interpace pipe manufactured prior to 1985-1988 have Class IV wire or Class III wire. These high strength wires are susceptible to hydrogen embrittlement. |
| Corrosion | Cathodic protection | Too strong CP currents (especially impressed current systems) may lead to hydrogen embrittlement, especially with Class I and II prestressing wires. |
| | Stray current | Stray current is known to accelerate corrosion unless adequate measures have been taken. |

(Kleiner et al., 2005)

**Table 2-7. Inferential Indicators for AC Pipes**

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| Pipe vintage | Material type, historic standards, and installation practices. | Pipes of specific vintages have experienced a higher breakage rate, (e.g., AC pipes of types I and II [free lime < 1%]). This can be a manifestation of manufacturing processes and standards or installation practices. Knowledge of the installer could also help to identify poor vs. adequate installation practices. |
| Water quality | Water pH | Water with low pH can leach the cement within the AC matrix. |
| | Water saturation index (SI) | Water with SI < 0.25 can leach the cement within the AC matrix. |
| Water pressure | Operating pressure (OP) | High pressure subjects pipe to high stress and hence higher propensity to failure. |
| | Pressure change amplitude (% OP) | Large pressure changes (% of OP) can induce higher stresses than expected by design. |
| | Pressure change frequency | Fatigue mechanism not observed or documented for AC pipes. |
| Location | Surface loads - traffic type | Heavy surface loads will subject the pipe to high stresses and hence to faster deterioration in the long term. |
| | Wet/dry cycle(s) | Changing environment promotes higher expansion of matrix than unchanging environment. AC type II offers better resistance to sulfate induced swelling. |

**Table 2-7. Inferential Indicators for AC Pipes (Continued)**

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| | Water table level | Water table position will indicate if wet/dry cycle is likely to occur. Soil sulfate attack only occurs if sulfate is in solution. |
| Soil | Soil type / backfills | Non-draining backfill leads to moisture retention and hence promotes external corrosion. |
| | Soil pH | Low pH (< 5) means soil is acidic and likely to promote corrosion. |
| | Soil sulfate | Soils with high sulfate (> 1000 ppm) can attack AC pipes with high free lime (type I AC pipes). |
| | Frost susceptibility (load) | AC pipes are not designed for frost loads. If conditions exist to develop significant frost loads then pipe will be subjected to additional stresses (annual) and lead to pipe failure if already significantly corroded. These conditions are: high water table; thermal gradient; right soil type to develop suction (i.e., silt or clayey silt). |

**Table 2-8. Inferential Indicators for PVC Pipes**

| Category (Level 1) | Agent (Level 2) | Comment |
|---|---|---|
| Pipe vintage | Material type, historic standards, and installation practices. | Most PVC pipes used in North America are of the unplasticized PVC type. Newer modified PVC and oriented PVC have recently appeared on the market. Failures could be tied to certain manufacturing processes and standards or installation practices. Knowledge of the installer could also help to identify poor vs. adequate installation practices. |
| Water pressure | Operating pressure (OP) | High pressure subjects pipe to high stress and hence higher propensity to failure. Time to failure can be substantially reduced in PVC pipes under high pressure since PVC is a visco-elastic material. |
| | Pressure change amplitude (% OP) | Large pressure changes (% of OP) can induce higher stresses than expected by design. |
| | Pressure change frequency | Fatigue mechanism is primary mechanism of PVC pipes if scratches or gouging are present. |
| Location | Surface loads - traffic type | Heavy surface loads will subject the pipe to high stresses and hence to faster deterioration in the long term especially if PVC pipes have been previously scratched or gouged. |
| Soil | Hydrocarbons | PVC pipes are impervious to high-octane gasoline and gasoline saturated water for periods of up to 2 years. |
| | Frost susceptibility (load) | PVC pipes are not designed for frost loads. If conditions exist to develop significant frost loads, then pipe will be subjected to additional stresses (annual) and lead to pipe failure if already significantly scratched. |

# 3.0: TECHNOLOGIES FOR CONDITION ASSESSMENT OF WATER MAINS

## 3.1 Nondestructive Testing and Evaluation

As described earlier, there are two types of observations to be made in the course of pipe condition assessment, namely observation of distress indicators and observation of inferential indicators. This report addresses both. While the observation of inferential indicators is always nondestructive and nonintrusive, the observation of distress indicators can be destructive or nondestructive as well as intrusive or nonintrusive. Destructive testing entails the removal of a sample from pipe wall to analyze remaining thickness, defects, damages, and residual strength. These types of tests are not addressed in this report. Nondestructive testing (NDT) techniques (also commonly referred to as NDE) include the direct visual observation of defects such as cracks, corrosion pits or holes, as well as techniques that provide signals or signatures that are interpreted into distress indicators.

Descriptions of NDT technologies can be found in several published reports (Dingus et al., 2002; Reed et al., 2004; Lillie et al., 2004; Marlow et al., 2007; Thomson and Wang, 2009; Feeney et al., 2009). This report makes maximum use of published reports and input from water utilities, vendors, and consultants to provide the most up-to-date information. The descriptions have been sent to technology vendors for comments. Detailed technical information for some of the technologies is not available from the vendors. Therefore, the information collected from their Web sites and publications will be used in this report. Figure 3-1 lists the inspection technologies covered in this section. Table 3-1 shows the potential to apply an inspection technology to different pipe materials. Each technology is described briefly in the main text followed by a short table summarizing the purpose, status, source of information, advantages, limitations, performance, breadth of use, and other available information. With few exceptions, all technologies are presented using the template in Table 3-2, for simplicity and ease of comparison. It should also be noted that whenever a vendor/developer of a technology was identified, a copy of the entry related to this technology was sent to them for review and verification. Consequently, the vast majority of the relevant entries have received vendor/developer feedback. Cost data were provided wherever available, but it was not available for most of the technologies covered in this section.

**Table 3-1. Summary of Condition Assessment Technologies Applicable to Different Pipe Materials**

<table>
<tr><th rowspan="2">Technology</th><th colspan="3">Metallic Pipes</th><th colspan="2">Concrete Pipes</th><th colspan="3">Poly Pipes</th></tr>
<tr><th>CI</th><th>DI</th><th>WS</th><th>CPP/PCCP</th><th>AC</th><th>GRP</th><th>PVC/uPVC</th><th>PE</th></tr>
<tr><td>Pit depth measurement</td><td colspan="3">√</td><td colspan="2">-</td><td colspan="3">-</td></tr>
<tr><td>Visual inspection</td><td colspan="3">√</td><td colspan="2">√</td><td colspan="3">?</td></tr>
<tr><td>Electromagnetic inspection</td><td colspan="3">√</td><td colspan="2">√</td><td colspan="3">-</td></tr>
<tr><td>Acoustic inspection</td><td colspan="3">√</td><td colspan="2">√</td><td colspan="3">√</td></tr>
<tr><td>Ultrasonic testing</td><td colspan="3">√[a]</td><td colspan="2">-</td><td colspan="3">?</td></tr>
<tr><td>Pipeline current mapper</td><td colspan="3">√</td><td colspan="2">-</td><td colspan="3">-</td></tr>
<tr><td>Radiographic testing</td><td colspan="3">√</td><td colspan="2">-</td><td colspan="3">-</td></tr>
<tr><td>Thermographic testing</td><td colspan="3">√</td><td colspan="2">-</td><td colspan="3">-</td></tr>
<tr><td>Pipe condition assessment from soil properties</td><td colspan="3">√</td><td colspan="2">?</td><td colspan="3">?</td></tr>
<tr><td>Sensor technologies[(b)]</td><td colspan="3">√</td><td colspan="2">√</td><td colspan="3">?</td></tr>
</table>

(a) Ultrasonic thickness methods may be less accurate for pit cast iron pipes because of the larger grain structure.
(b) Emerging sensors and sensor networks and their applicability to various pipe types are described in Section 3.13.
√: available; ?: may/may not work; CI = cast iron, DI = ductile iron, WS = welded steel, CPP/PCCP = concrete pressure/pre-stressed concrete cylinder pipe, AC = asbestos cement, GRP = glass-fiber reinforced polyester, PVC/uPVC= polyvinyl chloride/un-plasticized PVC, PE = polyethylene

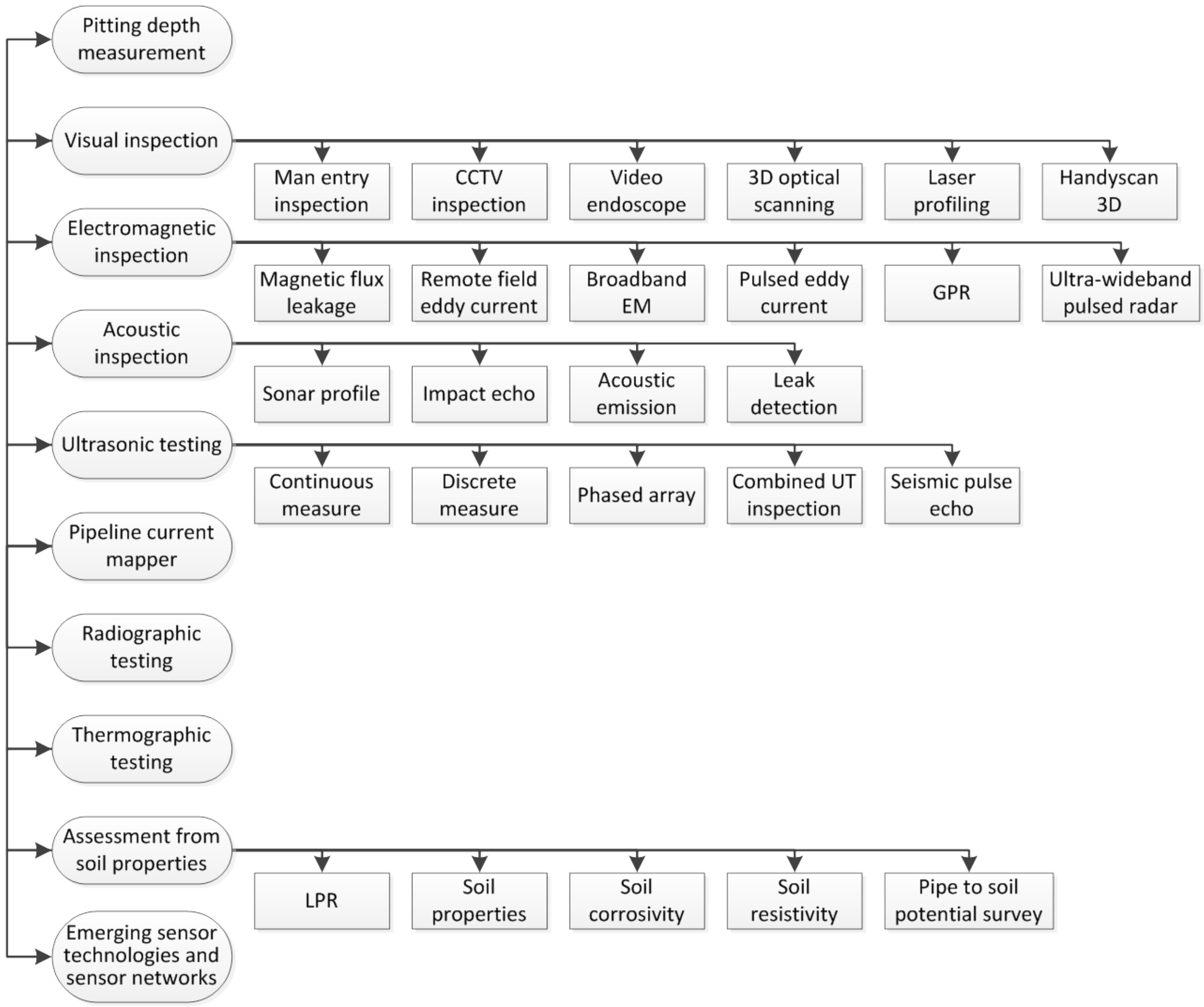



**Figure 3-1. Nondestructive Inspection Technologies for Condition Assessment of Water Mains**

**Table 3-2. Template Used for Description of Technologies**

| | |
|---|---|
| Name | Common name of technology |
| Purpose/Scope | Intended purpose or scope |
| Status | Commercially available/experimental/in development, etc. |
| Source of information | Identifies sources of information. |
| Advantages | Relative to similar or to other technologies |
| Limitations | Relative to similar or to other technologies |
| Performance | Accuracy, false positives, false negatives, etc. |
| Breadth of use | If currently used for water mains – to what extent?<br>If not currently used for water mains, where is it used? What is the potential for use in water mains? |
| Other information | If available |

### 3.2 Pit Depth Measurement

Pit depth can be measured with a pointed micrometer or needle-point depth gauge. Other methods include a grid with ultrasonic spot measurement, automated ultrasonic scanner, and laser range measurement. The pit depth measurement can be carried out in the field on exposed sections of the pipe (for external corrosion) or in a laboratory on pipe samples (for external and internal corrosion). Before pit measurement, pipe samples are sand/grit blasted to remove corrosion products. Pitting depth measurement can be applied methodically, within a general survey, or opportunistically when a pipe is exposed (e.g., upon breakage repair). Table 3-3 provides more information on pit depth measurement.

**Table 3-3. Pit Depth Measurement**

| | |
|---|---|
| Name | Pit depth measurement |
| Purpose/Scope | Measure the pit depth of ferrous pipes due to corrosion. Can help to evaluate historical pipe corrosion rate (subject to some fundamental assumptions that often cannot be verified). This rate, in conjunction with deterioration modeling, can be used to assess pipe remaining life. |
| Status | Various pit depth measurement devices are commercially available. Some devices (e.g., laser range finder) have been developed for research purposes only. |
| Source of information | SwRI, 2002; Marlow et al., 2007; many others available |
| Advantages | • Direct measurement, no need for interpretation<br>• Provides good indication of sample condition.<br>• Does not require special skills, easy to train personnel.<br>• For external corrosion, exposed pipe does not need to be taken out of service. |
| Limitations | • Can be practically applied only to samples, therefore requires some sophisticated statistical analysis to infer general condition of the entire pipe (or pipe segment).<br>• Need to expose the pipe or to cut coupon (destructive testing). When exposing a pipe, care needs to be taken to adequately protect the exposed pipe segments from future corrosion.<br>• Existing coating needs to be removed.<br>• Original pipe wall thickness must be available for corrosion rate estimation.<br>• For internal corrosion, pipe needs to be taken out of service. |
| Performance | Manual measurement does not need highly-skilled operators. Simple to implement. Only provides information that is specific to the sample. No issue with false positives, false negatives, etc. |
| Breadth of use | No direct information about breadth of use, but because of its simplicity, it is likely used by many to varying degrees. |
| Other information | Pit depth measurement of samples along the pipe can be used in a statistical analysis to infer pipe condition. Also, can be used as an input to pipe deterioration models to estimate time to failure. |

### 3.3 Visual Inspection

The condition of the internal surfaces of the pipe can be assessed by a visual inspection. It may be done without specialized equipment or a variety of vision aids (e.g., closed-circuit television, videoscope, or laser-based surface profiler) may be employed to augment human vision. It is generally used in conjunction with a library of defects/deficiencies.

**3.3.1 Man Entry and Visual Inspection.** Inspectors can record defects/deficiencies, including size, location, and extent, with hand-held video or still cameras. Acoustic tests are often performed concurrently to provide non-visible information about the pipe. By striking the pipe wall with a hammer, the sound, either dull or solid, provides qualitative information about the condition of the pipe wall. In the office, defects/deficiencies can be coded, assigned scores and aggregated to provide the overall condition of the pipe. Table 3-4 provides more information on man entry and visual inspection.

**Table 3-4. Man Entry and Visual Inspection**

| | |
|---|---|
| Name | Man entry and visual inspection |
| Purpose/Scope | Man entry inspection is suitable for relatively large diameter pipes. Visual inspection can also be applied to the external surface of an exposed pipe. |
| Status | Currently being applied mainly in sewers, but also in large transmission water mains. |
| Source of information | Marlow et al., 2007; many others available |
| Advantages | • Relatively simple, no special equipment necessary and training courses are widely available.<br>• The exposure of a buried pipe also allows the assessment of the quality and condition of the backfill.<br>• The assessment can provide an indication of the cause of the deterioration and the likelihood of being more widespread. |
| Limitations | • Internal inspection suitable only for relatively large diameter pipes.<br>• External inspection involves exposing of pipes — expensive.<br>• Not very effective to discover defects/deficiencies that are not manifested on the pipe surface.<br>• Water mains need to be taken out of service. |
| Performance | Depends on skills of personnel. |
| Breadth of use | Widely applied in water and sewer mains. |
| Other information | Visual inspection can be a precursor to other condition assessment techniques. |

**3.3.2 Closed Circuit Television Inspection.** The CCTV inspection records a close-up observation of the pipe surface. The CCTV system comprises a CCTV camera and lighting apparatus, mounted on a carrier. A winch and pulley system moves the CCTV module through the pipe. Larger modules can use an umbilical cord system, which can provide power and communication from and to the ground station, as well as serve to retrieve the device. The basic steps of CCTV inspection include:

- Introduce a carrier with the CCTV camera into the pipe via access points;
- The carrier travels along the pipe and the camera captures and transmits the images to a ground station (inspection truck);
- Analyze images in the field or office.

The procedure is illustrated in Figure 3-2 and more details are provided in Table 3-5. The live video images are sent back to the ground control center via coaxial or twisted pair cables so the operator can remotely control the CCTV module. Most CCTV modules are equipped with panned and tilted cameras, which can implement a close-up observation of the pipe surface. Local storage devices can also save image data on a hard drive, DVD disk or VHS tape.

**Figure 3-2. CCTV Inspection**

**Table 3-5. Closed Circuit Television Inspection**

| | |
|---|---|
| Name | CCTV inspection |
| Purpose/Scope | Visual inspection without man-entry. Particularly suitable for smaller diameter pipes. Applied mainly to sewers and stormwater pipes, but can also be applied to water mains for the inspection of inner surfaces after the line is emptied. Generally used in conjunction with a library of defects/deficiencies. |
| Status | Several CCTV systems are commercially available. |
| Source of Information | Hydromax, 2006; RapidView, 2007a; many others available |
| Advantages | • Simple, relatively inexpensive, suitable for small and large pipes<br>• New systems with multi-camera and/or fish-eye technology can record a full view of a pipe and allow relatively high scanning speed as well as full off-line inspection.<br>• Digital recording is convenient for data storage, as well as future developments in automatic data interpretation. |
| Limitations | • Provides information only on defects that are manifested on the pipe inner surface;<br>• Inspection results are qualitative and need interpretation.<br>• Quantitative rating requires trained inspectors.<br>• Limitations of traditional CCTV inspection include the need to pan and tilt to see sides and laterals, the camera has to stop at each defect's location for a closer look and identification, and to ensure an acceptable video quality; the carrier's speed is limited to 150 mm/s (5.9 in./s).<br>• Tuberculated pipes may need to be scrubbed and cleaned prior to inspection.<br>• Currently not available for in-service water main inspection.<br>• Requires a special launching and retrieval chamber in water mains. |
| Performance | Depends on skills of personnel. |
| Breadth of use | CCTV systems have been widely used for sewers. Usage in water mains is limited mainly due to the last three limitations listed above. |
| Other Information | Not available |

An improvement on the traditional CCTV is the side scanning evaluation technology (SSET), which provides both frontal and 360° images of the interior surface of the pipe wall (Hydromax, 2006). Two cameras simultaneously capture a forward view and a perpendicular view of the pipeline. The SSET system can travel through the pipeline at a constant speed without stopping to observe defects. A pan or tilt camera is not needed. A key benefit of the SSET is that it lends itself better to comparison of data from one year to the next. An advanced version of SSET is the DigiSewer system marketed by Envirosight (Envirosight, 2010). With DigiSewer side-scanning, pipe footage can be captured at a speed up to 70 ft/min without stopping to pan, tilt or zoom. The detailed flat scan can be further reviewed and annotated.

Another improvement on the traditional CCTV is the PANORAMO® optoscanner, which uses two integrated scanning units, one at the front end and one at the rear end as shown in Figure 3-3 (RapidView, 2007a). Each scanning unit consists of a 185° fish-eye lens and a high resolution digital camera. The two units take hemispherical images and create 360° spherical images. An unfolded, two-dimensional view of the entire section and a three-dimensional view of the pipe allow the viewer to pan the angle of view in all directions. This pan and tilt scanning of details can be done in the office without actually operating the camera during inspection. The operator can pan and rotate a virtual camera like a real one. Another advantage of the PANORAMO® system is that it can operate at a relatively high speed of 300 mm per second.

The inspection results need to be interpreted. This interpretation is currently done manually, but machine-vision techniques are likely to be developed in the future. In the office, defects/deficiencies can be coded, assigned scores, and aggregated to provide the overall condition of the pipe.

**Figure 3-3. The PANORAMO® System**
**(Reprinted with permission of RapidView)**

**3.3.3 Videoscope.** A borescope is an optical device consisting of a rigid or flexible tube with an eyepiece on one end and an objective lens on the other, linked together by a relay optical system. Videoscope is an advanced type of borescope that houses a very small charge-coupled device (CCD) chip embedded in the tip of the scope. Videoscopes are normally 10 mm (0.4 in.) or less in diameter and come in lengths up to 15.24 m (50 ft). Several integral features include the insertion probe section, the articulated tip, articulation controls, lighting bundle, high intensity external light source and cable interfaces, and external media recording device. The video image is relayed from the distal tip and focusable lens assembly back to the display via internal wiring.

This technique is used for the visualization of areas that are otherwise inaccessible. Videoscopes are easy to operate. The user can get a full control of the scope position with articulated controls and the captured video sequences/images can be analyzed with software. Table 3-6 provides more information on the videoscope.

**Table 3-6. Videoscope**

| | |
|---|---|
| Name | Videoscope |
| Purpose/Scope | Remote visual inspection. Suitable for the inspection of objects to which normal access is difficult or impossible. |
| Status | Equipment is commercially available. |
| Source of information | http://www.fiberscope.net/; many others available |
| Advantages | • Visualization of hidden areas with limited access<br>• High quality images<br>• Enables high quality control of inspected devices<br>• High-speed video capturing ability |
| Limitations | • Provides information only on defects that are manifested on the pipe inner surface.<br>• Inspection results are qualitative and need interpretation.<br>• Quantitative rating requires trained inspectors.<br>• Usage is limited to short-length and small diameter pipe. |
| Performance | Same as other visual inspection techniques. |
| Breadth of use | Videoscopes have been used for gas/oil pipeline inspection and many other applications such as aircraft engine, automotive transmission, concrete, security, as well as drinking water and wastewater pipes. |
| Other information | Not available |

**3.3.4 3D Optical Scanning.** The three-dimensional (3D) optical scanner in Figure 3-4 contains two high-resolution digital cameras with distortion-free, wide-angle lenses (RapidView, 2007b). Image data are captured and transmitted to a control vehicle for processing and storage. Maximum speed is 350 mm/s (about 14 in./s). Inspection results need to be interpreted by trained personnel. Similar to the optoscanner, a 360° pan/ zoom as well as unfolded view of the inner surface of the manhole can be obtained offline with software tools. Table 3-7 provides more information on 3D optical scanning.

**Figure 3-4. PANORAMO® SI 3D Optical Manhole Scanner (Reprinted with permission of RapidView)**

**Table 3-7. 3D Optical Scanning**

| | |
|---|---|
| Name | 3D optical scanning |
| Purpose/Scope | Inspection of manholes, drilled shaft, and boreholes. |
| Status | Commercially available (Panoramo® SI) |
| Source of information | RapidView, 2007b; http://www.rapidview.com/panoramosi.htm |
| Advantages | • Fast inspection<br>• Suitable for vertical pipes or pipe-shaped structures |
| Limitations | • There are no known limitations except those generally associated with all visual inspections. |
| Performance | Same as other visual inspection techniques |
| Breadth of use | Used mainly for manholes from 400 mm (16 in.) diameter upwards. |
| Other information | Not available |

**3.3.5 Laser-Based Pipe Surface Profiling.** Distance measurement by laser can be done using one of four principles, including triangulation, time-of-flight, pulse-type time-of-flight, and modulated beam systems. In a triangulation system, the detecting element measures the laser spot within its field of view. Usually, this type of laser measurement is used for distances of a few inches. Time-of-flight sensors derive range from the time it takes light to travel from the sensor to the target and back (Acuity, 2008). This technology is typically used for relatively long distance measurements. For very long distances, a pulsed laser beam is used. A modulated beam system also uses the time duration for light to travel to the target and back; however, in this case, time is not measured directly. Instead, the strength of the laser is varied to produce a signal that changes over time. The time delay is indirectly discerned by comparing the signal from the laser with the delayed signal returning from the target. Modulated beam sensors are typically used in intermediate range applications.

To acquire the pipe inner profile, a spinning apparatus is needed to control the laser beam. Such a laser range measurement does not require any special illumination and can be carried out in complete darkness. The speed of spinning, sampling rate, and carrier moving velocity determine the accuracy and resolution of the scanning. The inspection is affected by the roughness as well as the color of the pipe surface.

Another method makes use of a ring of laser light projected onto the pipe inner surface (Duran et al., 2003). The ring must be strong enough to be "seen" by a camera. The camera is used to capture the images of this projected ring. The laser device moves with the camera through the pipe. The analysis software extracts the laser ring from captured images and reconstructs a digital pipe profile. This profile can be easily unfolded or manipulated for review and analysis. The setup requires that the laser ring fall in the field of view of the camera. The accuracy depends on the fineness of the laser ring and the resolution of the camera.

The laser ring and camera are typically mounted on a carrier or robotic platform. Gyroscopic position data (i.e., pitch, yaw, and roll) of this platform are needed to achieve the required precision (Dettmer, 2007). Currently available laser profiling systems are only used in de-watered pipes. To date there is no known report on underwater laser profiling for in-service water mains. Table 3-8 provides more information on the laser-based pipe surface profiling technique.

**3.3.6 Handyscan 3D.** This portable device is a combination of laser and stereo vision (two cameras) for fast creation of an object surface profile with high resolution as shown in Figure 3-5 and summarized in Table 3-9. By tracking the laser beam (pattern) and positioning targets (marks on the surface to match images), separate images acquired by the two cameras are stitched together with the help of special software. Table 3-9 provides more information on Handyscan 3D.

**Table 3-8. Laser-Based Pipe Surface Profiling**

| | |
|---|---|
| Name | Laser-based pipe surface profiling |
| Purpose/Scope | Acquire the topography of the pipe surfaces, from which pitting corrosion can be inferred. |
| Status | Commercial systems are available. An advanced technique is in development. |
| Source of information | Acuity, 2008; Duran et al., 2003; Dettmer, 2007 |
| Advantages | • Potential to show the early signs of pipe degradation by corrosion<br>• Provides exact geometric dimensions for rehabilitation options.<br>• Enables inspection with minimum lighting requirements.<br>• Measures cross-sectional area.<br>• Can be applied in a wide range of pipe sizes. |
| Limitations | • Tuberculated pipes need to be scrubbed and cleaned prior to inspection.<br>• Pipeline needs to be de-watered.<br>• Data analysis combines measurements with software and automated processes.<br>• No documentation is available on capability to detect cracks. |
| Performance | • The laser profiling is accurate, but still needs data processing to compensate for errors introduced during scanning.<br>• Report on performance study is not available. |
| Breadth of use | The laser profiling technique has been applied to generate pipe inner surface profile and can also be used for quantifying the outer-surface metal loss of metallic pipes. |
| Other Information | Not available |

**Figure 3-5. Creaform Handyscan 3D**
**(Reprinted with permission from Creaform)**

**Table 3-9. Handyscan 3D**

| | |
|---|---|
| Name | Handyscan 3D |
| Purpose/Scope | Scanning process used for industrial design, manufacturing, and inspection (Creafrom, 2008). It is a non-contact inspection to acquire the geometric dimension of objects in various environments. |
| Status | Commercially available device. This technique is still under development for industrial inspection. A third modality (i.e., laser ultrasound) is being introduced to this scanner for detecting subsurface conditions by a company in Belgium (3DCorrosion, 2005). |
| Source of information | Creafrom, 2008 |
| Advantages | • This technique provides more efficient scanning than laser alone.<br>• No limitation on scan orientation<br>• Easy to set-up and operate |
| Limitations | • The scanner is a portable device, which needs an operator; therefore it is suitable only for large pipes that allow man-entry or for external inspection. For the same reason, it does not appear to be a convenient alternative to scan long stretches of pipe.<br>• For pipe inspection, the scanning requires a clean surface to map the corrosion pits. Tuberculated pipes need to be scrubbed and cleaned prior to inspection.<br>• Need to set up positioning targets. |
| Performance | Comparative study on the scanning of helicopter tail rotor blades with a 3D laser scanner from NRC Institute for Information Technology was carried out. The results were confidential and not available to the public. |
| Breadth of use | The device was exhibited at the 17th World Conference on Non-destructive Testing (Shanghai, China, 2008). No information is available on its use in water mains or any other type of pipe. |
| Other Information | The scanner, setup, and maintenance cost is low. Learning curve is short. |

## 3.4 Electromagnetic Inspection

**3.4.1 Magnetic Flux Leakage.** The magnetic flux leakage (MFL) method uses large magnets to induce a saturated magnetic field around the pipe wall. If the pipe is in good condition, a homogeneous distribution of magnetic flux is obtained. Anomalies such as metal loss will alter the distribution of the magnetic flux. Flux leakage is recorded by a detector coil as shown in Figure 3-6. The pipe surface needs to be cleaned for direct contact with the MFL detection device.

MFL inspection can be used inside the pipe (de-watering required) or outside an exposed pipe (pipe can be in service). However, it is not possible to inspect small diameter pipe internally due to the mass of the magnets and steel backups required. The MFL tool provides raw data that need to be interpreted. In the software developed by Advanced Engineering Solutions, algorithms to identify and characterize the metal loss are implemented. The raw data are interpreted to defect sizes at a known level of confidence. Table 3-10 summarizes more information on the MFL technology.

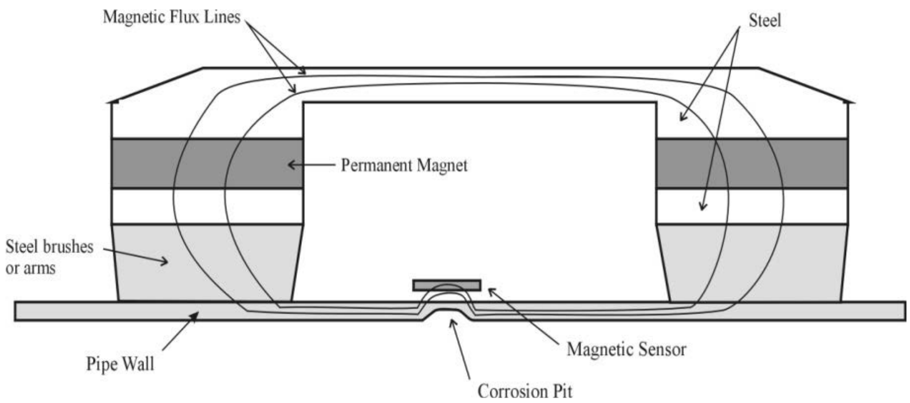



**Figure 3-6. The Principle of Magnetic Flux Leakage Inspection (Makar and Chagnon, 1999)**

**Table 3-10. Magnetic Flux Leakage**

| | |
|---|---|
| Name | Magnetic flux leakage (MFL) |
| Purpose/Scope | Identify and measure metal loss due to corrosion in ferrous pipes. MFL inspection can be used inside a pipe or outside an exposed pipe. |
| Status | MFL systems are available for the oil and gas industry. Commercial MFL system for wall thickness measurement from outside is also available for metallic water pipes. More advanced technique, namely pulsed MFL, is being developed. |
| Source of information | http://www.ndt-ed.org; Makar and Chagnon, 1999; Wilson et al., 2008; Marlow et al., 2007 |
| Advantages | • High degree of accuracy for wall thickness measurement<br>• External surface inspection does not require a service interruption. |
| Limitations | • Using MFL in metallic water pipes requires maintaining close contact with the pipe wall (Makar and Chagnon, 1999). This contact is strengthened by the magnetic forces between the tool and the wall, which pull the two together.<br>• Direct contact with the pipe wall is required and the surface of the pipe must be clean. Thus, for in-line inspection, MFL is limited to cleaned, unlined metallic pipes (otherwise, the tool is likely to damage interior coating and slough off tuberculation).<br>• It is not possible to develop internal tools to suit small diameter distribution pipes since the mass of the magnets and steel backups need to be greater than the pipe wall. Tools for external examination are available for small and large diameter pipes; however, excavation of buried pipes and replacement of coating or insulation are required, which make it economically questionable. |
| Performance | • The MFL test needs to be calibrated to interpret the acquired signal.<br>• It is mainly used for detecting corrosion pits and small defects.<br>• The detection of pipe wall remaining thickness is quite accurate. |
| Breadth of use | • MFL techniques are generally used in the oil and gas industry for metal loss detection and are not suitable for internal inspection of small diameter pipes due to the size of the probes.<br>• The use of in-line MFL in water industry is limited to cleaned, unlined ferrous pipes which are accessible.<br>• Although anecdotal information is available about its use for water mains, in-line MFL is not widely used due to the high costs associated with it. |
| Other Information | The pulsed excitation for MFL has been reported to extract depth information of defects in rolled steel water pipeline (Wilson et al., 2008). More information will probably be available from the response of a wider frequency band. |

**3.4.2 Remote Field Eddy Current.** A remote field eddy current (RFEC) system consists of an exciter coil and one or more detectors (see Table 3-11 for more information). The exciter coil is driven by a low-frequency alternating current signal. The interaction region can be divided into three zones (Crouse, 2009; Mergelas and Kong, 2001):

(a) Direct coupled zone: in this zone magnetic field from the exciter coil interacts with the pipe wall to produce a concentrated field of eddy current;

(b) Transition zone: just outside the direct couple zone. In this zone, there is much interaction between the magnet flux from the exciter coil and the flux induced by the eddy current;

(c) Remote field zone: the region in which direct coupling between the exciter coil and the receiver coil is negligible.

**Table 3-11. Remote Field Eddy Current**

| | |
|---|---|
| Name | Remote field eddy current (RFEC) |
| Purpose/Scope | Inspect ferromagnetic pipes as well as ferromagnetic components of composite pipes (Mergelas et al., 2001). |
| Status | Various proprietary commercial systems are available. Different inspection systems have been developed for different types of pipe. |
| Source of information | Crouse 2009; Mergelas and Kong, 2001; Russell, 2009; Thomson and Wang, 2009 |
| Advantages | • Can be applied to different applications (e.g. detect broken wire, measure corrosion pits).<br>• Can be operated in wet or dry conditions; therefore, inspection of in-service pipes is possible.<br>• Can be used for inspecting lined pipe; direct contact with pipe wall not required.<br>• Inspection systems are available for different pipe sizes. |
| Limitations | • Data interpretation needs experience and skill.<br>• Some tools require pipe cleaning and/or dewatering before inspection. |
| Performance | Proprietors do not publish information about false positives/false negatives; however, RFEC seems to be the prevailing technology in the drinking water industry for inspection of ferromagnetic pipes and ferromagnetic components in composite pipes (e.g., PCCP). |
| Breadth of use | • The RFEC/TC technique and P-Wave® are widely used for detecting broken wires in prestressed concrete pipes.<br>• The See Snake tool is applied to small diameter ferromagnetic pipes.<br>• The PipeDiver™ RFEC tool can be used to inspect large diameter, full, ferromagnetic pipes. |
| Other | Not available |

Two paths exist between the exciter and detector as shown in Figure 3-7. The direct electromagnetic field inside the pipe is attenuated rapidly by circumferential eddy currents induced in the conducting pipe wall (Mergelas and Kong, 2001). The indirect field diffuses radially outward through the pipe wall. This field spreads rapidly along the pipe with little attenuation. These two fields re-diffuse back through the pipe wall and are dominant at the remote field zone. Any discontinuities in the indirect path will cause changes in signal magnitude and phase. This is the principle of RFEC testing. This technology does not require the sensors to be in close contact to the pipe wall.

