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Condition Assessment of Ferrous Water Transmission and Distribution Systems

STATE OF TECHNOLOGY REVIEW REPORT

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

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State of Technology Review Report on Condition Assessment of Ferrous Water Transmission and Distribution Systems

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FOREWORD

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The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and groundwater; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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Sally Gutierrez, Director
National Risk Management Research Laboratory

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CONTENTS

APPENDICES

FIGURES

TABLES

ABBREVIATIONS AND ACRONYMS

AMR	automatic meter reading
AMSA	Association of Metropolitan Sewerage Agencies
ANSI	American National Standards Institute
API	American Petroleum Institute
AC	asbestos cement
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AUT	automated ultrasonic testing
BEM	broadband electromagnetic
CCTV	closed circuit television
CI	cast iron
CIP	cast iron pipe
CML	cement mortar lining
CSIRO	Commonwealth Scientific and Industrial Research Organization
DC	direct current
DDM	Design Decision Method
DI	ductile iron
DIP	ductile iron pipe
DIPRA	Ductile Iron Pipe Research Association
DMA	District Metering Areas
DSS	decision-support system
EC	eddy current
ECDA	External Corrosion Direct Assessment
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
EPTA	EPA Edison Pipeline Test Apparatus
ft	foot (feet)
gal	gallon(s)
GASB	Governmental Accounting Standards Board
GCM	Grand Central Model
GIS	Geographic Information System
GPR	Ground Penetrating Radar
GRP	glass reinforced plastic
GTI	Gas Technology Institute
GWRC	Global Water Research Coalition
GWUT	Guided Wave Ultrasonic Testing
hr	hour(s)
ILI	In-Line Inspection

in.	inch(es)
in^2	square inch(es)
IPWEA	Institute of Public Works Engineering Australia
IWA	International Water Association
LPR	Linear Polarization Resistance
LWC	Louisville Water Company
MFL	magnetic flux leakage
MIC	Microbiologically Induced Corrosion
min	minute(s)
NACE	National Association of Corrosion Engineers
NCER	National Center for Environmental Research
NDI	non-destructive inspection
NDT	non-destructive testing
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
NRC	National Research Council of Canada
NRMRL	National Risk Management Research Laboratory
NYCDEP	New York City Department of Environmental Protection
O&M	operations and maintenance
PCCP	prestressed concrete cylinder pipe
PE	polyethylene
PPIC	Pressure Pipe Inspection Company
PTA	Pipeline Test Apparatus
PVC	polyvinyl chloride
RFEC	remote field eddy current
RBI	risk based inspection
RFT	remote field technology
SAM	Strategic Asset Management
SBIR	Small Business Innovation Research
SF	safety factor
SRB	sulfate reducing bacteria
STAR	Science to Achieve Results
STREAMS	Scientific, Technical, Research, Engineering, and Modeling Support
TIP	Technology Innovation Program
TO	task order
UHF	ultra high frequency
UKWIR	United Kingdom Water Industry Research
UT	ultrasonic testing
WERF	Water Environment Research Foundation
WRc	Water Research Centre
WSAA	Water Services Association of Australia
WSSC	Washington Suburban Sanitary Commission

EXECUTIVE SUMMARY

As part of the U.S. Environmental Protection Agency's (EPA's) Aging Water Infrastructure Research Program, which supports the Sustainable Water 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). Task Order (TO) 62 (EPA STREAMS Contract No. EP-C-05-057) is being conducted by Battelle, in collaboration with Jason Consultants, Virginia Tech University, National Research Council of Canada (NRC), and PARS Environmental, Inc., to identify and characterize the state of the technology for condition assessment of drinking water transmission and distribution systems. This State of Technology Review Report is one of the first deliverables prepared under this project.

Purpose of the State of Technology Review Report

This State of Technology Review Report was developed to serve as the basis for discussion at a Technology Forum on Condition Assessment of Water Transmission and Distribution Systems that was held on September 9 and 10, 2008, at Edison, NJ. It was distributed to the Forum participants for review in advance of the meeting. The Forum and State of Technology Review Report focused on ferrous water mains, which represent two thirds of the installed network. The State of Technology Review Report covers transmission and distribution pipelines with diameters larger than 4 in., but does not include appurtenances or service connections. Comments received have been considered and incorporated, where applicable, into the final document.

The State of Technology Review Report summarizes the current state of the ferrous pipes in the water network, their defects and causes of failure, and the state of condition assessment technologies. It also discusses current barriers to effective use of condition assessment, prospects for short-term and long-term improvement, key performance and cost improvement areas, approaches for measuring success, potential roles of government in accelerating development and acceptance of innovative condition assessment technologies, and approaches for getting utilities to accept effective, innovative technologies and procedures.

Forum Objectives

The overall goals for the Technology Forum were to describe and discuss user needs, the state of the technology, and applied research and demonstration needs and opportunities regarding condition assessment of ferrous transmission and distribution mains. The Forum convened national and international experts in condition assessment to discuss several key issues. In cooperation with these key stakeholders, the Forum helped identify and characterize specific options for research to accelerate and expand the development and acceptance of innovative, cost-effective water main condition assessment approaches including technologies, procedures, and databases. Better condition assessment approaches can provide substantial added value to utilities by enabling: (a) early detection and economical correction of problem conditions, which reduce both maintenance costs and catastrophic failures, and (b) confirmation that high-risk pipelines are in good condition, which reduces premature replacement.

State of Technology Review Report Organization

Section 1 provides an overview and characterization of the U.S. drinking water transmission and distribution network in terms of miles of various types of pipe installed, pipe diameter, and pipe age. The focus of this State of Technology Review Report and the Forum is on ferrous pipe types, which make up approximately two thirds of the distribution network. The review covers ferrous pipe cast in its various forms, such as grey cast iron, ductile iron, and steel, together with an overview of failure modes by corrosion, mechanical causes, and leaks. Section 2 presents the current state of the art in condition assessment, specifically the key factors that are needed to evaluate both the likelihood and consequences of failure. Section 3 provides a review of the principal approaches and technologies employed for condition assessment with a focus on non-destructive inspection.

Section 4 gives an overview of the ways in which information from databases and inspection records is currently used to arrive at a condition evaluation. Any assessment must be based on a combination of available production/installation data, experience, and inspection records. Techniques such as belief networks, life cycles, and the methods to predict remaining service life by means of life predictions, modeling, and life expectancy curves are discussed. In addition, some of the barriers and limitations of the techniques are examined, together with the technical and economic problems associated with obtaining robust information from databases and inspection activities.

The information provided in Sections 5 and 6 was intended to stimulate discussion at the Forum. Section 5 identifies key performance and cost improvement outputs for consideration. Section 6 sets down some observations on the prospects for short-term and long-term improvements. Section 7 provides a list of references.

Appendix A provides descriptions of some current and emerging inspection tools to supplement the review in Section 3. Appendix B provides a summary of presentations, discussions, and key findings from the Forum.

Current Barriers to Effective Use of Condition Assessment

A number of barriers to effective use of condition assessment were identified in this State of Technology Review Report and acknowledged by the Forum participants:

- **Database Quality**. All condition assessment programs are based on high quality asset and failure databases. Lack of robust databases for many water utilities is a major barrier to condition assessment in painting a picture of failure patterns for pipes with different ages and types in a range of locations. The existing U.S. utility databases are incomplete and/or inaccurate. Failure databases are not standardized when kept, and failures are normally not recorded or attributed in a uniform manner to allow for any sensible comparison.

- **Regional and Local Variations**. Regional and local variations have not been given sufficient consideration in applying condition assessment and management tools. Some existing models and curves often need to be modified to reflect local conditions, such as soil conditions and support. For example, the relationship between corrosion of an unprotected cast iron pipe and local soil conditions should be taken into account. Lack of soil support, often coupled with increased external loadings, is another local factor that can alter life expectancy curves.

- **Inspection Data Set Requirements.** There is no consensus on what key data sets are needed or can be obtained from an inspection for a reliable condition assessment and life prediction. Inspection can only provide a snapshot of current conditions. To make predictions, basic pipe information including type, age, and original wall thickness is needed. Additional information such as how long corrosion has been taking place and if it has been uniform is also needed.

- **Current Condition Assessment Methodologies.** There is no consensus on what key parameters and what their comparative weighting factors should be used in a prediction model. Many models require a high level of technical input, which may be available only in large utilities. Level of sophistication of these models and multiplicity of the associated approaches often can be daunting to managers and engineers in small to medium size utilities. There is a need for improving the situation for utilities to conduct in-house condition assessment.

- **Current Inspection Technologies.** Some progress has been made on structural condition inspection tools and more developmental work is currently underway. However, to fully meet the needs of water utilities, there is still a long way to go.

