Deterioration and Inspection of Water Distribution Systems

A Best Practice by the National Guide to Sustainable Municipal Infrastructure

National Guide to Sustainable Municipal Infrastructure

Guide national pour des infrastructures municipales durables

Canada

NRC · CNRC

Federation of Canadian Municipalities

Fédération canadienne des municipalités

Deterioration and Inspection of Water Distribution Systems
Issue No. 1.1
Publication Date: April 2003

TABLE OF CONTENTS

TABLES

FIGURES

FOREWORD

In spite of recent increases in public infrastructure investments, municipal infrastructure is decaying faster than it is being renewed. Factors such as low funding, population growth, tighter health and environmental requirements, poor quality control leading to inferior installation, inadequate inspection and maintenance, and lack of consistency and uniformity in design, construction and operation practices have impacted on municipal infrastructure. At the same time, an increased burden on infrastructure due to significant growth in some sectors tends to quicken the ageing process while increasing the social and monetary cost of service disruptions due to maintenance, repairs or replacement.

With the intention of facing these challenges and opportunities, the Federation of Canadian Municipalities (FCM) and the National Research Council (NRC) have joined forces to deliver the *National Guide to Sustainable Municipal Infrastructure: Innovations and Best Practices*. The Guide project, funded by the Infrastructure Canada program, NRC, and through in-kind contributions from public and private municipal infrastructure stakeholders, aims to provide a decision-making and investment planning tool as well as a compendium of technical best practices. It provides a road map to the best available knowledge and solutions for addressing infrastructure issues. It is also a focal point for the Canadian network of practitioners, researchers and municipal governments focused on infrastructure operations and maintenance.

The *National Guide to Sustainable Municipal Infrastructure* offers the opportunity to consolidate the vast body of existing knowledge and shape it into best practices that can be used by decision makers and technical personnel in the public and private sectors. It provides instruments to help municipalities identify needs, evaluate solutions, and plan long-term, sustainable strategies for improved infrastructure performance at the best available cost with the least environmental impact. The five initial target areas of the Guide are: potable water systems (production and distribution), storm and wastewater systems (collection, treatment, disposal), municipal roads and sidewalks, environmental protocols and decision making and investment planning.

Part A of the *National Guide to Sustainable Municipal Infrastructure* focuses on decision-making and investment planning issues related to municipal infrastructure. Part B is a compendium of technical best practices and is qualitatively distinct from Part A. Among the most significant of its distinctions is the group of practitioners for which it is intended. Part A, or the DMIP component of the Guide, is intended to support the practices and efforts of elected officials and senior administrative and management staff in municipalities throughout Canada.

It is expected that the Guide will expand and evolve over time. To focus on the most urgent knowledge needs of infrastructure planners and practitioners, the committees solicited and received recommendations, comments and suggestions from various stakeholder groups, which shaped the enclosed document. Although the best practices are adapted, wherever possible, to reflect varying municipal needs, they remain guidelines based on the collective judgements of peer experts. Discretion must be exercised in applying these guidelines to account for specific local conditions (e.g. geographic location, municipality size, climatic condition).

For additional information or to provide comments and feedback, please visit the Guide Web site at www.infraguide.gc.ca or contact the Guide team at infraguide@nrc-cnrc.gc.ca.

ACKNOWLEDGEMENTS

The dedication of individuals who volunteered their time and expertise in the interest of the *National Guide to Sustainable Municipal Infrastructure* is acknowledged and much appreciated.

This best practice was developed by stakeholders from Canadian municipalities and specialists from across Canada, based on information from a scan of municipal practices and an extensive literature review. The following members of the National Guide's Potable Water Technical Committee provided guidance and direction in the development of this best practice. They were assisted by the Guide Directorate staff and by R.V. Anderson Associates Limited in association with Touchie Engineering, Urban Systems Limited and Reseau Environnment.

Carl Yates, Chair	Halifax Regional Water Commission, Nova Scotia
Fred Busch	Mayor, District of Sicamous, British Columbia
Sukhi Cheema	Government of the Northwest Territories
Normand DeAgostinis	Ductile Iron Research Pipe Association, Anjou, Quebec
Tim Dennis	City of Toronto, Ontario
Gordon Lefort	IPEX Inc., Langley, British Columbia
Andre Proulx	Delcan, Ottawa, Ontario
Diane Sacher	City of Winnipeg, Manitoba
Piero Salvo	WSA Trenchless Consultants Inc., Ottawa, Ontario
Ernie Ting	Town of Markham, Ontario
Normand Levac	Technical Advisor, NRC

In addition the Potable Water Technical Committee would like to thank the following individuals for their participation in working groups and peer review:

Chado Brcic	Regional Municipality of Niagara, Ontario
Brian Crowe	City of Vancouver, British Columbia
Normand DeAgostinis	Ductile Iron Research Pipe Association, Quebec
Gordon Lefort	IPEX Inc., British Columbia
Jon Makar	Institute for Research in Construction, Ontario
David Raymond	City of Ottawa, Ontario
Douglas Seargeant	EPCOR Water Services, Alberta

This and other best practices could not have been developed without the leadership and guidance of the Project Steering Committee and the Technical Steering Committee of *the National Guide to Sustainable Municipal Infrastructure*, whose memberships are as follows:

Project Steering Committee:

Mike Badham, Chair	City Councillor, Regina, Saskatchewan
Bill Crowther	City of Toronto, Ontario
Jim D'Orazio	Greater Toronto Sewer and Watermain Contractors Association, Ontario
Glen Everitt	Mayor, Dawson City, Yukon
Derm Flynn	Mayor, Appleton, Newfoundland
David General	Cambridge Bay, Nunavut
Ralph Haas	University of Waterloo, Ontario
Barb Harris	Whitehorse, Yukon
Robert Hilton	Office of Infrastructure, Ottawa, Ontario
Dwayne Kalynchuk	City of St. Albert, Alberta
Marie Lemay	Canadian Council of Professional Engineers
Wayne Motheral	City Councillor, Louise, Manitoba
Saeed Mirza	McGill University, Quebec
Lee Nauss	City Councillor, Lunenburg, Nova Scotia
Ric Robertshaw	Region of Halton, Ontario
Dave Rudberg	City of Vancouver, British Columbia
Van Simonson	City of Saskatoon, Saskatchewan
Basile Stewart	Mayor, Summerside, Prince Edward Island
Serge Thériault	Department of Environment and Local Government, New Brunswick
Alec Waters	Alberta Transportation
Wally Wells	Dillon Consulting Ltd., Ontario