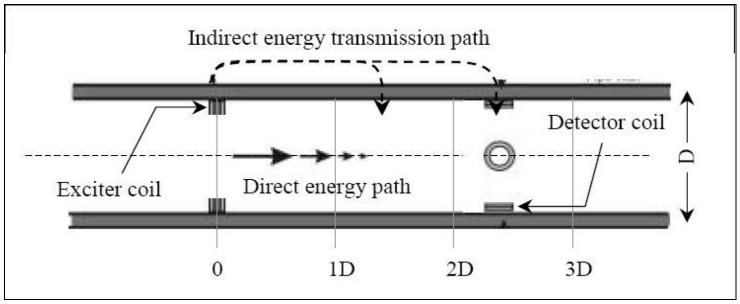



**Figure 3-7. Remote Field Eddy Current Testing (Rajani and Kleiner, 2004)**

***Remote field eddy current/transformer coupling***

PCCP pipes have two metallic elements, namely a steel cylinder and steel prestressing wire that is wrapped tightly around the core concrete to provide it with resistance to tensile stresses. Both metallic elements interact with the induced magnetic field. The interaction between the indirect transmission path and the prestressing wire is known as transformer coupling (TC). Thus, the received signal consists of two components, a remote field component and a TC component. The presence of broken wires will reduce the response of the transformer coupling component, thus allowing their detection (Figure 3-8). The remote field transformer coupling technique was developed by the Applied Magnetic Group in the Department of Physics at Queen's University in Kingston, Ontario, Canada.

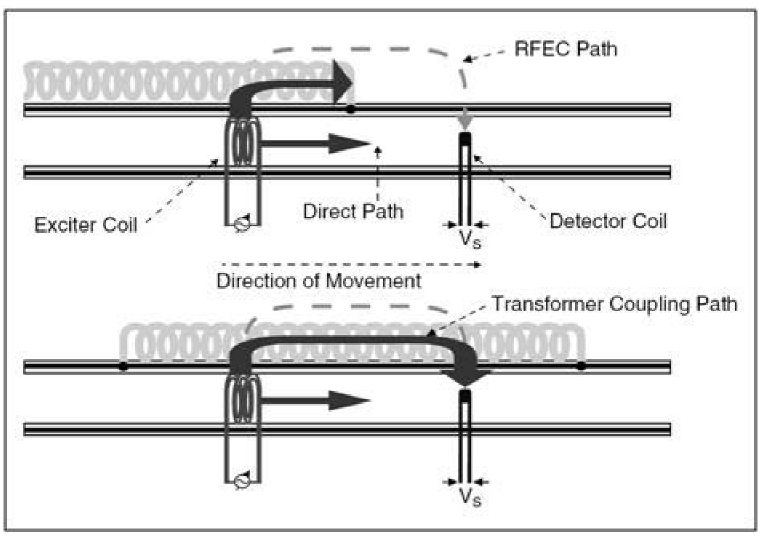



**Figure 3-8. The Breaking Wire Results in a Decrease in the Detector Signal (Reprinted with permission from PPIC)**

The proprietor of the commercial system is the Pressure Pipe Inspection Company (PPIC). The technique requires analyses and interpretation (proprietary) of the amplitude and phase signals. The amplitude represents the strength of the transmitted signal while the phase represents the time that the signal takes to arrive at the detector. According to PPIC, the technique, which is named RFEC/TC can:

- Detect broken wires in PCCP;
- Quantify the number of breaks along the length and anywhere around the circumference of PCCP;
- Quantify the wire breaks in embedded cylinder pipe (ECP), lined cylinder pipe (LCP), and noncylinder pipe;
- Quantify and spot wire breaks in pipes with or without shorting straps and in pipes with or without bonding straps.
- Services based on the manned (PipeWalker), tether robotic (PipeCrawler), and free swimming (PipeDiver™) tools are all commercially available from PPIC.

The free-swimming robotic tool PipeDiver™ was developed by PPIC to carry out in-service inspection of pipelines with diameters of 600 to 2,000 mm (23.6 to 78.7 in.). The tool is inserted into the live main using proprietary launch and retrieval devices, which attach to any full-bore tap of least 12 in. in diameter (18 in. for pipe diameters over 1,000 mm). The tool travels at roughly 90% the flow speed of the water, and is held in the center of the pipe by flexible fins.

***See Snake Tool***

See Snake Tool is an RFEC-based technology, developed by Russell NDE Systems Inc., to measure internal and external corrosion pits in ferromagnetic pipes (Russell, 2009). Tools are available for 50 to 400 mm (2 to 16 in.) and 500 to 700 mm (20 to 28 in.) diameter pipes in wall thicknesses up to 25.4 mm (1 in.). A picture of the See Snake system is shown in Figure 3-9. The tool can be free swimming or tethered on a wire line. Lengths up to 3,000 ft can be inspected from one launch point when wire line tethered (Thomson and Wang, 2009). The free swimming version can inspect lengths up to 15,000 ft from the launch point. The features of the See Snake tools include:

- Can negotiate multiple 90° welded elbows.
- Completely water and pressure proof for water and wastewater line pressures.
- Inspection speed is approximately 0.2 to 0.5 km/hour.
- Can measure remaining wall thickness, surface area (length and width), and stress.
- Can be tracked and detected from above ground.

**Figure 3-9. The See Snake Tool for Inspection of Pipe Internal and External Flaws (Reprinted with permission from Russell NDE Systems Inc.)**

The technique is able to distinguish internal defects from external ones with the addition of extra sense coils (not included in standard tools). Currently, See Snake tools are used to inspect water, wastewater, oil and gas pipelines with and without internal liners, downhole casings and large diameter raw water pipelines.

***P-Wave®***

P-Wave® is an RFEC-based system, developed by Pure Technologies, for the condition assessment of PCCP. P-Wave® detects breaks in prestressed wire and estimates the total number of breaks for each pipe section. The P-Wave® system can traverse the pipeline in either a manned or robotic manner. In the manned inspection, the P-Wave® system is pushed through a dewatered pipeline. In the robotic inspection, the pipe must be depressurized. In general, a manned inspection is preferred to facilitate a close-up visual inspection of interior surface of the pipe wall. However, if manned entry is not feasible due to pipe diameter and confined space entry requirements, a robotic inspection is applied (Figure 3-10). The system has a variety of configurations to accommodate all diameters of PCCP. The number of broken wires is derived from the acquired inspection data and will be used further as an input for a structural model.

**Figure 3-10. P-Wave® System for Manned and Robotic PCCP Inspection (Reprinted with permission from Pure Technologies)**

**3.4.3 Broadband Electromagnetic.** Unlike the conventional eddy current technique, which uses a single frequency for testing, the broadband electromagnetic (BEM) technique transmits a signal that covers a broad frequency spectrum (Hazelden et al., 2003). A transient input signal generates multiple frequencies, typically ranging from 50 Hz to 50 kHz. The recorded signal from a broadband transmission contains more information, and allows detection and quantification of various wall thicknesses as well as the effective conductivity of the complex through-wall components of the pipe. Changes in conductivity reflect changes in material properties.

A transmitter coil passes an alternating current to the pipe surface, which generates an alternating magnetic field. Flux lines from this magnetic field pass through the metallic pipe wall, generating a voltage across it. This voltage produces eddy currents in the pipe wall, which induce a secondary magnetic field. Wall thickness is indirectly estimated by measuring signal attenuation and phase delay of the secondary magnetic field.

External scanning requires excavation of buried pipes. Internal scanning can be carried out with an inline inspection pig, which is driven by hydraulics or by push/pull rod devices (Thomson and Wang, 2009). However, the pipeline needs to be out of service, emptied, and cleaned of loose deposits in order to run the pig. In CI, BEM can identify and locate metal loss and cracks. It does not require contact with bare metal to detect pits and other metal loss. It is possible to apply BEM for pipeline assessment through keyholes (GTI, 2005). Refer to Table 3-12 for more information on BEM.

**Table 3-12. Broadband Electromagnetic**

| | |
|---|---|
| Name | Broadband electromagnetic (BEM) |
| Purpose/Scope | Detect and quantify wall thickness, as well as the effective conductivity of the complex through-wall components of the ferrous pipes. |
| Status | Commercially available from Rock Solid Pty. Ltd. A hand-held tool based on the same principle is also available from the same company to measure corrosion pits. |
| Source of information | Feeney et al., 2009; Hazelden et al., 2003; Thomson and Wang, 2009 |
| Advantages | • Does not require contact with the metallic pipe wall and is not sensitive to the corrosion products.<br>• Can scan through coatings, linings, and insulation with a penetration depth of 2.5 times the transmitter diameter. |
| Limitations | • Measures average thickness in the area under the sensor's footprint; the resolution of the scan depends on the size of the sensor; unable to detect pin-hole failures or isolated pits.<br>• For in-line inspection, pipe needs to be emptied and cleaned.<br>• The inspection process is time consuming because the scanning process is not continuous. |
| Performance | • The mean value of wall thickness is measured for a square grid.<br>• A surface scratch or an isolated pit smaller than the square grid will not be detected. |
| Breadth of use | • BEM technology has been primarily used for condition assessment of water mains.<br>• It can only be used on ferrous materials.<br>• BEM can be used to measure wall thickness, quantify graphitization, and locate broken wires in PCCP (Feeney et al., 2009).<br>• Inspection of a 760 mm (30 in.) cast iron and steel lines was reported (Hazelden et al., 2003).<br>• Information about the limits on pipe size is not available. |
| Other information | The BEM system is being further modified to facilitate the inspection of pipes exposed in keyhole excavations. This will help acquire information about pipe condition without disrupting service or full access excavations. |

**3.4.4 Pulsed Eddy Current System.** Pulsed eddy current is a successful method to determine wall thickness of insulated and non-insulated steel pipelines from external inspection (Waters, 2005). A rectangular shaped eddy current is generated by a transmitter coil. Each cycle consists of one positive and one negative pulse. The strength of the eddy currents is measured at some distance from the pipe wall (e.g., due to liftoff or insulation thickness) by quantifying the magnetic reaction field picked up by the receiver coil (Waters, 2005). The strength is related to wall thickness. It computes the average thickness of the metal by comparing the transient time of certain signal features with similar calibrated signals (Waters, 2005). The contact between the magnetic field and the inspected component produces a footprint that represents the area inspected for wall thickness calculation. The diameter of the footprint varies between 25 and 150 mm (1 to 6 in.), depending on wall thickness, insulation thickness and sensor size. The inspection tool is compact and can be easily deployed by remotely operated vehicles. See Table 3-13 for more information on the pulsed eddy current system.

**Table 3-13. Pulsed Eddy Current System**

| | |
|---|---|
| Name | Pulsed eddy current system |
| Purpose/Scope | Primarily an external method for detecting corrosion in ferrous pipes and vessels without removing insulation, fireproofing concrete or similar coatings (MB Inspection, 2008). |
| Status | Commercial available (from Applus+RTD, formerly PNDT). |
| Source of information | MB, 2008; Waters, 2005; http:/www.pndt.com.au |
| Advantages | • Unaffected by the presence of insulating coatings and no need to remove them.<br>• All commonly used insulating materials like glass wool, rock wool, asbestos, polyurethane foam, scales of silicate, concrete and all kinds of fire proofing have no influence on the magnetic field and induced eddy currents. However, the binding ties, fitting supports, fixing materials and composition of the weatherproofing have influences on the examination. These influences can be compensated by properly tuning the measurement parameters.<br>• Can operate submerged (sub-sea inspection). |
| Limitations | • Interpretation of the signal requires a high level of skill. The pulsed eddy current data needs to be analyzed carefully because results are highly sensitive to variations in factors such as lift off and air gap.<br>• The measurement result is affected by a number of factors including variations in metallurgy and temperature.<br>• The size of the instrument's footprint will mask small areas of localized steel loss and appropriate selection of the sensor head (from 30 to 200 mm in diameter) is essential. |
| Performance | PNDT claims that the instrument is capable of high accuracy and good repeatability. |
| Breadth of use | • Used for inspection of insulated pipe/vessels in chemical plants and the oil and gas industry. Actual numbers were not reported.<br>• In-line operation is possible with battery supply without disrupting service. |
| Other information | Not available |

**3.4.5 Ground Penetrating Radar**. Ground penetrating radar (GPR) antennae transmit electromagnetic wave pulses into the ground. These pulses propagate through the ground and reflect off sub-surface boundaries. The reflections are detected by a receiving antenna and subsequently interpreted (Costello et al., 2007). See Table 3-14 for more information on GPR.

**Table 3-14. Ground Penetrating Radar**

| | |
|---|---|
| Name | Ground penetrating radar (GPR) |
| Purpose/Scope | Acquire subsurface information. It can be used to locate buried assets, such as plastic or clay pipes. |
| Status | Conventional GPR systems are commercially available. A prototype for ground penetrating image radar was recently developed. |
| Source of information | Costello et al., 2007; Makar, 1999; Marlow et al., 2007 |
| Advantages | • Able to locate pipes of all materials<br>• Inspection can be performed from the surface non-intrusively or from within the pipe for more detailed information. Antenna does not have to touch the pipe surface.<br>• Relatively high inspection speed<br>• A GPR survey also provides information on the condition of the soil surrounding the pipe and details of voids. |
| Limitations | • Air gap and variations in soil conditions will affect the GPR result;<br>• The pulses lose strength very quickly in conductive materials, such as clay and saturated soils, which is a limitation for these soil types.<br>• Limited ability to detect assets below the water table.<br>• Data interpretation needs highly skilled operators. |
| Performance | • The performance of GPR is highly dependent on soil conditions.<br>• No evidence of consistent ability to detect voids with GPR.<br>• Substantial operator interpretation of results is necessary (Makar, 1999). |
| Breadth of use | Limited use for locating non-metallic pipes and detecting pipe leakage. |
| Other information | Significant work needs to be done to process GPR data and signals. |

Conventional GPR systems are operated from the ground surface. In-pipe GPR systems were also reported (Costello et al., 2007). Such systems use two or three antennae with different frequencies to investigate the structure of the surrounding soil, the interface between the soil and pipe, and the structure of the pipe. GPR can potentially identify leaks in buried water pipes either by detecting underground voids created by the leaking water or by detecting anomalies in the depth of the pipe as the radar propagation velocity changes due to soil saturation with leaking water (Hunaidi and Giamou, 1998). The GPR technique was also applied to determine the degree of internal leaching of hydroxides in AC pipes (Slaats et al., 2004).

A prototype ground penetrating imaging radar (GPIR) was recently developed within a European Commission supported project “WATERPIPE” (WATERPIPE, 2009b). This high resolution GPIR is designed to detect leaks and image damaged regions in pipes. The capabilities of this high resolution GPIR reportedly include:

- Locate water pipe of all types of materials;
- Detect leaks and damages in water pipelines of all types of materials;
- Penetrate the ground to a depth of up to 200 mm (78.74 in.);
- Achieve an image resolution of less than 50 mm (1.96 in.);
- Survey velocity at approximately 0.36 km/hr (0.22 mi/hr).

The measurement results currently available were obtained in a laboratory environment. The inspection results were used to assess the structural reliability, leakage, and conformity to water quality standards of the pipes (WATERPIPE, 2009b).

**3.4.6 Ultra-Wideband Pulsed Radar System: P-Scan.** P-Scan is based on ultra-wideband (UWB) antennae capable of transmitting and receiving electromagnetic pulses in the nano- and pico-second ranges (see Table 3-15). For the inspection of buried pipes, it is desirable to operate in the picoseconds range because pulse widths in this region are equal to or less than the wall thickness of most non-ferrous buried pipes. The pulse repetition frequency (PRF) ranges from thousands to several billion pulses per second. Numerical experiments demonstrated the potential of this technique for pipe condition assessment. The use of ultra-short duration pulses makes it possible to obtain relatively high resolution results.

**Table 3-15. UWB Pulsed Radar System: P-Scan**

| | |
|---|---|
| Name | UWB pulsed radar system: P-Scan |
| Purpose/Scope | Detect below surface defects, corrosion, and out-of-pipe voids in non-metallic buried pipes (Allouche, 2007; Jaganathan et al., 2006). The UWB inspection is capable of providing higher resolution images of the pipe wall and a greater penetration depth than high-frequency GPR. |
| Status | Numerical simulation for P-Scan has been carried out and a pre-commercial prototype is not available yet. The system is still under development. |
| Source of information | Allouche, 2007; Jaganathan et al., 2006 |
| Advantages | • Accurate measurement of wall thickness of pipes<br>• Increased resolution of images<br>• The pipe wall thickness and other distinct layers can be measured in a continuous manner. Forward processing algorithms can be used to back calculate the dielectric constant of the various materials.<br>• Capability to inspect not only the pipe wall, but also the pipe liner. |
| Limitations | Not yet determined. |
| Performance | Not yet determined. |
| Breadth of use | Not yet determined. |
| Other information | Not yet determined. |

## 3.5 Acoustic Inspection for Structural Condition

**3.5.1 Sonar Profile System.** Sonar is an acoustic detection technology designed to operate under water (see Table 3-16). In the pipe inspection field, it has been adapted to provide information about elements in the pipe that are submerged below the water line. These may include submerged debris in the pipe (sewers), grease level (sewers), differential settling and other submerged deformations and defects. A sonar system may consist of an underwater scanner unit, collapsible sonar siphon float, sonar processor/monitor, skid set, and all necessary interconnect cables (CUES, 2008). It typically travels in pipes at velocities in the range of 0.1 to 0.2 m/s and sends a pulse approximately every 1.5 s. Each pulse provides an outline of the cross-section of the submerged part of the pipe (CUES, 2008). Accurate measurements can be performed based on these outlines.

The sonar profiling system can be used with different frequencies to achieve different goals (RedZone, 2008). High frequency sonar can provide a higher resolution scan, but a high resolution pulse attenuates quickly and therefore has a relatively low penetration capability. In contrast, low frequency sonar has a high penetration capability but is limited in its scanning resolution. Consequently, whereas high frequency sonar can be suitable for clear water conditions, turbid water with high concentrations of suspended solids may require a lower frequency signal. Small defects are more likely to be observed by a high frequency signal. Some systems are capable of a multi-frequency scan to obtain maximum information.

**Table 3-16. Sonar Profile System**

| | |
|---|---|
| Name | Sonar profile system |
| Purpose/Scope | Provides visual profile, profile comparison, and dimension data of significant items or defects on internal pipe below waterline. |
| Status | Commercially available. |
| Source of information | RedZone, 2008; CUES, 2008 |
| Advantages | • Can be operated on a robotic platform in both fully charged and partially charged lines without disrupting the service (sewers).<br>• Can work in conjunction with a CCTV system in the inspection of semi-submerged pipes. |
| Limitations | • Must be operated under water.<br>• Limited by the operating frequency |
| Performance | Can generate precise pipe cross-section via dwell scan. |
| Breadth of use | • Applied widely to the inspection of sewers<br>• No data found about its use in water mains. |
| Other information | • A system that integrates sonar and video for use in submerged and large semi-submerged pipelines is also available.<br>• The cost of sonar inspections varies depending on the diameter of the pipe to be inspected. |

**3.5.2 Impact Echo.** Impact echo testing is based on the use of impact-generated stress waves that propagate through and are reflected by the object under test (see Table 3-17). The impact echo equation is (Sack and Olson, 1998):

$$T = V/(2F_p)$$

where

T is thickness;
V is wave speed
$F_p$ is peak frequency.

The time domain test data of the impulse hammer and accelerometer are transformed to the frequency domain as illustrated in Figure 3-11. A transfer function is computed between the hammer and receiver as a function of frequency. Peaks in the transfer function reflect the thickness of the pipe wall at the test location. A more complicated model would be required to discern other properties of the object under test from frequency responses.

The test can be performed on concrete, stone, plastic, masonry materials, wood and some ceramics. Testing is conducted by hitting the test surface at a given location with a small instrumented impulse hammer or impactor and recording the reflected wave with a displacement or accelerometer receiver adjacent to the impact location (Sansalone and Streett, 1998). The receiver is mounted to or pressed against the test surface.

**Table 3-17.  Impact Echo**

| | |
|---|---|
| Name | Impact echo |
| Purpose/Scope | Determine the location and extent of flaws such as depth and width of surface cracks, delamination, voids and other damages.  Application suitability depends on the properties and internal structure of the material being tested (Marlow et al., 2007). |
| Status | Various instruments are commercially available. |
| Source of information | Marlow et al., 2007; Sack and Olson, 1998; Sansalone and Streett, 1998 |
| Advantages | • The impact echo test can be applied to varied materials.<br>• The test is easy to carry out.<br>• Works through paints, coatings, and tiles.<br>• Only one side of the structure needs to be accessible for testing. |
| Limitations | • Frequency domain analysis is complicated when information other than thickness and geometry is needed and experience is required.<br>• Embedded items may affect wave behavior and test results.<br>• This method is not limited by pipe size and can be applied both internally and externally only if the testing is executable.<br>• Not applicable to metals |
| Performance | • Accuracy is typically 2% at high resolution when properly calibrated on a known thickness location (Marlow et al., 2007).<br>• The typical thickness for the impact echo testing ranges from 66 mm to 1.8 m (2.6 to 70.9 in.). |
| Breadth of use | • Extensively used on flat surfaces (concrete slabs, bridge decks, etc.)<br>• Also used for inspection of water and sewer PCCP and concrete pipes, usually large diameter pipes with man access. |
| Other information | Not available |

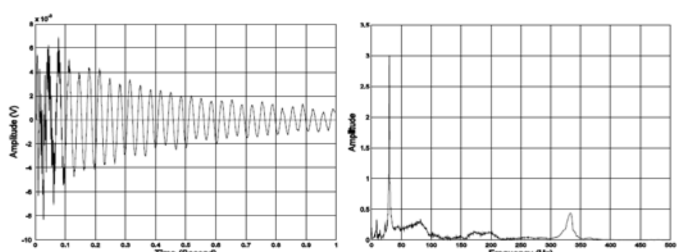



**Figure 3-11.  Impact Echo Testing**

**3.5.3 Acoustic Emission.** Acoustic emission testing (see Table 3-18) is based on the detection of sound waves generated from within the material itself (e.g., when a crack propagates). The monitoring sensors are placed in or on the pipe to monitor acoustic activity. Signals obtained by the monitors are typically compared to a library of acoustic signatures of known events (e.g., a wire break in PCCP) to identify activities. The sensors used for acoustic monitoring include (Higgins and Paulson, 2006):

- Hydrophone arrays: multiple hydrophones are mounted on a cable with specific spacing.
- Hydrophone station: single hydrophones are inserted into the water flow at convenient locations.
- Surface mounted sensor: piezoelectric sensors are placed on the surface of the pipe or appurtenances along the pipe.
- Fiber optic sensor: long jacketed cable containing glass fiber sensor is inserted into the pipe.
- Microelectromechanical system (MEMS) acoustic emission sensor: four resonant sensors of frequency range 100 to 500 kHz are integrated on a 5 mm (0.196 in.) square chip (Grevea et al., 2008).
- Wire-guided transducer: wire-guided transducer uses a steel wire to acoustically couple a piezoceramic wafer to a test structure (Neilla et al., 2007).

The two important variables for acoustic monitoring are sensor spacing and monitoring duration. The acoustic sensor should be spaced close enough to ensure two sensors detect the acoustic event and have sufficient acoustic information to identify the source. The short-term monitoring installs the acoustic sensors temporarily, while the long-term monitoring needs a permanent installation of the sensors for continuously tracking the performance of a pipe with time.

**Table 3-18. Acoustic Emission**

| | |
|---|---|
| Name | Acoustic emission |
| Purpose/Scope | Monitor the acoustic emission when a sudden appearance or propagation of a microscopic crack occurs within a material under load or the break of prestressed wire in PCCP (Marlow et al., 2007). |
| Status | Acoustic emission sensors (e.g., hydrophone, surface mounted sensor, and fiber optic sensor), are commercially available. New sensors are being designed and tested (e.g., MEMS acoustic emission sensor and wire-guided transducer). |
| Source of information | Grevea et al., 2008; Neilla et al., 2007; Higgins and Paulson, 2006; Holley and Buchanan, 1998 |
| Advantages | Implement real-time online monitoring. |
| Limitations | • Can only detect what is happening during monitoring period (no indication about past deterioration);<br>• Installation of sensors may need interruption of service;<br>• Quantitative information (e.g., size) about the crack is not available. |
| Performance | Not available |
| Breadth of use | Acoustic emission test is being applied to detect wire breaking and leakage of pipelines. |
| Other information | Not available |

## 3.6 Acoustic Inspection for Leak Detection

**3.6.1 SmartBall®.** SmartBall® comprises a range of acoustic sensors, as well as an accelerometer, magnetometer, ultrasonic transmitter, and temperature sensors, which travel with the water flow down a pipe and detects, locates, and estimates the magnitude of leaks as it rolls. The acoustic sensors are encased in an aluminum alloy core with a power source and other electronic components (Fletcher, 2008; Pure Technologies, 2009). The core is encapsulated inside a protective outer foam shell or sphere (see Figure 3-12). The outer foam shell provides additional surface area to propel the device and also eliminates the noise that the device might generate while traversing the pipeline. The diameter of the outer sphere depends on the pipe diameter and flow conditions. See Table 3-19 for more information on the SmartBall® technology.

**Figure 3-12. Pictures and Illustrations of SmartBall®: internal view (left) and external view (right) (Reprinted with permission from Pure Technologies)**

The SmartBall® is deployed into the water flow of a pipeline and captured at a downstream point. It continuously records acoustic data and emits an acoustic pulse every 3 seconds for tracking purposes while the device traverses the pipeline. A SmartBall® Acoustic Receiver, which is patented by Pure Technologies, is used to track the location of the ball. The above-ground markers can be laid at 2 km intervals and leak locations can be determined within 1 m. The recorded acoustic data are analyzed to identify air pockets and leaks. Other sensory data are used to determine the location of air pockets and leaks. The severity of leaks is estimated by calibrated baseline data. Frequency analysis needs to be carried out to confirm that an acoustic anomaly is actually a leak.

A resilient elastomeric coating is placed around the ball to minimize background noise, while the ball rolls through the pipe. The inspection route needs to be carefully planned to ensure that the ball does not block bypass lines. The effect of offtakes should also be considered. As the ball is smaller than the inside diameter of the pipe, with the required amount of fluid, the ball can traverse the pipe without any difficulties.

**Table 3-19. SmartBall®**

| | |
|---|---|
| Name | SmartBall® |
| Purpose/Scope | Detect leaks and air pockets in medium and large diameter (8 in. and greater) water and wastewater pipes. |
| Status | Commercially available (from Pure Technologies) since 2006. |
| Source of information | Fletcher, 2008; Pure Technologies, 2009;, http://www.puretechnologiesltd.com/html/smartball_water.php |
| Advantages | • Can be used for any pipe material (concrete, steel, PVC, GRP, etc).<br>• Can be applied to detect air pockets and leaks on medium and large diameter pipe (> 8 in.).<br>• Can survey long pipelines with a single deployment. The total length of survey capacity depends on flow rates in the pipeline and battery life. The longest water line survey presently is 15 miles (25 km) under 2 f/s flow. For higher flow rates, longer surveys could be performed.<br>• Can detect very small noise disturbances along the pipeline.<br>• Inspection is performed while a pipeline remains in service. |
| Limitations | • The conventional SmartBall® cannot be used for pipelines with very high water pressure (> 400 pounds per square inch [psi]).<br>• If the survey involves long pipe lengths, the surface sensor used for monitoring the pulses being emitted from the SmartBall® has to be moved along the pipe length.<br>• The estimation of the leak magnitude is qualitative. |
| Performance | • As reported by Pure Technologies, the device can detect leaks of less than 0.026 L/hr (0.1 gal/hr) under ideal conditions (high pressure and low levels of ambient noise) (Pure Technologies, 2009).<br>• Location accuracy depends on how well the configuration of a pipeline is known. Typically, the location accuracy of the device is within 3 ft (1 m). |
| Breadth of use | • SmartBall® is a relatively new technology and has seen significant entry into the marketplace.<br>• It has been used in many countries, including the U.S., Canada, and Mexico, on a wide range of pipe materials.<br>• It was commercially introduced in late 2006 and, as of August 2009, has been deployed through more than 900 miles of pressure pipe. |
| Other information | Further development of SmartBall® technology for natural gas pipeline applications is being supported by research funding from the U.S. Department of Transportation Pipeline and Hazardous Safety Administration. http://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=234 |

**3.6.2 LeakfinderRT™.** As illustrated in Figure 3-13 and summarized in Table 3-20, the LeakfinderRT™ system is composed of leak sensors, a wireless signal transmission system, and a personal computer. Acoustic sensors, such as accelerometers or hydrophones, are attached to two contact points on the pipe, such as a fire hydrant. Accelerometers are used to sense leak-induced vibration, while hydrophones are used for sensing leak-induced sound in water column. Accelerometers are sensitive to background noise and hydrophones are often used together with accelerometers to achieve a better signal to noise ratio.

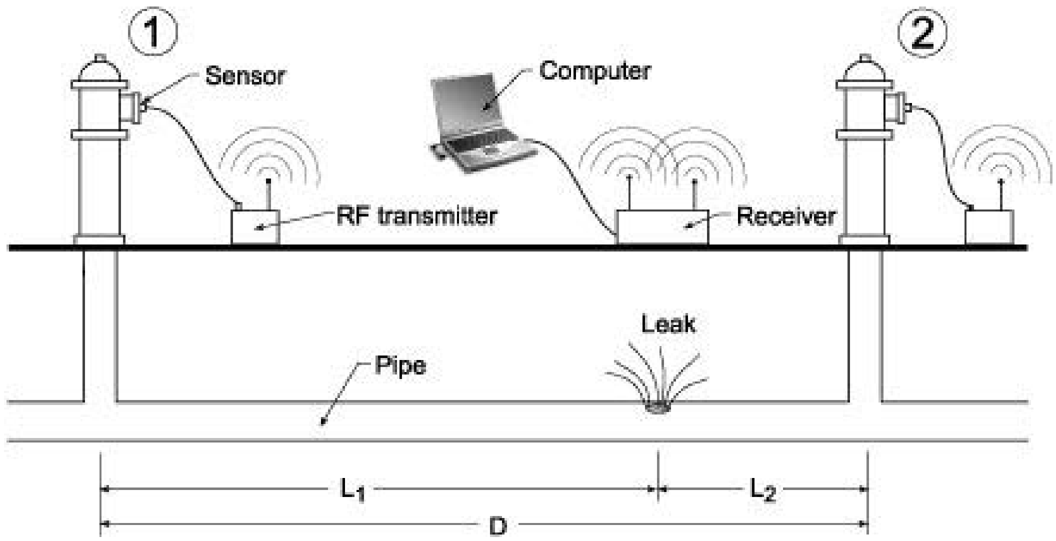



**Figure 3-13. Principle of LeakFinderRT™**
**(Hunaidi et al., 2004)**

The computer calculates the cross-correlation function of the two leak signals to determine the time lag ($\tau_{max}$) between the two sensors. Then the location of the leak can be derived from the equation below:

$$L_1 = \frac{D - c \cdot \tau_{max}}{2} \quad \text{and} \quad L_2 = D - L_1$$

where

$L_1$ and $L_2$ are the positions of the leak relative to sensors 1 and 2, respectively;
c is the propagation velocity of sound in the pipe;
D is the distance between location 1 and 2.

Propagation velocity is determined experimentally or estimated based on the type and size of the pipe. LeakfinderRT™ uses a patented, enhanced cross-correlation function that is calculated indirectly in the frequency domain using the inverse Fourier transform of the cross-spectral density function rather than using the shift-and-multiply method in the time domain (Hunaidi et al., 2004). The enhanced correlation function provides improved resolution for narrow-band leak signals. This is very helpful for plastic pipes (low frequency sound emission), small leaks, multiple leaks and situations with high background noise. Moreover, a major advantage of the enhanced function is that it does not require the usual filtering of leak signals to remove interfering noises (Hunaidi et al., 2004).

**Table 3-20. LeakfinderRT™**

| | |
|---|---|
| Name | LeakfinderRT™ |
| Purpose/Scope | LeakfinderRT™ is a computer-based system for locating leaks in all types of water and other fluid transmission and distribution pipes (Echologics, 2009; Hunaidi et al., 2004). |
| Status | LeakfinderRT™ is commercially available (from Echologics) since 2002. |
| Source of information | Hunaidi, 2006b |
| Advantages | • Non-intrusive tool used to locate leaks in pipes.<br>• Uses a proprietary, enhanced correlation method, which improves the effectiveness of locating leaks in all types of pipes including plastic pipes.<br>• Effective for small leaks and for situations with high background noise<br>• Uses a low-frequency vibration sensor to locate leaks in plastic pipes.<br>• Correlation implemented using software rather than hardware. |
| Limitations | • Information about the leak size is not available from the test.<br>• Sensor spacing is influenced by both the pipe diameter and pipe material due to the attenuation of the acoustic signal. More signal attenuation is experienced the larger the diameter of the pipe and the less rigid the material. This effect is present in all pipe types, but is most pronounced in PVC and PCCP due to their material properties.<br>• Maybe susceptible to interference from low-frequency vibrations (e.g., pumps and road traffic). |
| Performance | The performance of the LeakfinderRT™ system has been successfully tested for the following scenarios (Hunaidi et al., 2004):<br>• Narrow-band leak noise in PVC pipes<br>• Small leaks in PVC pipes under a very low pressure of 20 psi<br>• Locating small leaks in metal pipes<br>• Effective for situations with high background noise<br>• Improved peak definition for resolving multiple leaks<br>• The smallest PVC pipe leaks detectable with LeakfinderRT™'s low frequency vibration sensors (1.7 L/min) and hydrophones (0.85 L/min).<br>• Theoretical leak location error is less than 10 cm. Actual error depends on accuracy of sensor spacing and propagation velocity; The distance between acoustic sensors is determined by the pipe materials and size.<br>• The monitoring duration depends on the quality of the signal. More signal with much noises need a longer monitoring time. |
| Breadth of use | LeakfinderRT™ is used for locating leaks in all types of water and other fluid transmission and distribution pipes. |
| Other information | Based on principles similar to LeakfinderRT™, a technique was developed (WallThicknessFinder) and patented (but not yet commercialized) to estimate the average pipe wall thickness between two 'listening' points on the pipe (Hunaidi, 2006b). The average thickness of the pipe section between two acoustic sensors can be back calculated from a theoretical model, which incorporates the acoustic velocity, pipe diameter, Young's modulus of the pipe wall, and the bulk modulus of elasticity of water (Hunaidi, 2006a). Velocity measurement can be performed with the same hardware as LeakfinderRT™ by using the cross-correlation method. |

Leak signals are measured using either vibration sensors or hydrophones. Accelerometers, which sense the acceleration of vibration induced by leak signals in the pipe wall or fittings, are normally used to measure leak signals in metal pipes (Hunaidi et al., 2004). Sensors can be attached to the pipe directly; if not, they can be attached to fire hydrants or to the underground valves. Hydrophones are used through fire hydrants to pick up the leak signals propagating through water. It is good for non-metallic pipes. LeakfinderRT™ has a special low-frequency vibration sensor, which is more effective than accelerometers.