- **Physical Difficulties and Costs of Inspection.** Internal inspection has a significant cost in gaining access to the line. Many utilities have reservations about introducing inspection tools into operational mains due to concerns of potential contamination. Other internal technologies can only operate with the main out of service, emptied and cleaned. For an external investigation of a main under a roadway, activities such as excavation, traffic control, pavement removal, reinstatement, and dealing with existing utilities will add significant cost to the inspection.

- **Relationship between Information Needed and What Current Technologies Provide.** The quality of the information obtained by internal and external inspection technologies is not well defined. Currently, utilities have to adjudge any technology or method based on the sales pitch and cost. There is no independent testing and evaluation information to compare competing methods for their ability to provide the information needed.

- **Relationship between Performance and Cost.** The value of pipeline inspection information is not well quantified, thereby making cost/benefit decisions about assessment difficult or impossible.

Key Performance and Cost Improvement Areas

The State of Technology Review Report and the Forum together identified the following key performance and cost improvement areas, which fall into two main categories: 1) improving the consolidation, organization, analysis, and use of data that already have been, or are being, collected by utilities, and 2) improving the capability and cost-effectiveness of inspection technologies:

- **Standardized Asset and Failure Databases.** Adoption of a national standardized asset and failure database would be a major step in improving condition assessment.

- **Condition Assessment Priority-Setting & Implementation Guidelines.** User-friendly guidelines should be developed for utilities for identifying high risk scenarios, interpreting defects and distress indicators, developing pipe condition rating, and selecting specific investigation or monitoring techniques. Guidelines are also needed for utilities on undertaking a two-stage condition assessment after a decision has been made and the goals of condition assessment have been established. The first stage is an initial assessment based on asset and failure databases, which, in some cases, may be sufficient for a decision to be made without investigation. In other cases it will define and prioritize the second stage, which is a more detailed, specific investigation that will typically involve inspection.

- **User Friendly Residual Life and Deterioration Models.** User-friendly models to predict residual life and deterioration are needed that can be used by utilities to assist them in their asset management planning and expenditure forecasting. The prediction models for individual water mains need to be tailored to the local characteristics and experience, but not too complicated and costly to use. An evaluation of the effectiveness of the existing models and their extent of use by utilities will be valuable.

- **Better Inspection and Condition Forecasting.** Cost-effective inspection tools and methodologies are needed to provide data on existing structural condition and prediction of future deterioration. A consensus is required on what data need to be collected, over what percentage of a pipeline, to what accuracy, and what cost the utilities are willing to pay.

- **Determining an Acceptable Relationship between Cost of Inspection and Value of Asset.** Utilities seem prepared to pay the relatively high cost of inspection for large mains as the consequences of failure can be very high in terms of damage, loss of service, and repair cost. There is value, after cost of investigation is deducted from the benefit, in avoiding a failure. More in-depth studies on the value of inspection in relation to asset value for different diameter and types of pipes are needed. This could go hand in hand with alternative ways of condition assessment for smaller diameter pipes and justify the use of NDT inspection tools.

Short- and Long-Term Improvements to Condition Assessment for Ferrous Water Mains

The State of Technology Review Report and Forum contributions together provide clear guidance on the potential short- and long-term improvements to accelerate and expand the development and acceptance of innovative, cost-effective ferrous water main condition assessment approaches (i.e., technologies, procedures, and databases).

- **Short-Term Opportunities to Improve Condition Assessment.**
  - Improved effectiveness of collection, analysis, and use of existing information (i.e., environmental, historical, and operational) for condition assessment offers the best opportunity to improve the asset management performance of the water industry. The knowledge and understanding of local conditions, defects, and failures reside with the utility management, engineers, and operators and should be harnessed.
  - Recent and emerging advances in leak detection and structural inspection technologies show promise of providing relatively low-cost, low-intrusion capability for utilities to undertake inspection.

- **Long-Term Opportunities to Improve Condition Assessment.**
  - Utilities should be provided with better understanding of the behavior of different forms of ferrous pipes in the water network. A national database of assets and failures relating breaks and leaks to specific materials and environment can allow utilities to benchmark their own experience and support the decision-making process.
  - Long-term advances in inspection technologies can be accelerated by developing a consensus on cost and performance targets for next-generation inspection and condition assessment goals, technologies and procedures. Advances in electronics, sensor technology, and computer science will enable the emergence of new technologies that can be applied to the inspection, monitoring, and assessment of the conditions of water

mains. Technologies initially developed for non-water applications should be assessed for potential transferability to water main condition assessment.

- **Measuring Success.** Measuring success will take a number of forms. By the nature of the utility structure and the measures needed it will take time for the full benefits to flow. Over time, the improved condition assessment activities should result in reduced unforeseen failures and catastrophic events as well as the associated direct and indirect costs. Improved life prediction curves will provide a sound basis for budgeting for renewals and allow a running program to be developed

- **Accelerating Development – Potential Government Roles.** In cooperation and collaboration with relevant stakeholders, the government can play important roles in accelerating technology development. Examples include:
  - Support for guaranteed minimum work programs for internal inspection
  - Support for national database development
  - Defining next-generation inspection technology needs
  - Funding technology innovation research & development
  - Support of condition assessment technology test facilities, and
  - Support of field demonstrations.

- **Getting Utilities to Accept Effective, Innovative Technologies.** The benefits of condition assessment and the techniques used in inspection, assessment, and prediction should be communicated with utilities more effectively through various channels, including workshops, conferences, webinars, papers, and articles. By raising awareness and interest, the benefits of adopting the methods and technologies will become apparent to the utilities. They will adopt these techniques only if such an action helps them save money, make their work easier, and make their customers happier. Field demonstration will be a key way to show utilities what can be done and at what cost.

1.0 CHARACTERIZATION OF WATER NETWORK IN U.S.

1.1 Overview of U.S. Water Transmission and Distribution Network

The basics of the U.S. water transmission and distribution network are profiled in Tables 1-1, 1-2, and 1-3 based on studies and surveys conducted by American Water Works Association (AWWA) and AWWA Research Foundation (AwwaRF) (AWWA and AwwaRF, 1992; 1996; AWWA, 2004). Because these surveys are based on limited responses, there are some variations in percentage breakdowns by pipe materials. As shown in Table 1-1, about two thirds of the installed network consists of various forms of ferrous pipes, including cast iron, ductile iron, and steel pipes. This State of Technology Review Report and the Forum concentrated on ferrous pipes to allow for a more focused and in-depth evaluation of the condition assessment and inspection needs. This focus has the advantage that the causes of deterioration and the technologies of inspection to identify and quantify defects in ferrous pipes are common.

Table 1-1. Water Network by Pipe Material

Source of Data	**Water Industry Database[(a)]**		**Water://Stats 1996 Distribution Survey[(b)]**		**Water://Stats 2002 Distribution Survey[(c)]**	
Utilities Responded/Surveyed	1,097/3,000		898/3,200		337/3,000	
Response Rate	37%		28%		11%	
Pipe Material	Miles Installed[(d)]	Percent of Total	Miles Installed	Percent of Total	Miles Installed	Percent of Total
Cast Iron Unlined	153,415	17.8	NA	NA	37,433	18.5
Cast Iron Cement Mortar Lined	159,284	18.5	NA	NA	34,039	16.8
Cast Iron Other Lining/Unknown	28,476	3.3	NA	NA	NA	NA
Total Cast Iron	341,175	39.6	155,038	41.3	71,472	35.4
Ductile Iron Unlined	35,916	4.2	NA	NA	9,886	4.9
Ductile Iron Cement Mortar Lined	150,705	17.5	NA	NA	35,118	17.4
Ductile Iron Other Lining/Unknown	2,494	0.3	NA	NA	NA	NA
Total Ductile Iron	189,115	21.9	81,119	21.6	45,004	22.3
Steel	34,047	3.9	16,415	4.4	7,821	3.9
Subtotal for Ferrous Pipes	564,337	65.4	252,572	67.3	124,297	61.5
Asbestos Cement	136,196	15.8	56,360	15.0	30,484	15.1
Pre-stressed Concrete	23,584	2.7	15,921	4.2	4,774	2.4
Glass Reinforced Plastic	665	0.08	422	0.1	NA	NA
Polyethylene	3,349	0.4	1,318	0.4	1,377	0.7
Polyvinyl Chloride	114,152	13.2	42,125	11.2	29,835	14.8
Others/Unknown	20,169	2.3	6,719	1.8	11,391	5.6
Subtotal for Non-ferrous Pipes	298,115	34.6	122,865	32.7	77,861	38.5
Grand Total	862,452	100	375,437	100	202,158	100

NA = not available
(a) AWWA and AwwaRF, 1992.
(b) AWWA and AwwaRF, 1996.
(c) AWWA, 2004.
(d) Data represent population-based extrapolations to national totals.