Stakeholder Liaison:

Joan Lougheed	City Councillor, Burlington, Ontario

Technical Steering Committee:

Don Brynildsen	City of Vancouver, British Columbia
Al Cepas	City of Edmonton, Alberta
Andrew Cowan	City of Winnipeg, Manitoba
Tim Dennis	City of Toronto, Ontario
Kulvinder Dhillon	Regional Municipality of Halifax, Nova Scotia
Wayne Green	City of Toronto, Ontario
John Hodgson	City of Edmonton, Alberta
Bob Lorimer	Lorimer & Associates, Yukon
Betty Matthews-Malone	City of Hamilton, Ontario
Umendra Mital	City of Surrey, British Columbia
Anne-Marie Parent	Councillor, City of Montréal, Quebec
Piero Salvo	WSA Trenchless Consultants Inc., Ontario
Mike Sheflin	Former CAO, Regional Municipality of Ottawa-Carleton, Ontario
Konrad Siu	City of Edmonton, Alberta
Carl Yates	Halifax Regional Water Commission, NovaScotia

EXECUTIVE SUMMARY

This part B document outlines the best practice for inspecting water distribution systems to detect the signs of system deterioration. The deterioration processes for potable water distribution systems and the factors that can affect their rate of deterioration are described.

A strategic inspection program for a water distribution system is essential to minimize health and safety concerns and to ensure that a municipality (or a utility) can provide an adequate supply of safe water in a cost-effective, reliable and sustainable manner.

Deterioration of water distribution systems can be made evident by one or more of the following manifestations:

- impaired water quality – due to internal corrosion of unlined metallic components and/or poor maintenance practices;
- reduced hydraulic capacity – due to internal corrosion (i.e., tuberculation) of unlined metallic components;
- high leakage rate – due to corrosion and/or deteriorating joints; and
- frequent breaks – due to corrosion, material degradation, poor installation practices, manufacturing defects and operating conditions.

Since most water distribution systems have metallic components, corrosion can be the cause of deterioration in certain environments. An overview of internal and external corrosion processes is provided, as well as a brief description of some other physical, environmental and operational factors that can contribute to deterioration and failure.

The best practice for investigating the condition of water distribution systems is based on a two-phase approach. The first phase involves a preliminary assessment of the structural condition, hydraulic capacity, leakage and water quality on a system-wide basis using data that should be collected by every municipality on a routine basis. A preliminary assessment of water main breaks, customer complaints, unaccounted for water, and data on routine sampling and inspection which should be conducted each year, will identify both trends and the need for more detailed investigations.

The second phase involves a more detailed investigation of specific problems based on an evaluation of the level of service, economics, risk and benefits. This best practice identifies the limitations of some of the detailed investigation techniques.

1. GENERAL

1.1 INTRODUCTION

This document outlines the best practice for inspecting water distribution systems to detect the signs of system deterioration. The deterioration processes for potable water distribution systems and the factors that can affect their rate of deterioration are described. For the *National Guide for Sustainable Municipal Infrastructure*, a best practice is defined as "state of the art methodologies and technologies for municipal infrastructure planning, design, construction, management, assessment, maintenance and rehabilitation, that consider local economic, environmental and social factors."

This best practice is based on a review of existing literature as well as a 2001 survey of 68 municipalities and utilities across Canada. The questionnaire included 30 questions that covered the causes of water main deterioration, methods used to quantify deterioration and methods used to mitigate deterioration.

1.2 SCOPE

This best practice describes the methodologies and technologies to investigate and inspect water distribution systems. Although water distribution systems include water mains, water service connections, hydrants and valves, most of the discussion in this best practice will focus on water distribution and transmission mains. Water treatment plants, pumping stations and reservoirs are not addressed here.

1.3 GENERAL HEALTH AND SAFETY ISSUES

Water distribution systems should be designed, constructed, operated and maintained to deliver an adequate supply of water in a safe, cost-effective and reliable manner. An adequate water supply is required to maintain the health and economic viability of a community. In addition, an adequate supply of water is one of the primary requirements for fire suppression.

1.4 SUSTAINABILITY

Most Canadian municipalities[1] recognize the importance of managing their water distribution systems as "assets." This is driven by the growing financial needs as existing systems grow larger and older. The Canadian Water and Wastewater Association (CWWA) completed a study in 1997 to estimate the investment needs in water and wastewater infrastructure over the period 1997-2012. This study indicated that there were more than 112,000 kilometres of water mains in Canada with an estimated replacement cost of $34 billion. In addition, this study

[1] Reference to *municipality* (or *municipalities*) throughout this document is also intended to include *utility* (or *utilities*) or other purveyors of water.

estimated that $12.5 billion would have to be invested over this 15-year period to replace existing (deteriorated) water mains and to construct new mains to service the projected growth. Based on the magnitude of this projected need, it is apparent that available funds will need to be targeted as effectively as possible.

To ensure that municipalities can manage their water distribution systems to provide an adequate supply of safe water in a cost-effective, reliable and sustainable manner, it is essential that they develop a clear understanding of water main deterioration processes. This understanding will allow municipalities to implement mitigation measures in a timely manner so as to extend the useful service life of the systems to an optimum length of time and thereby minimize the overall economic, social and environmental costs of water distribution system operation.

1.5 GLOSSARY OF TERMS

Anode – the electrode in a galvanic corrosion cell from which electrons flow.

Aggressive – pertaining to a corrosive water or soil that will deteriorate material of water distribution piping.

Break – a mechanical or structural failure of a water main.

Cathode – the electrode in a galvanic corrosion cell to which electrons flow.

Critical water main – water main that would cause significant property damage and/or environmental damage if it failed catastrophically. Also includes water mains that are the primary source of water supply to a large population or to customers that require a high degree of reliability.

Failure – inability of a system to reliably deliver an adequate quantity of water at a minimum pressure with quality that meets the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 1996). A link to the Summary of the Guidelines can be found at:
http://www.hcsc.gc.ca/ehp/ehd/catalogue/bch_pubs/summary.pdf.

Leak – hole or joint failure in water distribution system that is generally less severe than a break.