Signals from leak sensors can be transmitted wirelessly to a computer for processing. Leak sounds are recorded and correlated by LeakfinderRT™ in a few minutes, but for noisy signals a longer duration is required. The cross-correlation results are displayed on screen and are continuously updated in real time, while leak signals are being recorded.

**3.6.3 Permalog®.** Permalog® is a semi-permanently or permanently installed system for detecting and logging leak noise in water distribution systems (Fluid Conservation Systems [FCS], 2011). The loggers (Figure 3-14) are installed on pipe fittings and valves and are retained in place by magnets and powered by replaceable batteries. The logger is 4.85 in. tall by 1.95 in. wide, weighs 1.5 lbs, and operates between 902 to 928 MHz.

**Figure 3-14. Picture of Permalog® (Courtesy of www.hwm-water.com)**

The noise loggers typically operate during the night when background noise is lowest and pressure is highest. If no leak is present, a radio signal transmits to indicate normal background conditions, but as soon as a possible leak is detected, the unit sounds an alarm and transmits a radio signal to indicate a leak condition (Butler, 2009). The logger has changeable alarm threshold settings and the data can be accessed by three methods: (1) lift and shift – the loggers are removed from the ground and the data is manually retrieved; (2) drive by – the data is transmitted via radio to a moving patrol vehicle using a patroller system; and (3) PermaNet – the data is transmitted directly to an office computer via radio network. See Table 3-21 for more information on the Permalog® technology.

The Permalog® system has been deployed by several water utilities such as West Virginia American Water, Birmingham Water Works Board, and Las Vegas Valley Water District to locate leaks. Permalog® has been deployed by West Virginia American Water as part of an advanced metering infrastructure (AMI) system for an area serving around 12,000 customers (Hughes, 2011). Birmingham has used Permalog® since 2004 and the devices have located more than 700 leaks and helped to reduce its non-revenue water rate by 57% (Birmingham Water Works Board, 2009). Las Vegas has used the technology since 2004 to locate more than 1,300 leaks and estimates they have saved more than 109 million gallons of water (Las Vegas Valley Water District, 2011).

Table 3-21. Permalog® Technology

| | |
|---|---|
| Name | Permalog® |
| Purpose/Scope | Continuous monitoring and leak detection for water distribution systems. |
| Status | Developed by FCS and commercially available from Halma Water Management |
| Source of information | www.hwm-water.com/leakDetectionPermalog.htm<br>www.datamatic.com/product_docs/Permalog.pdf<br>www.fluidconservation.com/permalog+AMR.htm<br>Hughes, 2011; BWWB, 2009; LVVWD, 2011; Butler, 2009 |
| Advantages | • Can be permanent, semi-permanent, or survey (as required by area).<br>• Responds to new leaks and breaks in a timely manner.<br>• Automated leak surveying<br>• Non-invasive method with no detrimental effects on the customer supply<br>• Can be quickly deployed and used repeatedly without disruption to the surrounding area.<br>• Low cost battery replacement with minimum maintenance (battery lasts 5 or more years depending on mode of operation) |
| Limitations | • Monitoring length varies based on pipe material, with plastic pipe requiring closer spacing than metallic pipe.<br>• Background noise can create issues in finding leaks. |
| Breadth of use | Over 200,000 units in use worldwide and used by more than 200 U.S. water utilities (FCS, 2011). |

**3.6.4 MLOG™**. MLOG™ is a permanently installed acoustic monitor used for locating leaks in water distribution systems. The monitoring device, contained in a black polycarbonate and brass hosing (Figure 3-15), is installed near the water meter and powered by an AA lithium battery with a battery life of 10 years or more. The device is 4.8 in. tall by 2.58 in. wide and operates at a frequency of 915 MHz.

Once the sensors are installed near the water meters every 500 ft, readings are taken each night and the data are sent for analysis. The network monitoring system then computes a leak index for each MLOG sensor and assigns a leak status as either: no leak; possible leak; probable leak; or out of status. Next, a communication module generates reports to direct leakage investigations and pinpointing activities. See Table 3-22 for more information on the MLOG™ technology.


**Figure 3-15. Picture of MLOG™ (Courtesy of www.itron.com)**

**Table 3-22. MLOG™ Technology**

| | |
|---|---|
| Name | MLOG™ |
| Purpose/Scope | Continuous monitoring and leak detection for water distribution systems |
| Status | Developed by Flow Metrix and commercially available from Itron |
| Source of information | www.itron.com/na/productsAndServices/Pages/MLOG.aspx?market=water<br>Hughes, 2011; |
| Advantages | • Can help reduce water loss in the distribution system.<br>• Can optimize system maintenance by locating pipeline leaks.<br>• Can improve effectiveness of water conservation.<br>• Low cost battery with minimum maintenance (battery last 10 or more years) |
| Limitations | • Sensor spacing is limited by metal covered meter pits (up to 100 ft) and obstructed views (up to 300 ft).<br>• Background noise can create issues in finding leaks. |

American Water has successfully piloted the MLOG technology at multiple locations including Connellsville, PA in 2005 where the non-revenue water was reduced from 25% to 12% in the first year, resulting in an estimated savings of $175,000 (Malone and Morgan, 2006). New Jersey American Water tested the technology in Irvington, NJ on a system which serves 9,000 customers. American Water largest deployment of MLOGs is California American Water's Monterey system, where 4,100 devices have been installed (Hughes, 2011). MLOG devices were also deployed in Clayton County, GA in March 2008 and the 585 sensors identified 11 leaks in the oldest part of the network, which totalled to a savings of more than 54,662,400 million gallons per year at a production cost of $41,000 (Itron, 2011).

**3.6.5 STAR ZoneScan™**. STAR™ ZoneScan™ (Figure 3-16) is an acoustic leak detection system that is installed on the operating nut of water valves via a magnetic bottom. The system, which can be deployed permanently or temporarily, analyzes noise on water lines at scheduled times to pinpoint the location of leaks. The battery lasts 10 or more years.


**Figure 3-16. Picture of STAR™ ZoneScan™ (Courtesy of www.aclaratech.com)**

**3.6.6 Sahara®.** The Sahara® system uses a hydrophone tethered to an umbilical cable, which travels inside in-service water mains to record leak noises (Costello et al., 2007; Mergelas and Henrich, 2005). A locator beacon can be tracked on the surface, enabling leaks to be marked for excavation and subsequent repair (PPIC, 2006).

Sahara® locates leaks through identifying the distinctive acoustic signals generated by leaks in the pipe wall, the joints or steel welds. The magnitude of the leaks can also be estimated from the acoustic signal (PPIC, 2006). Gas pockets in the pipeline are also detected by their unique acoustic signature. Figure 3-17 shows the Sahara® system in use. See Table 3-23 for more information on the Sahara® system.

A video and lighting sensor is also available on the Sahara® platform to provide CCTV inspection of in-service potable water pipelines. Wastewater force mains have also been successfully inspected by flushing the line with clean water during the inspection.

An average wall thickness calculation across a set interval of pipe (typically 30 ft) can be provided based on speed of sound measurements taken with the Sahara® system (in developmental stage).

The Sahara® sensors are launched into in-service water mains through a launching chamber that is mounted on a 2 in. (50 mm) or larger access hole. A small parachute uses the flow of water to draw the sensor through the pipeline; alternatively, a pre-installed pull-tape can be used to draw the sensor through the line when no flow is available, such as on pre-commissioned pipelines. The sensor is tethered to the surface control unit. The sensory data are displayed in real time.

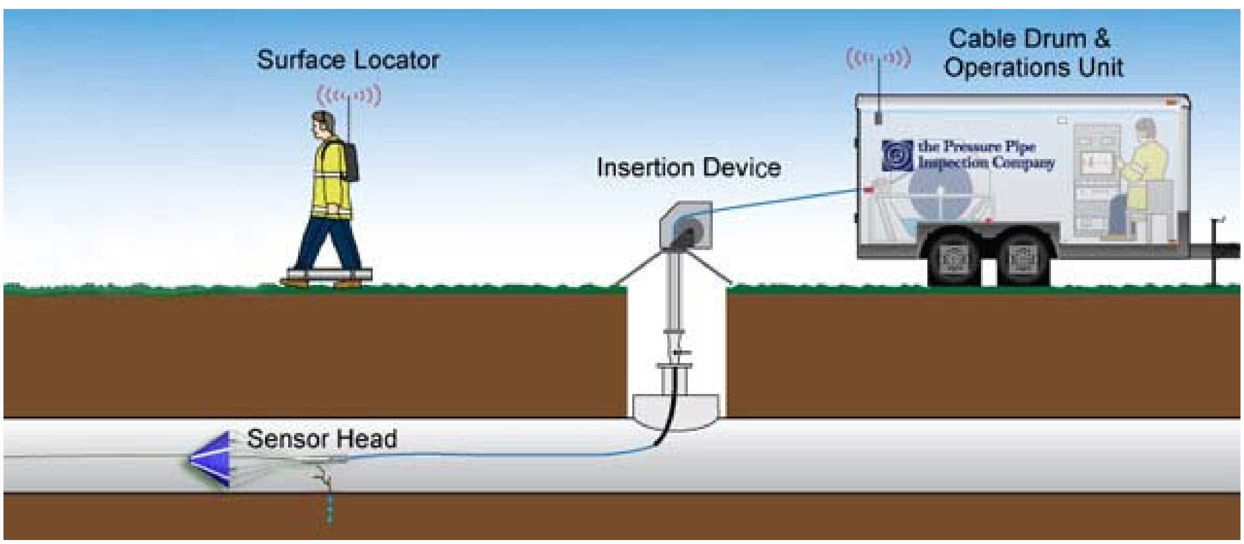



**Figure 3-17. The Sahara® System**
**(Reprinted with permission from PPIC)**

**Table 3-23. Sahara® Leak Detection and Sahara® Condition Assessment**

| | |
|---|---|
| Name | Sahara® leak detection and Sahara® condition assessment |
| Purpose/Scope | Inspect in-service water mains for leaks, gas pockets, visible defects, and wall thickness of metallic pipe (with acoustic technology). |
| Status | Commercially available for leak detection since mid-1990s. First developed by the Water Research Centre (WRc) in the UK. PPIC acquired the worldwide right for Sahara® leak detection in 2008. |
| Source of information | Costello et al., 2007; Mergelas and Henrich, 2005; http://www.ppic.com/services/sahara.shtml |
| Advantages | • Can be used for in-service pipe inspection.<br>• Can use existing 2-in. taps.<br>• Sensitive to small leaks<br>• Surface tracking can map the pipeline under inspection.<br>• Can be used for small mains (4 in.) and equally effective in large diameter mains because of the proximity of the sensor to the leak.<br>• Tether control allows withdrawal of the sensor when unexpected flow conditions are encountered. It also allows extending the listening period at a particular location, if needed. |
| Limitations | • Intrusive technology<br>• Requires access points at a frequency that is determined by bends and flow rates in the pipeline. |
| Performance | • Buried unknown leaks as small as 0.25 gal per hour have been successfully located.<br>• The accuracy of locating a leak is generally less than 1 m (40 in.). |
| Breadth of use | The Sahara® system is used for detecting leaks, pockets of trapped gas, and structural defects in large mains. In 2007, Sahara® live CCTV inspection was introduced to the market. It was also reported that the Sahara® in-line platform had been used to identify wall thickness loss levels of a 48 in. cast iron pipe. |
| Other information | The potential for using the Sahara® system as a platform for other sensors is being explored. |

## 3.7 Ultrasonic Testing

Ultrasonic testing (UT) is carried out by sending high frequency sound into the object under inspection and analyzing the received echo. UT has been widely applied for thickness measurements, corrosion monitoring, delamination checks, and flaw detection on forgings, castings, and pipes.

**3.7.1 Guided Wave Ultrasonic Testing.** The guided wave ultrasound technique is based on the capability of propagating waves for a long distance (Rose et al., 2008). Depending on the type of guided wave, the number of transducers can range between two and four. Torsional waves require two transducers, while longitudinal waves require three to four transducers. Torsional or longitudinal guided waves are induced into the pipe and propagated along the length of the pipe segment. A torsional wave system can be used in pipes filled with water, while the longitudinal system cannot. In a longitudinal system, three transducers can only operate on a single frequency. Multiple frequencies can be applied if four transducers are used; this arrangement leads to an improved inspection result.

When these guided waves meet an anomaly or pipe feature, waves reflect back to the transducer's original location. The time-of-flight for each signature is calculated to determine its distance from the transducer. The amplitude of the signature determines the size of the defect. See Table 3-24 for more information.

A probe in the form of a ring array of piezoelectric transducers is clamped around the pipe and an ultrasound is sent simultaneously in both directions along the pipe. The acquired signal is similar to conventional UT A-scans. The horizontal axis represents the distance along the pipe while the vertical axis represents signal magnitude, which can be used to characterize metal loss due to corrosion. This technique is suitable for pipes above 50 mm (1.97 in.) in diameter and wall thicknesses up to 40 mm (1.57 in.). Inspection for an elevated pipe can be conducted for a range of up to 30 m (98.4 ft) in either direction from a specific spot where the probe is placed. This technology is generally applicable to steel and iron pipe materials. Trials of guided wave systems on steel water mains are described in Reed et al. (2004). For CI and DI pipe, the most prominent pipe feature is the bell and spigot joint, which would reflect the propagating wave and therefore limit the inspection to one pipe length for external inspection tools. The U.S. EPA is sponsoring a grant to research the use of ultrasonic guided waves (using in-situ magnetostrictive sensors) to establish the feasibility for buried water pipe inspection. Magnetostrictive sensors are an alternate configuration of this technology as presented in Section 3.13. The types of pipe being tested in this research grant are steel and CI (with cement mortar lining). Both an external tool and an internal tool (to scan the entire pipe length from the inside) are being tested. The use of an internal tool that travels through the pipe would potentially help to overcome the attenuation of the signal at pipe joints (FBS, 2011).

**Table 3-24. Guided Wave Ultrasonic Testing**

| | |
|---|---|
| Name | Guided wave ultrasonic testing (continuous ultrasonic measurement) |
| Purpose/Scope | Implement rapid screening of pipes for material loss due to corrosion/erosion. |
| Status | Commercially available from many vendors and consulting companies. |
| Source of information | Rose et al., 2008; Marlow et al., 2007; Moore, 2007 |
| Advantages | • Inspection from a single probe position is possible. The initial screening only needs exposure of a small section of buried pipe to attach the probe.<br>• It is also possible to inspect hidden structures under coating, insulations and concrete. |
| Limitations | • The range of inspection is limited to 30 m (98 ft) for aboveground pipe with continuous joints. It has been applied to buried pipes, but with an even shorter range of inspection due to the rapid attenuation of the signals.<br>• Pipes with bell and spigot joints will limit the range of inspection to one pipe segment for external inspection.<br>• It is not applicable to heavily coated pipes due to wave attenuation.<br>• It cannot distinguish between internal and external corrosion. |
| Performance | Sensitivity can be as good as 1% loss of cross-section in ideal conditions (but is typically set at 5%). |
| Breadth of use | The guided wave system was originally designed for use on above-ground exposed or insulated pipes. |
| Other information | Electromagnetic acoustic transducer (EMAT) is a couplant-free transducer based on a different physical principle (Marlow et al., 2007). It generates ultrasound waves in electric conductive materials by Lorentz force known as the electro-magnetostrictive effect (Marlow et al., 2007). It can provide relatively consistent results in comparison to piezoelectric transducers.<br>The labor cost to perform guided wave ultrasonic inspections is expected to be the major cost. Equipment costs are estimated to range from $1,000 to $10,000 (Jolley et al., 2010; Marlow et al., 2007). |

**3.7.2 Discrete Ultrasonic Measurement.** Discrete ultrasonic measurement transmits a high-frequency short wave through a couplant to the material being tested (Figure 3-18). The wave can be generated by several methods, including piezoelectric ceramics, electromagnetic acoustic transducer, magnetostrictive sensor, laser and piezoelectric polymers. The waves propagate to the back wall of the specimen and are reflected back towards the transducer. Transit time is recorded and used in combination with the velocity of the wave propagating in the material to compute the travel distance of the wave. Materials with known thicknesses are used to calibrate the sensor.

A typical UT system consists of a pulser/receiver, transducer, and display unit. Driven by the pulser, the transducer generates a high frequency ultrasonic energy that propagates through the materials in the form of waves. When an object is encountered in its path, part of the energy is reflected back from the object's surface. The reflected wave is transformed into an electrical signal, from which information on the reflector's location, size, orientation, and other features is inferred.

Types of ultrasonic system displays include:

- A - scan: discontinuity depth and amplitude of signal;
- B - scan: discontinuity depth and distribution in cross sectional view;
- C - scan: discontinuity distribution in plane view.

Operation may need extensive skill and training. The UT inspection for pipe can be done both externally and internally. Usually, UT inspection needs couplant or water to transmit the wave between the transducer and the pipe wall. However, the EMAT does not need couplant. See Table 3-25 for more information on discrete ultrasonic measurement.

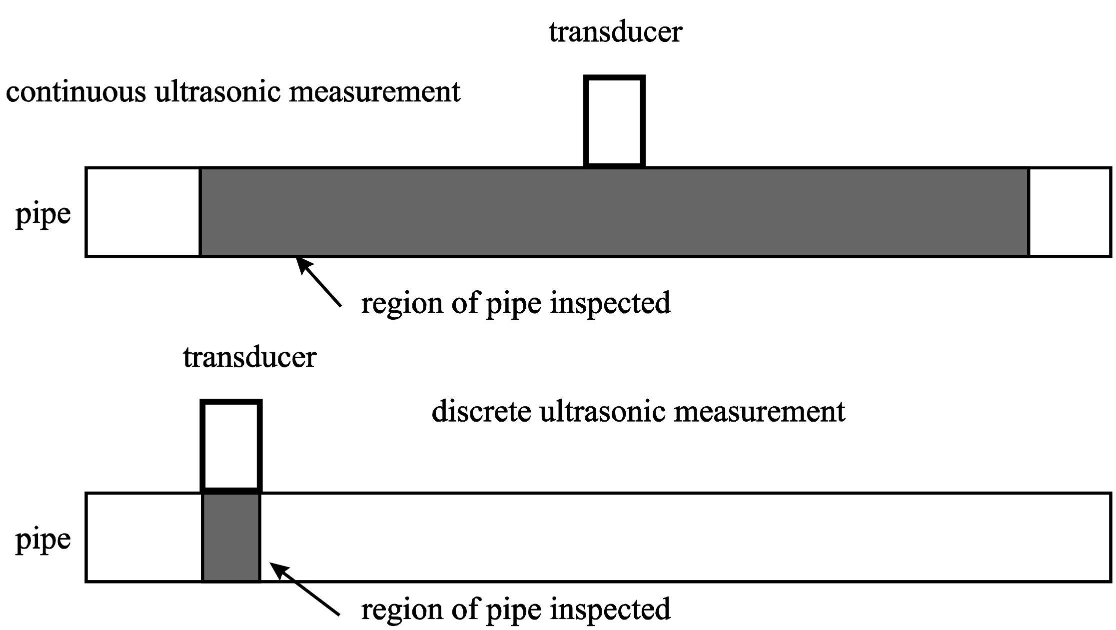



**Figure 3-18. Continuous and Discrete Ultrasonic Measurement**

**Table 3-25. Discrete Ultrasonic Measurement**

| | |
|---|---|
| Name | Discrete ultrasonic measurement |
| Purpose/Scope | Used externally or internally for screening of pipes for corrosion/erosion at discrete locations. |
| Status | Commercially available from many companies, for example GE Inspection Technologies, Olympus NDT, etc. |
| Source of information | Crouse, 2009; Moore, 2007; Marlow et al., 2007 |
| Advantages | • Sensitive to both surface and subsurface discontinuities<br>• Provides instantaneous results.<br>• Probes of different sizes and frequencies are available for different applications.<br>• Supply shutdown is not necessary when using external tools. Water can be the coupling medium. |
| Limitations | • Surface of object to be inspected must be accessible.<br>• Coupling medium is required.<br>• Difficult to inspect materials that are rough, irregular in shape, or not homogeneous, such as concrete<br>• CI and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.<br>• Calibration is required.<br>• Requires pipe cleaning prior to inspection. |
| Performance | Can achieve a reasonable degree of accuracy for the remaining wall thickness measurement. |
| Breadth of use | Used for thickness measurement, corrosion monitoring, delamination checks, and flaw detection in welds, forgings, castings, and ferrous pipes. |
| Other information | UT is relatively inexpensive for conventional applications. Manual discrete ultrasonic testing is estimated to cost $1,200 per day with an inspection rate of 200 ft per day. Ultrasonic pigs for pipeline inspections are expensive (Jolley et al., 2010). |

**3.7.3 Phased Array Technology**. Phased array ultrasonic has been used for medical imaging for over 20 years and has recently been adapted for industrial applications. An array transducer contains a number of individual sensor elements in a single package. With phased array technology, it is possible to detect wall thickness, corrosion, or cracks with one multi-element transducer. The phased array transducer is built up of composite sensor elements that are controlled individually by the ultrasound electronics (Bosch et al., 2004). The sound beam and its direction are determined by the time sequencing of the individual sensor elements. The sound beams are formed by shifting the phase of the signal emitted from each radiating sensor element. Constructive interference of the waves amplifies the signal in the desired direction, while destructive interference of the waves improves the sharpness of the sound beam.

Phased arrays use an array of sensor elements, all individually wired, pulsed, and time shifted (Moore, 2007). The elements can be organized as a linear array, a two-dimensional matrix array, a circular array or in more complex forms. Any set of sensor elements can be used as a virtual sensor. For a wall thickness measurement, all of the elements are triggered simultaneously and a sound beam perpendicular to wall surface is generated (as illustrated in Figure 3-19). For crack detection, the neighboring elements are triggered with a certain time shift from element to element and an angular sound beam is generated (as illustrated in 3-19). See Table 3-26 for more information on the phased array technology. Phased array ultrasonic technology has been used in the nuclear industry to inspect coarse grained stainless steel materials, where conventional UT methods were found to have significant limitations.

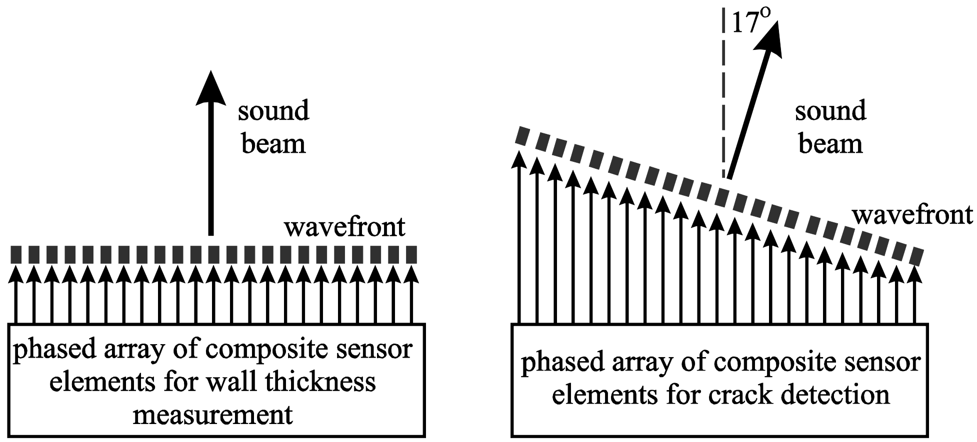



**Figure 3-19. Sound Beams Generated by Phased Array of Composite Sensor Elements (after Bosch et al., 2004)**

**Table 3-26. Phased Array Technology**

| | |
|---|---|
| Name | Phased array technology |
| Purpose/Scope | Phased array technique offers significant technical advantages over conventional single-probe UT: the phased array beams can be steered, scanned, swept, and focused electronically. |
| Status | Commercially available from Olympus NDT and GE Inspection Technologies; application to water mains not reported. |
| Source of information | Bosch et al., 2004; Moore, 2007; http://www.olympus-ims.com/en/ndt-tutorials/phased-array/ |
| Advantages | • Scanning is faster than single probe.<br>• Scanning can be done from different angles to obtain a better understanding of the geometry of defects.<br>• A wide variety of test angles can be used to distinguish complex defect types. |
| Limitations | • Cost may be higher than single-channel systems.<br>• Setups for three-dimensional applications are complex. |
| Performance | Phased array technique can optimize discontinuity detection while minimizing test time. |
| Breadth of use | Used in a wide variety of industries including aerospace, nuclear power plants, steel mills, pipe mills, petrochemical plants, and pipeline construction. Inspection of water mains with the phased array technique has not been reported. |
| Other information | Phased array technique is undergoing further development. |

**3.7.4 Combined UT Inspection.** A combined UT technique, which can simultaneously quantify metal loss and detect cracks, was reported by Beller and Barbian (2006). This technique uses a newly designed and optimized sensor carrier to perform both inspections in a single run. A sufficient number of UT sensors are placed to cover the pipe circumferentially. These sensors work in a pulse-echo mode with a high repetition frequency. Straight incidence of the ultrasonic pulses is used to measure the wall thickness and 45° incidence is used for the detection of cracks (Beller and Barbian, 2006). This is a pigging technology developed for oil and gas pipelines.

## 3.8 Seismic Pulse Echo

The seismic pulse echo technique uses impact from a metal sphere to generate ultrasonic compression, shear, and surface waves in the pipe wall. The combination of wave velocity and thickness resonance values can be used to determine the condition of the pipe.

A sensor array is used to pick up the response signals. From the recorded data, multiple measurements can be carried out, including the compression and shear wave velocity and resonant frequencies. The wave transmission velocity can be measured directly from the energy point of impact to the sensors at distances larger than the thickness of concrete being tested (Fisk and Marshall, 2006). Reflectors are measured individually or by examining the resonant frequency contents. Resonant frequency values are used to identify thin areas where the mortar coating is delaminated or missing. Loss of resonant frequency is an indication of micro-cracking and weakening of the core concrete as a result of prestressed wire breaking, poor manufacturing, or overloading (Fisk and Marshall, 2006). Low velocity is an indication of weakening of the core concrete.

The system typically consists of an energy source, an array of sensors, signal conditioner, analog to digital converter and a computer. The data acquired are a time-distance recording of the amplitude of a stress wave produced by a projectile impact. Data are recorded by an array of four sensors spaced approximately 1 foot apart. The data are interpreted by determining the time required for the compression and shear wave to travel to each sensor and then calculating average wave velocities given the known distances between the sensors. Fourier analysis is conducted on the time series to determine frequency content and resonances. See Table 3-27 for more information on the seismic pulse echo technique.

**Table 3-27. Seismic Pulse Echo**

| | |
|---|---|
| Name | Seismic pulse echo |
| Purpose/Scope | Seismic pulse echo is also known as the sonic/ultrasonic technique for evaluation of PCCP. This technique is used to assess the condition of PCCP by determining the strength of the core concrete. |
| Status | Commercially available (from NDT Corporation). |
| Source of information | Fisk and Marshall, 2006; Communications with Paul Fisk; Wardany, 2008; http://www.ndtcorporation.com/ |
| Advantages | • Can be conducted either from inside (dewatered) pipes or from outside (in-service) pipes. Repeating measurements at a later date provides two data sets in time to determine the deterioration rate (if any) of each pipe section.<br>• Inspection is not affected by overlying coatings or wearing surfaces. |
| Limitations | • The inspection of long distances is time consuming. The test is very local in nature.<br>• Skilled operators are required for field inspection. |
| Performance | The accuracy for the detection of PCCP broken wires is not known (Wardany, 2008). |
| Breadth of use | The results of sonic/ultrasonic testing provide baseline current condition and deterioration rate data to prioritize repair and developing a management program for large diameter PCCP lines. This technique inspects the strength of the core concrete and determines whether the pipe is acting as a composite structure. This technology can also be used to test the exterior of wastewater pipe for hydrogen sulfide corrosion. Applications have also been found in bridge deck evaluations. |
| Other information | Not available |

## 3.9 Pipeline Current Mapper

Pipeline current mapper (PCM) is a technology intended to locate leakage of electrical current in cathodically protected pipes. These leakages typically correspond to phenomena such as coating faults, shorts due to connection to other metallic structures, etc. CP is a technique to arrest/limit corrosion. It can be used for any metallic structure, including buried pipes, where it is often used in conjunction with external coatings for the protection of sensitive pipelines. In North America, CP is used heavily for oil and gas pipelines and to a much lesser extent in water mains (Radiodetection, 2002).

The PCM system consists of a portable transmitter and a handheld receiver. The transmitter applies a special near direct current (DC) signal to the pipe under investigation. Direct contact is required between the transmitter and the pipe. The receiver is carried along the pipe above ground, reading the transmitted signal remotely, and identifying the position and depth of the pipe, as well the magnitude and direction of the protective CP current. These readings are interpreted to identify deteriorated coating, specific coating faults and possible cross-connections with other metallic structures (Radiodetection, 2002). In a network where all (or most) pipes are electrically continuous, this technique provides fast location of potential problems while minimizing excavation.

## 3.10 Radiographic Testing

Radiographic testing uses a source of radiation, either gamma or x-rays, which passes through the material and onto a photographic film (see Table 3-28). The density changes on the film indicate possible imperfections. Nowadays, digital cameras have been used to replace film, but are limited by the size of the complementary metal oxide semiconductor (CMOS) photodiode array in the image sensor. Gamma rays emitted from isotopes are used for ferrous and cementitious materials. X-rays created by cathode-ray tubes are used for plastic materials. Details of the material structure can be seen on the radiograph and darker areas correspond to thinner or less dense material. It has technical limitations in that pipes of 38.1 cm (15 in.) inside diameter and greater must be emptied. Typical defects that can be detected include:

- Pits in ferrous materials. Corrosion byproducts are less dense and appear darker on the radiograph.
- Voids in cementitious materials.
- Inclusions or manufacturing voids.

There are basically three setups for radiographic testing as illustrated in Figure 3-20. Gamma or x-rays are used to penetrate a weld, valve, or pipe wall to create a latent image on a radiographic film. The radiation can pass through a single object onto the film (single wall-single image) or it can pass through two sections of the pipe wall onto the film (double wall–single image). The third configuration is referred to as double loading where two films of different speeds are used (one fast film and one slow film) to document the condition of two adjacent objects between the film and source. For the same exposure period, the slow film records the features of the first object closest to the source, while the fast film records the features of the second object (Randall-Smith, 1992).

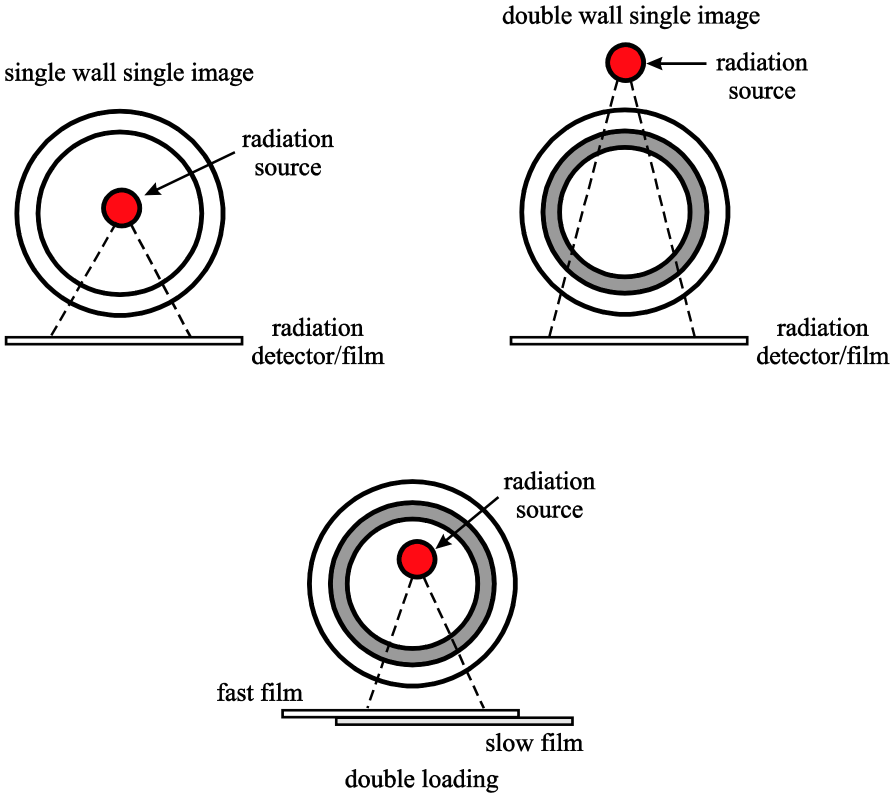



**Figure 3-20. Radiographic Testing**

**Table 3-28. Radiographic Testing**

| | |
|---|---|
| Name | Radiographic testing |
| Purpose/Scope | Show variants and thickness changes in material and structures, also applicable to inspection of valves. |
| Status | Commercially available |
| Source of information | Marlow et al., 2007; Galbraith et al., 2009; http://www.yxlon.com |
| Advantages | Can be applied to most materials. |
| Limitations | • The setups in Figure 3-20 may not be practical for field inspection of buried pipes.<br>• Examines only a small area at a time.<br>• Access is required to both sides of the inspected object.<br>• Radiation safety issues exist and inspection requires specialist operators. |
| Performance | • Can provide accurate measurements, but experience is required to interpret the inspection results. |
| Breadth of use | Radiography has been introduced to the water sector to examine pipe conditions and valves in situ. In the U.S., it is used widely in petrochemical processing plants, but also on water mains outside the U.S. |
| Other information | A recent development is the x-ray backscatter technique, which does not require film on the other side of the inspected object. This technology is currently being applied to thin structures, such as aircraft lap joints. No application on pipes is reported. |

### 3.11 Thermographic Testing

Thermographic testing is a non-contact method of detecting thermal anomalies (see Table 3-29). Infrared radiation has a longer wavelength than visible light (>700 nm). Any object above 0°K radiates infrared energy and the amount of radiated energy is a function of the object's temperature and emissivity, which is a measure of the surface efficiency in transferring infrared energy. Areas with different thermal masses have different rates for heat absorption and radiation.

The infrared radiation is converted into a visible image and objects under test can be viewed on the basis of their heat emission. In thermographic testing, an external heat source is typically used to heat the inspected object. Subsequently, the object's cooling characteristics are monitored by an infrared camera and these characteristics are then interpreted to provide object properties (Crouse, 2009). Varied active thermographic testing methods have been developed for different applications. These methods include pulse thermography, stepped heating thermography, lock-in thermography, and vibro-thermography.