Table 1-2. Water Network by Age

Age in Years	Miles Installed	Percentage
0 to 10	245,000	28.4
10 to 25	325,000	37.6
25 to 50	156,500	18.1
>50	137,000	15.9
Total	863,000	100

Source: AWWA and AwwaRF, 1992.

Table 1-3. Water Network by Diameter

Diameter Range (in.)	Miles Installed	Percentage
<6	107,200	12.4
6 to 10	523,200	60.6
12 to 16	138,600	16.3
18 to 24	29,700	3.4
30 to 48	57,700	6.7
>48	6,000	0.8
Total	863,000	100

Source: AWWA and AwwaRF, 1992.

Various forms of grey cast iron pipes account for nearly 40 percent of the network and are at least 40 years old with some well over 100 years old. The production of grey cast iron pipes ceased from the 1970s so all the iron pipes laid in the last 30 to 40 years have been ductile iron pipes. According to the AWWA 1992 Water Industry Data Base (AWWA and AwwaRF, 1992), 34 percent of the network was more than 25 years old and 72 percent was installed more than 10 years ago (see Table 1-2). Due to lack of recent survey data on pipe age, it is estimated that, at the present time (i.e., 17 years from 1992), about 75 percent of the current network is older than 25 years and that about half of the current ferrous pipe network is older than 50 years.

Water transmission mains usually range in diameter from 12 to 96 in. and greater. From Table 1-3, it is noted that over 70 percent of the network was in diameters of 12 in. or less. The smaller diameter pipes have more frequent failures than larger diameter pipes as a result of a greater installed length of small pipes and a higher failure rate than the larger pipes. While most of the failures occur in smaller diameters, the risk posed by single failure of a large transmission line can be orders of magnitude higher due to the significant damage and loss of service that can occur.

1.2 Types of Ferrous Pipes

1.2.1 Cast Iron Pipes. Cast iron usually refers to grey cast iron. Most grey cast iron pipes that are in service were manufactured by either pit casting or spin casting. The earliest cast iron pipes were vertically pit-cast grey iron. In the early nineteenth century, the first pit-cast iron pipes in the U.S. were imported, but from 1830, local production became more widely established. Pit-cast iron pipes were manufactured and installed until the 1940s.

Pit-cast iron pipes are characterized by:

- High degree of variability in wall thickness, often with an eccentric bore
- Casting defects such as blowholes, pinholes, etc.

- Mould parting seams
- Poured lead joints
- Easily fractured with a sharp impact
- Flake graphite form
- Unlined pipe.

Spun-cast iron pipes followed in the late 1920s and were extensively installed until the 1970s. Spun-cast iron pipes are characterized by:

- Thinner wall than vertically cast pipes, but uniform thickness
- Manufacturing defects, laps, laces, and pinholes
- Stress corrosion fissures
- Leadite joints and rubber gasket seals
- Easily fractured with a sharp impact
- Flake graphite form
- Unlined pipe.

1.2.2 Ductile Iron Pipes. Ductile iron pipes were commercially introduced in the 1950s and because of greatly improved characteristics, they replaced spun iron by the late 1960s. The characteristics of ductile iron pipes are:

- Thinner wall with uniform thickness
- Shrinkage porosity (angular pores resulting form non-uniform solidification)
- Reverse peen pattern on surface
- Not subject to brittle fracture
- Rubber gasket seals
- Spheroidal or nodular graphite form
- Approximately twice the strength of cast iron (tensile, beam, ring bending, and bursting tests)
- Increased use of scrap metal in pipe production changing the microstructure
- Generally lined pipe.

1.2.3 Steel Pipes. The level of carbon in the metal is what distinguishes steel from cast iron. Steel normally has less than 1.2 percent by weight of carbon and its structure is dominated by pearlite. Both grey and ductile iron pipes have a carbon content of 2 to 5 percent by weight. Various methods are used to fabricate steel pipes. One early form was Lock-Bar pipes (American Society for Testing and Materials [ASTM] -137-34), which originated in Australia, where pipes were made by rolling steel plate in two half cylinders and joining the two edges with a locking bar. In the early nineteenth century, pipes were formed by using riveted steel plates. Such pipes are still in operation in the cities of Toronto and Los Angeles. Since the 1930s, they have been fabricated as welded pipes.

Diameters up to 20 in. can be manufactured to produce seamless pipes. Larger diameter pipes use “O” or “U” dies to form plates into the required shapes and the longitudinal seams are welded. Other methods take plates and roll them to the required shapes, which are welded together by submerged arc with one or more circumferential and longitudinal seams. One technique is spiral fusion welding, in which coiled strip is formed helically into a pipe and the spiral seam is continuously welded.

Contemporary steel pipes in the water network typically have a diameter of 14 in. or greater. The characteristics of steel pipes are:

- Thinner wall than grey cast iron or ductile iron pipes
- High strength with ability to deflect without breaking
- Shock resistance
- Lighter weight than ductile iron pipe
- Ease of fabrication of large pipe
- Availability of special configurations by welding
- Ease of field modification
- Protective coating externally; cathodic protection is routinely installed
- Generally lined pipe.

1.2.4 Summary of Ferrous Pipes. A summary of the advantages and limitations of various types of ferrous pipes is provided in Table 1-4.

Table 1-4. Advantages and Limitations of Types of Ferrous Pipes

Advantages	Limitations
Grey (Pit and Spun) Cast Iron Pipes	
• Thicker wall than ductile iron or steel • Similar rate of corrosion to ductile iron and steel • Most pipes after 1950 supplied with cement mortar lining or retrofitted	• No elastic behavior and lower mechanical strength • Prone to external and internal corrosion in aggressive conditions • Older pipes having caulked joints with little flexibility • Often no external protection • Most pipes unlined before 1960 • Manufacturing defects including variations in wall thickness • Poor records
Ductile Iron Pipes	
• Greater ductility than grey iron • Greater impact resistance than grey iron • Greater strength than grey iron • Lighter and easier to lay than grey iron • Simplicity of joints • Joints can accommodate some angular deflection	• Similar rate of corrosion to grey iron and steel • Prone to external and internal corrosion • Internal and external protection systems required • Limited number of protection systems available in U.S. • Polyethylene wrappings can be damaged
Steel Pipes with Lining	
• High tensile strength • High compressive strength • Range of corrosion protection systems • Wide range of diameters and wall thickness Welded joints give continuity	• Prone to external corrosion • Electrolysis prone • Jointing requires skilled welders • Internal/external corrosion protection systems add to price • Coatings and linings can get damaged during installation and by third parties

The improved characteristics developed over the years allowed a significant reduction in the thickness of pipe walls permitted under AWWA recommendations, as shown in Table 1-5.

Pipes were, and are, manufactured in a range of pressure classes. The date of manufacture is significant in any consideration of ductile iron mains. The first AWWA standard C151/A21.51 was issued in 1965 and revised in 1971, 1976, 1981, and 1986. These standards were based on a series of seven thickness classes designated as Class 50 to Class 56. The wall thickness for a 42-in. pipe could vary from 0.47 in. at Class 50 to 0.83 in. at Class 56.

Table 1-5. Change in Wall Thickness Specifications for a 36-in. Pipe Operating at 150 psi

Year of Installation	Material	Wall Thickness (in.)
1908	Cast iron	1.58
1952	Cast iron	1.22
1957	Cast iron	0.94
1965	Ductile iron	0.58
1976	Ductile iron	0.43
1991	Ductile iron	0.38

Every pipe from the standard of the same class has the same d/t ratio. This links directly to pressure capability as the hoop stress is equal to Pd/2t, where P is internal pressure, d is internal diameter, and t is wall thickness. Therefore, for a given allowable hoop stress, every pipe of the same thickness class would have the same pressure rating, ignoring external load. In 1991, the standard was changed to a “pressure class” system and the “thickness class” was no longer standard. However, this change was not universally accepted and some engineers stayed with “thickness class” specifications. These are still included in the standards as “Special.”

Pressure to keep installed costs as low as possible often results in selecting the lowest pressure class of pipe for use. The use of a lower pressure class of pipe with a thinner wall frequently results in a shorter service life and in most cases, this disadvantage far outweighs any short-term economic advantage.

Ductile pipes normally are lined with cement mortar, and coatings and plastic sheaths help resist external corrosion.

Other forms of lining are used, including epoxies and urethanes. Water lines can be rehabilitated in-situ, with polyethylene (PE) and cure in place being the most widely used material and lining system, respectively.

Steel pipes used for water mains are normally lined internally and coated externally. Linings include cement mortar and polyurethane. Coatings include tape, coal tar enamel, cement mortar, epoxy, and polyurethane. Cathodic protection by an impressed current or sacrificial anode system for wrapped or coated steel lines is generally recommended and widely used. The continuity of welded joints facilitates the use of cathodic protection.