Pit cast – refers to the type of manufacturing process for cast iron mains in which molten iron was poured into vertical moulds that were set in pits.

Spun cast – refers to the type of manufacturing process for cast iron mains in which molten iron was poured into horizontal moulds that were spun and cooled externally with water.

2. RATIONALE

2.1 DETERIORATION OF WATER DISTRIBUTION SYSTEMS

Deterioration of water distribution systems becomes evident through one or more of the following manifestations:

- impaired water quality – due to internal corrosion of unlined metallic components; biofilm build-up and/or poor maintenance practices;
- reduced hydraulic capacity – due to internal corrosion (i.e., tuberculation) of unlined metallic components or calcium carbonate precipitation;
- high leakage rate – due to corrosion through holes in pipe barrels and/or deteriorating joints; and
- frequent breaks – due to corrosion, material degradation, poor installation practices, manufacturing defects and operating conditions.

2.1.1 WATER MAINS

Table 1 presents the range of sizes and installation periods for the most common water main materials as well as the relevant American Water Works Association (AWWA) standards and design manuals. Canadian Standards Association (CSA) has also published standards for the manufacture of several pipe materials.

Cast iron and ductile iron pipes account for more than two thirds of the existing water mains in use across Canada (R.V. Anderson Associates Ltd., 2002). Steel, polyvinyl chloride (PVC), high-density polyethylene (HDPE), asbestos cement (AC) and concrete pressure pipe (CPP) are also used for water mains.

Since most water distribution systems have metallic components, corrosion can be a cause of deterioration in certain environments. Deterioration of PVC pipe can occur as a result of chemical attack from certain solvents or as mechanical degradation from improper installation methods. HDPE pipe failures due to joint imperfections, material degradation and improper pipe installation have been experienced. Deterioration of AC pipe and cement mortar linings will occur if aggressive water leaches the cement (Rajani, B. and Y. Kleiner, 2001). The deterioration of CPP typically occurs through corrosion of the steel pre-stressing wires, which may lead to the rupture of the pipe. Other CPP problems may include the deterioration of the concrete in the pipe or corrosion of the internal steel barrel.

Table 1: Common Water Main Materials

Pipe Material	Range of Diameter	Period of Installation	CSA Standard	AWWA Standard	AWWA Manual
Pit Cast Iron (CI)	75-1,500 mm	1850s-1940s	-	C100[1]	-
Spun Cast Iron (CI)	75-1,500 mm	1930s-1960s	-	C100[1]	-
Ductile Iron (DI)	75-1,600 mm	Since 1960s	-	C151	M41
Steel	> 150 mm	Since 1850s	Z245.1	C200	M11
Polyvinyl Chloride (PVC)	100-1,200 mm	Since 1970s	B137.3	C900/905	M23
High Density Polyethylene (HDPE)	100-1,575 mm	Since 1980s	B137.1	C906	-
Asbestos Cement (AC)	100-1,050 mm	1930s to 1980s	-	C400	-
Concrete Pressure Pipe (CPP)	250-3,660 mm	Since 1940s	-	C300/301/ 302/303	M9

[1] British standard cast iron pipe is also common in Canada.

2.1.2 Water Services

Water services larger than 50 mm in diameter are typically constructed of cast iron, ductile iron or PVC. Water services that are 50 mm in diameter and smaller are typically constructed of copper, lead, galvanized iron or polyethylene. Deterioration processes for water services are similar to those for water mains.

2.1.3 Valves

Valves are used for various purposes in water distribution systems, including isolation, air release, drainage, checking and pressure reduction. Isolation valves are the most common type used in distribution systems. Buried gate valves with valve boxes are typically used for isolation of small-diameter water mains and water services whereas butterfly valves are direct buried or installed in chambers and are typically used for large diameter mains. Isolation valves require regular exercise to ensure that they are accessible, are in their proper position (open or closed), are operable and are not leaking. Isolation valves are prone to deterioration and failures such as stripped, broken or bent stems; leaking O-rings or packing; corrosion of the valve body and connecting bolts; and wear on the valve disk and seat.

2.1.4 HYDRANTS

Hydrants are similarly susceptible to deterioration, frost damage and failure. However, hydrant inspection and maintenance is typically more thorough than that for buried mains and valves.

2.2 EXTERNAL CORROSION

Corrosion is an important issue that is poorly understood by some municipalities. The AWWA Manual M27 (AWWA, 1987) describes in detail external corrosion chemistry and its control for common water main materials. The National Association of Corrosion Engineers (NACE International) has published a manual, *Control of Pipeline Corrosion* (Peabody, A.W., 2001), that provides a detailed description of corrosion processes. Several types of external corrosion can occur in water mains, including galvanic, electrolytic and microbiologically induced. Galvanic and electrolytic corrosion are the most common types of external corrosion in water distribution systems. Both are described below.

2.2.1 GALVANIC CORROSION

"The galvanic corrosion process is identical to the reactions in an electrical battery…" (AWWA, 1987). Galvanic corrosion is an electrochemical process which can occur when dissimilar metals are electrically connected and immersed in a uniformly conductive soil, or when a metal is immersed in a conductive soil of non-uniform character. If these conditions exist, electrical current will flow from the anode to the cathode through the connection. As the anode loses electrons, the anode metal is oxidized and ions are released into the electrolyte – resulting in corrosion of the anode. To complete the electrical circuit, cathode ions present in the electrolyte are reduced and deposited on the surface of the cathode – thus protecting the cathode from corrosion.

Under the same conditions, cast iron and ductile iron corrode at a similar rate (De Rosa, P.J. and R.W. Parkinson, 1986). Field observation have found that cast iron and at times ductile iron can leave a graphite matrix that retains the shape of the original casting. Although the graphite matrix has low mechanical strength, it can in some cases withstand normal operating pressures unless the pipe is disturbed.

A survey was recently conducted of selected water utilities in the United States and Canada to determine the most common causes of external corrosion of water mains (Romer, A.E. and G. Bell, 2001). This survey indicated that 67 percent of the respondents perceived that corrosive soils are the primary cause of external corrosion of water distribution mains in their systems. As well, 12 percent of the respondents believed that direct connection of dissimilar metals was the primary cause and 10 percent that coating damage or degradation was the primary cause.