**Table 3-29. Thermographic Testing**

| | |
|---|---|
| Name | Thermographic testing |
| Purpose/Scope | Detect material loss of relatively thin structures. |
| Status | Commercially available. |
| Source of information | Crouse, 2009 ; Marlow et al., 2007; http://www.flir.com |
| Advantages | • Allow rapid scanning of objects;<br>• No direct contact and intrusion is required;<br>• The thermographic system is easy to operate. |
| Limitations | • In order to identify the anomalies, a temperature difference is necessary. |
| Performance | The infrared sensor is sensitive and reliable. |
| Breadth of use | Thermographic testing has been used for leak detection of oil pipelines and many other applications. Its use for water mains has been limited to less accessible water pipes (Thomson and Wang, 2009). |
| Other information | Not available |

### 3.12 Using Soil Properties to Infer Pipe Condition

**3.12.1 Linear Polarization Resistance of Soil.** An electrochemical reaction with a weak electrical current is produced when a metal is immersed in an electrolyte solution, which leads to the corrosion of metal. The rate of corrosion is directly proportional to this current and inversely proportional to the electrical resistance (polarization resistance) of the metal/electrolyte pair. The direct measurement of corrosion current in the soil (electrolyte) is very difficult. Instead, it can be inferred by imposing a weak electrical potential (10 to 20 mV) between two electrodes. This potential produces small currents that are linearly proportional to actual corrosion current. The ratio between the imposed electrical potential and the resulting current provides the property known as the polarization resistance which, at low potential values, is nearly linear to the corrosion current.

Several methods are available to measure linear polarization resistance (LPR) in order to estimate corrosion rate. In the lab, a soil sample is brought to its wilting point and a small potential is subsequently applied across two identical electrodes in a cell containing the prepared soil sample. The current at each electrode is measured over a range of potentials. The resulting relationship between current and applied potential is called the polarization curve. LPR is independent of the corrosion potential of a specific metal in the soil (Marlow et al., 2007). This technique allows the assessment of corrosion rate in real time. It should be noted that lab-assessment of LPR to predict corrosion rate of water mains is common mainly in Australia, where it is believed that soil moisture at wilting point is a good approximation for long-term soil moisture (hence, no correction is made in the analysis for ‘true’ soil moisture [Ferguson, 2010]). It appears that more research might be needed to ascertain this assumption, especially if lab-LPR is to be adopted outside of Australia. Portable LPR instruments are commercially available from several companies, including Metal Samples Corrosion Monitoring Systems, Caproco, Rohrback Cosasco Systems, Inc. (Figure 3-21) and others. Multiple readings can be taken at different locations to check the consistency of the soil corrosivity. For the device shown in Figure 3-21, two carbon steel electrodes are contained within a single probe head, which has a pointed tip that is used to facilitate pushing the probe head into the soil.


**Figure 3-21. Corrater® Aquamate™ Portable Instrument with Soil Corrosion Rate Probe (Reprinted with permission from Rohrback Cosasco Systems, Inc.)**

**3.12.2 Soil Characterization.** Soil characterization is used to explore the soil parameters relevant to the deterioration of buried pipes. Samples from the locations near the pipe are collected for lab characterization or in-situ testing. The following is a list of the main soil parameters of interest (Marlow et al., 2007):

(a) Soil resistivity: Low resistivity is likely to have high corrosion rates.

(b) pH value: Low pH value (pH <4) is generally associated with corrosion of ferrous materials and deterioration of cementitious materials. However, high alkalinity soils (pH > 8) can also lead to corrosion of metallic pipes as well as the prestressing wire and steel cylinder in PCCP.

(c) Redox potential: The redox potential of soil is a measure of soil aeration and provides an indication of the suitability of conditions for sulfate reducing bacteria. High availability of oxygen promotes MIC in the presence of sulfates and sulfides.

(d) Sulfates: Sulfates react with cementitious materials, forming gypsum and ettringite. Sulfate attachment only occurs where the sulfate salts are in solution.

(e) Chloride content: chloride ions in moist soil act as electrolyte and reduce soil resistivity, which encourages corrosion in CI and DI pipes, where the metal is in contact with the soil. In the case of PCCP, if there are cracks in the outer mortar layer, ingress of chlorides in the presence of oxygen will promote corrosion in the prestressing wire and steel cylinder.

(f) Moisture content: Soil moisture acts as the electrolyte in electrochemical corrosion of ferrous pipes. It also defines the degree of soil saturation.

(g) Shrink/swell capacity: High shrink/swell capacities are known to have an increased failure rate due to the stresses imparted by the soil during the shrink/swell cycle.

(h) Buffering capacity: A soil's buffering capacity is the degree to which it is able to resist changes in pH in particular acidification.

(i) LPR: High LPR indicates low corrosion rates. The corrosion rate can be roughly estimated from LPR measurements.

(j) Contaminants: Soil contaminants can have negative effects on polymeric materials. High levels of acidic constituents can also cause environmental stress cracking of polymers, dramatically reducing lifetime.

(k) Soil compaction: The susceptibility of the trench filling and the surrounding sediments for compaction.

Soil corrosivity is not a directly measurable parameter and there is no explicit relationship between the soil corrosivity and pipe deterioration rate. Consequently, Table 3-30 provides a number of empirical approaches that have been proposed in the literature to consider some or all of the above listed parameters in the determination of soil corrosivity and potential pipe deterioration.

**Table 3-30. Comparison of Soil Corrosivity Rating Approaches Based on Soil Properties**

| Methods | Factors | Classification Results | Corrosivity Potential | References |
|---|---|---|---|---|
| 10-point scoring method | resistivity, pH value, redox potential, sulfide, and soil type | Binary | Corrosive or non-corrosive | AWWA, 1999 |
| 12-factor evaluation | Soil type, soil resistivity, water content, pH value, buffering capacity, sulfide, chloride and sulfate concentration, groundwater level, horizontal and vertical soil homogeneities, and electrochemical potential | Four categories | Highly corrosive, corrosive, slightly corrosive, virtually not corrosive | Metalogic, 2003 |
| 25-point scoring method | pH value, sulfate content, redox potential, soil type, resistivity, sulfides, moisture, pipe size, pipe maximum design surge pressure factor, pipe minimum design life factor, pipe location and leak repair difficulty factor, potential interference sources, pipe zone back fill materials, and additional factors to consider. | Four categories | Mildly corrosive, moderately corrosive, appreciably corrosive, severely corrosive | Spickelmire, 2002 |
| Fuzzy-based method | Same as in 10-point scoring method | Three categories | Non-corrosive, moderately corrosive, corrosive | Sadiq et al., 2004 |
| Fuzzy inference | Same as in 10-point scoring method | Numerical value between [0,1] | Non-corrosive = 0 and most corrosive = 1 | Najjaran et al., 2006 |

**3.12.3 Pipe to Soil Potential Survey.** Pipe-to-soil potential reflects the interaction between ferrous pipes and the surrounding soil. The measurement can be done with a voltmeter and a reference electrode (Marlow et al., 2007). There are two types of pipe potential survey. The first is the direct current voltage gradient (DCVG) survey that can be used to determine the location of gaps in a pipe's protective coating. A DC is introduced to the pipe and the difference between two reference electrodes is measured in the pipe-to-soil voltage. The two electrodes are gradually moved along the whole length of the pipe. If a gap exists in the coating, there will be a significant increase in voltage gradient compared with the gradient found when the coating is intact. The second type of potential survey consists of using a single reference electrode ($Cu/CuSO_4$) without an imposed current to determine the pipe-to-soil potential along the pipe. The pipe-to-soil potential can be used to estimate corrosion rate with calibration data. Calibration is carried out by directly assessing the external conditions of mains in different soils. The soil is sampled every 50 or 100 m and sections of the main located in different soil types are then exposed and their external condition directly assessed to relate this information to a pipe-to-soil potential value. It should be noted that the potential survey reflects a propensity for corrosion rather than actual corrosion.

## 3.13 Emerging Sensor Technologies and Sensor Networks

Advances in electronics, sensor technology, information science, electrical and computer engineering give rise to emerging technologies and some of these advances could be applied to the inspection, monitoring, and condition assessment of buried water mains. The applicability to buried pipes of the emerging sensors described here has not yet been fully verified in the field.

In addition, the growing use of sensor networks (some of which are already commercially available) and multi-sensor approaches may also improve the prospects for real-time data acquisition and monitoring for water mains. Several examples of sensor networks are discussed below.

Tables 3-31 to 3-40 provide detailed technology information for emerging sensors, sensor networks, and multi-sensor approaches.

**3.13.1 Corrosion Rate Sensor.** The corrosion rate sensor uses the electrical resistance (ER) technique, which is one of the most widely used methods to measure metal loss due to corrosion in buried DI pipes (Bell and Moore, 2007). A trench must be dug to expose the surface of the pipe in order to install the sensor. An exposed ferric element in the ground will experience metal loss due to corrosion and consequently see a change (increase) in its electrical resistivity. The ER method compares this change to a sealed reference element (Khan, 2007). The probe is typically placed in close proximity to the exposed element of interest so that this element is subjected to exactly the same temperature as the reference element (metal resistivity is affected by temperature).

It is not practical to use an entire pipe as the exposed element. Consequently, a coupon from the pipe of interest (or a coupon of the same type of material) is used (Figure 3-22). This type of probe can also measure the effectiveness of pipe cathodic protection by measuring the metal loss (in terms of electrical resistivity) of a coupon that is cathodically protected. The exposed element doesn't need to be a metal coupon. It can also be the soil in the vicinity of a structure (pipe) of interest to provide changes in soil resistivity (relative to the reference element). It should be noted, however, that pipes rarely corrode in a uniform manner due to material heterogeneity and soil variability. Therefore, a single sensor is not likely to provide a good representation for the condition of long pipes. Table 3-31 provides more information on the corrosion rate sensor.

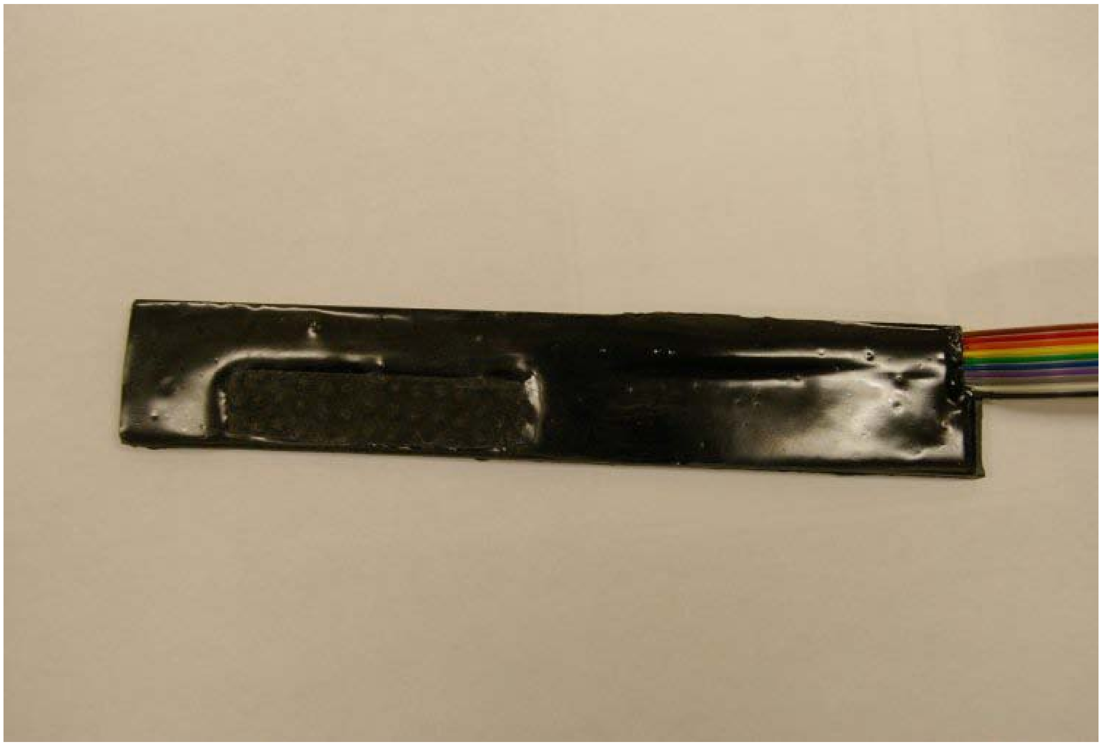


**Figure 3-22. Picture of Corrosion Rate Senor with Embedded Metallic Coupon**

**Table 3-31. Corrosion Rate Sensor (Probe)**

| | |
|---|---|
| Name | Corrosion rate sensor (probe) |
| Purpose/Scope | Measures cumulative corrosion and calculates in-situ corrosion rates for ductile iron pipes (as referenced to an embedded ductile iron coupon). |
| Status | Commercially available. |
| Source of information | Bell and Moore, 2007; Khan, 2007; http://www.tinker-rasor.com |
| Advantages | • Compatible with all standard ER instruments.<br>• Low profile of element makes it easy to install under polyethylene encasement.<br>• End user's calibration is not required. |
| Limitations | • Provides point measurement. Multiple sensors required to provide a good representation for the condition of long pipes.<br>• A period of monitoring is necessary to obtain reliable measurements of corrosion rates.<br>• Not applicable in cast iron pipes or non-metallic pipes. The company does offer a similar sensor with an embedded carbon steel coupon. |
| Performance | The accuracy in corrosion rate measurement has not been verified. |
| Breadth of use | Used for monitoring the corrosion rates of DI pipes. This product is relatively new and has not been widely applied. |
| Other information | Not available |

**3.13.2 Magnetostrictive Sensor.** Magnetostrictive sensor (MsS) is based on the principles of magnetostrictive (Joule) and inverse-magnetostrictive (Villari) effects (Kwun, 1991; Kwun, 2000). The magnetostrictive effect refers to a small change in the physical dimension of ferromagnetic materials caused by an externally applied magnetic field. The inverse-magnetostrictive effect refers to the change in the magnetic induction of ferromagnetic material caused by mechanical stress or strain. The generation and detection of guided waves are based on the Joule and Villari effect, respectively.

MsS typically consists of two magnetic fields. A bias magnet (Figure 3-23) establishes a magnetic field in the pipe and the dimension changes due to magnetostriction. A short-duration pulse is sent to the transmitting coil that produces a magnetic field that opposes the bias magnetization. Then a time-varying magnetic field causes the pipe to change dimension, hence causing an elastic wave pulse (Bartels et al., 1999). The generated waves propagate along the pipe in both directions. When the wave passes by the receiving coil, the magnetic induction changes and an electric voltage signal is induced. The duration of the pulse defines the frequency of the elastic wave, which is often in the ultrasonic range for pipe inspection, on the order of a few hundred kilohertz. This signal is then amplified, filtered, and digitized. There are many magnet and coil configurations for generating elasticity waves in pipe. The magnetostrictive method for wave generation is an alternative to the piezoelectric method presented in Section 3.7.1 on guided wave ultrasonic testing.

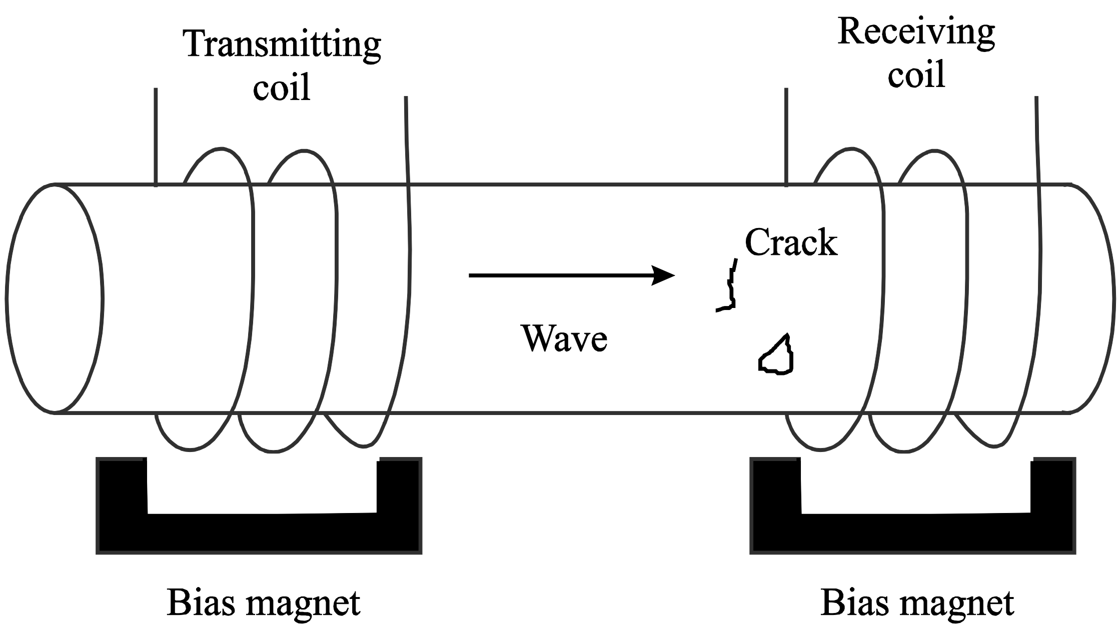



**Figure 3-23. Pipe Inspection with MsS**

Figure 3-24 shows a typical MsS system setup. The MsS device is ring-shaped to encircle the inspected pipe (Kwun et al., 2003). At the transmitting coil, the operation wave mode is controlled by the relative alignment between the DC bias magnetic field and the time-varying magnetic field produced by the MsS. Applicable guided wave modes include: longitudinal, torsional, and flexural wave modes for cylindrical objects. The coil and magnet configuration defines the wave types and are selected to maximize the inspection distance and sensitivity to defects. For longitudinal wave modes in cylindrical objects and Lamb wave modes in plates, a parallel alignment is used. For torsional wave modes in cylindrical objects and shear horizontal wave modes in plates, a perpendicular alignment is used. For buried pipelines, the signal loss into the external coating and soil and internal fluid is prominent. The inspection distance is a challenge and limitation of the guided wave inspection technology. For CI and DI water mains, the bell and spigot joint will reflect the propagating wave limiting inspection to one pipe length for external inspection of pipes with this joint type.

The MsS can be implemented in two modes: survey mode and monitoring mode. With the survey mode, the MsS strips are temporarily attached to a de-insulated pipe. Both inside diameter/outside diameter defects and circumferential cracks (>2% cross-sectional area) can be detected. Once complete, the strips are removed and the pipe section is reinsulated. In the monitoring mode, the MsS strips are permanently bonded to the pipe outside diameter using epoxy-based compounds and protected by a sealed clamshell cover. The survey mode is ideal for aboveground pipes, while monitoring mode is primarily for underground pipes. See Table 3-32 for more information about the MsS technique.

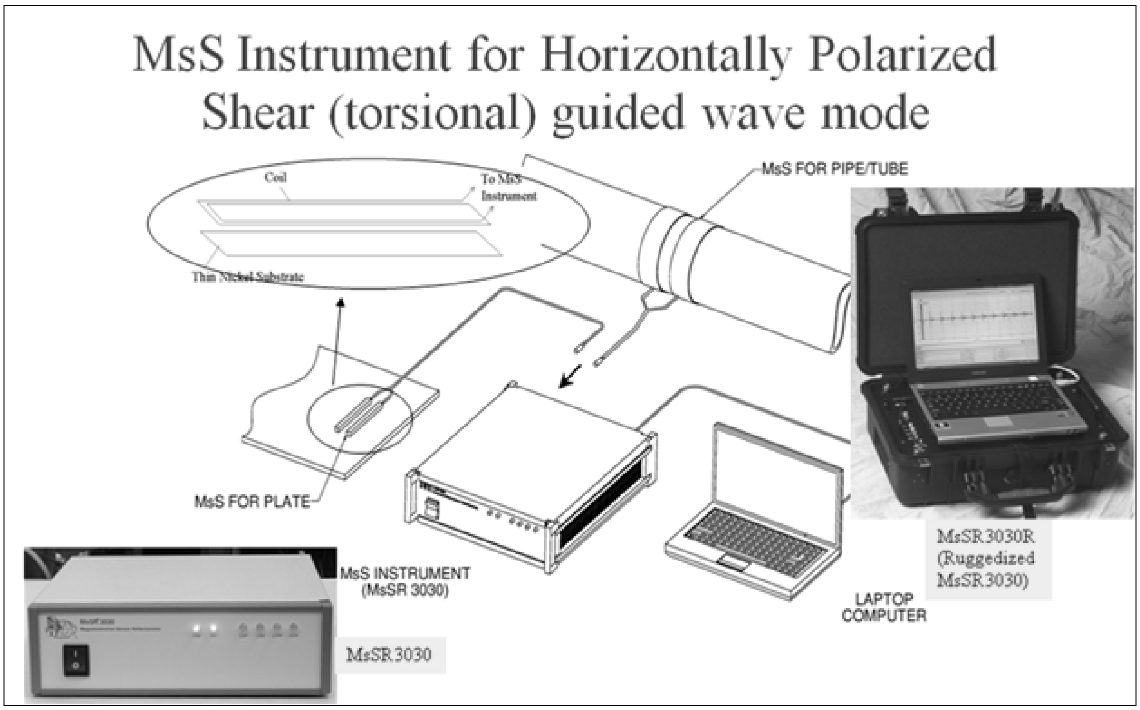



**Figure 3-24. The MsS System for Pipe Corrosion Monitoring (Reprinted with permission from SwRI)**

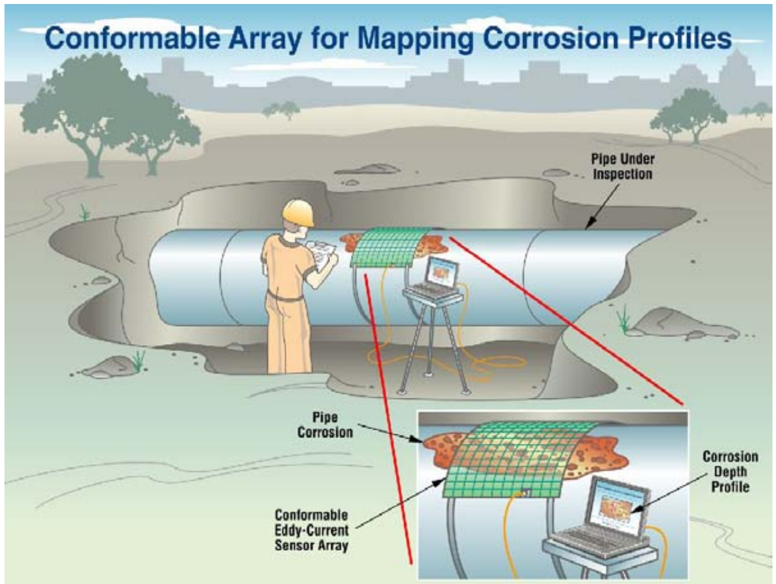
The U.S. EPA is sponsoring a grant to research the use of ultrasonic guided waves (using in-situ magnetostrictive sensors) to establish the feasibility for buried water pipe inspection. Magnetostrictive sensors are an alternate configuration of the guided wave technology that was presented in Section 3.7.1. The types of pipe being tested in this research grant are steel and CI (with cement mortar lining). Both an external tool and an internal tool (to scan the entire pipe length from the inside) are being tested. The use of an internal tool that travels through the pipe would potentially help to overcome the attenuation of the signal at pipe joints (FBS, 2011).

**Table 3-32. Magnetostrictive Sensor**

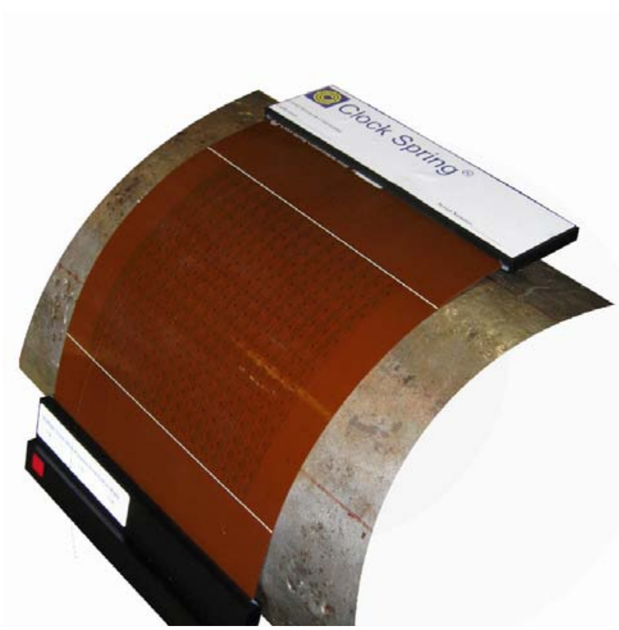
| | |
|---|---|
| Name | Magnetostrictive sensor (MsS) |
| Purpose/Scope | Long-range inspection and structural health monitoring using guided waves. |
| Status | Commercially available from SwRI (http://www.swri.org) |
| Source of information | Kwun, 1991; Kwun, 2000; Bartels et al., 1999 |
| Advantages | • Does not need couplant.<br>• Can be operated with a gap between the sensor and material under test.<br>• Detects both ID/OD wall loss and circumferential cracks.<br>• Low cost sensor for long-term structural health monitoring. |
| Limitations | • Pipes with bell and spigot joints will limit the range of inspection to one pipe segment for external inspection.<br>• Guided wave technology cannot differentiate between ID and OD damage.<br>• Inspection capability past elbows is limited due to the distortion of the shape of the wave.<br>• Coated and buried piping reduces the test range to less than 9.14 m (30 ft). |
| Performance | • Can inspect inaccessible areas from a remote accessible pipeline location to detect erosion, corrosion, and other defects for a full or empty pipeline. Sizes the area of the defect in the radial circumferential plane. Detection of 2 to 5% change of cross-sectional area using the survey mode or 1% using the monitoring mode.<br>• Accuracy of defect location is within 2.5 in.<br>• Test range varies depending on piping condition; up to 500 ft in straight, aboveground piping. There is a limitation for buried pipes because of the rapid attenuation of wave propagation. |
| Breadth of use | MsS relies on magnetostrictive effects, so it is applicable to ferrous materials such as carbon steel, alloy steel, and ferritic stainless steel. For nonferrous materials, the MsS can be operated over a thin strip of ferromagnetic material (such as nickel) bonded to the material. The applications include boiler piping, piping crossing over roads or small streams, and insulated pipes. MsS is currently being investigated for use with buried water mains under a U.S. EPA grant. |
| Other information | Not available |

**3.13.3 Conformable and Flexible Eddy Current Array.** The principle behind the conformable eddy current sensor array is the traditional eddy current theory, i.e., the change of coil impedance (phase and magnitude) reflects the properties of the conducting object under test. For the pipe pitting measurement, the displacement between the eddy current probe and bottom of the pit is detected by using an eddy current probe (Crouch and Goyen, 2003).

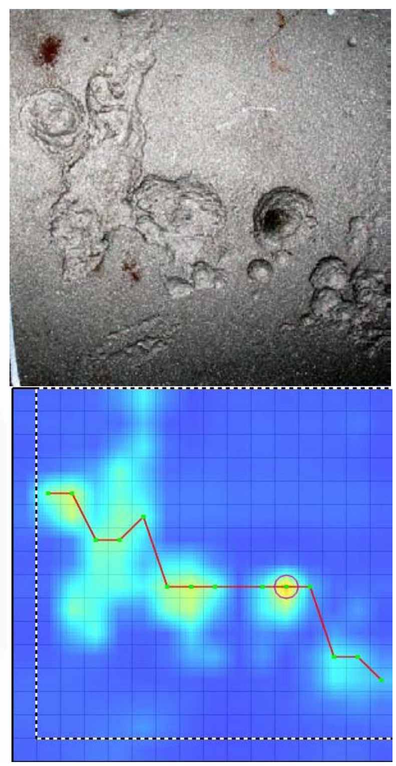
The conformable array was designed to transform discrete measurements into a two-dimensional scan (image). A picture of such an array (implemented with the flexible printed circuit board technology) is shown in Figure 3-25. Similar technology was reported by (Chen and Ding, 2007). The conformable array can be easily adapted to the surface curvature of pipes, however, this entails excavation and cleaning to expose the bare pipe. Table 3-33 provides more information about conformable and flexible eddy current array technique.




(a)




(b)



(c)

**Figure 3-25. (a) Inspection of Pipeline with Flexible Eddy Current Array, (b) the Sensor Array, and (c) Samples of Inspection Results (Reprinted with permission from Clock Spring)**

**Table 3-33. Conformable and Flexible Eddy Current Array**

| | |
|---|---|
| Name | Conformable and flexible eddy current array |
| Purpose/Scope | Generate contour map of corrosion, which identifies the depth and location of the deepest pit. |
| Status | A prototype was developed at SwRI and passed a field test (Anna, 2004). |
| Source of information | Anna, 2004; Crouch and Goyen, 2003 |
| Advantages | • No special apparatus is needed for the scanning.<br>• Does not require sandblasting, but the cleaner the pipe surface, the better the depth measurement.<br>• The measurement system can be easily operated. |
| Limitations | • There is limitation in pit depth measurement. Improvement is needed for measuring deeper pits.<br>• There are limits to sensor density.<br>• Pipe has to be excavated.<br>• Measurement is local. |
| Performance | • The typical accuracy of depth measurement is: ±0.020 in. (0.50 mm). The scan area is about 6 by 6 in. (152 by 152 mm) (single scan).<br>• The eddy current response is non-linear and sensitive to liftoff. Any material that creates liftoff appears to have a great depth. Coating left on the pipe causes liftoff and results in higher depth readings.<br>• The deepest pit and smallest (in diameter) pit that can be measured are not known. Extra care is suggested to verify depth above 0.250 in. The measurement variation becomes large for depth above 0.300 in.<br>• Pit diameter less than 0.250 in. can result in low depth measurements (this depends on proximity to a coil). |
| Breadth of use | The conformable eddy current array targets the gas transmission pipelines and is designed for hands-on use by field technicians at spots of interest. |
| Other information | Not available |

**3.13.4 Flexible Ultrasonic Transducer.** The flexible ultrasonic transducer (FUT) consists of a metal foil, a piezoelectric ceramic film, and a top electrode. Top electrodes can be fabricated of silver or platinum paste, while the metal foil (e.g., stainless steel) serves as both the substrate and bottom electrode. The porosity of piezoelectric film and the thinness of metal foil provide this sensor with sufficient flexibility for application to curved and irregular surfaces (Figure 3-26). FUT can be easily formed into an array by placing many electrodes into a desired configuration.

This type of transducer operates in the pulse-echo (i.e., the subject of interest needs to be excited by an external source of energy), transmission and pitch-catch modes. They can be used as phased array for fast electronic scanning and imaging. Table 3-34 provides more information about the flexible ultrasonic transducer.

**3.13.5 Damage Sensor.** The damage sensor is a combination of distributed electrochemical impedance spectroscopy (EIS) and time domain reflectometry (TDR). The EIS measurement provides information about the effectiveness of a coating over a relatively small area. An alternating voltage is applied between corroding material and a reference electrode. The impedance measurement reflects the condition of the pipe coating. Modeling of the EIS system can provide the location and status of flaws in the pipe. More information about the damage sensor is available in Table 3-35.

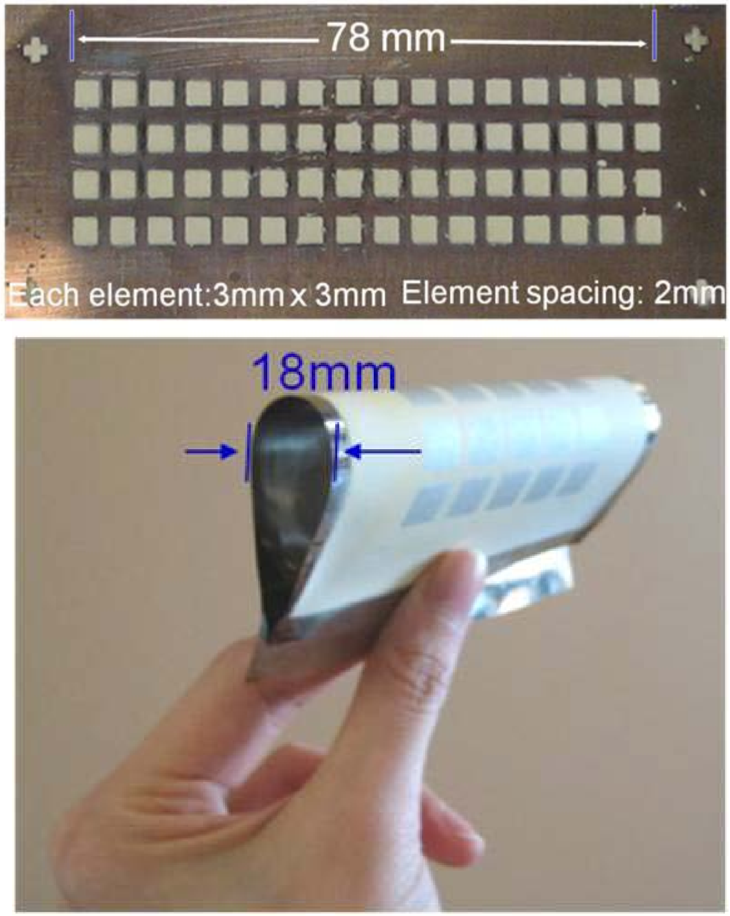



**Figure 3-26. The Flexible Ultrasound Transducer Array**
**(Reprinted with permission from NRC IMI)**

**Table 3-34. Flexible Ultrasonic Transducer**

| | |
|---|---|
| Name | Flexible ultrasonic transducer (FUT) |
| Purpose/Scope | Monitor pipe structural health and perform on-line diagnostics. |
| Status | Available from the NRC's Industrial Materials Institute.<br>License issued for aerospace structural health monitoring applications and being negotiated for power plant and oil and gas industries. |
| Source of information | Kobayashi et al., 2006; Kobayashi et al., 2007; Mrad et al., 2006; Kobayashi et al., 2009 |
| Advantages | • Can operate through a wide range of temperatures (-80°C to 500°C).<br>• Can be self-aligned to object surface with curved or complex geometry.<br>• Can be used to excite and receive guided acoustic waves along pipes to perform long distance defect evaluation.<br>• Can be used to perform electronic scanning and imaging.<br>• Has low cost.<br>• Can be miniaturized.<br>• Can be operated using a wireless network. |
| Limitations | • One FUT covers limited area. A large area may need an FUT array with a number of FUTs. |

**Table 3-32. Flexible Ultrasonic Transducer (FUT) (Continued)**

| | |
|---|---|
| Performance | Ultrasonic performance is better than commercial broadband ultrasound transducers, but without their disadvantages (e.g., large size, small operation temperature ranges [up to 70°C]). FUT has been tested on curved surfaces with curvatures of 25 mm in diameter with no observable damage. |
| Breadth of use | Applied to structural health monitoring of gas turbine engines, aircraft frames, power plant and oil refinery pipes.<br>A variety of commercial applications in industrial plants for in-situ characterization of materials and real-time process monitoring at high temperatures. |
| Other information | Research and development contracts established to perform NDT and structural health monitoring of pipes for oil-sand transportation, oil refinery and electrical power and chemical plants. |

**Table 3-35. Damage Sensor**

| | |
|---|---|
| Name | Damage sensor |
| Purpose/Scope | Defect location and characterization |
| Status | In research and development |
| Source of information | Juliano et al., 2005 |
| Advantages | • With the potential to integrate/fuse the information from multiple sensors for a more accurate result. |
| Limitations | • Only detects changes in the local environment. Need to develop a distributed sensing system along a full section of pipe. |
| Performance | Not available |
| Breadth of use | Not available |
| Other information | Not available |

The TDR measurement sends an electromagnetic or sharp DC pulse and analyzes the reflected signal from discontinuities. Discontinuities include pipe failures and accidental impact damage. The TDR technique can identify fault locations with high precision.