Early cast iron pipes were jointed rigidly with metal to metal contact with a bell and spigot. Lead and leadite were used for jointing. Semi-rigid joints, with a packing material such as jute or yarn and caulked with lead, became the predominant method.

Ductile iron pipes can have a variety of joints; bell and spigot push fit type is used primarily for pipes in trenches, with an elastomeric seal. Bolted mechanical and flanged joints are also available.

Steel pipes used for water mains principally have welded or flanged joints.

1.3 Overview of Failure Modes of Ferrous Pipes

The primary research focus of this project is on structural condition of water transmission and distribution mains as opposed to hydraulic or water quality condition. It is estimated that there are 300,000 main breaks a year for all types of pipe material in the U.S. (Grigg, 2007). The modes of structural failure for ferrous pipes have been extensively researched, and this section provides a summary of the literature search.

Causes of failure can be considered under two categories: corrosion and mechanical failures. Although these causes are distinct, they are related in that mechanical failures may result from corrosion such that the pipe is no longer able to resist applied internal and external forces.

Leakage is an additional category that may or may not be classified as a structural failure depending on its location and its severity. Corrosion of the pipe wall may lead to perforation and leakage. Leakage can also occur at joints and contribute to mechanical failures in eroding pipe bedding support. Leakage can be seen as an indicator of wall penetration by pitting.

1.3.1 Corrosion – Internal and External. Many different mechanisms and parameters are involved in corrosion and failure of ferrous pipes. This complexity has given rise to controversy and differences of opinion about the relative performance of different forms of ferrous pipes.

Overview of Corrosion Mechanisms

The criteria essential for corrosion by oxidation include

- Oxygen supply
- Moisture
- Soluble salts
- Cathodic and anodic sites.

Conditions may vary widely along the length of a buried pipeline and can result in considerable variability found when investigating external corrosion. It is common to find a section of badly corroded pipe adjacent to a sound section. This situation is emphasized by the observation of corrosion “hot spots” in which accelerated corrosion can be focused on one location in the pipe exposed to conditions that are conducive to corrosion.

A more detailed consideration to mechanisms of external corrosion is presented in “Corrosion Control Measures for Ductile Iron Pipe” (Stroud, 1989). More in-depth information on the mechanisms of internal corrosion can be found in “Iron Pipe Corrosion in Distribution Systems” (McNeill and Edwards, 2001).

Graphitization

For iron pipes, graphitization is an important form of corrosion. Graphitization occurs where soil conditions including pH, dissolved salts, and organic content are favorable to anaerobic bacterial growth. For grey iron, the metal goes into solution leaving behind a corrosion product that consists of a mass of residual graphite flakes interspersed with iron oxides. Over time the wall becomes a composite of grey cast iron and a graphite matrix with the corrosion product occupying the space previously occupied by the grey iron. An example is shown in Figure 1-1. It is difficult to identify graphitization during visual inspection because there is no apparent wall thickness loss. The graphitized material has some strength, although possibly greatly reduced, which explains why some extensively graphitized grey cast iron pipes have continued to function.

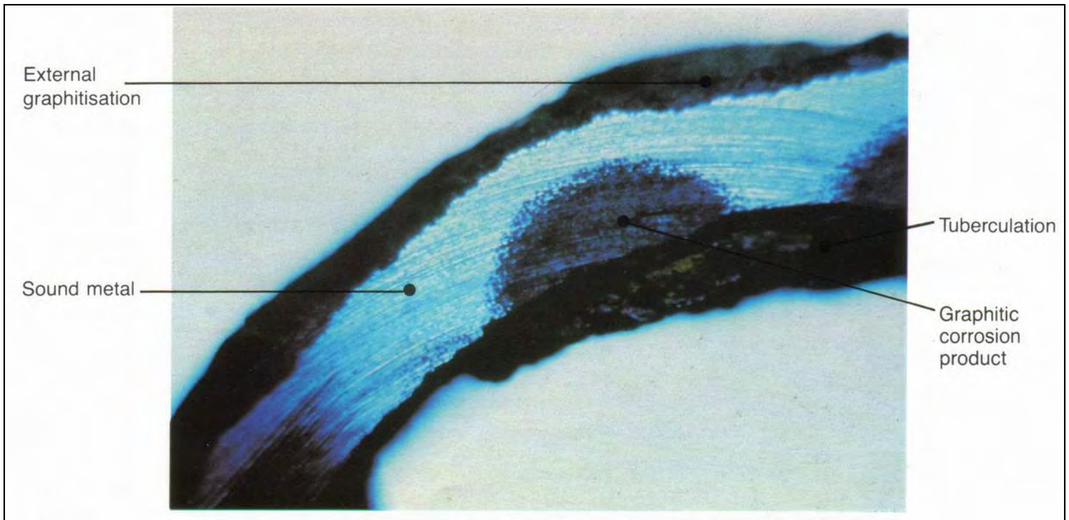


Plate 2 Detail of a section through the site of an internal pit

Source: Dempsey and Manook, 1986.

Figure 1-1. External and Internal Graphitization in a Cut Section of Grey Iron

Often grey cast iron pipe failure comes from mechanical stress or a hydraulic shock (roadwork, transport damage, or ground movement) acting on the weakened structure. This is then classified as a mechanical failure rather than a corrosion failure.

General corrosion can occur in ductile iron in the form of graphitization, but the corrosion material that forms is weaker and more friable than that in grey iron. The graphite corrosion products are in the form of discrete nodules that are easily detached, and a structure is not retained. This can lead to leakage and break failure occurring more quickly than in grey cast iron (Vrab, 1992).

The relative merits of the different metallurgical forms of grey cast iron and ductile iron and their resistance to graphitization have been an area of some disagreement among researchers.

Graphitization does not occur in steel pipes.

Pitting Corrosion

For all types of ferrous pipes, external corrosion in the form of isolated pitting, general corrosion, and graphitization is the most common form of deterioration, which can lead to leakage or failure.

Pitting corrosion is a concentration of corrosion in one particular area. The metal goes into solution preferentially at that spot rather than adjacent areas. Figure 1-2 shows a pipe corroded externally.

Pitting corrosion is the most common deterioration mechanism for all ferrous pipes. It can occur internally, although it is more likely to be found externally. Pitting occurs quite randomly, usually leading to wall penetration and leaks rather than failures. A group of pits in one area can weaken the wall sufficiently for the pipe to fail. Figure 1-3 shows external pitting on a pipe.

Plate 6 General corrosion damage over part of external surface

Source: Dempsey and Manook, 1986.

Figure 1-2. External Corrosion of a Grey Iron Pipe

Plate 7 Isolated external pitting (narrow)

Source: Dempsey and Manook, 1986.

Figure 1-3. External Pitting after Shot Blasting

The AwwaRF report "The Effect of Corrosion Pitting on Circumferential Failures in Grey Cast Iron Pipes" gives a detailed presentation on pitting in grey cast iron pipes (Makar, 2005).

The extent and rate of external pitting on an unprotected pipe is governed primarily by the corrosivity of the environment. Consequently, various protective measures are installed to counter external corrosion.

The most common form of external protection in North America is polyethylene encasement (AWWA C105 issued in 1972), and its use has been specified in ASTM D1248 since the 1950s. This is a site operation where the pipe is wrapped in polyethylene sheet at the time of laying. The objective is to isolate the pipe from the soil environment. The Ductile Iron Pipe Research Association (DIPRA) sets out a strong case for this as the only protection system needed. However, cases of failure of wrapped ductile iron pipes have been reported. Damage to the polyethylene wrap during installation or subsequently by third party activities can allow ingress of groundwater, creating corrosive conditions. Some utilities base decisions on the grounds of non-corrosive condition and/or cost reduction and have not followed DIPRA recommendations. It is thought that as much as 50 percent of ductile iron pipes have been laid without poly-wrap.

Bonded coatings normally are not recommended on ductile iron pipes, while bonded coatings on steel pipes are readily supplied. The only AWWA standards for ductile iron cover polyethylene encasement and the standard asphaltic shop coating.

Lining the ferrous pipe interior with cement mortar maintains water potability. It also protects the metal from corrosion by providing a coating of electrically inert material between metal and liquid. High pH of the conveyed water can be incompatible with cement mortar lining (CML). Deterioration takes the form of leaching of lime from the cement matrix, causing calcium loss. An on-going Water Research Foundation project, "Life Expectancy of Field and Factory Applied Cement Mortar Linings in Ductile Iron and Cast Iron Water Mains" (Project #3126), will address such issues in more detail.

Leakage

Leakage can occur both from joints due to poor installation and from the body of the pipe where perforations occur due to pitting. Leakage through perforations in the pipe wall is common to all ferrous pipes. Leakage from joints is probably most common due to incorrect installation. Another cause is movement of adjacent pipe lengths. In the case shown in Figure 1-4, the deep corrosion pitting perforating the pipe wall did not lead to a structural failure.