2.2.2 ELECTROLYTIC CORROSION

Electrolytic (also referred to as stray current) corrosion will occur in a water main if the main picks up "stray" electrical current from a direct current (DC) source such as impressed current cathodic protection systems on an adjacent pipeline, electric railway or subway systems, and electric welding systems. Electrolytic corrosion is similar to galvanic corrosion except that outside current sources drive the electrolytic cell whereas chemical reactions drive the galvanic cell. As stray current is forced through a water main by an outside current source, corrosion occurs at the point where stray current leaves the main and joins the electrical current source (i.e., at the anode).

Alternating current (AC) can also produce stray current corrosion. The AWWA Research Foundation (AWWARF) has investigated the effects of electrical grounding of AC sources on water main integrity (Duranceau, S. and G. Bell, 1995). However, this study indicated that "alternating current causes corrosion albeit at a much lower rate compared to direct current…about 1% of the rate of a similar amount of direct current."

2.3 INTERNAL CORROSION

Modern metallic pipes are all manufactured with internal linings to prevent internal corrosion from soft or aggressive waters. However, older metallic pipes may be unlined and would therefore be susceptible to internal corrosion. The AWWA Research Foundation has published two manuals that provide a detailed description of internal corrosion processes and control (AWWARF/DVGW, 1986; AWWARF, 1989). Internal corrosion can manifest itself in different ways. They are commonly grouped as follows:

- pipe degradation (e.g., pitting), which can result in leakage or vulnerability to mechanical failure;
- tuberculation and scale formation can reduce hydraulic capacity and impair water quality; and
- corrosion by-product release (e.g., rusty or red water), which can impair water quality.

The rate of internal corrosion can be influenced by the physical, chemical and biological characteristics of the water. It is important to note that deterioration of a water distribution system could affect water quality. At the same time, water characteristics could affect the rate of deterioration of a water distribution system.

The metal oxides resulting from pitting corrosion may form tubercles over the pits. These tubercles will gradually grow and restrict the hydraulic capacity of the pipe. In addition to this, if water flowing through a pipe is supersaturated with calcium carbonate, the calcium carbonate can precipitate and lead to encrustation of the pipe.

2.4 FACTORS THAT CONTRIBUTE TO WATER MAIN DETERIORATION

Many factors can affect the rate of deterioration of water distribution systems and lead to their failure. Table 2 summarizes some of these physical, environmental and operational factors.

Table 2: Factors that Contribute to Water System Deterioration

Factor		**Explanation**
Physical	Pipe material	Pipes made from different materials fail in different ways.
	Pipe wall thickness	Corrosion will penetrate thinner walled pipe more quickly.
	Pipe age	Effects of pipe degradation become more apparent over time.
	Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.
	Pipe diameter	Small diameter pipes are more susceptible to beam failure.
	Type of joints	Some types of joints have experienced premature failure (e.g., leadite joints).
	Thrust restraint	Inadequate restraint can increase longitudinal stresses.
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.
	Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.
	Trench backfill	Some backfill materials are corrosive or frost susceptible.
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.
	Groundwater	Some groundwater is aggressive toward certain pipe materials.
	Climate	Climate influences frost penetration and soil moisture. Permafrost must be considered in the north.
	Pipe location	Migration of road salt into soil can increase the rate of corrosion.
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.
	Stray electrical currents	Stray currents cause electrolytic corrosion.
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.
Operational	Internal water pressure, transient pressure	Changes to internal water pressure will change stresses acting on the pipe.
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
	Water quality	Some water is aggressive, promoting corrosion
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.
	O&M practices	Poor practices can compromise structural integrity and water quality.

2.5 STRUCTURAL FAILURE OF WATER MAINS

Water mains typically break when the extent of corrosion (or degradation) is sufficient that the main is no longer able to withstand the forces acting on it. Figure 1 illustrates the most common types of water main breaks as well as the forces acting on the pipe that cause the break to occur. Recent work at the NRC indicates that failure often takes place in multiple stages rather than in a single episode. A pipe experiencing beam failure may crack part way through, sit in the ground for a while, possibly with an associated leak, and then crack the rest of the way through. Table 3 summarizes the structural failure modes for each of the common water main materials.