The combination of the EIS and TDR sensors takes advantage of each sensor to obtain maximum information regarding defect location and characterization. This is still in development and has not been fully implemented yet.

**3.13.6 Microwave Back-Scattering Sensor.** The microwave back-scattering **(**MBS) sensor is based on the principle of transmitting continuous electromagnetic microwaves at a frequency of 2.45 GHz and receiving the back-scattered signals (Munser et al., 1999). It detects nonhomogeneities in terms of dielectricity, such as holes caused by erosion and humidity changes due to leaking water. The inspection with the MBS sensor is from the inside of the pipe.

The MBS sensor consists of four transmission patch antennae and four staggered receiving patch antennae. The whole inner surface of the pipe is covered for inspection. The absolute amplitude and relative phase for each signal channel are processed to characterize the detected anomalies. See Table 3-36 for more information on the MBS sensor.

**Table 3-36. Microwave Back-Scattering Sensor**

| | |
|---|---|
| Name | Microwave back-scattering (MBS) sensor |
| Purpose/Scope | Detect hidden objects or material anomalies by penetrating the pipe surface. |
| Status | The MBS sensor had been tested in a sewerage test bed (Munser et al. 1999). No commercial product is available. |
| Source of information | Eiswirth et al. 2000; Munser et al. 1999 |
| Advantages | May provide complementary information to other types of sensors (such as ultrasonic sensor, camera, etc.). |
| Limitations | Not available |
| Performance | Not available |
| Breadth of use | Used for inspecting sewerage systems experimentally. Usage in water mains is not reported. |
| Other information | Not available |

**3.13.7 Fiber Optic Sensor for Corrosion Monitoring.** Changes in pipe wall thickness will lead to the change of the outer surface strain (for a given stress level). The fiber optic sensor monitors and records changes in strain and the wall thickness can be derived from this measurement.

Three fiber optic sensors are needed to calculate pipe wall thickness. One is to measure the strain due to wall thinning that depends on the internal pressure and the other two to compensate for the operational variation in temperature and pressure. The sensitivity of the system depends on wall thickness, pressure, and pipe materials, but can be as high as 0.002 in. (50.8 microns) as reported in Morison (2007). Up to eight fiber optic sensors can work simultaneously with one monitoring unit. The monitor units can also be networked together, making remote access possible. The client can access real-time data over a Web-based application. Portable instrumentation that is battery powered is also available.

The fiber optic sensors can also be designed to measure pipe bending due to ground movement (Cauchi et al., 2007). Linear and coiled fiber optic sensors were designed and used for monitoring gas transmission pipes (Figures 3-27 and 3-28). See Table 3-37 for more information about the fiber optic sensor for corrosion monitoring.

**Figure 3-27. FOX-TEK Coil Sensor**
**(Reprinted with permission from FOX-TEX)**

**Figure 3-28. Monitoring Corrosion and Bending of Pipelines with Fiber Optic Sensors (Reprinted with permission from FOX-TEX)**

**Table 3-37. Fiber Optic Sensor Corrosion and Bending Monitoring**

| | |
|---|---|
| Name | Fiber optic sensor for corrosion monitoring |
| Purpose/Scope | Direct measurement of pipe wall thickness. |
| Status | Commercially available from Fiber Optic Systems Technology Inc. (FOX-TEK). |
| Source of information | Morison, 2007; Cauchi et al., 2007 |
| Advantages | • Suitable for monitoring many types of problems, including corrosion and pipe bending<br>• Faster access to corrosion data from difficult-to-access locations<br>• Can maintain a database on direct measurement of the pipe wall thickness.<br>• Continuous Web-based monitoring |
| Limitations | • Internal corrosion is an extremely slow process. It may take more than 30 days to separate the signal of wall thickness loss from background signals.<br>• Need to expose the pipe to attach fiber optic sensors from outside. |
| Performance | The strain sensitivity of the sensor will be dependent upon operating pressure, initial wall thickness, pipe diameter, and pipe material. |
| Breadth of use | • The fiber optic sensors have found their applications in the oil, gas, pertrochemical, and chemical processing industries, where corrosion is severe and failures are of high consequence.<br>• This technology also has potential for applications in water industry. |
| Other information | The use of fiber optics for distributed temperature monitoring has also found its application for leak detection in oil and gas pipelines (Nikles et al., 2004). The detection is based on the fact that when there is a leak, the surrounding soil temperature changes accordingly. This technique uses a similar concept to optical time-domain reflectometry for the localization. |

**3.13.8 Fiber Optic Acoustic Monitoring Network.** Acoustic fiber optic (AFO) cable is installed inside a PCCP main and is connected to a laser at a data acquisition system. Light is projected through the AFO cable. When there is only ambient noise in the pipe, the reflected light is relatively constant and the resulting signal does not have a significant dynamic component. When a wire break occurs in the pipe, the sudden strain energy release generates pressure waves acting on the AFO cable. A dynamic pattern of light is obtained and can be used to evaluate the acoustic properties of the event. Frequency, acoustic magnitude, attenuation characteristics, and other acoustic variables are analyzed to determine when and where a wire break has occurred (Higgins and Paulson, 2006).

The AFO cable may consist of four or more long continuous glass fibers. A picture showing the installation of the AFO sensors is provided in Figures 3-29 and 3-30. These fibers, together with a strength fiber that provides strength to resist tension, are encased in a protective jacket. The monitoring results for each pipe section are available on a secure Web site, where the pipes are mapped on Google Earth for easy identification. See Table 3-38 for more information on the AFO monitoring sensor.

**Figure 3-29. (Left) Installation of Fiber Optic Sensor in a Dewatered Pipeline. (Right) Fiber Optic Sensor Installed on a Stainless Steel Hoop with a Strain Relief Device (Reprinted with permission from Pure Technologies)**

**Figure 3-30. (Left) Installation Parachute Used to Install an AFO Cable in an in-Service Pipeline and (Right) Parachute Caught and Extracted at Two Miles Downstream from Insertion Point (Reprinted with permission from Pure Technologies)**

**Table 3-38. Fiber Optic Acoustic Monitoring Network**

| | |
|---|---|
| Name | Fiber optic acoustic monitoring sensor |
| Purpose/Scope | Identifies wire breaks as they occur in PCCP |
| Status | Commercially available (Pure Technologies Ltd. and the Pressure Pipe Inspection Company) |
| Source of information | Higgins and Paulson, 2006;, Higgins et al., 2007 |
| Advantages | • The entire AFO cable acts as a sensor and is therefore acoustically sensitive. This means that the acoustic sensor is not further than a pipe diameter from a wire break, which results in negligible acoustic attenuation of the acoustic activity associated with a wire break.<br>• Acoustic data are acquired continuously and wire breaks are identified and reported in near real time. This allows a water/wastewater utility to know on an ongoing basis where wire breaks are occurring in a pipeline and the risks associated with each pipe section and they can intervene to mitigate risk as needed.<br>• No electronics are placed in the water flow.<br>• Long lengths of a pipeline can be monitored with one data acquisition system. Up to 12 miles (20 kilometers) can be monitored from one data acquisition system.<br>• Electronic noise in monitoring is negligible.<br>• The monitoring sensor is always near a wire break.<br>• The AFO cable can be installed either while a pipeline is out of service or in service. Installing it while a pipe is in service may result in an increased need for tapping outlets into the pipeline. |
| Limitations | • Transduction mechanisms may result in the light intensity change and thus introduce errors. Pure Technologies reports that this has negligible effects on data quality.<br>• Other potential errors may be introduced by variable losses due to connectors and splices, and misalignment of light sources and detectors (Gholamzadeh and Nabovati, 2008). Pure Technologies reports that this has negligible effects on data quality.<br>• The monitoring system does not provide information on wire breaks that occurred prior to the installation of the AFO cable.<br>• The AFO cable is installed while the pipe is out of service; it is periodically attached to the invert of the pipe and is routed around inline valves. |
| Performance | • The AFO cable-based monitoring was compared with hydrophone-based monitoring by Pure Technologies (Higgins and Paulson, 2006). Better performance was observed from the experiments. An accuracy of +/- 5 ft to locate wire breaks was reported by Pure Technologies.<br>• In addition, a second comparison was also performed during an experiment on the Great Man-made River in Libya and also documented better performance. |
| Breadth of use | The AFO system is presently being used to monitor more than 150 miles of PCCP mains in the U.S. In addition, the AFO cable is being installed on an ongoing basis for the Great Man-made River Authority where 250 miles of AFO cable have been installed as of August 2009 (NACE International, 2011). |
| Other information | Not available |

**3.13.9 Wireless Sensor Network for Pipe Condition Monitoring.** The MEMS sensors that measure the acceleration change at the pipe surface were connected through a wireless network. The basic principle is that a sharp transient change in hydraulic (water) head in the pipe flow induces a correspondingly sharp change in the acceleration of pipe vibration on the pipe surface. The inverse analysis may locate the damage in a pipe segment between two neighboring sensors. Accelerometers H34C and SD 1221 made by MEMS technology were integrated with two sensor units respectively (Shinozuka et al., 2007). Three-axial vibration data were collected. The change in the water pressure due to pipe damage can be identified by the change in acceleration on the pipe surface. However, the algorithm to locate the damage through the captured transient signal has not been developed. Only this concept is being developed.

A wireless sensor network (WSN) system called PipeNET was described in (Stoianov et al., 2007). The architecture of this system is illustrated in Figure 3-31. Piezoresistive silicon sensors were used to measure the pressure. Acoustic/vibration data were collected by accelerometers installed along the pipe. The third function block included a different set of applications such as monitoring water quality in transmission and distribution water systems, and monitoring the water level in sewer collection systems. The WSN can increase the spatial and temporal resolution of operational data from pipeline infrastructures and implement near real-time monitoring and control. Table 3-39 provides more information on wireless MEMS sensor network.

**Figure 3-31. The System Architecture of PipeNET**

**Table 3-39. Wireless MEMS Sensor Network**

| **Wireless MEMS Sensor Network** |
|---|
| Capabilities:<br>• Identify the damage locations from three-axial vibration data over a vast lifeline network.<br>• Real-time monitoring<br>• Data transmission via wireless network |
| Benefits:<br>• Can be easily integrated into a supervisory control and data acquisition (SCADA) system.<br>• MEMS sensor is power-efficient. |
| Limitations:<br>• Can only point to a problem occurring while monitoring is active.<br>• Installation of the MEMS sensor unit to existing pipes remains a challenge. Possible solution is to install at hydrant locations. |

**3.13.10 Multi-Sensor Approaches.** Any individual non-destructive inspection technique may not be able to fully characterize the condition of pipes. Multi-sensor technologies incorporate multiple sensors for a comprehensive pipe inspection and assessment. This technology encompasses two aspects. One is the sensor selection; the other is the sensor fusion. The choice of sensors depends on the particular requirements of an application. The sensor fusion algorithms take care of processing the signals acquired by heterogeneous sensors. A multi-sensor experimental platform called sewer assessment with multi-sensors was developed with the support of the German Research Foundation. The sensors reported in Eiswirth et al. (2001) include:

(a) Optical triangulation sensor: optical 3D measurement of a sewer pipe;

(b) Microwave sensor: inspect the soil state behind sewerage pipes;

(c) Geoelectrical sensor: detect leak points;

(d) Hydrochemical sensor: detect groundwater infiltration;

(e) Radioactive sensor (neutron and gamma ray probes): investigate soil density and soil moisture content;

(f) Acoustic systems: detect leaks, cracks and determine the state of connections and pipe bedding.

The basic steps include sensor data acquisition, signal processing, feature extraction, data fusion and diagnosis. The sensor fusion algorithm is implemented with the fuzzy-logic method. However, a report on the overall performance is not available.

The data acquired by multiple sensors need to be synchronized or registered so that the correspondences between the data can be established. This is the first step in processing multi-sensor data. See Table 3-40 for more information on the multi-sensor technology.

**Table 3-40. Multi-Sensor Technology**

| **Multi-Sensor Technology** |
|---|
| Capabilities:<br>• Can provide more reliable data and continuous profile of pipe walls. |
| Benefits:<br>• Higher benefit/cost ratio is anticipated compared to single sensor technologies.<br>• Can be implemented as a robotic module. |
| Limitations:<br>• The performance of overall system is not known. |

**3.13.11 Smart Pipe.** The so-called "smart pipe" concept has been around for the last 15 years or so. It is a loosely defined concept, whereby the pipe is equipped with a range of sensors (embedded or otherwise) that provides a complete monitoring network of the pipe condition and performance. A smart pipe project for deep-sea pipelines was initiated in Europe in 2006 and is slated for completion in 2012. The objective is to develop a complete monitoring system for pipelines, integrating sensor technology, data acquisition, data interpretation, and decision support for on-line, real-time management of pipeline assets (SINTEF, 2008). The entire length of each pipeline is to be monitored by sensors throughout the life of the pipe. The expected benefits include, but are not limited to, improved basis for decision making, improved residual life prediction, and decreased need for inspection. In the U.S., Smart Pipe® is also a registered technology commercially available from the Smart Pipe Company Inc. in Katy, TX. It is a reinforced thermoplastic pipe designed for use as a tight fit liner in high pressure applications such as gas/liquid lines from 150 to 1,440 psi. Within the high strength fiber windings, a monitoring system is secured, which consists of longitudinally oriented fiber optic sensors that send signals for strain and temperature anomalies that can be used to detect damage and potential leaks.

## 3.14 Additional Leak Detection and Monitoring Methodologies

The main objectives of leak detection are the reduction (or elimination) of water losses through leaks, as well as reducing the possibility of small leaks developing into pipe failures. However, while addressing these two main objectives, information about leakage rates provides an important indication about the condition of the pipe. This subsection provides additional information about leak detection and monitoring methodologies to supplement information already provided in earlier subsections on acoustic and non-acoustic inspection technologies for leaks (some overlap exists between this and previous subsections). A summary of technologies and computational methods for leak detection and monitoring is given in Figure 3-32, followed by brief descriptions of hydraulic transient-based methods, measurement-based leak monitoring methods, model-based leak monitoring methods, and information fusion with neural networks.

**Figure 3-32. Summary of the Technologies for Leak Detection and Monitoring (Misiunas, 2005)**

**3.14.1 Hydraulic Transient-Based Methods.** Besides the NDT methods described in previous sections of this report, hydraulic transient-based techniques are also available to detect and locate existing leaks. The information regarding the presence of a leak is extracted from a measured transient trace. Various computational approaches have been proposed to analyze the hydraulic information for both detection and monitoring purposes. Techniques such as inverse transient analysis have been verified in laboratory settings, but their feasibility and limitations under actual field conditions require further verification. NRC Canada is conducting a pilot study into the use of inverse transient analysis for the detection of leaks in the City of Regina's municipal water distribution network (Karney et al., 2009).

*Leak reflection method*. The method is based on the principle of time domain reflectometry. A transient wave is reflected at the leak and can be identified in a measured pressure trace. The location of the leak can be calculated.

*Inverse transient analysis*. Least square regression is applied to the modeled and measured transient pressure traces. The minimization of the deviation between the measured and calculated pressures gives the leak location and size.

*Impulse response analysis*. The impulse responses of the same pipeline with and without a leak are compared. The presence of a leak will introduce the change of the impulse response.

*Transient damping method*. A leak detection and location method was developed based on the rate of leak-induced damping. This rate depends on leak characteristics, pressure, location of the transient generation point, and the shape of the transient.

*Frequency domain response analysis*. The analysis of transient response in the frequency domain compares the dominant frequencies of non-leaking and leaking pipelines. The leak location can be obtained.

**3.14.2 Measurement-Based Leak Monitoring Methods.** A brief description is provided below of measurement-based methods used to detect leaks.

*Acoustic monitoring*. Through analyzing the acoustic signals with a leak and without a leak, the situation is identified. A correlator is often used to locate the leaks. The cross-correlation methodology relies upon detecting noise emitted by a leak from two sensor locations and analysis of the acoustic signature from each location.

The noise emitted by a leak is detected by the two sensors and produces an acoustic signature in each. These signatures are identical in shape, but offset from each other. The size of the offset is determined by the difference in time at which the noise is detected by each sensor. Since sound velocity is constant, the time gap $\tau_{max}$ is proportional to the respective distances of the sensors from the leak. The location of the leak with respect to the sensors can then be computed by (Hunaidi et al., 2004):

$$\tau_{\max} = \frac{L_2 - L_1}{c}$$

where $L_1$ and $L_2$ are the positions of the leak relative to sensor 1 and 2, respectively, and $c$ is the propagation velocity of the leak sound in the pipe. The distance between the sensors ($D$) is equal to $L_1$ + $L_2$. Therefore, $L_1$ can be expressed as:

$$L_1 = \frac{D - c \cdot \tau_{\max}}{2}$$

The propagation velocity can be determined onsite or calculated based on pipe material and diameter. However, the acquired signals are prone to distortion. LeakfinderRT™ uses an enhanced cross-correlation function, which is implemented in the frequency domain using the cross-spectral density function. Thus, a better resolution and definition of peaks can be achieved (Hunaidi et al., 2004).

Another robust method was implemented by the Central Research Laboratories at Thames Water (MathWorks, 2007). Complex discrete Fourier transform (DFT) is used to transform the input time domain signal to the frequency domain. The echo of the signal is removed/cancelled by analyzing the auto-correlation of each channel. Phase coherence analysis is used to determine which parts of the frequency spectrum contain useful information. The output of the analysis constructed a weighted frequency filter, which achieved an optimal performance in the detection of leak signals (MathWorks, 2007).

*Volume balance method*. The basic principle is that the amount of fluid that goes into the pipe should be equal to the amount that comes out of the pipe. The flow measurements will calculate:

$$VB = V_{in} - V_{out} - \Delta V$$

where:

$VB$ : volume balance;
$V_{in}$ : inlet volume;
$V_{out}$ : outlet volume;
$\Delta V$ : volume of fluid contained in the pipe (line pack).

Any leak will give a positive value of *VB*.

*Pressure-point analysis*. This method is implemented by monitoring the leak-induced pressure drop. Statistical techniques are applied to identify the leak signature in the measured pressure trace.

*Negative pressure wave method*. This method is based on monitoring the pressure for the leak-induced pressure wave. The location of the leak can be determined from the wave arrival times and wave speed.

*Statistical pipeline leak detection*. The statistical method uses flow rate, pressure, and temperature measurements to carry out a sequential probability ratio test.

*Statistical data analysis-based methods*. An autoregressive model, which uses two consecutive time sequences of pressure gradients at both ends of the pipeline, was established to detect the leak. The parameters and residual variance of the fitted models are dependent on the condition of the pipeline and reflect the presence of a leak.

*District meter areas*. This method conducts a water audit in district meter areas. Flow and/or pressure sensors are placed on the boundary of the district meter area. The collected data are analyzed for leakage trends.

**3.14.3 Model-Based Leak Monitoring Methods.** A brief description is provided below of model-based methods used to detect leaks.

*Real-time transient model-based methods*. Two techniques are considered: one is the deviation analysis and the other is the model compensated volume balance method.

In the pressure-flow deviation method, the flow rate and pressure at one boundary can be calculated from the flow rate and pressure values measured at another boundary using the transient simulation model.

The calculated values should match the measured values if no leak is present. The discrepancy between the measured and calculated values indicates a leak.

The model compensated volume balance approach implements the real-time comparison of the measurement generated flow balances and model generated line packing rates, which are computed from measured pressures and temperatures at the end points of a pipeline segment with the model. In the case of leakage, the measured flow balance and the model generated line packing will diverge.

*Steady-state inverse analysis*. A leak is detected and located by solving an inverse problem using measurements of pressure and/or flow rate.

*Inverse transient analysis*. This method can be applied to an unsteady flow situation. The responses of transient events are measured and interpreted by calculating the model parameters using the inverse method.

*State estimation approaches*. The flow in pipelines can be represented by a distributed parameter system, which is implemented with a state estimator or a filter. An extended Kalman filter can be used to estimated leaks (Misiunas, 2005).

**3.14.4 Information Fusion.** A framework for leak detection from multiple acoustic emission (AE) sensors was proposed by Jiao et al. (2007). The idea is illustrated in Figure 3-33. The AE signal is processed with a wavelet transform to extract signal features. Next, a neural network is trained to provide a mass function. The Dempster-Shafer evidence theory is then employed to combine the mass function values from multiple sensors. The fused result will identify the pipe leak.

**Figure 3-33. Sensor Data Fusion for Leak Detection (Jiao et al., 2007)**

The fusion of hydraulic data for burst detection and location in a treated water distribution system was reported by Mounce et al. (2003). An artificial neural network is used to model the time series data acquired by a flow sensor. A mixture density network was employed to predict the conditional probability distribution of the target data. The actual observed value is analyzed in the context of the predicted probability distribution. A normal (non-leak) or abnormal (leak) state is understood. The classification results from various zones are fused by a rule-based expert system implemented by Mounce et al. using PROLOG (a general purpose programming language).

## 3.15 Supplemental Information on Inspection Platforms, Intelligent Pigs, and Robotic Survey Systems

This section includes additional information on advances in inspection and monitoring platforms including computer-aided augmented reality, intelligent pigs, and robotic survey systems.

**3.15.1 Computer-Aided Approach: Augmented Reality.** Augmented reality (AR) is a technology that blends in real-time, real-world footage and computer-generated graphics. The AR system described in Lawson and Pretlove (1998) consists of a stereo robotic head device, virtual reality graphics engine, scan converters, head mounted display, and stereo monitor. The AR system itself does not introduce any new method for pipe inspection, but it provides a human-computer interface, which facilitates advanced data manipulation and enhanced visualization of faults and deficiencies in the pipe.

**3.15.2 Intelligent Pigs and Robotic Survey Systems.** Pigs and robots serve as platforms for the introduction of one or more sensory payload into the pipe for assessing its conditions (Schemph, 2004). The fundamental requirements of such systems include (Jamoussi, 2005): ability to traverse the entire pipe in a reasonable time without getting stuck; ability to inspect the pipe with acceptable accuracy and resolution, and ability to transmit the inspection data to the outside for reporting or save the data locally. Most of the robotic systems for water and sewer mains are tethered for power and communications. A list of available platforms is given in Table 3-41. Although not all platforms are intended for water mains, it is still a good source of reference for the development of the robotic platforms.

An inspection system is preferred that can be operated on-line without an interruption of service. A robotic system for internal inspection of water pipelines was presented (Moraleda et al., 1999). From their research, the authors learned (Moraleda et al., 1999):

- No cost-effective system will be able to negotiate through all possible scenarios that may exist inside a water pipeline network;
- A tethered solution could be adopted for recoverability, despite the greater autonomy that a non-tethered vehicle could provide.

**Table 3-41. Robot Systems for Pipe Inspection**

| System | Description | Sensors | Date |
|---|---|---|---|
| PIRAT (Kirham et al., 2000) | Pipe Inspection Real-Time Assessment Technique (PIRAT) is a non-autonomous tethered robot for the quantitative and automatic assessment of sewer conditions. A human operator can operate the robot from a surveillance unit via a cable, with a length of 250 meters (maximum). An expert system running on a workstation was responsible for data interpretation and damage classification. | Video camera and laser scanner | 2000 |
| KARO (Kuntze and Haffner, 1998) | Kanalroboter (KARO) is an experimental semi-autonomous platform for sewer inspection. It is tethered via a cable to a surveillance unit. With on-board inclinometers, KARO is able to correct for tilt in its pose and wheel slippage. | Standard video camera, ultrasound transducer, microwave sensor, and 3D optical sensor | 1998 ~ 2000 |

## Table 3-41. Robot Systems for Pipe Inspection (Continued)

| System | Description | Sensors | Date |
|---|---|---|---|
| KURT (Kirchner and Hertzberg, 1997) | Kanal-Untersuchungs-Roboter-testplatform (KURT) is a six-wheeled autonomous un-tethered robot. A map of pipe net is needed for the navigation. | Ultrasound transducer, inclinometers, CCD camera | 1997 |
| KANTARO (Nassiraei et al., 2006) | KANTARO is a fully autonomous, untethered robot for pipes of diameter 20 to 30 cm. It was designed to move in straight pipes and pass different kinds of pipe bends without any special controller or sensor. | Fish eye camera and 2D laser scanner | 2006 |
| MAKRO (Rome et al., 1999) | Multi-segmented autonomous sewer robot (MAKRO) is a fully autonomous, un-tethered, self-steering articulated robot platform for sewer inspection. It has six segments connected via flexible joints. This enables MAKRO to crawl along narrow pipes. The on-board batteries can support a two-hour operation of the robot. | Infrared sensors, ultrasonic sensors, camera, laser crosshair projector | 2002 |
| RoboScan (Vradis and Leary, 2004) | RoboScan is a modular platform for unpiggable gas distribution pipelines. Each module has its own micro-controller, which is connected through a network. A fiber optic cable is used to connect RoboScan and the base station. A magnetic flux leakage module was used for pipeline inspection. | Magnetic flux leakage | 2004 |
| Explorer-II (Schempf, 2006) | Explorer-II (X-II) is a modular robot platform for inspection of live gas mains. | Digital camera | 2008 |
| Ultrasonic inspection robot | Ultrasonic inspection robots were developed by Inspector Systems for use in refinery pipes, buried pipes, and pipes with long vertical inclines. The robots are made of three modules connected with flexible folding bellows. One of the three modules is the ultrasonic element, which consists of an ultrasonic sensor unit for measuring pipe wall thickness, a camera, and a positioning unit. The robot can move both horizontally and vertically along pipes about several hundred meters long. It can pass bends and turns of 1.5 diameter. A fiber optic cable is used to connect the control unit for transmission of control commands as well as inspection data. A special fluid is used as the couplant for the inspection. http://www.inspector-systems.com/ultrasonic_robots.html | Ultrasonic sensor and camera | Information retrieved in 2009 |
| Robots for video and laser inspection | These robots from Inspector Systems can be applied to nuclear power industry, refineries, chemical plants, petrochemical plants, offshore industry, gas pipelines, beverage industry, and other types of pipes. The maximum distance that the robot can travel is about 500 m. A color camera with a ring of light emitting diode lights is mounted on the head with pan and tilt functions for video inspection. An adjustable point laser is used for internal measurement and classification of defects and corrosion. The robot has three drive elements and an inspection head as standard. The drive elements are connected via flexible folding bellows and each of them contains two direct current motors. A fiber optic cable is used to transmit inspection data and control commands. http://www.inspector-systems.com/video_robots.html | Color camera and point laser | |

**Table 3-41. Robot Systems for Pipe Inspection (Continued)**

| System | Description | Sensors | Date |
|---|---|---|---|
| PipeDiver$^{TM}$ | At the 2009 International No-Dig Show (Toronto, Ontario, Canada), the PPIC demonstrated a prototype of its modularized free-swim platform, PipeDiver$^{TM}$, for the inspection of in-service PCCP with diameters ranging from 0.6 (24 in.) to 1.5 m (60 in.). Driven by water flow, the platform has three modules, which are used for vehicle tracking, pipe inspection, and power supplying, respectively. The RFEC/TC technique is integrated in the inspection module. Two challenges for PCCP inspection were considered in the design of the first generation of PipeDiver$^{TM}$, platform launch and retrieval, passing pipe bend and butterfly valve. A version of PipeDiver$^{TM}$ was field tested at Louisville, KY in 2009 summer on 24-in. CI pipe. | RFEC | 2009 |
| Super-Pig (Clay, 2009) | Super-pig is a platform with an ultrasonic module to measure the pipe wall thickness loss, longitudinal and circumferential cracks, damage to linings, and leaks. The targeted mains are in the range of 200 to 300 mm. The super-pig can operate for water mains in service. Special launch and retrieval facilities are needed. | Ultrasonic transducer array | 2009 |

### 3.16 Current Use of NDE and Condition Assessment

Although the subject of condition assessment of water mains has received increasing attention in the last 10 to 20 years, it is not clear at what rate and what type of condition assessment practices water utilities are actually adopting. Anecdotal evidence and limited surveys (e.g., Deb et al., 2002; Deb et al., 1990; Dingus et al., 2002; Grigg, 2007; Marlow et al., 2007; and others) suggest that many medium and large water utilities have adopted some form of condition assessment and pipe renewal decision process, either from the literature, developed in-house, or a combination of both. Many of these water utilities use some form of inspection including visual, destructive or nondestructive techniques (the latter predominantly on large transmission mains). Information about smaller water utilities is scant. Thomson and Wang (2009) reported the existence of a number of barriers to effective use of condition assessment technologies, including lack of data for comparison, lack of consensus on what are the key required data, the limited availability of proven inspection techniques to discern pipe structural condition, cost of inspection and condition assessment, lack of confidence in the adequacy of existing techniques and level of expertise required for the implementation of various techniques and models.

In this subsection, the results of two limited surveys are presented to provide additional information about current practices of condition assessment of water mains. The first part provides the results of an anonymous survey conducted by NRC, while the second part describes a survey of nine utilities carried out by Virginia Tech.

**3.16.1 NRC Survey.** The NRC collected information from technology vendors and water utilities in order to assess the usage and application of inspection technologies from both perspectives.

A questionnaire was issued to ten technology vendors and six responses were received. The information received has been incorporated into Section 3. For the technology vendors, the following information was requested:

- Main features of the technology (what are the distinct features of this technology);
- About the inspection results:
  - What is the inspection result, or what types of data are acquired during the inspection?

- How are the data interpreted?
- Will the inspection data be transferred to condition rating? How?

- About the cost: what is the major cost of this technology, including equipment costs, the need for well-trained operators or the operational cost?
- Technology usages (practitioners): how is this technology being used by municipalities and water utilities?
- Other information.

Most vendors were reluctant to provide sales data (considered as confidential). Only PPIC provided some relevant data pertaining to mileages of RFEC inspection for PCCP pipes. These data are presented in Figure 3-34.

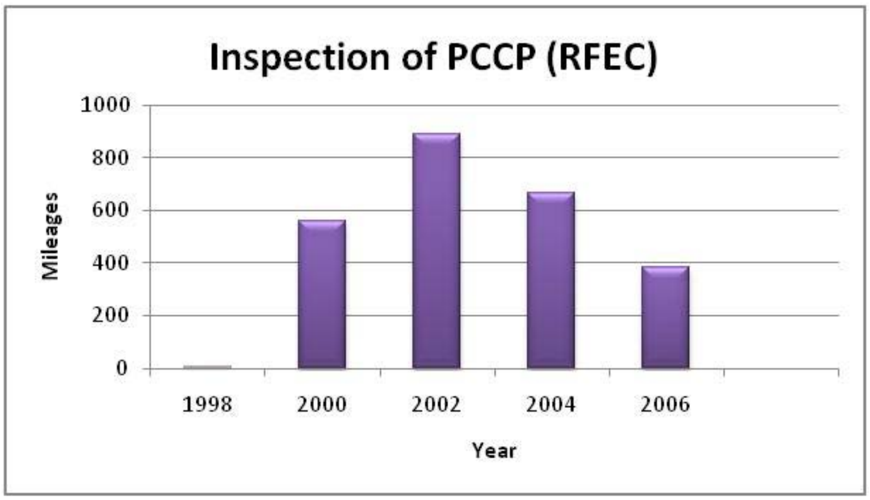



**Figure 3-34. The Mileages of RFEC-TC Inspection for PCCP**

A separate questionnaire was sent to ten water utilities in the U.S. and Canada with five responses received. The questionnaire included the following items:

- Did you use NDT to assess the condition of your water pipes?
- What NDT techniques/systems are currently being used?
- How many miles of pipes are inspected (roughly) and how often (frequency)?
- Did you purchase the NDT equipment for inspection or purchase the service from another company?
- How do you use the inspection data? Was any decision made based on the inspection?

The responses from five utilities are summarized in Table 3-42. All respondents used the services from contractors or third parties to carry out the inspection. The inspection results, to some extent, were used in the decision making for the maintenance or rehabilitation of water mains, but the information regarding the strategy for repairing and rehabilitating was not available. The frequency of inspection was not explicitly defined or determined by any of the respondents.

**Table 3-42. Use of Condition Assessment Technologies for Water Mains by Five Water Utilities**

| Utility | Pipe Type | Use of NDT | NDT Techniques Currently Used | Miles of Pipes Inspected | Frequency of Inspection | Use of Inspection Data | Inspection Service |
|---|---|---|---|---|---|---|---|
| A | PCCP | Yes | RFEC, leak detection, impact echo, acoustic, etc. | 5~8 miles/year; Re-inspect high-risk areas | Re-inspect 8% over the last 3 years | Rate the residual strength and damage with models | Third party |
| B | CI | Yes (in the past) | Hydroscope | 50 miles | Information not available | Used in a prioritization process for pipe replacement | Third party |
| C | PCCP, steel | Yes | SmartBall®, RFEC | Few miles | Wall thickness along the same steel pipe sections in 14 years | Used in a repair or replacement strategy | Third party |
| D | PCCP, DI | Yes | RFEC, acoustic monitoring and correlators for leak detection | 6.2 miles of PCCP in history; hundreds of miles of leak detection in DI pipes | 2.5 mile/year for PCCP inspection (planned from 2009) | Used for risk assessment and renewal decisions | Third party for PCCP inspection; In house staff and equipments for leak detection |
| E | DI, thin-wall CI, PCCP | Yes | Hydroscope, RFEC, fiber-optic monitoring, hydrophone, etc. | 3 miles of PCCP; 70 miles of DI and CI pipes | Information not available | Inspection data integrated into CAD/GIS for making decisions on pipe renewal | Contractors |

**3.16.2 Virginia Tech Survey.** The Virginia Tech survey was designed to understand issues related to condition curves or any deterioration models used across the U.S., Canada, and Australia. The participating utilities included:

- EPCOR Water Services Inc., (Edmonton, Alberta, Canada)
- Las Vegas Valley Water District (Las Vegas, Nevada)
- Newport News Waterworks (Newport News, Virginia)
- Seattle Public Utilities (Seattle, Washington)
- Sydney Water (Sydney, Australia)
- Washington Suburban Sanitary Commission (Laurel, Maryland)
- City of Hamilton Public Works Department (Hamilton, Ontario, Canada)
- Louisville Water Company (Louisville, Kentucky)
- Philadelphia Water Department (Philadelphia, Pennsylvania)

In this report, only the information related to condition assessment of pipes is included, namely, the use of NDT techniques and deterioration/failure models as summarized in Table 3-43.