Often small leakage from water mains goes undetected and therefore continues without remedial action. All forms of leakage can in theory lead to erosion of the pipe bedding and to structural failure. In practical terms most leaks, particularly from joints, are defects rather than failures and do not create conditions leading to failure. This is not to undervalue the serious costs and problems that arise from leakage.

The interaction between a leaking pipe and its surrounding soil is complex (Van Zyl and Clayton, 2005). The relationship between head loss and flow is not linear, as a result of the interaction of the soil particles with the orifice, turbulent flow in the soil, the changing geometry of the unconfined flow regime, hydraulic fracturing, and piping. Theoretical considerations suggest that small continuous leaks will drain away without trace into underlying granular soil. This cannot be expected to occur in lower permeability clays and silts, where hydraulic fracture is more likely, with leaks rapidly becoming visible as wet patches and bursts at the ground surface.

Plate 10 Holes (FWG) produced by deep external corrosion pits – spun grey iron pipe from a non-failure site

Source: Dempsey and Manook, 1986.

Figure 1-4. Deep Corrosion Pits Leading to Perforation

Microbiologically Influenced Corrosion

Buried ductile iron and grey cast iron pipe can be subject to microbiologically influenced corrosion (MIC). There are two forms – anaerobic and aerobic. Anaerobic corrosion is what is often referred to as hydrogen sulfide corrosion.

Sulfate reducing bacteria (SRB) are a typical example of anaerobic bacteria. The attack is ascribed to the bacteria's ability to make the oxygen that is present in sulfates, nitrates, and carbonates available for a cathodic reaction. This is significant in that it means that corrosion can occur even in the absence of dissolved oxygen. It is calculated that the corrosion rate of iron under anaerobic conditions is nearly 20 times as great as under sterile conditions. According to a study in Australia, it is estimated that 50 percent of their studied failures that occurred on buried metal were due to MIC (Ferguson and Nicholas, 1984).

Galvanic Corrosion

Galvanic corrosion is an electrochemical process that occurs when dissimilar metals are electrically connected and installed in a uniformly conductive soil, or when a metallic pipe is installed in a soil that has a non-uniform character. In both cases, electrical current flows from the anode to the cathode. As the anode loses electrons, the anode metal is oxidized, and corrosion results.

Galvanic corrosion can be found where a ferrous pipe is connected to copper service lines. The service piping used in North America is almost exclusively copper, with a small amount of lead and galvanized steel pipe used in the older areas. When ferrous and copper pipes are connected, the mixed metal system may accelerate corrosion where the iron piping acts as the anode of a galvanic corrosion cell and the copper acts as the cathode.

Corrosion cells develop on a ferrous pipe exposed to different electrolytes (Fitzgerald, 1984). This situation may occur on a long pipeline that passes through different types of soils, i.e., one portion of the line might be laid in sandy loam while another in clay. Substantial natural pipeline currents may occur, which leads to corrosion cells. In soils of low resistivity, such currents exit from the pipeline, causing the loss of metal at the exit points by anodic dissolution (corrosion). Anodes and cathodes may be miles apart. Similarly, mixtures of soils in the backfill will cause corrosion. Lumps of clay mixed into a sand backfill will lead to severe corrosion where the clay contacts the pipe. The same phenomenon causes corrosion on pipe exposed to soil and concrete or other highly alkaline backfill.

Electrolytic Corrosion

Electrolytic corrosion, also called stray current corrosion, occurs when the pipeline picks up stray electrical current from a direct current (DC) source. Electrolytic corrosion is similar to galvanic except that an outside source rather than a chemical reaction drives the cell. Ferrous pipelines buried in the ground can offer a better path for conducting earth return currents from electrified transport systems, electrical installations, and cathodic protection systems. The point of corrosion normally is located at the point where the positive current exits the pipe and enters the earth.

Pipes that are bell and spigot and jointed with a rubber gasket are not considered as being electrically continuous. However, several case histories are reported in which cathodic protection has been installed after experiencing high rates of failure (Rajani and Kleiner, 2007). The City of Calgary, Canada requires sacrificial anode cathodic protection for all metal pipe systems. Some grey cast iron pipes had a jointing system that involved metal to metal contact, which theoretically could provide a continuous electrical path. Retrofitting by opportunistic fitting of anodes to pipes when exposed has also been increasingly used.

Steel pipelines with welded joints offer a continuous electrical path, but are normally protected by an impressed current or sacrificial anode system.

Both ductile iron and spun-cast iron pipes can become subjected to corrosive conditions as a consequence of damage to the annealing oxide scale formed during manufacture. The action appears to be the electrochemically more noble thermal oxide scale forming a galvanic cell with any damaged area of bare iron that becomes the anode. Because of the relatively large ratio of cathodic to anodic area, this can provide conditions for rapid localized corrosion attack.

Crevice corrosion occurs where the surface is flawed by mill scale, scratches, or rust. This is found to be more prevalent in spun-cast iron pipes.

Tuberculation

Internal corrosion of iron can lead to the formation of loose porous rust, i.e., ferric iron hydroxide $Fe(OH)_3$, which can transform into a crystallized form called tubercles on the internal unlined surface of a ferrous pipe. Depending on the pH and other ions present, a variety of precipitates can mix with the iron oxide forming an internal “lining” of tuberculation. This “lining” can slow corrosion by cutting off the metal from the water and air supply. Figure 1-5 shows a tuberculated water pipe.

It has been observed that pitting is often present below the tuberculation. The removal of tuberculation will cause the pitting to continue at an accelerated rate until a new coating is formed. Utilities normally line a pipe with cement mortar after cleaning, which protects the internal surface.

Source: provided by John Black of Opus Consultants in Australia

Figure 1-5. Tuberculated 6-in. Cast Iron Water Pipe

Tuberculation creates problems of flow and water quality. It also creates a barrier for many internal inspection tools. Disturbing the tuberculation "lining" without subsequent lining can lead to water quality problems and further accelerated internal corrosion. For this reason, cleaning or seriously disturbing the tuberculation by internal investigation is generally avoided.

Relative Resistance to Corrosion of Cast and Ductile Iron

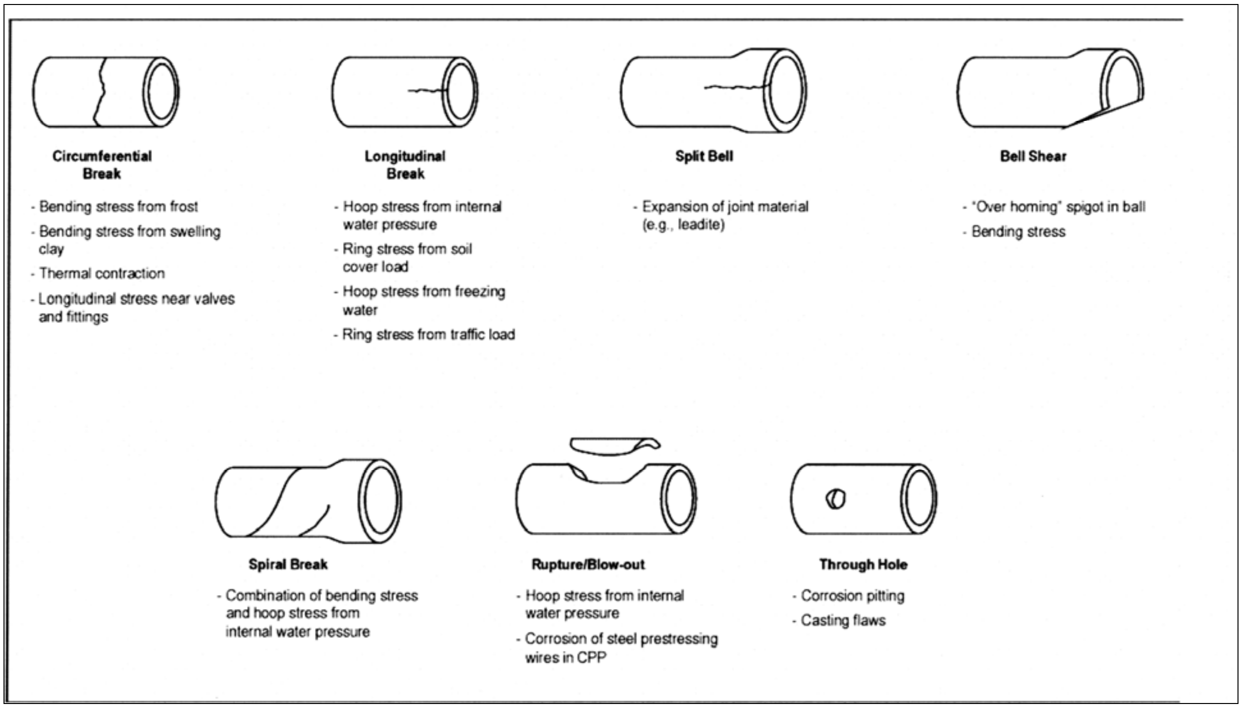
There have been many published discussions on the relative resistance of cast and ductile iron, and some organizations suggest that in terms of corrosion resistance, ductile is superior to cast iron. This is considered to be an optimistic conclusion by De Rosa and Parkinson (1986), who, after reviewing a large range of investigations and evidence, determined that:

- The evidence that ductile iron exhibits superior pitting resistance is not conclusive; for all practical purposes, there is no significant difference
- External pitting rates depend on the aggressivity of the soil environment
- For equal thickness, steel is the best material when buried bare.