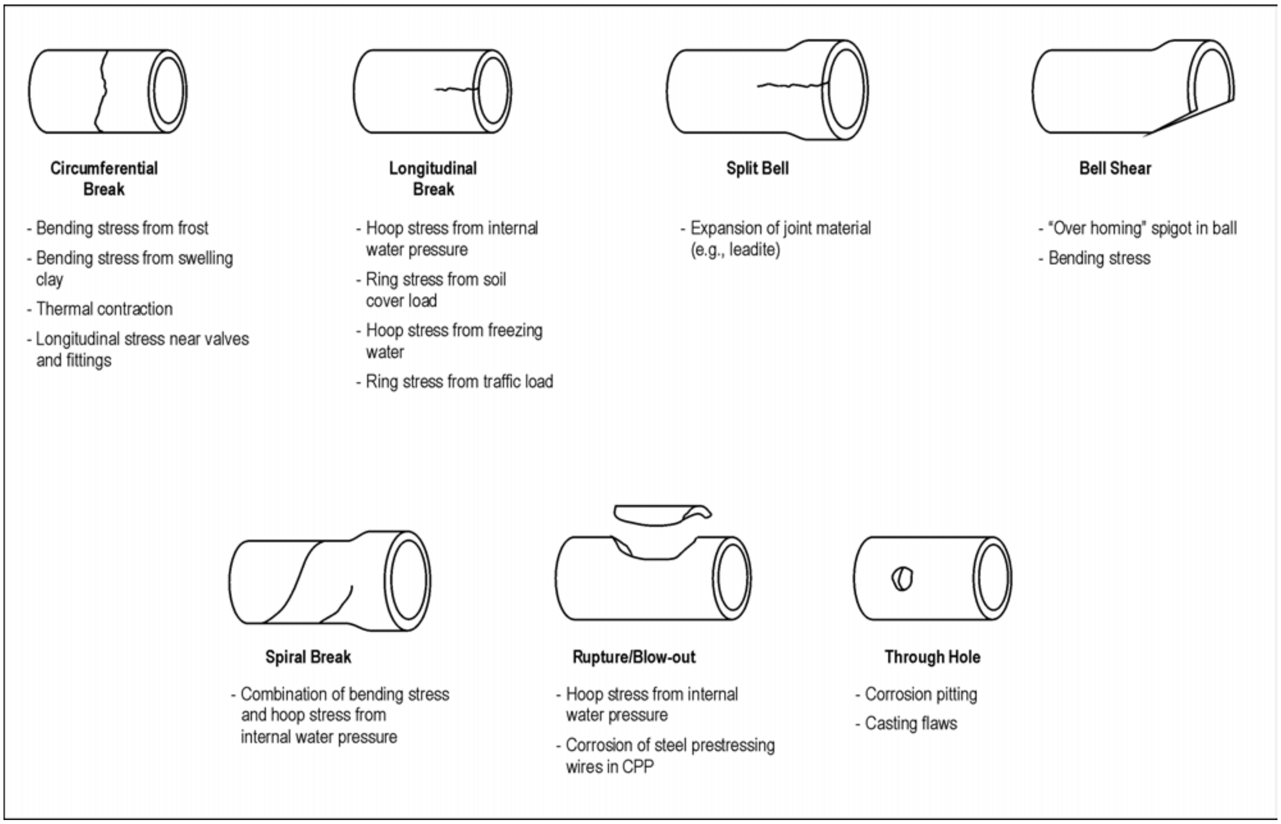

Figure 1: Structural Failure Modes for Water Mains

Table 3: Structural Failure Modes for Common Water Main Materials

Water Main Material	**Structural Failure Modes** (see Figure 1)
Cast Iron (CI)[1] Small diam (<375 mm) Large diam (>500 mm) Medium diam (375-500 mm)	• Circumferential breaks, split bell, corrosion through holes • Longitudinal breaks, bell shear, corrosion through holes • Same as small, plus longitudinal breaks and spiral cracking, blown section
Ductile Iron (DI)	• Corrosion through holes
Steel	• Corrosion through holes, large diameter pipes are susceptible to collapse
Polyvinyl Chloride (PVC)	• Longitudinal breaks due to excessive mechanical stress • Susceptible to impact failure in extreme cold condition (i.e. far north)
High Density Polyethylene (HDPE)	• Joint imperfections, mechanical degradation from improper installation methods, susceptible to vacuum collapse for lower pressure ratings
Asbestos Cement (AC)	• Circumferential breaks, pipe degradation in aggressive water • Longitudinal splits
Concrete Pressure Pipe (CPP)	• Pipes with pre-stressed wires may experience ruptures due to loss of pre-stressing upon multiple wire failure. • Pipe degradation in particularly aggressive soils, corrosion of pipe canister, concrete damage due to improper installation methods

[1] See Makar, J.M., R. Desnoyers and S.E. McDonald (2001) for description of failure modes and mechanisms in grey cast iron pipe.

2.6 Benefits of Monitoring Deterioration of Water Distribution Systems

The following list summarizes some of the reasons why it is beneficial to monitor the deterioration of water distribution systems:

- to maintain the water quality in the distribution system;
- to improve or enhance maintenance and capital planning;
- to identify urgent repair and replacement needs;
- to update the system condition inventory;
- to facilitate strategic planning and cost-effective inspection;
- to provide input to risk analyses;
- to facilitate asset management programs;
- to show due diligence;
- to provide input to design standards and construction specifications;
- to minimize energy input requirements in the north;
- to improve asset planning and prioritisation of non-critical mains;
- to facilitate risk management of critical mains;
- to allow lifetime prediction of water assets for asset management; and
- to provide feedback on manufacturing and installation problems.

3. WORK DESCRIPTION

3.1 GENERAL

The best practice for investigating the condition of water distribution systems is based on a two-phase approach. The first phase involves a preliminary assessment of the structural condition, hydraulic capacity, leakage and water quality on a system-wide basis using data that should be collected by every municipality on a routine basis. The second phase involves a more detailed investigation of specific problems based on findings of the preliminary assessment.

This best practice addresses both critical and non-critical water mains. Critical mains include those that:

- would cause significant property or environmental damage if they break catastrophically; and/or
- are the primary source of water supply to a large population or to customers that require high reliability (e.g., hospitals, some industries).

Municipalities should monitor the condition of their non-critical water mains to "manage" their failures to minimize the cost for operation of and maintenance on these mains. On the other hand, municipalities should monitor the condition of critical mains to minimize failures. Failure of a water distribution system can be defined as the inability of the system to deliver, reliably, adequate quantities of water at a minimum pressure with quality that meets the *Guidelines for Canadian Drinking Water Quality* (Health Canada, 1996) as a minimum. A link to the Summary of the Guidelines can be found at: http://www.hc-sc.gc.ca/ehp/ehd/catalogue/bch_pubs/summary.pdf.

Failure of individual water mains through high break rates or excessive leakage typically dictates the need to replace the mains or, in some cases, to use structural liners. However, failure of individual water mains in terms of hydraulic capacity or water quality does not always require replacement since rehabilitation might be a more cost-effective solution. An asset management program should indicate appropriate action, that is, for replacement or rehabilitation.

3.2 PRELIMINARY ASSESSMENT

The most effective way to investigate the condition of a water distribution system is through regular analysis of readily available data. Table 4 summarizes the type of data that should be used to complete a preliminary assessment of each of the four common types of problems that can occur in water distribution systems.

Table 4: Investigation of Water Distribution Systems

<table>
<tr><th>Problem</th><th>Preliminary Assessment</th><th>Reasons For More Detailed Investigation</th><th>Detailed Investigation</th></tr>
<tr><td>Structural Condition</td><td>• Spatial and temporal analysis of water main breaks
• Compilation of soil map
• Routine inspection of valves and hydrants
• Routine inspection of insulation and heat tracing in northern areas</td><td rowspan="4">Level of Service
• Preliminary investigations indicate an excessive break rate, excessive leakage, inadequate hydraulic capacity and/or impairment of water quality

Cost Effectiveness
• To facilitate capital planning and asset management programs
• Pilot testing of new technologies to facilitate long-range planning support
• Opportunistic work, such as when a water main is temporarily out of service