**Table 3-43. Summary of Utility Inspection Methods and Models**

| Utility | Inspection Methods | Models |
|---|---|---|
| EPCOR Water Services, Inc. | Cathodic Protection Program, Pipe Sampling, Leak Detection, Uni-Directional Flushing Program, Water Main Internal Lining Program, Valve and Hydrant Replacement Program, Neighborhood Program, and Hydroscope | 1. Reactive Renewal Program |
| | | 2. Proactive Renewal Program |
| | | 3. Hydraulic Model |
| Las Vegas Valley Water District | Non-Invasive Technology, Cathodic Protection, Forensic, Sahara®, SmartBall® , and Echologics Acoustic Wave Technology | 1. Computer Aided Rehabilitation of Water Networks (CARE-W) |
| | | 2. Linearly Extended Yule Process (LEYP) |
| Newport News Waterworks | Hazen Williams C-Factor Test and Corrosion Monitoring Stations | 1. Nessie Curve (Long-Term Economic Forecast) |
| | | 2. Pipe Prioritization Replacement Model |
| | | 3. Hydraulic Model |
| Seattle Public Utilities | Spot checks of exposed pipes for general exterior condition assessment | 1. Wave Rider (Long-Term Economic Forecast) |
| | | 2. Water Main Replacement Model |
| Sydney Water | Linear Polarization Resistance, Magnetic Flux Leakage, Ultrasonics | 1. KANEW (Long-Term Capital Investment Forecast Tool) |
| | | 2. PARMS-PRIORITY (Water Main Prediction Model) |
| Washington Suburban Sanitary Commission | Internal Visual/Sounding Inspection, Electromagnetic Inspection, Sonic/Ultrasonic Pulse Echo, Sahara®, SmartBall®, LeakFinder RT™, Acoustic Fiber Optics, and Electrochemical Potential Survey | 1. Nessie Curve (Long-Term Economic Forecasting Model) |
| | | 2. UMP Condition Rating System |
| City of Hamilton Public Works Department | Unavailable | 1. Hansen Asset Management System |
| Louisville Water Company | Unavailable | 1. Point-Score System referred to as LWC's Pipe Evaluation Model (PEM) |
| Philadelphia Water Department | Unavailable | 1. Point-Score System |

***3.16.2.1 EPCOR Water Services Inc.*** EPCOR Water Services Inc. is a corporatized public utility located in Edmonton, Alberta, Canada. Its governance structure is the same as a private utility; however, it is wholly-owned by the municipality of Edmonton.

- Inspection and condition assessment:

  *Pipe sampling* – Samples of various pipe materials (AC and PVC) are tested to evaluate the condition and remaining life.

*Leak detection* – Leak detection is to pinpoint the location of active leaks and breaks of CI and steel pipes. This inspection aids in limiting the amount of surface disruption due to excavation.

*Hydroscope* – Originally, the hydroscope was used to determine the remaining wall thickness in CI pipes. However, the program was stopped because only a limited benefit was achieved and many water quality complaints were received while utilizing this technology.

- Models:

  EPCOR had experimented with failure models and artificial neural network analysis to predict the residual life of water pipes. However, these efforts did not succeed and EPCOR decided to continue using its renewal program, which consists of a reactive and a proactive program. The reactive renewal program identifies the deteriorating distribution water mains with a geographic information system (GIS) application that calculates the break frequencies for candidate stretches between valves. EPCOR utilizes a ranking system within its proactive renewal program to prioritize water pipes. The proactive renewal program consists of area criteria rankings as well as candidate criteria rankings. The area criteria rankings are useful in pinpointing locations where infrastructure requires more work, while candidate criteria rankings help to choose a specific section of a pipe over another. The proactive renewal program analyzes area and candidate criteria ranking for water pipes. It helped EPCOR understand the interconnected piping system.

EPCOR's main focus is minimizing the impacts and response times to breaks, improving tools for renewal candidate selection, and reducing the construction impact during actual renewal. Even though validation of its program with respect to predictive effectiveness has not been a main focus, EPCOR has evaluated the replacement priority value (RPV) renewal qualification criteria. It was shown that, once a pipe reached the renewal qualification criteria and it was not renewed, the break rate would increase on that particular section of pipe.

It is estimated that EPCOR spends approximately $50,000 to $100,000 per year on the analysis of identifying pipes at risk, pipe inspection and data collection, data management, modeling software, and interpreting results. Reactive and proactive renewal programs serve as EPCOR's prediction model in determining water pipe replacement.

***3.16.2.2 Las Vegas Valley Water District.*** The Las Vegas Valley Water District (LVVWD) is a public utility located in Las Vegas, Nevada.

- Inspection and condition assessment:

  LVVWD inspects AC pipes larger than 4 in. and steel pipes greater than 12 in. The inspection and condition assessment techniques include:

  *Non-invasive technology* – Acoustic wave velocity measurements in in-service water pipes (AC and steel) is performed to estimate the percentage loss of pipe strength.

  *Cathodic protection* – The assessment of steel pipes is implemented through analyzing CP.

  *Forensic* – Forensic condition assessment is applied to AC pipes. Pipe samples are analyzed and crush tests are performed on AC pipes in the lab.

  *Sahara®* – Sahara® is used to detect leaks and structural defects in large mains.

  *SmartBall®* – SmartBall® is used to detect and locate leaks.

*LeakfinderRT™* – LeakfinderRT™ is used to locate leaks in water pipe.

*Wall thickness assessment* – The wall thickness assessment is implemented by measuring the acoustic wave velocity within a pipe using sensors attached to two longitudinal points along a pipe. This is still an experimental technology provided by Echologics (see "Other information" in Table 3-20 in Section 3.6.2).

- Models:

The LVVWD utilizes several types of models/systems to analyze water pipes.

*CARE-W* – Computer Aided Rehabilitation of Water Networks is computer software that includes fundamental instruments for estimating the current and future condition of water networks. Detailed information about CARE-W is available in Section 6. LVVWD uses the Annual Rehabilitation Plan (ARP) and Long-Term Planning (LTP) to identify the pipes that should be considered for rehabilitation and obtain the information on the future investment needs for the water network.

*Linearly Extended Yule Process (LEYP)* – The LEYP statistical failure model predicts break rates. This model uses the software for analyzing break data and making break predictions. Two types of data are input into the LEYP model: pipe data and break data. The analysis is only applied to AC pipes.

The LVVWD does not perform any kind of statistical evaluation involving the CARE-W ARP and LTP models; however, they do feel confident that their models are practical.

The average cost for non-invasive acoustic wave assessment is $2 per foot and increases exponentially the more invasive the technology becomes. The LVVWD did incur a one-time cost for implementing the CARE-W program. Currently, there are no ongoing annual fees for using the software. The main advantages of LVVWD's models are the capabilities of prioritizing pipe condition assessment and planning for long-term capital replacements. Disadvantages of the models include the need to acquire reliable data and the cost of in-house analysis.

***3.16.2.3 Newport News Waterworks.*** Newport News Waterworks is the public utility of Newport News, Virginia.

- Inspection and condition assessment:

*Hazen Williams C-Factor Test* – The Hazen Williams C-Factor Test indicates the water pipe wall roughness. The higher the C-factor, the smoother the pipe is. Newport News performs two types of tests: one test isolates a section of a pipe and records the water flow per pressure gradient along the pipe; the other test places up to 11 electronic pressure recorders on hydrants around a flow hydrant.

*Corrosion Monitoring Stations* – Newport News installed the corrosion monitoring stations in 1994.

- Models:

Newport News utilizes several types of models/programs to analyze water pipes.

*Long-Term Economic Forecast Model* – This model, known as the "Nessie Curve" (developed by the South Australian Water Company), projects replacement costs and "wear-out" cost together to support the total lifecycle cost analysis. A "Nessie Curve" is a graph of estimated annual expenditure needed for replacement of pipe infrastructure. It reflects an echo of demographic waves (i.e., cohorts of pipes with their respective installation years and assumed end of life). The rising shape of this graph has caused it to be named a "Nessie Curve" after the Loch Ness Monster. The Nessie curves help utilities estimate the long-term pipe replacement budgets.

*Prioritization Model* – The initial priority program consisted of a point-score system evaluating 10 different pipe criteria. However, it was found that several of these pipe criteria did not affect the priority ranking over time. The revised and updated program assigns points based only on the number of breaks, life expectancy, and maintenance cost.

Newport News does not perform any kind of statistical evaluation for these models. They feel confident that their models are practical.

***3.16.2.4 Seattle Public Utilities.*** The Seattle Public Utilities (SPU) is a private utility located in Seattle, Washington.

- Inspection and condition assessment:

  SPU does not utilize routine inspections and/or condition assessment techniques for water transmission and distribution pipes. SPU's primary focus is on leak and break data in which the leak rate is assumed to be a surrogate for condition assessment. A condition assessment program was conducted for several years in the 1990s; however, it was discontinued since costs exceeded the value of the information obtained. This program primarily consisted of the opportunistic collection of samples (e.g., from a new tap or repair event) for analysis.

- Models:

  *Wave Rider (long-term capital planning) Model* – The Wave Rider model forecasts the repair and replacement expenditures by year for each of nine classes of pipe material and size, where a Weibull distribution is assumed for the economic life of pipes in each class. The Wave Rider model is very similar to the 'Nessie curves' described earlier, except it addresses repair costs as well as replacement costs (repair rates are assumed to grow as the pipe approaches end of life). The nine classes of pipe considered are DI, CI (divided into four subcategories by size and vintage), steel, concrete, galvanized, and other. The calibration of the model is implemented by comparing actual repair rates since the year 1990 to those predicted by the model.

  *Prediction (pipe replacement) Model* – The prediction model is for the repair/replacement decisions of individual pipes. This model is primarily based on water pipe leak history and standards for all pipe materials, sizes, and locations.

  *Water Main Replacement Model* – The water main replacement model uses the deterioration model described above to compare the expected cost of failure and repair against the estimated replacement cost. Data classes used in analyzing the water main replacement consist of pipe, construction, service, traffic, lost water, damage, fire risk, water quality, and benefits.

No statistical analysis has been completed to evaluate the validity of the models. One reason for this is that it is difficult for the SPU to validate the predictive effectiveness of the failure curve since the majority of its pipes have remained in the flat part of the curve.

In 2008, the SPU spent an estimated $43,000 on asset data, decision models, and related support. The SPU is not considering any alternative methods and it periodically updates the water main failure rates. The SPU plans to implement weighted factors to replace major transmission pipelines prior to expected failure.

***3.16.2.5 Sydney Water.*** Sydney Water is the public utility of Sydney, Australia, responsible for the management of water and wastewater systems.

- Inspection and condition assessment:

  Sydney Water mainly focuses on the condition assessment of CI water mains. For NDE, it utilizes LPR to evaluate corrosion potential, and MFL and ultrasound to evaluate the extent of corrosion in pipes. Sydney Water has conducted condition assessment for over 10 years.

- Models:

  Sydney Water utilizes several types of models/programs to analyze water pipes for various pipe materials, including CI, DI, AC, steel, and plastic.

  *KANEW* – Sydney Water used the KANEW program to generate and analyze long-term capital investment needs for renewal of water pipes. The long-term capital forecast tool is based on the asset deterioration curve, which is deterministic. Detailed information about KANEW is available in Section 6.2.

  *PARMS* – Sydney Water is implementing PARMS to predict the condition of water pipelines. It supports pipeline renewal prioritization focusing on the analytical assessment such as pipeline replacement and pressure reduction in terms of associated risks.
  Detailed information about PARMS is also available in Section 6.2.

  Both software programs are described in detail in Section 6.

Sydney Water constantly validates and calibrates the failure curves based on analysis and failure history. In its experience, the accuracy of the forecast from the PARMS model is close to the actual asset performance.

Advantages of utilizing KANEW consist of benefiting from the long-term capital investment forecast as well as the prediction of asset deterioration. Limitations of KANEW include that the failure curve represents a cohort of pipes and not a specific individual asset that is based on limited variables. The analysis only utilizes historical data to develop rates based on estimated averages. Furthermore, Sydney Water feels that there is no explicit relationship between the asset performances versus the deterioration curve. In the end, KANEW is not suitable for critical water mains and does not take risk into account.

***3.16.2.6 Washington Suburban Sanitary Commission.*** The Washington Suburban Sanitary Commission (WSSC) is a public utility located in Maryland.

- Inspection and condition assessment:

  WSSC uses several inspection and condition assessment techniques. WSSC is primarily focused on the inspection of large diameter PCCP transmission mains (greater than 48-in. diameter). They expect to increase their inspection budget to allow for the inspection of up to

12 mi per year of PCCP transmission mains with a target of every 6 years for the interval between repeat inspection events (WSSC, 2011).

*Internal Visual/Sounding Inspection* – to detect visible cracks, damage, and delaminations within the PCCP.

*Electromagnetic Inspection* – RFEC/transformer coupling is used to detect and quantify the number of wire breaks in PCCP. WSSC has primarily used the P-Wave® system (Section 3).

*Sonic/Ultrasonic Pulse Echo* – The sonic/ultrasonic velocity and resonant frequency (pulse echo) measurements are used to identify deficiencies in pipe condition, such as broken pre-stressing wires and damaged or deteriorated concrete.

*Long Term Acoustic Monitoring* – Acoustic fiber optic cable (see Section 3) has been permanently installed in 16.9 mi of PCCP transmission mains to listen for additional wire break activity, as an early warning sign and to establish the rate of deterioration after a baseline condition assessment is conducted (WSSC, 2011).

Other techniques used by WSSC include Sahara®, SmartBall®, LeakfinderRT™, and electrochemical potential survey (see Section 3).

- Models:

The WSSC prioritizes the inspection, maintenance, repair, rehabilitation, and replacement of water pipes utilizing various methods for pipe material type and diameter. The WSSC is currently in the process of developing a Utility Master Plan (UMP).

*Nessie Curve Model* – See description provided earlier for the Newport News System.

*Risk Model* – developed in house and includes six parameters to aid the WSSC in prioritizing rehabilitation, repair, replacement or inspection of pipes. The risk factors include:

(1) Land use factor
(2) Repair history
(3) Operational needs
(4) Known manufacturing defects
(5) Last inspected
(6) Diameter

Each of these risk factors has a defined set of ratings per specific description of the risk factor.

*Risk Model for Large Diameter PCCP (>48-in.)* – WSSC has developed a specific program for condition assessment of its PCCP transmission mains (48-in. diameter or greater). A risk rating is generated based factors including the pipe size, pipe age, pipe design standards and manufacturer, land use, operational criticality, repair history, and date of last inspection (WSSC, 2011).

***3.16.2.7 City of Hamilton Public Works Department.*** The City of Hamilton Public Works Department Water and Wastewater Division is a public utility located in Hamilton, Ontario, Canada. Hamilton's water infrastructure program consists of an asset management program that includes a GIS. Hamilton has developed a replacement profile for water mains utilizing the Hansen asset management system, which is a key component for analysis required to estimate the timing of major interventions, such as rehabilitation and replacement. The replacement profile is primarily based on the age of the asset.

***3.16.2.8 Louisville Water Company.*** The Louisville Water Company (LWC) was established in 1860. The LWC's Pipe Evaluation Model (PEM) is a comprehensive planning and decision support tool designed to assess priorities for the replacement and rehabilitation of water pipes. The PEM is a detailed scoring system that assigns points based on over 23 assessment factors that can take on different weighting schemes to allow LWC to adjust its model based on annual priorities. The main assessment factors included within this model are categorized as follows:

- Geographical (central business district, redevelopment areas, and roadway classifications)
- Hydraulic (main size, fire flow availability, number of parallel mains, high pressure frequency, and low pressure frequency)
- Maintenance (main break frequency, joint leak frequency, material samples, corrosive soil data, installation date, pipe type, joint type, and maintenance record)
- Quality of Service (taste and odor complaints, discolored water complaints, water quality data, number of domestic/fire services, lead service frequency, dead-end water mains, and paving age).

The renewal projects are scored according to all of these criteria and then the projects are ranked based upon their degree of importance. LWC uses a criterion of 2 breaks per mile per year as the threshold for replacement. Additional information about LWC's PEM approach can be found in Bhagwan (2009).

***3.16.2.9 Philadelphia Water Department.*** The Philadelphia Water Department (PWD) has the distinction of being one of the first water distribution systems in the U.S. with operations beginning in 1815. PWD collects data on the maintenance history, date and location of main breaks, installation year, size of main, and other information that is compiled in a database. PWD has developed a point-score system for water main replacement, which was first described in O'Day et al. (1986). Based on input from PWD to the Virginia Tech Survey, the scoring system is currently comprised of a combination of the age of the water main and its break frequency as shown in Table 3-44. The goal of the PWD is to further assess mains with scores of seven or more points.

**Table 3-44. PWD Point Score System**

| Year of Installation | Points Assigned |
|---|---|
| pre 1854 | 5 |
| 1854-1877 | 4 |
| 1878-1900 | 3 |
| 1901-1938 | 2 |
| 1939-1966 | 1 |
| 1967-present | 0 |
| **Break Frequency (Block-by-Block Basis)** | **Points Assigned** |
| A. Two or more breaks in the most recent year OR | 2 per break |
| B. Three or more breaks within the past 5 years AND | 2 per break |
| C. Each break not accounted for in A or B above | 1 per break |

## 4.0: FROM DISTRESS/INFERENTIAL INDICATORS TO CONDITION RATING

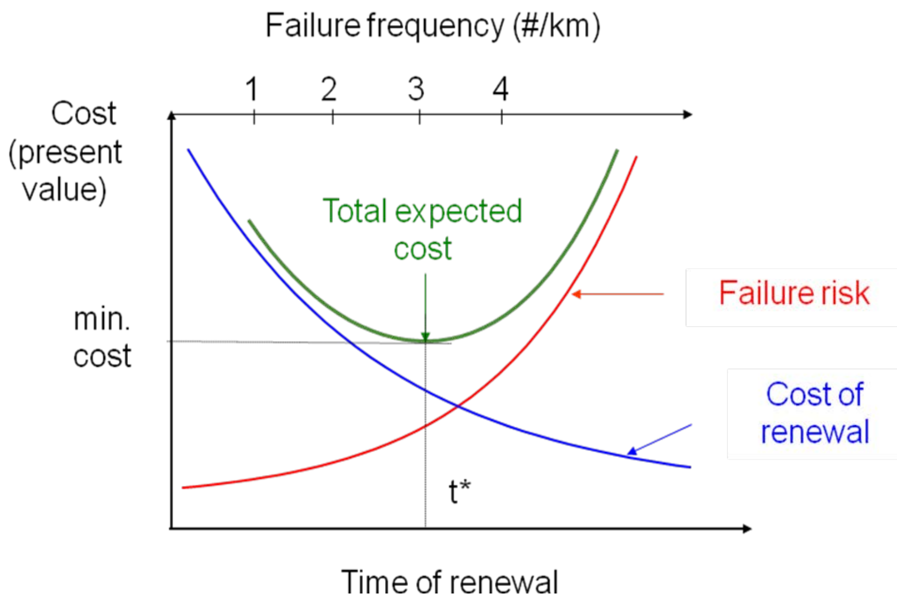
### 4.1 Background

As water mains age they deteriorate. As discussed in Section 1, this deterioration can be classified into two categories: (i) structural deterioration, which diminishes the pipe's structural resiliency and ability to withstand the various types of stresses; and (ii) deterioration of the pipe's inner surfaces, resulting in diminished hydraulic capacity, degradation of water quality and even diminishing structural resiliency in cases of severe internal corrosion.

The probability of a water main failure due to structural deterioration can be estimated using physical (mechanistic) models (Rajani and Kleiner, 2001) and/or statistical (empirical) models (Kleiner and Rajani, 2001). Statistical models develop empirical relationships between the pipe, its exposure to the external and operational environments, and its observed failure frequency. Physical models attempt to mimic realistic (albeit simplified) field conditions taking into account both the external environment and internal pipe operational conditions. Empirical models typically over-simplify a complex reality in order to (hopefully) achieve "80% of the answer with 20% of the effort." In contrast, physical models, because they are based on universal physical/mechanistic principles, can theoretically be applied in any circumstances provided all pertinent data are available. However, pertinent data usually comprise a substantial amount of data to represent specific conditions and environments. These data are either unavailable or very costly to obtain for even a modest portion of a distribution network. Therefore, physical models are useful to gain good insight into deterioration and failure mechanisms, as well as to explore small-scale critical cases, but are impractical for large-scale implementation.

The essence of asset management is the balance between system performance and cost. This balance behaves differently in small distribution mains compared to large transmission mains, and this difference leads to different forms of management for the two classes of assets. Figure 4-1 illustrates these differences qualitatively. As a pipe ages and deteriorates (without renewal), its probability of failure (or failure frequency) increases and the risk increases as well. Note that the risk is expressed as the present value (PV) of expected cost (or consequences) of failure. At the same time, the discounted (or PV) cost of the renewal declines as pipe renewal is deferred. The total expected life-cycle cost typically forms a convex shape, where the minimum point depicts the optimal time of renewal (t*). The top part of Figure 4-1 illustrates a typical case of small distribution mains, where the cost of failure is relatively low; as a consequence, the optimal time of renewal corresponds to a relatively higher failure frequency. In contrast, the bottom part of Figure 4-1 illustrates that for large transmission mains, where the cost of failure is typically very high, the optimal strategy is to avoid failure altogether, i.e., failure prevention rather than failure frequency management. It must be noted that there is no clear cutoff pipe diameter below which a pipe is considered 'small' and above which it is considered 'large'. For a metropolitan like New York City, for example, large transmission mains could be pipes of at least 30-in. (750 mm) in diameter, while for a small town a 12-in. (300 mm) diameter pipe might be considered large. It appears that in the context of asset management the relative importance of the pipe in the network, or even more precisely, the relative magnitude of the consequences of its failure, are the prevailing factors in considering the pipe as 'small' or 'large.'

In addition to the economic difference between small distribution and large transmission mains described above, the reality is that failure frequency in large transmission mains is a rather rare event, whereas in small distribution mains failure is much more frequent, which facilitates the ability (generally absent in large mains) to use the statistical analysis of historical failure patterns to discern deterioration rate and forecast future failure rates. This statistical exercise is a de facto condition assessment of small distribution mains. In large transmission mains, this type of analysis is not practical because of the rarity



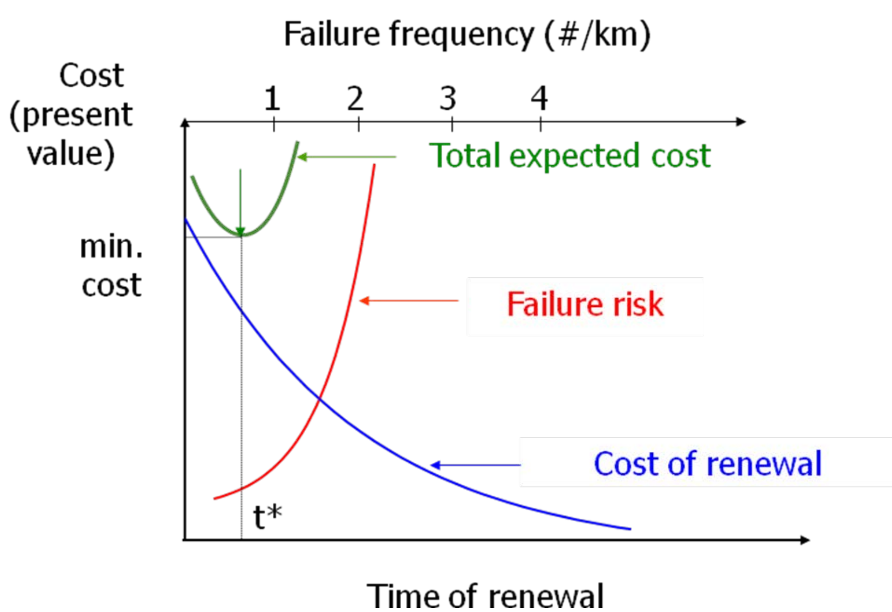




**Figure 4-1. Optimal Renewal Frequency for Distribution Mains (top) versus Transmission Mains (bottom). (Time scale not necessarily same in both graphs.)**

of failures. Failure prevention in large transmission mains requires knowledge about the condition and deterioration rate of the pipe before it fails. Distress and inferential indicators obtained from inspection of these large pipes provide information about the condition of the pipe; however, in order to estimate deterioration rate (i.e., changes in condition over time) as well as prioritize assets for renewal (i.e., compare condition of different pipes), these distress/inferential indicators need to be translated into a rating scale that is consistent over time as well as over different types of pipe.

Note that Figure 4-1 illustrates idealized cases, where the minimum point on the convex curve is quite clear. There are cases where this curve is not as well behaved. When the aging rate (i.e., the rate at which failure frequency increases) is similar in magnitude to the discounting factor (the "interest" rate used to compute PV), the convexity of this curve can become quite flat, and the point of minimum cost becomes less crisp. When the cost of failure is relatively low compared to the cost of renewal and the discounting factor relatively high, the curve can take the shape of the "hammock-chair" as described by Herz (1999), with no definite minimum, indicating that renewal could perhaps be postponed indefinitely.

Currently, most NDT technologies intended to identify distress indicators are too costly to be justified for small water distribution mains. Some of the technologies intended to identify inferential indicators (e.g., those related to soil properties) are used for both small and large pipes. However, the predominant approach for assessing the condition of small diameter distribution mains is based on the observation of historical failure frequency (in many publications also referred to as number of previous failures). Historical failure frequency is, strictly speaking, neither exactly a distress indicator nor a pure inferential indicator, but can be viewed as a little of both and interpreted as a surrogate measure. This issue is discussed in more detail in the next section. Also, in this context the definition of pipe 'failure' is an important issue. In most cases, for practical reasons pipe 'failure' is defined as a 'maintenance event' (for which there is a work order recorded). However, if a utility endeavors to differentiate between the break types, and if staff is sufficiently trained and experienced and willing to do so credibly, then any statistical/empirical analysis could be refined to gain better insight into the true deterioration patterns of the pipe inventory.

Two types of raw data can be obtained from the inspection technologies described in Section 3: visual-based technologies provide direct information about actual, observable distress indicators (cracks, delamination, etc.), while most other NDT technologies (UT, magnetic, etc.) provide signal patterns that require interpretation into distress indicators. In the latter case, signal interpretation is almost always proprietary knowledge and is not the focus of this section, which concentrates on techniques and methods intended to interpret distress/inferential indicators into pipe condition ratings.

Techniques and methods to interpret distress indicators into condition ratings started predominantly in sewer condition assessment (late 1970s, early 1980s) and are in the process of evolving into the realm of large water transmission mains (since the mid 1990s). One obstacle to this evolution is the fact that large diameter water transmission mains are inherently expensive components of the water supply system, and due to their high cost, the system often does not have enough redundancy to function while they are off-line for inspection. Some of the developers and/or providers of NDT services developed their own methods to interpret distress indicators into condition ratings, but these are generally proprietary and often appropriate for a specific NDT technology (e.g., RFEC/TC by PPIC in Section 3) and therefore are not addressed here.

## 4.2 Point-Score Protocols for Sewers

Many water utilities use some type of point score method, usually developed in house, for the evaluation of their water mains. These point score methodologies are typically customized for use by a single utility and the scoring criteria and weighting factors (although published in the literature) have not been standardized across the water industry. Examples of customized approaches implemented by the Louisville Water Company and the Philadelphia Water Department are provided in Section 3.16. In contrast, the point score method is a fairly established and consistent practice in the condition assessment of sewer mains, therefore the sewer examples are provided here as an illustration.

A few protocols are available in the literature to record distress indicators in sewers and then translate them into condition rating, e.g., WRc of UK, NRC of Canada, Water Services Association of Australia

(2002), Cemagref (2003) and the National Association of Sewer Service Companies (NASSCO). The WRc protocol is perhaps the most widely used protocol today. It was initiated in 1978 as a five-year research project to investigate failures of sewer mains. Based on this research, the *Sewerage Rehabilitation Manual* was developed (WRc, 1986; WRc, 1993; WRc, 1994; WRc, 2001). The latest manual includes a computerized grading system compatible with European defect coding systems, and new design methods for renovation techniques (WRc, 2001). The NRC's protocol is known as *Guidelines for Condition Assessment and Rehabilitation of Large Sewers* (Zhao et al., 2001). These guidelines were developed in partnership with several Canadian municipalities and consulting engineers and are intended for large diameter sewers (>900 mm) only. NASSCO developed a similar set of coding standards based on the WRc system (WRc, 2001).

Virtually all protocols largely use a point scoring approach, whereby each type of defect is assigned a score ("deduct value"). After a score is assigned to each observed defect, all of the scores are tallied and the totals are used to rate the condition of the pipe. While WRc uses a scale of 165 deduct values for condition rating, NRC uses a 20-point scale. Table 4-1 illustrates the point score schemes of both protocols. Note that both protocols contain separate scoring schemes for structural and operational observed defects. This report addresses only the structural aspects of pipe condition. It is clear that while WRc uses a five grade rating, NRC uses six, from zero to five where 0 = excellent, 1 = good (G), 2 = fair (F), 3 = poor (P), 4 = bad (B) and 5 = imminent collapse (IC). Table 4-2 provides a summary of structural distress indicators (defects) and their associated point scores (deduct values) in the two protocols.

**Table 4-1. Comparison of Two Point Scoring Protocols**

| **Protocol** | **Condition states (structural)** | | | | | |
|---|---|---|---|---|---|---|
| | 0 (E) | 1 (G) | 2 (F) | 3 (P) | 4 (B) | 5 (IC) |
| WRc scores | N/A | < 10 | 10 - 39 | 40 - 79 | 80 - 164 | > 165 |
| NRC scores | 0 | 1 - 4 | 5 - 9 | 10 - 14 | 15 - 19 | 20 |

Note: N/A = not applicable

The process of applying the protocol to real situations is inherently imprecise and subjective. Often, two different evaluators will provide different scores to the same observed defects. Moreover, from Table 4-1, it can be seen that a score of 80 (WRc protocol) is in fact equivalent to 164 because both scores would translate to the same condition state of 4.

### 4.3 Fuzzy Theory Based Techniques

The interpretation of pipe distress indicators (observed through NDT) into a condition rating involves a certain amount of subjective judgment. Fuzzy sets with their notion of membership functions are very well suited to accommodate this subjectivity. Further, practitioners have an intuitive understanding of the deterioration process in buried pipes, although many of the relationships between cause and effect are not well understood, let alone quantified. Fuzzy techniques seem well suited to capture this intuition.

**4.3.1 Fuzzy Synthetic Evaluation.** The fuzzy synthetic evaluation (FSE)-based approach comprises three steps: fuzzification of raw data, aggregation of the various types of observed distress indicators, and de-fuzzification that adjusts the fuzzy condition rating to a practical crisp format (Kleiner et al., 2005; Rajani et al., 2006).

**Table 4-2. Distress Indicators and Their Assigned Scores (Deduct Values)**

| Distress indicator (defect)[a] | Distress level[b] | Unit | Scores NRC | Scores WRc |
|---|---|---|---|---|
| Longitudinal crack | • Light (up to 3 cracks, no leakage) | m | 3 | 10 |
| | • Moderate (> 3 cracks, leakage) | m | 5 | 40 |
| Circumferential crack | • Light (up to 3 cracks, no leakage) | m | 3 | 10 |
| | • Moderate (> 3 cracks, leakage) | m | 5 | 40 |
| Diagonal crack | • Light (up to 3 cracks, no leakage) | m | 3 | N/A |
| | • Moderate (> 3 cracks, leakage) | m | 5 | N/A |
| | • Severe (multiple cracks, leakage) | m | 10 | 40 |
| Longitudinal fracture | • Light (< 10 mm) | m | 5 | 40 |
| | • Moderate (10 – 25 mm or more than one) | m | 10 | 80 |
| | • Severe (> 25 mm) | m | 15 | N/A |
| Circumferential fracture | • Light (< 10 mm) | m | 5 | 40 |
| | • Moderate (10 – 25 mm or more than one) | m | 10 | 80 |
| | • Severe (> 25 mm) | m | 15 | N/A |
| Diagonal fracture | • Light (< 10 mm) | m | 5 | 40 |
| | • Moderate (10 – 25 mm or multiple) | m | 10 | 80 |
| | • Severe (> 25 mm) | m | 15 | N/A |
| Deformation | • Light (< 5% change in diameter) | m | 5 | 20 |
| | • Moderate (5% – 10% change in diameter) | m | 10 | 80 |
| | • Severe (11% – 25% change in diameter) | m | 15 | 165 |
| Surface damage (spalling) | • Light | m | 3 | 5 |
| | • Moderate | m | 10 | 20 |
| | • Severe | m | 15 | 120 |
| Joint displacement | • Light (< ¼ pipe wall thickness) | each | 3 | N/A |
| | • Moderate (¼ – ½ pipe wall thickness) | each | 10 | 1 |
| | • Severe (> ½ pipe wall thickness) | each | 15 | 2 |
| Broken pipe | - | each | 15 | 60 |
| Collapse | - | each | 20 | 165 |

(a) This is a partial list, based on the cited references.
(b) Definitions sometimes vary between the two protocols.

For example, if a distress indicator shows loss of 50% of pipe wall thickness, given a pre-defined fuzzy scale of mild, medium, severe, or critical for wall loss, the observed 50% loss could be fuzzified to somewhere between severe and critical, say 0.7 membership to severe and 0.3 membership to critical. It follows then that if multiple distress indicators are provided, each is fuzzified in this way into an appropriate, pre-defined fuzzy scale.

In the next step, the fuzzified values of the various distress indicators are aggregated with appropriate weights (weights are assigned according to the importance of a given distress indicator to the determination of the overall condition rating) to provide a fuzzy condition rating. Rajani et al. (2006) proposed a seven-state condition rating (excellent, good, adequate, fair, poor, bad, and failing).

On such a scale, an example of a fuzzy condition rating could be 0, 0.1, 0.3, 0.4, 0.15, 0.05, 0, where these values denote membership values corresponding to the seven condition states. As practitioners intuitively understand that realistically the condition rating of a pipe cannot have non-zero membership values to more than three contiguous states, the proposed method provides a process to re-distribute membership values (wherever needed) to conform to this practical constraint.

In the final step, the fuzzy condition rating can be de-fuzzified into a representative (equivalent to mean) value. This is done to enable comparisons as needed.

This method was proposed to facilitate a deterioration model based on a so-called fuzzy Markov process, which is described in the next section. It should be noted that fuzzy-based methods require mathematical training that is typically not provided to practitioners, therefore these methods do not lend themselves to easy in-house implementation. However, computer software (e.g., T-WARP – see Section 6.2) can make the technique available through an easy-to-understand user interface.

**4.3.2 Fuzzy Composite Programming.** Fuzzy composite programming (FCP) is a mathematical programming technique that employs a single level normalized/non-normalized distance-based technology to rank a discrete set of solutions based on their distances from an ideal solution. Pipe condition assessment needs to combine completely different variables into an overall condition indicator. This problem is actually making decisions based on multiple criteria (often formally known as multiple-criteria decision making). Vairavamoorthy et al. (2006) applied this method to the condition rating of pipe, with condition indicators considered in the FCP method shown in Figure 4-2. The following steps are involved (Vairavamoorthy et al., 2006):

- Identify the pipe condition indicators;
- Prepare the hierarchical structure of pipe condition indicators;
- Obtain the weightings for each indicator and decide the balance factor (balance factor determines the degree of compromise between indicators of the same group);
- Normalize all of the indicators into scale [0, 1];
- Obtain a fuzzy member by using the FCP-based hierarchical aggregation process for each pipe;
- Rank the fuzzy numbers.