The Water Research Foundation study "Long Term Performance of Ductile Iron Pipe" (Project #3036) is expected to provide valuable information on this contentious topic when it is completed in 2010.

1.3.2 Mechanical Failures. Mechanical failures are more complex to investigate and interpret. Undoubtedly for a utility operator repairing a failure, it would be very difficult to distinguish between a corrosion and mechanical failure. A survey by the National Research Council of Canada (NRC) reported that 23 out of 25 mechanical failures investigated were associated with corrosion pitting (NRC, 2003).

Figure 1-6 illustrates the most common failure modes of water main breaks, as well as the forces acting on the pipe that cause breaks to occur (NRC, 2003).



Source: NRC, 2003.

Figure 1-6. Examples of Structural Failure Modes for Water Mains

Exposed fracture surfaces and cracks indicate a mechanical failure. Six different mechanical failure modes have been identified for cast iron pipes (Makar, 2001). These modes are:

- **Circumferential failures**, typically found in smaller diameter pipes and due to longitudinal stresses
- **Longitudinal failures**, typically found in larger diameter pipes and caused by internal pressure or compressive forces which push spigots into bells
- **Shearing failures**, typically found in large diameter pipes often associated with over forcing of spigots into bells
- **Spiral failures**, which have been found in medium diameters of up to 20 in.
- **Bell splits**, normally associated with leadite-sulfur based joint sealant, and caused by differing thermal expansion between metal and non-metallic leadite
- **Perforations**, normally created by through-wall pitting. The failure will be leakage rather than structural.

The seventh failure mode – rupture/blow-out, mainly occurs in prestressed concrete cylinder pipes (PCCP) due to prestressed wire failure. Often what is described as blow-out in ferrous pipes is actually one of the other six modes.

Circumferential or circular failures may be caused by one or more of the following:

- Thermal contraction
- Bending stresses arising from differential soil movements or voids in the bedding, which in turn may be caused by leaks
- Bad installation practice
- Third party impingement
- Internal pressure in combination with one of the above.

Longitudinal breaks are caused by transverse stresses, and one or more of the following factors are involved:

- Internal pressure
- Hoop stress due to live loads
- Increased ring stress due to thermal changes (frost loads).

From a study of 72,000 data records of U.K. ferrous water mains laid in the period between 1880 and 1980, the overall percentage of failure types is shown in Table 1-6 (United Kingdom Water Industry Research [UKWIR], 2001).

Table 1-6. Percentages of Failures of Iron Pipe with Different Modes in U.K.

Circumferential	Longitudinal	Hole	Joint
66.4%	13.3%	16.1%	4.2%

The large percentage of circumferential failures was concentrated in the smaller diameters up to 12 in., which also represent the greatest length of the network. Longitudinal failures became dominant in the larger diameters.

Mechanical failure for steel pipe is by longitudinal crack propagation.

1.4 Main Break Occurrence Factors

Table 1-7 summarizes the main break occurrence factors. It is based on Table 1 from an EPA "White Paper on Improvement of Structural Integrity Monitoring for Drinking Water Mains" (Royer, 2005).

1.5 Causes of Failure and Indicators in Ferrous Pipes

Table 1-8 is a summary of main causes of failure and indicators in ferrous pipes. Break failure refers to situations where pipe loses its functionality and is no long serviceable; structural failure refers to presence of cracks, holes, and other defects on serviceable pipes.

Table 1-7. Summary of Factors Leading to Main Break Occurrences

Factor	Description
Chemical stressors	• Internal and external corrosion caused by factors such as aggressive water or soil, microbes stray currents, oxygen gradients and bi-metallic connections
Physical stressors	• Damage during transport, unloading, storage and installation • Traffic loads • Soil loads from differential settlement caused by soil movement • Point loads (impingement) • Internal radial loads from internal pressure fluctuation • Axial loads from seismic activity, soil movement and water hammer • Thermal stress from temperature differences between water, pipe and soil • Damage by third parties – dig-ins • Damage to external coatings or internal linings
Other factors	• Aging – accumulation over time of chemical and physical stressors • Pipe flaws – inadequacies in design, raw materials or manufacturing • Installation defects – incorrect bedding, backfill, jointing, encapsulation and coatings

Table 1-8. Main Forms of Failure and Indicators in Ferrous Pipes

Form of Failure	Causes of Failure	Indicators of Failure
	Cast Iron Pipes	
Break failure	Internal pitting and graphitization corrosion weakening wall often combined with induced strain	Lining damage, wall loss from internal pitting, graphitization, leaks, external loads, and pressure variations
Break failure	External pitting and graphitization corrosion weakening wall often combined with induced strains	Coating damage, wall loss from external pits, graphitization (hard to detect), leaks, external loads, and pressure variations
Break failure	Third party impact damage	Construction activity
Break failure	Manufacturing defects coupled with fatigue and/or soil movements	Cracks in body or bell
Structural failure	Movements from thermal, seismic, external loading	Joint leaks, poor bedding, and pipe movements
Structural failure (Circumferential cracking smaller diameters <12 in.)	Thermal contraction, poor support leading to movement, internal pressure	Circumferential cracks, frost regions, leaks, pipe movements, and expansive clays
Structural failure (Longitudinal cracking larger diameters >12 in.)	Internal pressures, external loadings, thermal stresses	Longitudinal cracks, frost regions, and changed internal/external loads
Structural failure (bell splits)	Leadite joints	Cracking at bell
Leaks (joints)	Loss of soil support and bending failure	Leak noise, wet areas, and pressure variations

Table 1-8. Main Forms of Failure and Indicators in Ferrous Pipes (Continued)

Form of Failure	Causes of Failure	Indicators of Failure
	Ductile Iron Pipes	
Break failure	External pitting and graphitization corrosion weakening wall often combined with induced strains	Damaged protection, wall loss from external pitting, graphitization (hard to detect), leaks, external loads, and pressure variations
Break failure	Internal pitting and graphitization corrosion weakening wall often combined with induced strains	Damaged lining, wall loss from internal pitting, graphitization (hard to detect), leaks, external loads, and pressure variations
Break failure	Third party impact damage	Construction activity
Structural failure	Movements from thermal, seismic, external loading	Joint leaks, poor bedding, and pipe movements
Structural failure (Circumferential cracking-smaller diameters <12 in.)	Thermal contraction, poor support leading to movement, internal pressure	Circumferential cracks, frost regions, leaks, pipe movements, and expansive clays
Structural failure (Longitudinal cracking-larger diameters >12 in.)	Internal pressures, external loadings, Thermal stresses	Longitudinal cracks, frost regions, and changed internal/external loads
Leaks (wall perforations and joints)	Loss of soil support and bending failure	Leak noise and wet area
	Steel Pipes with Cement Mortar Lining	
Break failure	Pitting corrosion weakening wall	Damage to coating/linings, wall loss, pitting, and leaks
Longitudinal cracking	Thinning from general corrosion, and areas of pitting corrosion	Graphitization, groups of pitting, and wall loss
Pipe bursts	Third party damage	Construction activity

2.0 STATE-OF-THE-ART CONDITION ASSESSMENT OF WATER MAINS

2.1 Role in Relation to Asset Management

Asset management is playing an increasingly important role in utility operations. It is defined in the *International Infrastructure Management Manual* (Institute of Public Works Engineering Australia [IPWEA], 2006) as:

> *"Asset management is a combination of management, financial, economic, engineering, and other practices applied to (physical) assets with the objective of maximizing the value derived from an asset stock over the whole life cycle, within the context of delivering appropriate levels of service to customers, communities and the environment and at an acceptable level of risk."*

Asset condition assessment is an important component of asset management in terms of quantifying and determining asset performance. Condition assessment is used to provide accurate information about current and likely future conditions of an asset. Table 2-1 is a summary of drivers and areas of focus for undertaking a condition assessment, based on the Governmental Accounting Standards Board (GASB) (Marlow and Burn, 2008).