Risk Management
• Risk analysis identifies critical water mains that have a high potential for significant property damage, environmental impact or loss of service
• Due diligence (e.g., failure analysis of a failed critical water main)</td><td>• Detailed analysis of break patterns, rates and trends
• Statistical and physical models
• Pipe sampling
• Soil corrosivity measurements
• Pit depth measurements
• Non-destructive testing
• Failure analysis
• Visual inspection
• Thermal analysis (far north)</td></tr>
<tr><td>Hydraulic Capacity</td><td>• Low-pressure complaints
• Hydrant flow tests
• Rusty/coloured water occurrences
• Visual inspection of pipe interior
• Monitoring of pressure and pumping costs</td><td>• Hazen-Williams C factor tests (pipe roughness)
• Computer modelling</td></tr>
<tr><td>Leakage</td><td>• Water use audit
• Per capita water demand
• Routine leak detection survey</td><td>• Leak detection survey
• Detailed limited area leakage/demand assessment</td></tr>
<tr><td>Water Quality</td><td>• Water quality complaints
• Routine sampling data
• Results of flushing program</td><td>• Detailed water quality investigation
• Computer modelling</td></tr>
</table>

3.2.1 Structural Condition

Municipalities should record the location and details of water main breaks in electronic format, although this practice may require a phase-in period for small municipalities with limited resources. There are numerous observations that can be made when a break is repaired to facilitate a detailed analysis of the break records and to update the system inventory. Appendix A includes a form that summarizes the data that should be recorded for each break occurrence.

The total number of breaks occurring each year should be compiled and reviewed to identify any trends. The acceptable total number of breaks in a given year varies from municipality to municipality and it is not as important as the long-term trends. It is crucial to collect sufficient data to be statistically significant.

The location of all breaks should be displayed on a system map to determine whether some areas exhibit a higher break frequency than others. A spatial and temporal analysis of the breaks is facilitated if the records are compiled in electronic format. For example, if the break records are compiled using a geographic information system (GIS), it is possible to display the breaks occurring in any given year as well as the entire period of record. Ideally, the break records should be overlaid on a soil map to determine if there is any correlation between soil types and break frequency. To facilitate this spatial analysis, it would be prudent to record the location of each break accurately. Global positioning system (GPS) can be used to locate breaks spatially with accuracy.

3.2.2 Hydraulic Capacity

Low-pressure complaints can be used in a preliminary assessment of a water distribution system. All municipalities should record the location and details of low-pressure complaints in electronic format. If the number of low-pressure complaints is increasing over time, it may suggest that the hydraulic capacity of a system is deteriorating. A spatial analysis of low-pressure complaints might help identify the possible causes of low pressure (e.g., unlined cast iron mains that are heavily tuberculated, or elevation-related pressure variations). Low-pressure complaints related to construction and maintenance activities (e.g., flushing, repairs, new construction) should be excluded from the analysis to reflect the condition of the system properly.

Hydrant-flow test results should be compiled in a format which facilitates a spatial and temporal analysis similar to that for water main breaks and low-pressure complaints. Low fire flows might be due to tuberculation in the mains or partially closed isolation valves. The AWWA Manual M32 (AWWA, 1989) describes a procedure for a hydrant flow test.

A visual or camera inspection of the interior of water mains can also indicate the degree of tuberculation and encrustation in water mains. The interior condition of a water main can also be determined by visually inspecting the water when a water main is flushed.

3.2.3 LEAKAGE

Leak detection can be an important tool to determine the deterioration of water distribution systems. Detailed information on water use and loss is provided in another *National Guide to Sustainable Municipal Infrastructure* best practice.

3.2.4 WATER QUALITY

A preliminary assessment of the water quality in a distribution system can be completed using water quality complaint records and routine water quality monitoring data. The water quality complaint records should be recorded and tracked in a manner similar to that for low-pressure complaints or breaks. Water quality complaints related to construction and maintenance activities (e.g., flushing, repairs, new construction) should be excluded from the analysis to reflect the condition of the system properly but should be reviewed to determine if operational changes are necessary.

Ongoing analysis of the water quality data will indicate if the water quality is changing through the distribution system over time and how it varies spatially. In particular, low chlorine residuals in some parts of a system may demonstrate that the mains in these areas are deteriorating. Similarly, the concentration of iron in the water may denote the degree of internal corrosion of unlined mains.

3.3 DETAILED INVESTIGATION

Based on the results of a preliminary assessment, the need for a more detailed inspection program can be determined. The scope of a detailed inspection program should be built on an evaluation of level of service, economics, risk and benefits. These benefits may be cost, social or environmental in nature. For example, the cost of a detailed investigation of the structural condition of a water distribution system should not be greater than the potential benefit. Similarly, the cost of a program to reduce water losses should be less than any potential benefit. Table 4 shows the methodologies and technologies that could be applied in a detailed investigation of a water distribution system.

3.3.1 STRUCTURAL CONDITION

If the preliminary assessment of break records indicates that the structural condition of a water distribution system is deteriorating, then a more detailed investigation of these records might be warranted. The detailed investigation could include one or more of the following analyses.

a) Break patterns

Break records can be analyzed to identify system-wide patterns such as:

- material – correlation between material types;

- vintage – some vintages of pipes are more prone to failure than others;
- diameter – small diameter grey cast iron mains typically account for most of the breaks in a system since they are more susceptible to beam failure than larger diameter mains;
- type of break – as discussed in Section 2.5, the type of break is a good indicator of its cause (circumferential breaks are more prevalent on small diameter cast iron mains while longitudinal breaks and holes are more prevalent on large diameter mains);
- seasonal variation – in most Canadian municipalities, there is a significant increase in cast iron main breaks during the winter months, usually attributed to the additional stress on the pipe resulting from frost loads and thermal contraction; and
- soil type – some soils are much more corrosive or reactive than others.

b) Spatial analysis of breaks
A Geographic Information System (GIS) can be used to conduct a spatial analysis of the break rates. As examples, types of information such as pipe materials, pipe diameters, pipe vintage, soil type, soil corrosivity, soil reactivity, seismic fault lines, water services and stray current souces could be entered into a GIS system to assess their potential impact on break rates.

c) Break rate
An inventory of a water distribution system typically includes the diameter, length and material for each section of water main.[2] In this case, the break rate for each section can be normalized by dividing the total number of breaks in that section by the length of the water main and the period of record (expressed as breaks/km/year). In this way, mains with high break rates can be easily identified. Economic analyses can be conducted to determine the critical break rate, which defines when it is more cost effective to replace a main rather than continue to repair it.

d) Statistical and physical models
The National Research Council (NRC) recently conducted a comprehensive review of statistical and physical models developed to assess the structural deterioration of water mains (Rajani and Kleiner, 2001; Kleiner, Y. and B. Rajani, 2001).