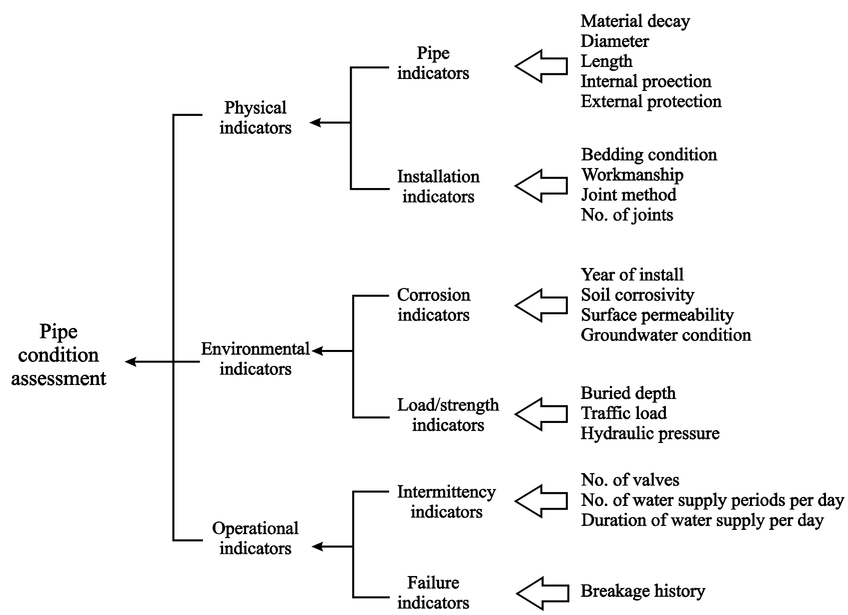



**Figure 4-2. Pipe Condition Assessment Indicators (Vairavamoorthy et al., 2006)**

It should be noted that some of the raw criteria (Figure 4-2 right column) such as bedding condition and workmanship are not easily quantified. Also, some of these raw criteria (no. of supply periods) may be appropriate only for developing countries. Furthermore, the FCP method can be sensitive to the weights and balance factors. An example of the calculation is available in Vairavamoorthy et al. (2006).

This methodology was tested for utilities in India and Uganda. In these countries, water supply can be intermittent leaving periods of time where the water mains are unpressurized, which increases the risk of contaminant ingress. For this reason, the results of the FCP method for water main condition were compared to seepage envelopes from foul water bodies (ditches, sewers, etc) to create maps of regions with high risk for cross contamination. For example, a pipeline predicted to be in poor condition via the FCP model and in close proximity to seepage sources was given a high risk for cross contamination. Although significant data was collected from each utility as shown in Figure 4-2, these were largely indirect indicator data on the pipe condition and the results of the FCP model were not verified to pipe condition in the field (Vairavamoorthy et al., 2006).

## 4.4 Data Fusion and Data Mining

The purpose of data fusion is to combine the capabilities of each sensor modality with historic data to provide more accurate and complete information (Juliano et al., 2005). Three factors should be considered:

(a) Redundancy of information presented in the sensor modalities;
(b) Diversity in the sensor modalities;
(c) Complementary sensor modalities.

Data fusion is not limited to sensory data. The analysis benefits from multi-source information to diminish the uncertainties and inaccuracies in the data.

Data mining is defined as a technique to identify useful patterns or trends from data. Where pipe condition assessment is concerned, the data mining technique is applied to predict the residual life, burst rate, and/or leakage based on historical records, or other attributes, e.g., pipe age, diameter, soil type, etc., (Savic and Walters, 1999).

**4.4.1 Hierarchical Evidential Reasoning.** A hierarchical evidential reasoning (HER) model was proposed to combine different distress indicators at different hierarchical levels using the Dempster - Shafer's (D-S) rule of combination (Bai et al., 2008).

The framework of the HER model is illustrated in Figure 4-3. The attribute at a higher level is evaluated based on the assessment of its associated lower-level factors. In the HER model, elements of basic evidence are referred to as factors, which are essentially distress indicators. Attributes are the categories (Rajani et al., 2006). The distress indicators (factors) are aggregated to evaluate categories (attributes). The overall condition is obtained by the aggregation of categories.

The most important part of applying the D-S fusion rule is the definition of basic probability assignment (BPA). The BPA for each factor is derived based on a degree of confidence assigned to these condition states as well as the associated importance and reliability of the data.

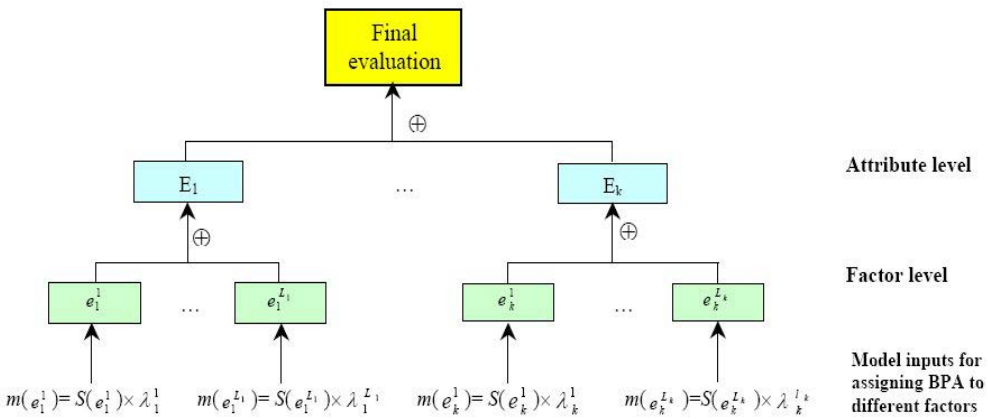



**Figure 4-3. The Framework of Hierarchical Evidential Reasoning**
**(Bai et al., 2008)**
**Note: where *m* represents the bodies of evidence, *S* the condition rating, and *e* the contributing factors.**

**4.4.2 Incremental Learning.** LEARN++ is a supervised learning algorithm that makes it possible for a classifier to learn incrementally from new data without forgetting what has been learned in earlier training sessions (Polikar et al., 2001). The current LEARN++ algorithm is implemented for the classification with multilayer perceptron (MLP) neural networks. The idea is to assemble weak classifiers to achieve an improved performance in classification. This makes LEARN++ very useful for the interpretation of pipe inspection data. The inspection data may not be sufficient or good enough when a classifier is being trained. Nevertheless, the classifier can be further improved when new data become available. Fusion of MFL, thermography, and ultrasonic data for gas transmission pipeline was described in a technical report (Mandayam et al., 2006). Improved performance for defect identification and characterization was reported.

**4.4.3 Genetic Algorithm.** A genetic algorithm (GA) is a search technique that can be applied in large, complex, and multimodal search spaces. It emulates biological principles, such as inheritance, mutation, selection, and crossover, to solve complex optimization problems. The GA has the ability to locate regions that potentially contain an optimal solution for a given problem by searching the solution space (Shaw et al., 2004).

Three researchers were identified in the literature as having applied this technique to water mains including Babovic et al. (2002), Vitkovsky et al. (2000), and Dandy and Englehardt (2001). GA was used to search the best scoring model to determine the risks of pipe bursts (Babovic et al., 2002). The scoring model that is a function of associated characteristics of bursting pipe can be established by analysis of burst events that have already occurred. GA was also employed as a search method in the inverse transient technique for leak detection (Vitkovsky et al., 2000). GA has also been applied to identify the schedule of pipe replacement in a deteriorating water distribution system (Dandy and Engelhardt, 2001).

### 4.5 Data Driven Approaches to Predict Condition Rating Based Only on Inferential Indicators

The high cost of thorough inspection to observe distress indicators has motivated researchers to try and predict the condition of pipes based on a reduced set of indicators, or just on inferential indicators, which are generally easier and cheaper to obtain.

The data driven approaches comprise multiple input data, the corresponding observed output data, and a mathematical relationship that is supposed to link a set of inputs with a corresponding output. This mathematical process is usually not a-priori known. However, given sufficient data, it can be discerned by a process known as 'training'. Whereas the mathematical relationship (sometimes also called 'model') comprises mathematical operators and coefficients, the training process in essence finds the coefficients that, given a set of inputs, computes outputs that match the observed outputs as closely as possible. In the context of interpretation of inferential indicators to condition ratings of pipes, the input is a set of observed distress indicators and the output is the condition rating of the pipe. The general steps involved are:

(a) For a sufficiently large and diverse inventory of pipes, perform full inspection, including distress and inferential indicators. The inferential indicators will serve as input data.

(b) Based on these distress indicators, obtain condition ratings for these pipes. These condition ratings will serve as a set of output data.

(c) Model training (or calibration): calibrate the proposed mathematical relationship (by varying the various coefficients) so that given a set of inputs (inferential indicators), the model computes an output (condition rating) that is as close as possible to the observed condition rating that corresponds to the same inputs. Repeat for all pipes.

(d) Validation: once the model has been calibrated, examine its ability to predict condition rating (based on inferential indicators only) on a set of pipes that were not used in the calibration process.

It should be noted that so far, these efforts have been applied only to sewers and not to water mains. Some of the mathematical relationships or models documented that have been used for this purpose include the following (non-exhaustive) list:

- Logistic regression (e.g., applied by Ariaratnam et al. [2001] to the sewer system in Edmonton Canada). Distress indicators were largely obtained by CCTV inspection (Davies et al., 2001).
- Artificial neural networks (e.g., Najafi and Kulandaivel, 2005; Tran, 2007; Moselhi and Fahmy, 2008; Al-Barqawi and Zayed, 2006; Achim et al., 2007).
- Bayesian statistics (e.g., Fenner and Sweeting, 1999).
- A metaheuristic linear classifier model (Wright et al., 2006).
- A fuzzy-based method to estimate soil corrosivity from soil properties (Sadiq et al., 2004).
- A fuzzy expert system to estimate the soil corrosivity potential from soil properties (Najjaran et al., 2006).
- Fuzzy PROMETHEE (preference ranking organization method for enrichment evaluation) (Zhou et al., 2009).

The benefits of this class of methods would depend on three main issues: (a) the ability of the model to predict asset condition in a credible manner, (b) the ratio between the cost of obtaining inferential data and that of actual inspection, and (c) the general state of the asset network. Given a large network and limited resources to inspect its entirety in a reasonable time period, and given a relatively credible model and inexpensive inferential data, the use of such a model could be quite beneficial in screening assets for detailed inspection.

# 5.0: WATER MAIN DETERIORATION MODELS

Deterioration models of water mains can be classified into two main categories, physical (or mechanistic) models and statistical/empirical models. While physical models are scientifically more robust and widely applicable (i.e., they could be applied to various pipe materials and external conditions, given data availability), they are limited by existing knowledge and available data. Some of the data required for the physical models are very costly to obtain if at all available at a resolution of an individual pipe. These costs may be justified only for major transmission water mains, where the cost of failure is significant and failure needs to be prevented. In contrast, the empirically derived statistical models can be applied with various levels of input data and may thus be useful in relatively small water mains for which the low cost of failure entails failure frequency management (not prevention), and therefore expensive data acquisition campaigns cannot be economically justified.

## 5.1 Physical/Mechanistic Models

The physical mechanisms that lead to pipe breakage are often very complex and are not completely understood, but recent efforts look promising. These physical mechanisms involve several aspects including pipe-intrinsic properties (e.g., material type, pipe geometry, type of joints, quality of installation); loads (including internal loads due to operational pressure and external loads due to soil overburden, traffic, frost and third party interference); and finally material deterioration (due to external and internal chemical, bio-chemical and electro-chemical environment). The principles of the structural behavior of buried pipes are, for the most part, fairly well understood. However, the understanding of issues such as frost loads and structural deterioration due to chemical processes and fatigue, is still quite varied, but substantial progress has been made in this direction in recent years.

In North America in the 1990s, a water mains survey concluded that about two thirds of the installed water mains inventory was CI and DI pipes, about 15% was AC pipes, and the rest was plastic, concrete, steel, and others (Kirmeyer et al., 1994; Rajani and McDonald, 1995). In the last decade and a half, these proportions have likely changed to some degree (as the shares of PVC and concrete pressure pipes have increased at the expense of metallic and AC pipes); however, the majority (>60%) of existing water mains is still CI and DI pipes.

The predominant deterioration mechanism on the exterior of CI and DI pipes is electro-chemical corrosion causing damage in the form of corrosion pits. The damage to grey CI is often disguised by the presence of graphitization. Graphitization is a term used to describe the network of graphite flakes remaining behind after the iron in the pipe has been leached away by corrosion. Either form of metal loss represents a corrosion pit that will grow with time and eventually may lead to a water main break. The physical environment that surrounds the pipe has a significant impact on the deterioration rate. Factors that accelerate corrosion of metallic pipes are stray electrical currents, and soil characteristics such as moisture content, chemical and microbiological content, electrical resistivity, aeration, redox potential, etc. The interior of a metal pipe may be subject to tuberculation, erosion and crevice corrosion resulting in a reduced effective inside diameter, as well as a breeding ground for bacteria. Severe internal corrosion may also impact pipe structural deterioration. The supply water affects the internal corrosion in pipes through its chemical properties, e.g., pH, dissolved oxygen, free chlorine residual, alkalinity, etc., as well as temperature and microbiological activity.

The long-term deterioration mechanisms in PVC pipes are not as well documented mainly because these mechanisms are typically slower than in metallic pipes and also because PVC pipes have been used commercially only in the last 35 to 40 years. A recent WaterRF research report (Burn et al., 2005) provides a rather comprehensive account of available pertinent information on the structural properties of

PVC pipes as well as on the impact of water quality on the pipe material. Additionally, while hydrocarbons such as high octane gasoline do not affect PVC, other contaminants such as toluene can permeate the pipe wall if present in sufficiently high concentration levels (Ong et al., 2008).

AC and concrete pipes are subject to deterioration due to various chemical processes that either leach out the cement material or penetrate the concrete to form products that weaken the cement matrix. The presence of inorganic or organic acids, alkalis, or sulfates in the soil is directly responsible for concrete corrosion. In reinforced and prestressed concrete, low pH values in the soil may lower the pH of the cement mortar to a point where corrosion of the prestressing or reinforcing wire will occur, resulting in substantial weakening of the pipe (Dorn et al., 1996).

There are four general classes of pipe failures: holes due to corrosion; circumferential breaks caused by longitudinal or bending stresses; longitudinal breaks caused by hoop stresses; and split bells. Split bells can be the result of pipe rotation due to differential movement or small cracks introduced during transportation and/or installation which, over the years, were subjected to cyclical loads until fatigued to failure (Rajani, 2010).

Circumferential breaks are typically the result of thermal contraction acting on a restrained pipe, bending stress (beam failure caused by soil differential movement or prolonged leaks creating large voids in the bedding), inadequate trench and bedding practices, or third party interference or a combination of one or more of the above. The contribution of operating pressure to longitudinal stress, although small, may increase the risk of circumferential breaks when occurring simultaneously with one or more of the other sources of stress. In some circumstances (e.g., power failure in a pumping station, fast closure of a valve on a pipe that is subject to high flow velocity), transient pressures can introduce large stresses in the pipe.

Longitudinal breaks caused by transverse stresses are typically the result of either hoop stress due to pressure in the pipe, ring stress due to soil cover load, ring stress due to live loads caused by traffic, increase in ring loads when penetrating frost causes the expansion of frozen moisture in the ground, or a combination of one or more of the above.

Rajani and Kleiner (2001) provided a comprehensive review of the main physical models found in the literature through the end of the 1990s. It is not the intent of this report to duplicate their review. Instead, Table 5-1 provides the main points of each model reviewed by Rajani and Kleiner (2001), along with some additional models published in the last 10 years. Table 5-1 is by no means an exhaustive list of all relevant models. Table 5-1 is presented in chronological order of year of publication of reference.

**Table 5-1. Physical/Mechanistic Models for Pipe Deterioration**

| Reference | Issues Addressed | Data Requirement | Comments |
|---|---|---|---|
| Spangler, 1941; Watkins and Spangler, 1958 | Pipe-soil interaction analysis | Pipe elastic modulus, internal pressure, pipe geometry, trench geometry, some soil/backfill properties, vehicle impact factor and wheel load on surface. | Assumes in-plane action only – appropriate for large diameter pipes, but not for small diameter pipes. Thermal issues not addressed, as well as material deterioration and soil shrinkage effect. |

**Table 5-1. Physical/Mechanistic Models for Pipe Deterioration (Continued)**

| Reference | Issues Addressed | Data Requirement | Comments |
|---|---|---|---|
| Rossum, 1969; Doleac, 1979; Doleac, et al., 1980 | Predict remaining wall thickness of pit cast mains | Soil properties such as pH, resistivity and redox potential. | Time to failure estimated using a power law as a function of soil properties and time. |
| Kumar et al., 1984 | Corrosion status index | Pipe age, type, wall thickness, diameter, joints, soil properties – resistivity, chlorides, sulfides, pH, moisture, year of first leak (if available). | Power-law model used for corrosion rate. Empirical/statistical formulation (time-exponential to forecast breaks). |
| Kiefner and Vieth, 1989 | Residual structural resistance | Material properties, 3D characteristics of pipe corrosion pits. | Developed for oil and gas steel pipelines. Appropriate for ductile materials, e.g., DI and steel, but not CI. |
| Randall-Smith et al., 1992 | Estimate remaining service life of water mains | Current age and maximum pit depth. | Time to failure estimated assuming that corrosion is a linear function of time. |
| Ahammed and Melchers, 1994 | Estimate the probability of failure in steel pipelines | Mechanical properties of steel and constants for power-law corrosion model. | Probability of failure was found to be most sensitive to constants for the corrosion model |
| Rajani et al., 1996 | Pipe-soil interaction analysis of jointed pipe | Same as Watkins and Spangler (1958) plus thermal properties of pipe and special soil properties to simulate pipe-soil adhesion. | Longitudinal bending is considered as primary action – appropriate for small diameter pipes. No account for material deterioration and for soil shrinkage effects. |
| Rajani and Zhan, 1996; Zhan and Rajani, 1997 | Frost loads | Continuous freezing index, soil backfill porosity, segregation potential, unfrozen water content, thermal gradient at the freezing front, frost depth. | Provides frost load as a function of time |
| Pandey, 1998; Hong, 1997 | Estimate the probability of failure in steel pipelines | Mechanical properties of steel and constants for power-law corrosion model. | Pipeline reliability estimated with a probabilistic analysis framework that incorporates impact of inspection and repair activities. |
| Rajani and Makar, 1999 | Residual structural resistance | Similar to that proposed by (Kiefner and Vieth, 1989). | Addresses fracture toughness. Appropriate for brittle material for CI. Needs large-scale validation. |
| Rajani and Makar, 1999 | Estimate the remaining service life of grey cast iron mains | Pipe geometry and mechanical properties of cast iron and soil properties used in the Rossum (1969) model or empirical parameters used to define two-phase corrosion model. | Time to failure estimated assuming that corrosion pits grow as predicted by Rossum or two-phase corrosion models. |

**Table 5-1. Physical/Mechanistic Models for Pipe Deterioration (Continued)**

| Reference | Issues Addressed | Data Requirement | Comments |
|---|---|---|---|
| Hadzilacos et al., 2000 | Reliability-based prediction of pipe residual life. | Pipe elastic modulus, internal pressure, pipe geometry, trench geometry, some soil/backfill properties, vehicle impact factor and wheel load on surface, and information of loss of bedding support. | Probability of failure determined for different failure modes. |
| Deb et al., 2002 | Mechanistic models to rank deterioration of cast iron pipes. | Pipe geometry and mechanical properties of cast iron, soil properties, and climate data. Rossum's pit growth model was used to determine pit growth from soil properties. | Mechanistic model is essentially the same as developed by Rajani and Makar (1999) except that out-of-plane response was included besides the in-plane response. Modifications to the parameters in Rossum's pit growth model were not explained. |
| Rajani and Tesfamariam, 2004; Tesfamariam et al., 2006 | Pipe-soil interaction analysis of partially supported jointed pipes. | Pipe elastic modulus, internal pressure, pipe geometry, trench geometry, some soil/backfill properties, vehicle impact factor and wheel load on surface, thermal properties of pipe and special soil properties to simulate pipe-soil adhesion and information of loss of bedding support. | Longitudinal bending is considered as primary action – appropriate for small diameter pipes. Does not account for material deterioration and for soil shrinkage effects. |
| Davis et al., 2007 | Prediction of failure in PVC pipes. | Pipe geometry, material properties (Young's modulus, yield strength, other coefficients), Soil properties, internal pressure, burial depth, crack growth parameters. | Fracture mechanics used to model failure stress as a function of internal pressure, external loads, residual stresses in the pipe, pipe and crack geometry. Paris law assumed for crack growth. Probabilistic treatment of variability in material properties and degradation rate. |
| Moglia et al., 2008 | Failure prediction in cast iron pipes. | Pipe geometry, age, operating pressure, corrosion rate, pipe material properties (to determine tensile strength), soil properties (to determine dead load), dynamic external loads. | Deterministic limit state (based on fracture mechanics), with probabilistic inputs. Monte-Carlo simulation used to compute failure time, where corrosion rate is assumed linear over time. |

**Table 5-1. Physical/Mechanistic Models for Pipe Deterioration (Continued)**

| Reference | Issues Addressed | Data Requirement | Comments |
|---|---|---|---|
| Rajani and Tesfamariam, 2007 | Estimate the remaining service life of grey cast iron mains with consideration of partially supported jointed pipes. | Pipe elastic modulus, internal pressure, pipe geometry, trench geometry, some soil/backfill properties, vehicle impact factor and wheel load on surface, thermal properties of pipe and special soil properties to simulate pipe-soil adhesion and information of loss of bedding support and corrosion model constants. | Longitudinal bending is considered as primary action – appropriate for small diameter pipes. Corrosion, loss of bedding support, temperature differential and pipe material toughness are identified as the most important parameters to influence pipe longevity. |
| Davis et al., 2008 | Prediction of failure in asbestos cement pipes. | Pipe geometry and material properties extracted by testing of specimens, soil/bedding properties, burial depth, operating pressure. | Model assumes linear rate of strength loss. Probabilistic treatment of variability in material properties and degradation rate. |

## 5.2 Statistical/Empirical Models

Statistical/empirical models quantify the structural deterioration of water mains by analyzing historical performance data. In small distribution water mains, this historical performance is manifested in observed breakage frequency. Historical performance of large transmission mains is usually measured on an ordinal condition rating scale. Kleiner and Rajani and (2001) provided a comprehensive review of the major statistical/empirical models found in the literature through the end of the 1990s. Table 5-2 provides the main points of each model reviewed by Kleiner and Rajani (2001), along with some additional models published in the last 10 years. Table 5-2 is by no means an exhaustive list of all relevant models. Table 5-2 is presented in chronological order of year of publication of reference.

**Table 5-2. Statistical/Empirical Models for Pipe Deterioration**

| Reference | Type | Type Of Deterioration | Data Required | Comments |
|---|---|---|---|---|
| Shamir and Howard, 1979 | Deterministic | Breakage frequency | Pipe length, installation date, breakage history. | Time exponential model. Analysis more effective on homogenous cohorts, therefore data on pipe diameter, material, soil type, break type, etc. very useful. |
| Clark et al., 1982 | Deterministic | Breakage frequency | Time of installation, breakage history, type and diameter of the pipe, operating pressures, soil corrosivity and zoning composition of area overlaying pipe. | Mixed time-linear and time-exponential model. Additional types of data such as the type of breaks and pipe vintage required to enhance model. |
| McMullen, 1982 | Deterministic | Breakage frequency | Saturated soil resistivity, soil pH, redox potential. | Model predicts time to first break. |
| Kettler and Goulter, 1985 | Deterministic | Breakage frequency | Same data as Shamir and Howard (1979). | Time linear model. |

**Table 5-2. Statistical/Empirical Models for Pipe Deterioration (Continued)**

| Reference | Type | Type Of Deterioration | Data Required | Comments |
|---|---|---|---|---|
| Kulkarni et al., 1986 | Probabilistic | Breakage frequency | Pipe length, breakage history, data to create pipe cohorts (more data more refined analysis). | Based on Bayesian analysis of relative breakage frequencies in the various cohorts. |
| Walski, 1987 | Deterministic | Breakage frequency | Same data as Shamir and Howard (1979) plus information on the method of pipe casting and pipe diameter. | Time exponential model. Data to enable homogenous cohorts very useful. |
| Andreou et al., 1987a; 1987b; Marks et al., 1987; Brémond, 1997; Eisenbeis, 1994; Rostum, 2000 | Probabilistic | Breakage frequency | Pipe length, installation year, operating pressure, % low land development, breakage history, soil corrosivity. | Proportional hazards model for inter-break duration. Not all listed data are essential. Other data types could be incorporated if available. |
| Constantine and Darroch, 1993; Miller, 1993; Constantine et al., 1996; Rostum, 2000; Economou et al., 2008 | Probabilistic | Breakage frequency | Mean static pressure, overhead traffic conditions, pipe diameter, material length soil type. | Time-dependent Poisson-based models. Not all listed data are essential. Other data types could be incorporated if available. |
| Jacobs and Karney, 1994 | Deterministic | Breakage frequency | Pipe length, age, breakage history. | Time linear model. Data to enable homogenous cohorts very useful. |
| Li et al., 1997; 1996; 1995 | Probabilistic | Condition rating | Asset condition rating and age. | Markov-based model with non-homogeneous transition probabilities. |
| Madanat et al., 1995; Mauch and Madanat, 2001 | Probabilistic | Condition rating | Asset condition rating. | Markov deterioration processes, with underlying latent continuous deterioration process. Models were developed for general infrastructure assets, not specifically pipes. |
| Herz, 1996; Kropp and Baur, 2005 | Probabilistic | Survival analysis | Data to create pipe cohorts, installation year, historical replacement year, expert opinion on pipe life expectancy. | Cohort survival model base on the Herz probability distribution. |
| Lei, 1997; Eisenbeis et al., 1999 | Probabilistic | Breakage frequency | Pipe age, diameter, length, material, traffic loading, soil acidity, soil humidity, breakage history. | Accelerated life-based models. Not all listed data are essential. Other data types could be incorporated if available. |
| Hong, 1998 | Probabilistic | Condition rating | Pipe operating pressure and remaining strength. | Markov-based model. Condition states defined as ratio between pressure and strength. |

**Table 5-2. Statistical/Empirical Models for Pipe Deterioration (Continued)**

| Reference | Type | Type Of Deterioration | Data Required | Comments |
|---|---|---|---|---|
| Rostum et al., 1999 | Probabilistic | Condition rating | Pipe condition ratings, age. | Time duration between deterioration states a random variable with a Herz probability distribution. |
| Gustafson and Clancy, 1999a | Probabilistic | Breakage frequency | Detailed breakage history, data to create pipe cohorts. | Breakage history modeled as a semi-Markov process in which each break order (e.g., 1st, 2nd, 3rd break, etc.) is considered a "state" in the process and the inter-break time it is considered the "holding time" between state (i - 1) and state i. |
| Abraham and Wirahadikusumah, 1999;, Wirahadikusumah et al., 2001 | Probabilistic | Condition rating | Pipe condition rating. | Markov chain process applied to sanitary sewers. Four phases considered in pipe life. Transition probabilities stationary within each phase. |
| Kathula and McKim, 1999; McKim et al., 2002 | Probabilistic | Condition rating | Pipe condition rating. | Markov chain process applied to sewers. Expert opinion used to derive transition probabilities. Later introduced risk ratios. |
| Ariaratnam et al., 1999; 2001; Davies et al., 2001; Cooper et al., 2000 | Probabilistic | Condition rating | Various inferential indicators. | Models base on multi-covariate logistic regression, where one of the covariates is pipe age. |
| Dandy and Engelhardt, 2001 | Deterministic | Breakage frequency | Breakage history, data to create pipe cohorts. | Model based on power law increase in breakage frequency. Coefficients extracted by pure regression. |
| Kleiner, 2001 | Probabilistic | Condition rating | Pipe condition ratings preferably based on two or more consecutive inspections. Alternatively – expert opinions. | Semi-Markov based model. |
| Micevski et al., 2002 | Probabilistic | Condition rating | Pipe condition rating. | Markov-based model for deterioration of storm water sewers. Transition probabilities assumed homogeneous over time. |
| Park and Loganathan, 2002 | Deterministic | Breakage frequency | Breakage history, data to create pipe cohorts. | A mixed time-exponential/time-linear model. |

**Table 5-2. Statistical/Empirical Models for Pipe Deterioration (Continued)**

| Reference | Type | Type Of Deterioration | Data Required | Comments |
|---|---|---|---|---|
| Mailhot et al., 2003; Dridi et al., 2005 | Probabilistic | Breakage frequency | Breakage history, data to create pipe cohorts. | Distinguish between inter-break time in lower order breaks (Weibull or gamma distribution) and higher order breaks (exponential distribution). Assume linear or power law relationship between mean duration and age in the higher order breaks. |
| Watson et al., 2004 | Probabilistic | Breakage frequency | Breakage history, data to create pipe cohorts. | Deterioration model based on the nonhomogeneous Poisson process. No explicit time-dependency is assumed, rather it is implied based on Bayesian updating. |
| Kleiner and Rajani, 2004 | Deterministic | Breakage frequency | Breakage history, data to create pipe cohorts, history of cathodic protection, climate history. | D-WARP. Time exponential model. Can consider dynamic (time-dependent) covariates (e.g., climate, cathodic protection). |
| Kleiner et al., 2006a | Probabilistic. | Condition rating | Distress indicators from at least one inspection – interpreted into condition rating. | T-WARP. Deterioration of large water transmission mains modeled as fuzzy Markov deterioration process. |
| Giustolisi and Berardi, 2007; Berardi et al., 2008 | Deterministic | Breakage frequency | Breakage history, data to create pipe cohorts. | Model(s) based on evolutionary polynomial regression (EPR): fit a parsimonious polynomial to observed historical breakage rates, using genetic algorithm. |
| LeGat, 2008a | Probabilistic | Breakage frequency | Breakage history, pipe data (material, diameter, etc. that could have potential influence on breakage rates. | Model based on Yule (pure birth) process, with a linear extension. |
| LeGat, 2008b | Probabilistic | Condition rating | Asset condition rating (preferably more than one), and age. Covariates can be considered if known. | Model for drainage pipes, based on nonhomogeneous Markov chain. Transition probabilities are derived from Gompertz survival probabilities. |
| Kleiner and Rajani, 2009 | Probabilistic | Breakage frequency | Breakage history, data to create pipe cohorts, history of cathodic protection, climate history. | I-WARP. Model based on the nonhomogeneous Poisson process, with capability to address dynamic (time-dependent) covariates. |

Tables 5-1 and 5-2 provide models found in the literature for pipe deterioration.  This compilation was not intended to provide practitioners with sufficient information to decide which of the models is most suitable for their own circumstances; as such a decision would require a level of details that is beyond the scope of this report.  Further, it would have been useful to know which of these models have actually been used in practice, by whom and under what circumstances, and to what degree of success.  However, such information is usually not available.  For example, Grigg (2007) reported on a survey that comprised 45 water utilities, where only a few employed break prediction methods from the literature and some developed their own method.

As a general observation, it may be safely assumed that the likelihood of a model to be used in practice increases significantly if the model is implemented in a software program that is publicly available.  In Section 6.2, a list of publicly available software programs is provided, some of which are based on models described in Table 5-1 or 5-2.  Consequently, these models are likely to have been (or to be) used in practice, while others are likely to have been used sporadically at best.

# 6.0: DECISION SUPPORT FOR WATER TRANSMISSION AND DISTRIBUTION SYSTEMS

There are a vast number of models in the literature intended to optimize or near-optimize decisions related to the renewal of water mains, addressing issues such as prioritization of water mains for renewal, scheduling water mains for renewal, and also selection of renewal alternatives for water mains. These models may differ from each other by the number and nature of objectives addressed, the data required, the solution method, and the constraints considered. The detailed description of all of these models is beyond the scope of this report. The objective of this section is therefore twofold: to provide the reader with a general overview of most of the relevant decision support models (Section 6.1), and to provide a general description for those models that have been transformed into actual decision support tools in the form of software products that are publicly available either as a commercial product, a research tool or a prototype computer program (Section 6.2). Additional information on decision support tools for predicting the performance of water distribution and wastewater collection systems can also be found in Stone et al. (2002).

## 6.1 Decision Support Models

Table 6-1 provides an extensive (though not exhaustive) list of decision-support approaches/models found in the literature. Many of the entries in this table correspond to entries in Table 5-1, as the decision-support approach was offered as a natural continuation of the pipe deterioration models. Some entries in Table 6-1 correspond to (usually components of) some software packages.

Table 6-1 is presented in chronological order of year of publication of reference.