Table 2-1. Drivers for Undertaking Condition Assessment (Marlow and Burn, 2008)

Driver	Focus of Condition Assessment Program
Assessments of renewal budgets and timing of spending	Provide data for use in budget setting and/or justifying capital deferment
Prioritization of capital programs	Target priorities for renewal spending
Determination of appropriate intervention	Determine the level of renovation required; select the most cost-effective whole life approach
Regulatory requirements	Comply with regulatory or financial reporting
Forensic investigations	Understand failure and support litigation

The foundation for asset and condition assessment lies in a comprehensive asset inventory. The pipe inventory should ascertain characteristics for each pipe segment: size, material (including lining and external protection, if any), and age. This covers a great deal more than the pipe network and is outside the scope of this paper. Numerous publications provide guidance on asset management and development of asset inventories (Association of Metropolitan Sewerage Agencies [AMSA], 2002; IPWEA, 2006).

To facilitate benchmarking and comparisons, it is necessary to have a robust asset management framework together with standardized data reporting. In order to undertake robust appraisals within an asset management framework, some form of national standard for asset inventory would be of considerable value. Research bodies such as AwwaRF have undertaken extensive research and published numerous reports, including "Asset Management Planning and Reporting Options for Water Utilities" (Matichich et al., 2006), which reviews how utilities handle asset management and defines three options for utilities to use.

2.2 Condition Assessment

Condition assessment may have a variety of goals including strategic, tactical, and operation and maintenance (O&M), which determine the condition assessment implementation and affect the type and accuracy of predictions required.

According to Commonwealth Scientific and Industrial Research Organization (CSIRO), there are two types of condition assessment:

- Assessment of an individual pipe
- Assessment of a collection (cohort) of pipes.

An assessment of individual or short sections of the network is usually undertaken when there is a reason to believe that the particular pipe is in a condition leading to its failure. An assessment of a cohort of pipes gives a general overview of the overall condition of a group of pipes and is often used in strategic decision making. Additional information can then be used to develop the condition assessment to focus on individual pipes. In either cohort or individual condition assessment, it is implicit that a condition assessment be based on asset and failure data, which then dictate what procedures and locations will be critically rated and prioritized for inspection and development of life predictions.

In the EPA's water infrastructure research plan (EPA, 2007), condition assessment is defined 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. The primary research emphasis in this project is structural condition assessment, as opposed to hydraulic or water quality condition assessment.

Condition assessment should be a structured and logical process. The need is to determine quantifiable objectives and understand causes of deterioration, then quantify deterioration in order to reach a sound understanding of the condition.

A comprehensive assessment can be viewed as a four-stage process:

- Stage 1. Initial identification of physical characteristics of a pipeline in terms of historical, environmental, and operational data
    - From this data identify and prioritize assets for condition inspection based on the consequences of failure
    - Determine what information is required from an inspection program. "If you don't know what you are looking for, you are unlikely to find it."
- Stage 2. Evaluate the possible methods of inspection for their appropriateness and cost effectiveness to provide the required type and level of information. Undertake an inspection using an appropriate technology
- Stage 3. Carry out a final condition assessment based on the information from stage 1 and inspection to provide an assessment of the likelihood and consequences of failure. Bear in mind that inspection provides data, not assessment, and needs to be interpreted. Interpretation may include developing life expectancy curves and predictions of time to failure
- Stage 4. A final stage should be to measure the success of the undertaking.

2.3 Condition Assessment – Risk and Prioritization

Risk is defined as the consequences of failure times the likelihood of failure. In any program of condition assessment and prioritization, it is necessary to determine not only the likelihood, but also the consequences of failure. This Risk Based Inspection (RBI) approach has been successfully used for some years in the oil and gas industry. This is represented in Figure 2-1, which graphically shows the combination.

The reality of water utility management, with limited resources, is that when the likelihood of failure may be high but consequences are low, the cost of investigation may not be justified. For example, with a 4-in. cast iron main in open ground in a rural area it will be more economical to repair any failure and replace when an unacceptable level of failure is reached. Any condition assessment should include such a risk evaluation, because it is a key factor in prioritization of investigation.

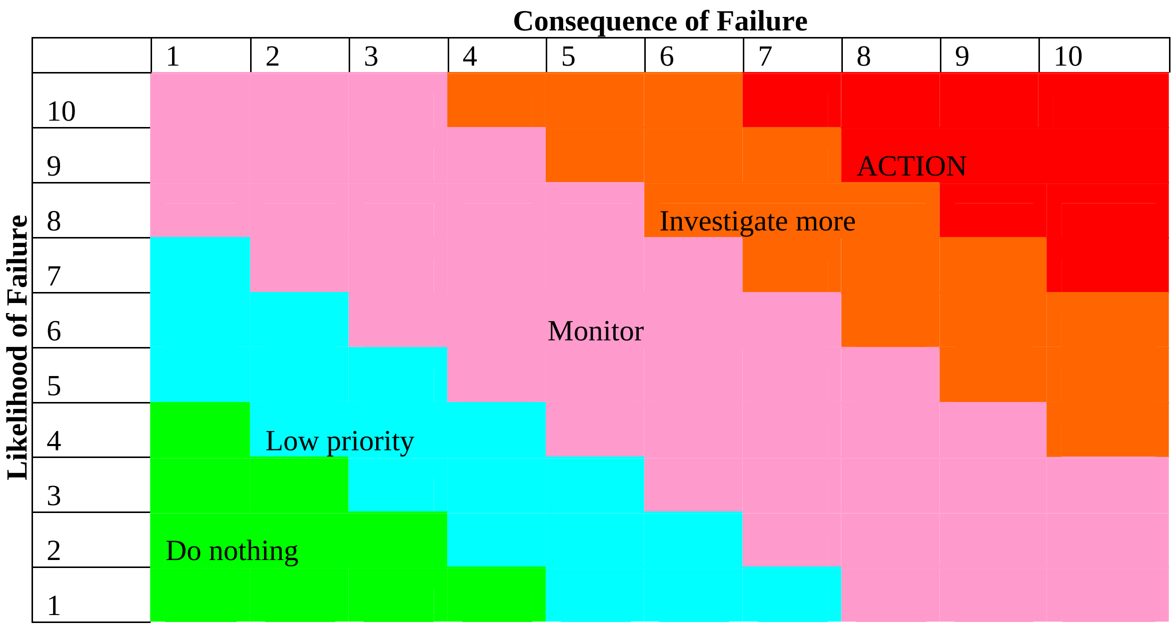


Figure 2-1. Risk: Consequences and Likelihood of Failure

2.3.1 Consequences of Failure. The consequences of failure can be evaluated under three main headings:

- Direct costs
- Environmental costs
- Socio-economic costs.

Each individual main can be assessed on the basis of these headings. If the assessment to any of these headings indicates a high impact and cost, then the main would have a high rating in terms of consequences of failure.

Some of the factors that increase the consequences of failure are set out in Table 2-2.

Table 2-2. High Consequence of Failure

Critical Customers	Critical Locations	Difficult Physical Factors
• Large populations • Government, defense sites • Hospitals • Key industries • Critical care individuals	• Industrial/commercial/residential • Highways, bridges, tunnels, railroads, airports, subways • Potential landslips • Water courses • Areas prone to flooding • Major utility crossings	• No alternative routes • Large diameter lines • Difficult terrain • Heavy traffic • Remote sites • No alternative water supply lines

A program under development by UKWIR called "Failure of Large Diameter Trunk Mains" is expected to provide a flexible framework tool for utilities estimating this kind of risk.

2.3.2 Likelihood of Failure – Key Indicators. In this section some of the key and secondary indicators of likelihood of failure are reviewed. Four key indicators are critical in carrying out a condition assessment and criticality review. These are defined as three types of burst or break together with leakage failure. There are also secondary indicators that will modify the assessment.

It should be noted that there is no agreed definition of failure terms in the industry. An on-going Water Research Foundation/WERF project "Key Asset Data for Water Sector Utilities" (Project #4187) may help address this problem.

The term "burst" is commonly used internationally for a structural failure, which makes the pipeline no longer operable. The term "break" is sometimes used in the same sense as "burst" but it has also been used for a crack in the pipe where the pipe is still serviceable.

Burst/Break Failures

For all types of ferrous water mains, the most critical data set is the number of failures (or bursts and breaks), their location, and the nature of the failure. Bursts could be further subdivided according to their significance, as follows.