[2] A section of water main is defined by its “from and to” nodes. A node is a connection between two pipes (e.g., a tee or cross), a valve or a change in pipe characteristics (e.g., diameter, material, direction).

e) Pipe sampling

Pipe sampling involves removing sections of pipes from distribution and transmission mains when the pipes are exposed, both during the repair of breaks and at other opportunities. The main goal of pipe sampling is to determine the condition of the local pipeline by examining the pipe material for deterioration as described in Section 3.2 of this best practice document. Sampling can also provide an opportunity to examine the success of rehabilitation methods such as lining or cathodic protection, provided that the condition of a main was known before its rehabilitation.

Periodic sampling may be helpful in tracking the long-term deterioration of water mains. Ideally a sample should be taken from every broken main, even if a full-scale failure analysis is not being contemplated. However, the cost of taking and analyzing the samples may preclude this frequency. Therefore, water utilities should establish a percentage of the total annual pipe failures where samples are to be collected. The location and timing of the samples collected each year should be decided on the basis of either a set number of pipe breaks or in specific locations within the water system.

f) Soil corrosivity measurements

Soil type and degree of corrosivity can be a key factor in determining the likelihood of deterioration of metallic components of water distribution systems. Taking soil samples for corrosivity measurements can help determine the vulnerability of these components at a low cost, especially when the samples are collected on an opportunistic basis such as during excavations for pipe repair. Soil corrosivity can vary considerably even in areas of the same soil type, making it necessary to collect samples when possible, rather than relying on soil maps.

Resistivity is one of the most important parameters in evaluating soil corrosivity; however, it is not the only parameter that one should consider. A wide variety of soluble salts are typically found in soils some of which may be introduced via road salt migration. These soluble salts will have a tendency to produce lower resistivity values for soils that contain them. Soluble salts will also affect different pipe materials in different ways. The majority of constituents that accelerate corrosion are chlorides, sulphates and soil acidity (pH) (Peabody, A.W., 2001). Depending on the material being used, an analysis of soil corrosivity should take all of these parameters into consideration. Other elements in the soil such as calcium, magnesium and bicarbonates in a basic environment may serve to protect the pipe from corrosion and can also be considered in a soil analysis.

Soil samples can be analyzed on site or at a laboratory. On site analysis should be limited to simple measurements such as soil resistivity, while more complex analysis is best performed in a laboratory setting. The soil samples should be taken at the depth of the pipeline and include individual samples both from the soil at the break and from farther away in the excavation. Taking multiple samples from a single excavation helps identify areas of changing resistivity, which represent an increased probability of the formation of a differential corrosion cell. Peabody describes appropriate procedures for the collection of soil samples. AWWA Standard C105 describes a 10-point system for assessing soil corrosivity.

g) Pit depth measurements

Pit depth measurements can also be used in a detailed investigation of water mains. It should be noted that single pipe samples are not particularly useful for assessing the condition of a section of water main. However, pit depth measurements can be useful for verification of non-destructive testing. The National Association of Corrosion Engineers (NACE International, 1992) has published *Standard Recommended Practices and Standard Test Methods* for evaluating pipeline integrity.

h) Cathodic protection monitoring

In some cases, cathodic protection systems are installed on existing water distribution systems to reduce the rate of corrosion. Any type of cathodic protection systems are active operating systems. These systems require monitoring and occasional maintenance. Good cathodic protection designs will provide test facilities and procedures for monitoring the system once it is in operation (NACE International, 1992). Periodic measurements of the pipe to soil potential along a water main will provide an indication of the level of protection that has been achieved by cathodic protection. In addition, the life expectancy of anodes can be estimated from periodic measurements of the current flow at the test stations.

i) Non-destructive testing

The NRC (Makar, J. and N. Chagnon, 1999) has recently investigated several types of non-destructive testing methods for iron pipes and concrete pressure pipes. Particularly significant methods include the use of remote field effect to find corrosion pits in small diameter cast and ductile iron mains and the remote field-eddy current technique and acoustic emission monitoring to find broken or breaking wires, respectively, in concrete pressure pipes. Linear polarisation resistance has been shown to be able to relate corrosion rate with soil characteristics in certain types of soils. Other new technologies may be developed in the future and should be considered as they become available.

j) Failure analysis

The NRC (Makar, J., 2001) has developed a procedure to analyze water main breaks to gain a better understanding of the causes of a break so that this information can be used to improve the management of the water distribution system. It is recommended that failure analysis be conducted in the following situations:

- in old pit-cast pipes that are failing frequently since they may be weaker than would be expected from the manufacturing standards of the time;

- in areas with exceptionally high break rates where there is not a readily apparent reason for failure; and

- in large diameter mains.

Failure analysis typically includes an analysis of the fracture surface, measurements of mechanical strength and identification of casting flaws.

3.3.2 Hydraulic Capacity

Hazen-Williams C factor tests can be conducted to quantify the hydraulic capacity of a water main. The AWWA Manual M32 (AWWA, 1989) describes the procedure for a C factor test. Computer modelling can also be used to identify the potential reduction in hydraulic capacity due to tuberculation or encrustation. Comparison of the results obtained from testing with published data can provide an assessment of the hydraulic capacity of a water main relative to the expected value.

3.3.3 Leakage

There are several technologies that can be used to identify leakage in a water distribution system. Additional information is available in the Guide best practice on water use and loss.

3.3.4 Water Quality

If the preliminary assessment indicates a potential water quality problem, a more detailed monitoring and modelling program can be undertaken to focus on the parameters of concern. For example, high iron concentrations in water samples might indicate internal corrosion of water mains.

There are several corrosion indices that have been developed to assess the water quality corrosion potential. The Langelier Saturation Index (LI) which indicates that the water is scale forming or corrosive is the most suitable index for unlined iron pipes. The LI has been widely applied by water utilities to control corrosion of many materials in the past because it had been assumed that $CACO_3$ was a critical component of protective scales. However, in light of significant empirical evidence contradicting the presumed connection between the LI and corrosion, the AWWA Research Foundation recommends that this practice be abandoned (AWWARF/DVGW, 1996).