**Table 6-1. Decision Support Methods and Approaches Found in the Literature**

| Reference | Objectives | Constraints | Optimization Method | Comments |
|---|---|---|---|---|
| Shamir and Howard, 1979 | Minimize cost | No | Calculus | Optimal pipe replacement timing is that which minimizes the discounted costs of pipe replacement and breakage. Simplified approach laid basis for numerous extensions and enhancements. |
| Clark et al., 1982 | Minimize cost | No | Calculus | Similar to Shamir and Howard (1979). |
| Walski, 1987; Walski and Pelliccia, 1982 | Minimize cost | No | Calculus | Optimal pipe replacement timing is that which minimizes the discounted costs of pipe and valve replacement, leakage and leak detection, pipe and valve breakage. Alternatively, corresponding critical break rate can be computed. |
| Lansey et al., 1992 | Minimize cost | Hydraulic, (minimum pressure, continuity, mass conservation) | Coupled network solver (KYPIPE) and General Reduced Gradient (GRG2) | Define planning periods, each with associated breakage frequency, demand flows, pipe friction coefficients. For every pipe find the period in which to replace/reline/reinforce, and for every pump the period in which to replace/reinforce, so as to minimize total discounted cost of replacement, repair and pumping energy. |

**Table 6-1. Decision Support Methods and Approaches Found in the Literature (Continued)**

| Reference | Objectives | Constraints | Optimization Method | Comments |
|---|---|---|---|---|
| Li and Haims, 1992a; 1992b | Maximize water main availability, allocate funds to maximize overall system availability | Available funds | Calculus | Two-stage decision-making process based on Andreou et al.'s (1987a; b) proportional hazard method (PHM) deterioration. A. Semi-Markovian model applied to individual water mains to optimize repair/replace decision while maximizing the availability of the water main. B. Multilevel decomposition approach to optimally distribute available funds among the distribution network components, so as to maximize overall system availability. |
| Kim and Mays, 1994 | Minimize cost | Hydraulic (minimum pressure, continuity, mass conservation) | Implicit enumeration scheme using a branch and bound algorithm along with a generalized reduced gradient procedure | Finds which pipe to replace/reline/ rehabilitate/continue repair, while minimizing total cost of replacement, rehabilitation, reline, repair and pumping energy. Time dimension not considered. |
| Halhal et al., 1997 | Multi-objective (cost and improved service) | Cost (pressure shortfall is considered an objective) | Structured Messy genetic algorithm | Produce a Pareto front of non-dominated solutions with tradeoff between cost and level of service, defined in four dimensions, including improved pressure, improved maintenance, improved operations and improved water quality. The four dimensions are combined using weights. |
| Kleiner et al., 1998a; Kleiner et al., 1998b | Minimize cost | Hydraulic (minimum pressure, continuity, mass conservation) | Dynamic programming & partial enumeration coupled with network solver EPANET | Each pipe in the network assumed to have exponential increase in break frequency and logarithmic decline in hydraulic capacity. Schedules pipe replacement/relining to minimize total life-cycle discounted costs. Life-cycle costs consider perpetual deterioration/replacement cycles. |
| Gustafson and Clancy, 1999b | Minimize cost | N/A | Calculus | Based on their pipe deterioration model, generate potential breaks history, using Monte Carlo simulations. Optimal replacement timing is that which minimizes total discounted cost of replacement and breakage. |
| Cooper et al., 2000 | Prioritize pipes for renewal based on failure risk scores | N/A | Risk-based ranking | Failure probability determined by logistic regression, using multiple covariates (soil, bus and car traffic, peak pressure, etc). Failure consequences determined by various factors (affected properties, repair cost, etc.) that are discerned from GIS. |
| Kleiner, 2001 | Minimize risk | N/A | Calculus | Optimal time for intervention is that which minimizes the expected cost of failure. Expected cost of failure is calculated as product of probability of failure and its consequence. |

### Table 6-1. Decision Support Methods and Approaches Found in the Literature (Continued)

| Reference | Objectives | Constraints | Optimization Method | Comments |
|---|---|---|---|---|
| Dandy and Engelhardt, 2001 | Minimize costs | Hydraulic, (minimum pressure, continuity, mass conservation), budget | Genetic algorithms coupled with network solver EPANET | Assumes breakage frequency follows power law; minimize the present value of replacement, repair, and damage costs, by scheduling pipe replacement, including selection of appropriate diameters. |
| Loganathan et al., 2002; Park and Loganathan, 2002 | Minimize cost (by replacement after the threshold break) | N/A | Calculus | Total cost of pipe when it is replaced after the nth recorded break includes n breaks since installation + pipe replacement. The nth break is a threshold break if total discounted cost associated with it is smaller than that associated with the (n + 1)th break. |
| Hahn et al., 2002 | See comments | N/A | N/A | Expert opinion pooled to build knowledge base 'SCRAPS' to support an expert system intended for the prioritization of the inspection of sewers. |
| Burn et al., 2003; Moglia et al., 2008 | Prioritize pipes for replacement | N/A | Calculus | PARMS. Pipe deterioration modeled as Nonhomogeneous Poisson Process. Alternatively, in some cases, physical models are used. Probability of failure is combined with consequences to obtain risk. Whole life costing can be considered. Decision based on scenario-generation and analysis. |
| Kleiner and Rajani, 2004 | Minimize cost, analyze scenarios | N/A | Calculus | D-WARP. For a cohort, find optimal renewal time. Also examine scenarios that combine mixed strategies of replacement and cathodic protection. |
| Watson et al., 2004 | Minimize costs | Hydraulic constraints only in the discrete event simulator | Calculus + Monte-Carlo simulations to propagate uncertainty | Power law deterioration model (derived from his nonhomogeneous Poisson process). Optimal pipe replacement timing is that which minimizes costs of pipe replacement and breakage (no discounting). Incorporates some MCS to consider uncertainties in the model coefficients. |
| Kleiner et al., 2006b; Kleiner, 2005 | Minimize cost given acceptable risk level | N/A | Fuzzy mathematics and calculus | T-WARP. Combine fuzzy Markov deterioration with fuzzy failure consequences to define fuzzy risk over pipe life. If risk tolerance is exceeded then renew pipe, otherwise schedule next inspection. Alternatively, select desired risk/cost tradeoff from a Pareto front of non-inferior strategies. |
| Alvisi and Franchini, 2006a; 2006b | Minimize cost, leakage, unserved demand | Hydraulic, (minimum pressure, continuity, mass conservation) | Multi-objective GA | Assumes power law increase in breakage rate. Considers multiple demand patterns to calculate shortfall in supply (vs. demand) when a pipe fails. Leak rate calculated under the assumption that un-reported (and un-repaired) breaks (or leaks) are a known proportion of total reported (and repaired) breaks. |

**Table 6-1. Decision Support Methods and Approaches Found in the Literature (Continued)**

| Reference | Objectives | Constraints | Optimization Method | Comments |
|---|---|---|---|---|
| Dandy and Engelhardt, 2006 | Multi-objective (cost, reliability) | Budget, hydraulic (minimum pressure, continuity, mass conservation) | Multi-objective GA | Assumes breakage frequency follows power law. Reliability comprises total number of customers affected by failure. This number includes customers whose supply is cut off (local interruption) and customers who experience too low pressure (global interruption). |
| Hong et al., 2006 | Minimize cost | N/A | Calculus | Nonhomogeneous Poisson process assumed for increase in pipe breakage frequency. Minimize life-cycle costs (repair and replacement), where life-cycle costs consider perpetual deterioration/replacement cycles. |
| Berardi et al., 2007 | Multi-objective (cost, reliability) | Hydraulic, (minimum pressure, continuity, mass conservation) | Multi-objective genetic algorithm coupled with network solver EPANET | Cost includes pipe break and replacement. Reliability is defined as the number of customers affected by a broken pipe. Breakage frequency discerned using Evolutionary polynomial regression. |
| Renaud et al., 2007 | Prioritize pipes for replacement | Hydraulic (continuity, mass conservation) | Point score (weighted) | Part of SIROCO. Uses PHM for breakage prediction. Pipe hydraulic criticality calculated as the demand shortfall resulting from the pipe failure. Scores are assigned to each pipe based on hydraulic criticality, impact of failure on traffic, on service level, expected damage, and repair/replace costs. In addition, two so-called opportunity criteria, namely coordination with roadwork and need for rehabilitation index. |
| Cabrera et al., 2007 | Minimize cost | N/A | Calculus | Similar to Shamir and Howard (1979) but considers also water loss during repair, energy vested in this water loss, social and other occasional costs that typically accompany a breakage event. |
| LeGauffre et al., 2007 | Multi-objective prioritization of pipes for replacement | N/A | Prioritization process follows the Electre-Tri method | Basis for Care-W ARP. Compile a list of evaluation criteria, each with a quantitative or qualitative rating scheme. Using these criteria, define n (typically n = 2) threshold profiles that define (n + 1) grades (e.g., poor, adequate, good). Classify pipe inventory into the (n + 1) grades using the Electre-Tri process. Select the worst ranking pipes for renewal. Threshold profiles can be re-calibrated to given budget. |
| Dridi et al., 2008 | Minimize cost | Hydraulic, (minimum pressure, continuity, mass conservation) | Genetic algorithm coupled with network solver EPANET | Based on deterioration of breakage frequency model by Mailhot et al. (2000). Considers also deterioration of hydraulic capacity. For a given planning period, schedule for replacement those pipes that yield minimum discounted cost. |

**Table 6-1. Decision Support Methods and Approaches Found in the Literature (Continued)**

| Reference | Objectives | Constraints | Optimization Method | Comments |
|---|---|---|---|---|
| Davis et al., 2008 | Maximize PV of cost benefit difference | N/A | Calculus | Probability of pipe failure based on their model of AC pipe deterioration. Benefits include the cost of breaks avoided (by pipe replacement) through the period of pipe physical existence. Costs include replacement as well as pre-replacement inspection costs. |
| Nafi et al., 2008 | Multi-objective (cost, hydraulic reliability) | Hydraulic (continuity, mass conservation) | Multi-objective, modified GA | All pipes with at least three historical breaks for which failure probability is greater than 0.5 within the planning horizon are candidates for replacement. Two hydraulic reliability indices, i.e., proportion of peak demand the network can supply when a pipe fails, and the proportion of the nodes the network can feed with a pre-defined minimum pressure. |
| Nafi and Kleiner, 2009 | Minimize cost | Budget | Heuristics - GA | Given break predictions (e.g., with I-WARP), perform medium-term replacement planning while considering economies of scale, and adjacent infrastructure. |

N/A = information not available.

Table 6-1 provides approximately 29 models found in the literature for decision support of pipe renewal. As in Section 5, this compilation was not intended to provide practitioners with sufficient information to decide which of the models is most suitable for their own circumstances; such a decision would require a level of detail that is beyond the scope of this report. Some of these models are simple enough for a competent engineer to implement in a spreadsheet environment, while others require expertise and resources that most water utilities do not have.

As for the deterioration models, it may be safely assumed that the likelihood of a model to be used in practice increases significantly if this model is implemented in a software program that is publicly available. In Section 6.2, a list of publicly available software programs is provided, some of which are based on models described in Table 6-1. Consequently, these models are likely to have been (or to be) used in practice, while others are likely to have been used sporadically at best.

## 6.2 Publicly Available Decision Support Software Tools

The available decision support (DS) software tools are described below in alphabetical order.

**6.2.1 Computer Aided Rehabilitation of Water Networks (CARE-W).** CARE-W was a European Union-sponsored collaborative research effort (under the fifth Framework Programme of the European Commission 2001 to 2004) intended to improve decision support tools in water supply systems. The outcome of this project was a decision support toolbox carrying the same name. As of August 2009, the software package is not commercially available, nor is it available for the public at large. It is available for consultancy services through its principal developers and it may also be selectively available for research (Saegrov, 2009).

CARE-W is a toolbox software package. It contains several independent decision support tools (developed by several participating researchers) that are connected to the database module, which is the only common link between them. Some of the tools described below, in particular CARE-W FAIL and CARE-W LTP, have been further advanced in recent years by Cemagref of France and Baur and Kropp of

Germany. CARE-W has been used for rehabilitation planning in several cities worldwide, including Las Vegas, U.S., Lyon, France and Oslo, Norway (Saegrov, 2010).

The tools included are:

- CARE-W PI (Performance Indicator): used to estimate the current and future condition of water network against a range of key performance indicators. It is based on the International Water Association (IWA) PIs. There are a total of 49 PIs in five groups, including operational, quality of service, financial, water resources, and physical indicators. There is an allowance for additional PIs that are more difficult to define and quantify, such as network reliability, remaining life, and others. It is noted that 153 single pieces of utility information are required to assess the 49 PIs. In addition, 29 external indicators, not under utility control, such as climate, soil, and topography, are considered in the evaluation (Batista and Alegre, 2002).
- CARE-W FAIL comprises five different models/tools to forecast pipe failure: (a) Failnet-Stat, developed at Cemagref (France) based on the proportional hazards model (Table 5-2); (b) Winroc, developed at NTNU (Norway), based on the non-homogeneous Poisson process (Table 5-2); (c) AssetMap1, developed at INSA-Lyon (France) based on the Markov chain (Table 5-2); (d) AssetMap2, developed at INSA-Lyon, which uses a technique called "Poisson regression" to help users identify cohorts that are significantly different from one another; and (e) Utilnets, developed at SINTEF (Norway) (Table 5-1) (Eisenbeis et al., 2002).
- CARE-W REL (Reliability) comprises three different models to compute network reliability: (a) AquaRel, developed by SINTEF, Department of Water and Wastewater, Norway, couples a hydraulic simulator (EPANET) and pipe failure rate to quantify the impact of pipe condition on the reliability of the network. This impact is measured as the number of nodes that suffer critical pressure reduction due to pipe failure; (b) FailNet-Reliab, developed by the Hydraulic and Civil Engineering unit of Cemagref in France, also couples a hydraulic simulator and pipe failure rate to quantify the impact of pipe condition on the reliability of the network. However, this impact is measured as the shortfall of supply versus demand flows due to the failure of one or more pipes; and (c) RelNet, developed at the Brno University of Technology, Czech Republic, also couples a hydraulic simulator (ODULA) and pipe failure rate; however, it does so probabilistically using Monte-Carlo simulations. Subsequently, a probability distribution of entering into a deficient pressure state is computed for every node in the network. These distributions are converted to nodal reliabilities, which can be aggregated to provide network reliability (Eisenbeis et al., 2002).
- CARE-W ARP (Annual Rehabilitation Project) is a multi-objective decision support tool to prioritize water mains for renewal based on CARE-W analysis tools, as well as on any additional relevant information that is available to the user. A more detailed description is provided in Table 6-1.
- CARE-W LTP (Long Term Planning) comprises three tools (Scenario Writer, Rehabilitation Strategy Manager and Rehabilitation Strategy Evaluator), all developed at the Technical University of Dresden. The Scenario Writer is a tool intended for the development of consistent scenarios. This form of analyses is essential for a fair and robust comparison of scenarios, which require many assumptions about the future. The Rehabilitation Strategy Manager is largely based on the KANEW model (described below) and is intended to simulate the long-term effects of specific rehabilitation options. The Rehabilitation Strategy Manager is used to identify the best long-term rehabilitation strategy, using techniques based on the "Formalized Weighting and Ranking Procedure" (Rostum et al., 2004).

**6.2.2 KANEW.** KANEW is a cohort survival model for infrastructure assets that was developed by Professor Herz while at Karlsruhe University in Germany. Later, after joining the Technical University of Dresden (Germany), Professor Herz and his students continued to evolve the initial model both independently as well as within the framework of CARE-W. In 1995-1998, the Roy Weston Research Group, in collaboration with Professor Herz, developed a computer application based on the model and applied it to several water utilities in North America (Deb et al., 1998). This project was sponsored by the American Water Works Association Research Foundation, which is now called the Water Research Foundation (WRF). This early and limited software version is available in Microsoft® Access format to Foundation subscribers. KANEW is based on a probability distribution proposed by Professor Herz (1996). This probability distribution is fitted to (i.e., its parameters are discerned for) a cohort of pipes (i.e., a relatively homogeneous group of pipes with the same age, same material, diameter, etc.). Initially, this fitting was done based on the water utility's historical practices of pipe replacement, or alternatively, based on expert opinion as to the proportion of pipes (or quantiles) expected to survive to various age levels. Over the years the fitting techniques evolved to rely more on actual failure data rather than perception. Since this is a three-parameter probability distribution, the knowledge (or guess) of three quantiles (typically 10th percentile, median and 90th percentile) is sufficient to compute these parameters. Once the parameters are computed, service life prediction of the cohort can be estimated. Typically pessimistic, most probable, and optimistic scenarios are explored for each cohort to account for uncertainties in the accuracy of the estimated parameters.

The current version of the KANEW software includes a module to manage pipe inventory, a module to perform the cohort survival calculations, a failure and break forecasting module, a module to perform cost calculation, a module to support decision making by running and comparing various scenarios, an economic data module, and a strategy comparison module. In evaluating scenarios, the software enables the consideration of short-, medium- and long-term impacts of a given policy on the population served, on the structural condition of the network, and costs. KANEW is currently used mainly in Germany, but also in the U.S. and Australia for long-term renewal planning of water and gas mains.

**6.2.3 Pipeline Asset and Risk Management System (PARMS).** PARMS is a suite of computer applications based on models that have been developed by Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia. Currently, two PARMS applications are publicly available as commercial products, PARMS-Planning and PARMS-Priority, both used by several Australian water utilities (Marlow et al., 2007). While PARMS-Planning forecasts the number of pipe failures and assesses cost implications of various high-level, long-term pipe renewal scenarios, PARMS-Priority allows prioritization of individual pipes for renewal and facilitates low-level planning of pipe replacement and some aspects of network operations.

PARMS-Planning uses two types of pipe deterioration models, a non-homogeneous Poisson based model (Table 5-2) (Jarrett et al., 2003) for high probability, low-consequence failure of pipes, requiring reactive renewal strategies (management of failure frequency) and probabilistic/physical models (Table 5-1) (Davis et al., 2007; Davis et al., 2008; Moglia et al., 2008) for low-probability, high-consequence failure of pipes requiring proactive renewal strategies (failure prevention). After calibration using the recorded history of failures, these models are used to forecast the number of failures expected in the planning period. The cost of failure is computed based on user-input, including cost of repair, extent of the network that experiences interruption of service, penalties and rebates. Based on future failure frequency and cost, as well as pipe replacement cost, candidate pipes for replacement are identified. These are either replaced or the costs associated with their failure are reduced by installing additional isolation valves to reduce impact on the network.

PARMS-Priority enables the prioritization of candidate pipes for replacement or alternatively for the installation of additional pressure reducing valves and/or additional isolation valves. It focuses mainly on high probability, low-consequence failure of pipes, requiring reactive renewal strategies (management of failure frequency). It uses the same non-homogeneous Poisson-based model as PARMS-Planning for pipe deterioration. Cost calculations are also similar to PARMS-Planning except for a more refined, probabilistic approach to the computation of failure consequence. PARMS-Priority allows the examination of complex scenarios, involving single and pipe cluster replacements, pressure reduction and shutoff block reduction (Moglia et al., 2006).

**6.2.4 Pipe Rehabilitation Management (PiReM).** PiReM is a decision support tool for the rehabilitation management of water supply systems (TuGraz, 2006). It is based on the doctoral thesis of Daniela Fuchs-Hansuch at the Graz Technical University (Austria), which was not available at the time this report was prepared. The PiReM software currently consists of two modules: long-term (20 to 50 years) rehabilitation management, and medium-term (5 years) rehabilitation management. From the general description provided in TuGraz (2006), it appears that the underlying approach used in PiReM is similar to the KANEW method, i.e., analysis of cohorts of pipes using the Herz distribution, and the examination of rehabilitation scenarios subject to assumptions about the deterioration characteristics of replacement pipes. The long-term planning module of the program is said to also consider environmental influences but an explanation of how this is done was not available. The medium-term rehabilitation planning module ranks individual pipes for renewal based on forecasted failure rate, risk of corrosion, obsolescence of pipe material and diameter (old types that are difficult to repair and maintain) as well as other technical, economical, and business management criteria that are not specified (TuGraz, 2006).

**6.2.5 Water Main Rehabilitation Planner (WARP).** WARP comprises a set of planning tools, developed by NRC, for effective planning of water main renewal. WARP currently comprises four individual (non-integrated) tools: D-WARP (Distribution mains-WARP), T-WARP (Transmission mains-WARP), Q-WARP (Water Quality-WARP), and I-WARP (Individual [mains]-WARP).

D-WARP models the deterioration of water distribution pipe cohorts (in terms of the increase of their breakage rates) as an exponential function of age (see Table 5-2). The analysis of water main breakage patterns takes into consideration time-dependent factors such as temperature, soil moisture and rainfall deficit, and CP strategies, including both hot-spot and methodical retrofit CP. D-WARP allows the user to see the "optimal" time of pipe replacement (Table 6-1), as well as to generate, examine, and compare complex scenarios that include combinations of replacement and CP strategies. D-WARP is currently a stand-alone program, available for free download at the NRC Web site.

T-WARP models the deterioration of large diameter water transmission mains using a so-called fuzzy rule-based Markov deterioration process (Table 5-2). It requires that the pipe be inspected at least once to establish its condition rating. Future deterioration is forecasted to provide failure likelihood in the future based on past condition rating(s). The pipe owner is required to rate the consequences of pipe failure on a fuzzy scale. Given the likelihood and consequences of failure, a fuzzy risk of failure can be computed and a rehabilitation strategy can be formulated (Table 6-1). T-WARP is currently a software prototype, publicly available through WRF.

Q-WARP is a tool to predict the potential occurrence of various mechanisms of water quality deterioration that lead to water quality failures in the distribution network. Q-WARP models the complex nature of water quality processes in the distribution network as a set of so-called fuzzy cognitive maps. It enables the evaluation of multiple strategies (e.g., pipe renewal, cross connection control program) for reducing the risk of water quality failures, which leads to better-informed decision making. Q-WARP is currently a software prototype, publicly available through the WRF.

I-WARP models the deterioration of individual water distribution pipes (in terms of the increase of their breakage rates) as a nonhomogeneous Poisson process (Table 5-2). I-WARP is different from other nonhomogeneous Poisson process-based models in that it allows the consideration of time-dependent factors such as temperature, soil moisture and rainfall deficit, CP strategies, including both hot-spot and methodical retrofit CP, as well as user defined qualitative/quantitative factors (e.g., changes in operational conditions, leak-detection campaigns, etc.). I-WARP is currently a software prototype, publicly available through the WRF.

**6.2.6 WilCO.** WilCO is a modeling approach to manage resources or assets. It was developed by Peter Skipworth and Mark Engelhardt, who also founded the SEAMS Corporation, which currently markets WilCO in the form of a software package and/or a service. Although the approach was later made into a generic tool, it was originally developed specifically for water mains, with the intent of supporting water utilities in the UK in their quest to meet regulator's (Office of Water - OFWAT) requirements (Engelhardt and Skipworth, 2005).

The heart of WilCO is the so-called "model builder." It allows the user to define the performance of the asset (pipes) in terms of key performance indicators – KPIs (e.g., reliability, serviceability, customer complaints, breakage frequency, etc.) as well as the associated whole life costs. The software does not oblige the user to use a pre-defined deterioration model, but rather allows the users (for better or for worse) to define their own models and train (or calibrate) the models using their own data or expert opinion. Once the objective of the asset renewal planning is defined (e.g., maximize cost effectiveness or alternatively maximize cost benefit), WilCO employs search algorithms to find an 'optimal' solution. For example, to maximize cost-effectiveness subjected to predefined levels of KPIs, the user must provide the desired levels of KPIs. Alternatively, if the objective is to maximize cost-benefit, the user must provide the appropriate relationship between each KPI and its associated benefit. The software also includes "add-ons" that enable users to examine and compare scenarios, as well as rank, and prioritize and schedule individual assets for renewal action (Engelhardt and Skipworth, 2005).

## 7.0: TECHNOLOGY GAPS AND RESEARCH AND DEVELOPMENT NEEDS

Technology gaps in the area of condition assessment technologies for water transmission and distribution systems can be generally classified into four types:

- A complete absence of technology or method, capable of achieving a stated objective(s). Such objectives could include effective detection of distress indicators, accurate interpretation of distress indicators to condition rating, effective forecasting of deterioration, decision optimization, etc.
- A technology exists, but is too costly to apply for the required objective.
- Promising technology exists in other domains, but development work is required for adaptation to the domain at hand.
- Technology exists that is potentially useful, affordable, and valuable, but these attributes have not been adequately demonstrated, documented, and justified so that utilities are convinced that the investment in the technology will be worthwhile in the long run.

In the scope of water main NDE and condition assessment, many of the gaps are of the second and third types, but there are also gaps of the first and fourth types. The following is a list of gaps identified in the course of preparing this report. Although beyond the scope of this project, it would be a useful effort to rank the gaps and future research identified below by the impact and value to the water community. This could be accomplished through collaboration with the Water Research Foundation (WaterRF), water utilities, and other key stakeholders in order to determine the most pressing research needs and future technology investment efforts.

*NDE technologies:*

- **NDE of Small Diameter (≤12 in.) Metallic (CI and DI) Distribution Pipes.** CI and DI are the predominant pipe materials in distribution networks in North America and in most of Europe, Australia, South Korea and Japan. As alluded to in Section 2, elaborate inspection and condition assessment is economically justified only when it costs less than letting the pipe fail. Failure consequences of small distribution mains are currently low compared to the cost of most inspection technologies. Therefore, there is an urgent need to develop new, low cost NDE technologies for small diameter CI and DI pipes. These technologies will need to be reliable with operational costs low enough to justify wide usage for pipes that are relatively inexpensive to replace and whose failure consequences are relatively low.

  Existing technologies suitable for small diameter CI and DI pipes include RFEC, MFL, and ultrasound. Hydroscope, which was based on the RFEC technology, was available commercially in the late 1990s and early 2000s. Hydroscope could be launched into pipes through fire hydrants, but required pre-cleaning of tuberculated pipes. Further, it appears that it did not gain wide acceptance (probably due to its high cost). Recent developments indicate that the See Snake Tool (described in Section 3), also based on RFEC technology, has superseded Hydroscope. The See Snake Tool requires a dedicated launching chamber, but appears to be less restrictive on pipe pre-cleaning requirements. In-line MFL has size limitations (not suitable for small pipes) and external MFL requires costly excavation of pipes. The ultrasonic-based Super-pig reportedly achieves good results, but is currently a prototype (suitable for 10 to 12 in. diameter pipes only) that is not publicly available and the costs involved in its acquisition and operation are not yet known. Non-intrusive technologies, such as WallThicknessFinder (Section 3), capable of evaluating a relatively long section of pipe between two points, is a promising prospect, but is currently limited in providing the average condition of a pipe section (cannot locate corrosion pits) and, as such, is limited to function as a screening tool to identify candidates for intrusive (and expensive) inspection.

- **NDE of Large Diameter (>16 in.) Metallic (CI and DI) Transmission Mains.** Although corrosion is still a dominant mode of failure in these pipes, other important modes of failure include pipe rotation and cracks introduced in the pipe during transportation, installation and lead/leadite caulking (Section 2). These cracks typically occur near the joint, either at the bell or (less frequently) at the spigot end. Many of these cracks eventually develop into failure due to fatigue. There is a need for NDE technology capable of identifying such cracks, as well as joint rotation, preferably from the inside of the pipe to minimize pipe excavation with all its associated costs and disruptions. Early knowledge about the presence of such cracks and the prevention of excessive joint rotation could potentially result in tremendous savings of losses due to catastrophic failures of these large mains. Several innovative inspections technologies for CI pipes were tested under a separate task of this EPA TO 62 project to inspect a 2,000-ft long, 24-in. cast iron transmission main at Louisville, KY (in progress). This included a prototype PipeDiver™ and a custom See Snake Tool developed for a 24-in. diameter cast iron pipe, as well as several leak detection and acoustic pipe wall inspection technologies.

- **NDE of PCCP.** Current technologies for PCCP inspection are based on magnetic techniques (RFEC and its derivatives, see Section 3.4.2) and sound emissions. Magnetic techniques are capable of detecting discontinuities in the prestressing wire (i.e., wire breaks) but they cannot detect deteriorated (corroded) wires where breakage is imminent. Additionally, they cannot detect the presence of hydrogen embrittlement which, if present, can cause a sudden failure of wire(s). NDE technologies capable of detecting these phenomena, or perhaps inferring other signs of wire deterioration (e.g., delamination, concrete deterioration), would be beneficial for the early detection of PCCP pipe failures. The AE techniques (hydrophones, fiber optics) endeavor to capture the sound that a prestressing wire creates when it snaps. Properly placed and spaced sensors will detect wire snaps, but are not capable of quantifying damage that occurred prior to monitoring.

- **NDE of AC pipes.** There currently are no known NDE technologies for AC pipes. Early trials by Echologics to test an acoustic-based method for the evaluation of the remaining wall thickness of AC pipes (see Section 3) has shown some promise, but rigorous testing has yet to be done (Bracken, 2009).

- **NDE of PVC and PE pipes**. The predominant failure mode of PVC pipes is associated with scratches, voids and inclusions. NDE technology to detect these factors in buried water mains does not yet exist. Further, although laser- and sonar- based techniques exist for the detection of out-of-roundness in sewers, equivalent techniques have not been developed for in-service plastic water mains. This out-of-roundness deformation is a useful indicator of distress in plastic pipes.

- **NDE of Large Diameter Transmission Mains.** Large transmission mains are typically the backbone of water distribution systems. Based on input from water utilities, the sizes of their water transmission mains range from 12-in., 16-in., 18-in., 20-in., and up in diameter. Although there is no formal cutoff point between small distribution and large transmission mains, larger than 16-in. diameter would be a typical cut-off value for mid- to large size water utilities. Due to the high costs of large diameter water mains, networks often do not have the redundancy required to take them offline. Consequently, water utilities are reluctant to perform inspections, which would require pipe dewatering. Therefore, there is an urgent need to develop technologies capable of performing NDE for in-service pipes. This requires the development of sensors, as well as robotic platforms, to introduce these sensors into the pipe. This also requires the development of launching and retrieval chambers that are not prohibitively expensive.

- **NDE technologies to estimate the loss of pipe bedding and support do not currently exist.** Deterioration of pipe bedding and surrounding backfill is an important indication of distress leading to failure, especially for thermoplastic pipes since its strength is augmented by soil support. In CI pipes, loss of bedding may lead to joint rotation and eventual failure. GPR has been tried to detect voids around pipes but this application has not yet matured.

- **The reliability of many of the available NDE technologies for buried water mains is not known.** There is a need to establish protocols for standard tests and ratings that would address issues such as probability of detection (PoD), rate of false positives, false negatives, etc. This will enable users to select appropriate technologies, with a robust understanding of advantages and limitations under different conditions.

- **There is a need for detailed protocols of forensic analyses of the failure of all pipe materials, with special focus on pipes whose failure would be associated with high consequences.** This will enhance the understanding of failure modes and their associated telltale signs and potentially lead to the development of improved NDE technologies capable of detecting these signs. Adopting such practices will necessitate appropriate training of staff and possibly a wide access depository of information and results.

*Condition rating:*

- **There is a limit to the accuracy in which deterioration models (both physical and empirical) are able to predict failure.** This limit can be overcome if these models were combined with reliable data on the current condition of the pipe. Consequently, there is a need to develop methods that are capable of fusing sensory data and historical performance records/states. The multi-source data will enhance the reliability of any prediction effort.

- **Buried pipes have a useful life spanning many decades. Pipe inspection technologies probably evolve and change during the life of a pipe.** In large diameter mains, where distress indicators are eventually transformed into an ordinal condition rating, historical condition rating data that deterioration models use would then require appropriate updating or normalization to account for the different types of technologies used to discern these distress indicators during the pipe's lifetime. The intent of this updating or normalization would be to make the (ordinal) condition ratings independent of the technology used to produce this condition rating.

*Failure risk:*

- **More efforts should be invested in formalizing and automating the quantification of the consequences of a failure.**
- **There are insufficient historical data to validate and refine the existing deterioration models of large diameter pipes. Research efforts should be directed more towards validation, calibration, and refinement of existing models (using real field data) than developing new models.**

*Decision support:*

- **The ultimate goal of decision making is to provide service at stated levels (where levels are defined for reliability, pressure, water quality, environmental impact, etc.) at the lowest life-cycle cost (often with budget constraints).** While the state of the art is still far from formulating an all-encompassing model, achievable interim goals should include the consideration of structural condition, hydraulic reliability, and impact of pipes on the water quality in the network, while on the cost side, decision making should consider economies of scale and interaction with adjacent infrastructure.

- **Additional outreach is needed to assist water utilities to better understand where the many available inspections tools and models fit within their investment decision making process.** Further outreach could help utilities to better understand the following:
    - The key inspection data required to help improve deterioration modeling, risk assessment, and decision support tool outputs;
    - The processes, tools, and costs to provide this data at the various levels for both distribution and transmission mains; and
    - What tools require development to fulfill any gaps in these data requirements (given that the gaps identified above are primarily related to technology requirements rather than utility data requirements)

Condition assessment data ultimately lays the foundation for decision making regarding repair, rehabilitation, or replacement of deteriorated water mains. Currently, this decision making is based largely on performance factors such as main break frequency or severity, water quality problems, or poor hydraulic characteristics. As the state of the art in inspection technologies improves, this will also improve the ability to incorporate valuable data on the host pipe's structural condition into the selection of appropriate renovation techniques. The decision making steps involved in the selection of repair, rehabilitation, and replacement techniques is beyond the scope of this research project and is explored in other EPA research (Matthews et al., 2011).

# 8.0: SUMMARY AND CONCLUDING REMARKS

As water mains age, they are increasingly exposed to continuous stress from operational and environmental conditions. These mains deteriorate structurally and hydraulically, adversely impacting water quality, leakage, and reliability. Effective management of these assets requires condition assessment, which includes the collection of information about their condition, analysis of this information, and ultimately transformation of this information into knowledge, leading to effective decision about renewal. In the introduction, several key issues were identified for the assessment of the structural condition of water mains and decision making on pipe renewal. The following summarizes the manner with which these key issues have been addressed in this report:

(1) *Physical modeling of the pipe in the soil.*

This issue was addressed briefly in Section 2 through the description of the physical manifestation of pipe performance in the soil. Also, brief descriptions were provided in Section 5 of physical/mechanistic models found in the literature for the performance and deterioration of buried pipes.

(2) *Understanding of pipe failure modes, including observable or measurable signs (or distress indicators) that point to these modes, as well as inferential indicators that point to potential existence of deterioration mechanisms.*

In Section 2, an overview of pipe deterioration mechanisms was provided with comprehensive lists of how these mechanisms manifest themselves in different pipe materials. Section 5 provided brief descriptions of physical/mechanistic models to describe pipe deterioration in the ground. The list comprises a total of 17 such models from the literature and is believed to be quite comprehensive, if not exhaustive.

(3) *Inspection of the pipe to discern distress indicators.*

Section 3 provided descriptions of approximately 70 technologies/techniques/methods for inspection and evaluation of distress indicators in pipes. These include visual, electromagnetic, ultrasonic, and laser-based technologies, leak detection, direct distress indicators (indicators observed and measured on the pipe itself) and inferential indicators (soil and environmental properties). Emerging sensor technologies with potential application in the water supply industry, along with sensor networks were also reviewed.

(4) *Interpretation of distress indicators to determine pipe condition.*

Section 4 described a range of methods/approaches used to interpret distress indicators into condition ratings, including point score, fuzzy-based techniques, data fusion, data mining and data-driven approaches.

(5) *Empirical/statistical modeling of historical failures (mainly in small diameter distribution mains).*

Section 5 summarizes statistical/empirical models that appeared in the literature in the last 30 years. Both deterministic and probabilistic models are included. In most models that address small diameter distribution mains, deterioration is defined as the increase in breakage frequency. In contrast, models addressing large diameter transmission mains define deterioration in terms of condition ratings. This difference is inherent in the manner with which these two classes of assets are managed (i.e., manage break frequency vs. failure prevention).

(6) *Modeling deterioration to forecast future failure rates and pipe residual life.*

Section 5 provided descriptions of 17 physically based deterioration models and 31 statistical/empirical deterioration models for water mains that have been proposed in the literature over the years. These two lists are believed to be very comprehensive.

(7) *Assessment of failure consequences (direct, indirect and social costs).*

This element was not addressed in this report.

(8) *Scheduling pipe renewal so as to minimize life-cycle costs while meeting or exceeding functional objectives of water distribution (quantity, quality, reliability, etc.)*

Section 6 provided descriptions of 29 decision support models that have been proposed in the literature over the past few years. In addition, detailed descriptions were provided for decision support software tools that are publicly available, either in a commercial or research version.

Section 7 provided a list of identified technology gaps and research and development needs, addressing aspects of NDE technologies, condition rating techniques and decision-making techniques including risk-based techniques requiring the quantification of failure consequences.

This report reflects a substantial amount of work and effort that has been invested in developing approaches and tools for the condition assessment of water mains. There are currently a number of technologies that are commercially available for leak detection and structural integrity monitoring of water mains. In particular, the development of inspection technologies for large diameter PCCP has been a success story where the cost of gathering the inspection data was superseded by the benefit in improved data that it provided on the pipe condition, which allowed detailed engineering analysis to determine if pipes required repair or replacement. Because of the high consequence of large diameter PCCP failures, the cost of inspection was readily justified and allowed utilities to make more informed and proactive decisions on whether or not to renew a given PCCP segment based upon its likelihood of failure as identified from inspection. In addition, the use of leak detection technologies is growing as water utilities focus their efforts on reducing water losses in order to maintain or increase their revenue, conserve water resources, and reduce public health risks (EPA, 2009).

Any asset management program must start with a thorough review of available historical data about pipe performance and failure. Once the necessary data is gathered, deterioration models (some of which are quite affordable) can go a long way in providing insight into the condition of these assets, especially for small diameter pipes. A well-defined and cost-effective inspection program that complements the historic data can then be used to fill in gaps that remain and/or to validate the results of modeling efforts for the specific conditions faced by a water utility.

Currently, the relatively high cost of various NDE technologies justifies their use mainly on large water transmission mains, where the consequences of failure are relatively high. However, it is foreseen that as novel technologies develop and competition intensifies, prices will decline and NDE inspection will become justified even for pipes with relatively moderate consequences of failure. This will result in higher uptake rate, which in turn will drive unit prices down.

Further research and development by key stakeholders including the federal government, non-profit research organizations, and industry could aid in the acceleration of this process. As described in Section 7, there are a number of technology gaps and research needs including: the need for live internal insertion and retrieval of inspection tools for large diameter pipes; the need to assess joint condition in metallic pipes; the need to develop technologies for asbestos cement and plastic pipes with few options currently available; and the need for low cost inspection methods to conduct screening for high risk locations in all pipe types for further assessment. To overcome the barriers and challenges identified in Section 7, field demonstrations and further research efforts are warranted in order to test promising technologies that could fill these gaps against well defined performance criteria and to identify the critical performance, cost, and/or value added attributes of emerging and innovative technologies for water main inspection.

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