The Aggressiveness Index is the most suitable for asbestos cement pipe (AWWARF, 1989). These indices should be checked regularly and the water quality adjusted accordingly to ensure that internal corrosion is minimized.

4. APPLICATIONS AND LIMITATIONS

4.1 APPLICATIONS

Municipalities should respond to reports of water main breaks and complaints immediately. Standard operating procedures should be in place to deal with these situations.

A preliminary assessment of data concerning water main breaks, complaints, unaccounted for water and routine sampling and inspection should be conducted each year to identify trends and the need for more detailed investigations.

Detailed investigations should be conducted when warranted by one or more of the following conditions:

- preliminary investigations indicate an excessive break rate, excessive leakage, inadequate hydraulic capacity and/or impairment of water quality;
- risk analysis identifies critical water mains with a high potential for significant property damage, environmental impact and/or loss of service;
- due diligence is required (e.g., failure analysis of a failed critical water main);
- to support capital planning (e.g., other construction is proposed within the road allowance) and asset management programs;
- when pilot testing new technologies to support long-range planning; and
- during opportunistic work, such as when a water main is temporarily out of service.

4.2 LIMITATIONS

There are some limitations to the detailed investigation techniques that were outlined in Section 3, including:

- small municipalities typically do not have all the necessary resources to conduct a detailed investigation of their water distribution systems;
- non-destructive testing techniques and leak detection methods can be limited in a variety of different ways, such as pipe material, pipe size, cost, level of technical development, amount of water in the main being tested, access to the pipe, the pipe location and the pipe depth.

4.3 EXPECTED OUTCOMES

- A strategic investigation program will provide a better understanding of the condition of a water distribution system as well as the deterioration processes and trends. It should achieve the benefits outlined in Section 2.6.

- Evaluating the condition data within an assessment framework will help ensure a high level of service provided in a cost-effective and sustainable manner.

By implementing a strategic inspection program, a utility can avoid declines in service levels, reduce operating and maintenance costs, and minimize future system failures.

APPENDIX A: WATER MAIN BREAK REPORT

General

Date and time break reported ________

Time when water was shut off ________

Time when water was turned on ________

Properties affected ________

Air temperature ________

Repair by ________

Property damage ________

Location

Nearest property address ________

Distance from nearest property line ________

Distance from nearest intersection ________

Northing and easting ________

Isolation valves operated ________

Physical Data

Pipe diameter ________

Pipe material ________

Year of installation ________

Pipe wall thickness or pipe class ________

Type of lining ________

Type of joint ________

Type of water service ________

Normal operating pressure ________

Under boulevard or road ________

Depth of cover ________

Depth of frost ________

Type of native soil ________

Type of backfill ________

Soil resistivity ________

Soil sample collected (Yes / No) ________

Pipe sample collected (Yes / No) ________

Type of Failure

- ☐ Circumferential break
- ☐ Longitudinal break
- ☐ Split bell
- ☐ Corrosion pit hole
- ☐ Leaking joint
- ☐ Leaking valve
- ☐ Leaking service connection
- ☐ Broken fitting

Probable Cause of Failure

- ☐ Corrosion
- ☐ Ground frost
- ☐ Joint failure
- ☐ Disturbance (third party)
- ☐ High pressure
- ☐ Frozen pipe

Type of Repair

- ☐ Repair clamp
- ☐ Replace pipe section
- ☐ Replace valve
- ☐ Replace service connection
- ☐ Anode installed
- ☐ Repair joint

REFERENCES

American Water Works Association (AWWA), 1980. *PVC Pipe – Design and Installation – Manual M23.*

American Water Works Association (AWWA), 1985. *Steel Pipe – A Guide for Design and Installation – Manual M11.*

American Water Works Association (AWWA), 1987. *External Corrosion – Introduction to Chemistry and Control – Manual M27*.

American Water Works Association (AWWA), 1989. *Distribution Network Analysis for Water Utilities – Manual M32*.

American Water Works Association (AWWA),1995. *Concrete Pressure Pipe – Manual M9.*

American Water Works Association (AWWA), 1996*. Ductile Iron Pipe and Fittings – Manual M41.*

American Water Works Association Research Foundation (AWWARF), 1987. *Water Main Evaluation for Rehabilitation/Replacement*.

American Water Works Association Research Foundation (AWWARF), 1989. *Economics of Internal Corrosion Control*.

AWWARF / DVGW, 1986. *Internal Corrosion of Water Distribution Systems*.

Burn, L.S., 1998. *An Analysis of Water Reticulation Pressure Fluctutions and their Effect on PVC Pipe*. Transactions of the Institution of Engineers, Australia.

Duranceau, S. and G. Bell, 1995. *Effects of Electrical Grounding on Pipe Integrity and Shock Hazard.*

Health Canada, 1999. Guidelines for Canadian Drinking Water Quality. http://www.hc-sc.gc.ca/ehp/ehd/catalogue/bch_pubs/summary.pdf

Kleiner, Y. and B. Rajani, 2001. *Comprehensive Review of Structural Deterioration of Water Mains: Statistical Models*.

Makar, J., 2001. *Investigating Large Gray Cast Iron Pipe Failures: A Step By Step Approach.*

Makar, J. and N. Chagnon, 1999. *Inspecting Systems for Leaks, Pits and Corrosion.*

Makar, J.M., R. Desnoyers and S.E. McDonald, 2001. *Failure Modes and Mechanisms in Gray Cast Iron Pipe.*

Male, J.W. and T.M. Walski, 1990. *Water Distribution Systems – A Trouble Shooting Manual.*

McNeill, L. and M. Edwards, 2001. *Iron Pipe Corrosion in Distribution Systems*.

NACE International, 1992. *NACE Book of Standards – Volume 1, Standards and Recommended Practices, Control of External Corrosion on Underground or Submerged Metallic Piping Systems*.

Peabody, A.W., 2001. *Peabody's Control of Pipeline Corrosion (2nd Edition)*, National Association of Corrosion Engineers.

Rajani, B. and Y. Kleiner, 2001. *Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models.*

R.V. Anderson Associates Ltd. (RVA), 2002. *Best Practice Scan – Potable Water PW2.*

Ripp, K., 2000. *Causes and Cures of Distribution System Corrosion*.

Romer, A. and G. Bell, 2001. *Causes of External Corrosion on Buried Water Mains.*