- **Class A Failures** have greater operational, environmental, and consequential impact and cannot be repaired routinely. It is particularly important for the utility to carry out, in such cases, as comprehensive an investigation and interpretation as possible. Undoubtedly, it is difficult for a utility operator to distinguish between a corrosion and mechanical failure. In many cases both types of failure will be involved. The larger the diameter of the pipe, the more important is the quality of the investigation.
- **Class B Failures** are considered routine pipe breaks and are repaired as they occur, usually for smaller diameter pipes and often involving circumferential breaks. Their impact is much less in terms of cost and environmental, operational, and consequential damage. It was noted earlier that circumferential breaks, predominantly in small pipes, represent a large percentage of structural failures. Such breaks are often caused by excess stress due to factors like soil movement, external loading, and lack of bedding support.
- **Class C Failures** are those that occur due to third party activities and that fall outside the scope of likelihood evaluations. They are not easily predicted, although many Class C failures are avoidable if proper procedures are followed by third parties.

This failure information is most readily available from maintenance records and failure databases developed by the utilities. It should be possible to identify the number, location, and type of breaks, as well as repairs undertaken. Many utilities take the number of failures per mile as the only factor in determining the likelihood of failure and the need to replace a pipe. This is a very common approach in smaller diameters where the cost of structural investigation and assessment may be a significant percentage of the replacement cost.

Leak Failures

Leak failures may be sub-classified into:

- Joint and fitting leaks
- Pipe wall leaks.

Most leaks can be considered as defects as the line remains in service until such time as it is repaired. Leaks in pipe walls can be important, because they are likely to indicate perforation in the pipe wall, which in some mains is considered to lead to structural failure. Stress raisers around the pitting create high local stress leading to fracture.

An AwwaRF study "Leakage Management Technologies" examines the use of proactive leakage management techniques in the U.K and assesses the practicality of applying them to North American utilities (Fanner et al., 2007). An upcoming Water Research Foundation report by American Water will examine the application of continuous acoustic monitors placed throughout a distribution system (Hughes, 2008).

Pipe Wall Corrosion

Pipe wall corrosion indicators are considered in terms of direct data and by inference from environmental conditions, particularly soil aggressivity. Knowing the extent of the metal loss will allow calculation of the current beam and hoop strength and the factor of safety.

Investigation Data. The presence of corrosion in the form of pitting occurring internally and externally is used as a basis for the likelihood of break and predicted life. When inspection data on wall thickness, such as wall thickness loss and pitting depths, are available, this quantitative information can be used to predict the remaining pipe life based on the original pipe wall thickness and the age of the pipe. A major problem in the U.S. is that the availability and quality of data from U.S. utilities are extremely variable, and there is no common reporting standard, which makes comparison difficult.

The findings of a UKWIR study using data from a large utility set out in Table 2-3 may warrant further consideration of the assumption for cast iron pipes that failure will occur when a corrosion pit just penetrates the pipe wall (UKWIR, 2000). It should be noted that corrosion holes only account for 14.3 percent of failures, and most of these failures are concentrated in smaller diameter pipes. Some of the findings of the study were:

- Cast iron pipes do not fail when graphitization just penetrates the wall. It has been found that 9 to 10 percent of random samples of pipes operating successfully had holes in the walls after shot blasting
- When penetration is through the pipe wall, a fracture analysis shows that there is insufficient stress concentration to cause cracking by internal pressure alone

Table 2-3. Number of Different Types of Failure in a U.K. Utility (1991-1997)

Size Range (in.)	Failure Type (count)			
	Hole	Fracture	Joint	Other
2 to 3	1,022	5,947	232	381
4 to 7	3,152	17,237	678	1,136
8 to 10	156	449	53	29
12 to 14	70	226	55	16
15 to 18	17	226	55	29
20 to 24	3	15	5	0
>24	29	88	61	7
Percent	**14.3**	**77.0**	**3.7**	**5.1**

- Leakage in cast iron pipes after wall penetration does not always occur as graphitization product acts as a plug.

The UKWIR study findings need to be compared to the findings on the main failure mode for ductile iron. This was identified not as general corrosion or graphitization, but as pitting attack (Rajani and McDonald, 1995). A study of 359 failures on 118 ductile iron water mains in U.K. suggested that pitting was the primary mode of failure (De Rosa and Parkinson, 1986). The pitting rate appears to be similar for all types of ferrous pipe so that the wall thickness and external protection become key issues. An AwwaRF study "The Effect of Corrosion Pitting on Circumferential Failures in Grey Cast Iron Pipes" focused on small diameter pipes (Makar, 2005). Spun cast iron pipes with pits larger than 1.6 in. in diameter were vulnerable to failure. Pit-cast iron pipes were vulnerable with pits larger than 0.8 in. in diameter. The thinner wall pipes were more prone to circumferential failure than thicker wall pipe. Large changes in soil support were found to be an important factor producing substantial levels of bending stress.

Environmental Corrosion. Environmental corrosion applies to both external and internal pipe corrosions. External corrosion is related to environmental conditions, specifically the corrosivity of the soil. It is necessary to use this information as a proxy to assess the likelihood of corrosion. It is important that a utility populate a database with soil conditions in the area of its water mains. However, natural or man-made changes to the soil environment can create significant differences over the same pipeline. For internal corrosion, there are only some broad indicators, such as aggressive water with low pH that may signify internal corrosive conditions leading to pipe wall loss. For both external and internal corrosion, likelihood of failure will be modified by the type of protection provided, taking into account any defects or damage.

Soil chemistry is an indicator in screening for the likelihood of failure from external corrosion. Soil chemistry and its potential for causing corrosion to ferrous material have been known for many decades. It is recognized in numerous codes and guides as a key factor. Soil chemistry is a particular concern for pit-cast, spun-cast and some ductile iron mains installed without external protection..

The research on corrosion to ductile iron pipe and the use of polyethylene wrap dates back to the early 1950s. Even where corrosive soil is known to exist, the potential for external pipe corrosion may, to some extent, be discounted if the utility has taken precautions to protect the pipes from the aggressive soil conditions. Protection measures include encapsulating in PE, external coatings and wrappings, and cathodic protection. In some cases retrospective protection has been provided.

2.3.3 Likelihood of Failure – Secondary Indicators. Several of the indicators listed below are not indicators of failure in the narrow sense but important factors in the nature and likelihood of failure.

Pipe Age

Pipe age is often used as a direct basis for making replacement decisions. However, it needs to be placed in the context of a rate of deterioration or corrosion in order to have a rational basis for replacement decisions based on remaining service life. Undoubtedly, older pipes have had more time to suffer various forms of corrosion and stress. Older pipes may not have been designed for the stresses being imposed today. In addition, they have not been provided with the level of protection required on more recent installations. Thus, if two pipes have been subject to identical environmental and operational conditions, the younger pipe will have a longer life. The problem is that identical conditions seldom occur and many factors need to be considered when using age as an indicator for predicting remaining life.

Predicting failure purely based on age could be misleading when one considers in detail the causes and complexities of failure. Some failures occur in the early life of a pipe due to manufacturing and installation defects.

The variability in service life is well illustrated in Table 2-4, which shows average remaining life in years for ferrous water pipes for a U.K. water utility for pipe sizes of 6-in. diameter and greater (UKWIR, 2001). These are predictions from an analysis of condition data taken from pipes adjacent to a burst.

Table 2-4. Average Remaining Life Predictions in Years for Ferrous Water Mains Based on Period of Installation (UKWIR, 2001)

Diameter (in.)	**Date Range of Installation**					**Avg. RL [(a)] (yr)**
	1880 to 1899	**1900 to 1919**	**1920 to 1939**	**1940 to 1959**	**1960 to 1980**	
6		99	71	59	57	69
9		95	53	52	72	60
12	112	107	57	18	33	91
15			150	62	73	102
18			68			68
Avg. RL[(a)] (yr)	**112**	**100**	**80**	**48**	**59**	**78**

(a) Average Remaining Life (Yr)

Certainly age is an indicator that can be taken into account as an adjunct to the key critical factors. Age can be a guide to the type of pipe in that dates for the introduction of spun-cast iron and ductile iron pipe introduction are well established.

Pipe Diameter

As noted in Table 2-3, the number of failures is much larger for the smaller diameter pipes. This is the result of a combination of greater installed lengths of small pipes, and a higher failure rate than the larger pipes. The predominant failure type, regardless of diameter, was found to be fracture failure with a much higher number of failures at the smaller diameters. While most of the failures occur in smaller diameters, the risk posed by single failure of a large transmission line can be very high due to the large amount of damage and loss of service that can occur.

Pipe Thickness

The initial pipe thickness when installed is of importance. This is taken as the calibration base point from which loss of metal is calculated. Together with pipe age, this provides a theoretical rate of corrosion. Variation in wall thickness can be large for cast iron pipe. Pipe thickness can be found in contemporary AWWA Standards that are used in procuring the pipe.

Type of Internal Lining

CML is the standard form of lining provided since the 1950s with most spun-cast iron pipes and all ductile iron pipes. It will provide internal protection unless damaged or deteriorated. Pipe lining rehabilitation methods are available and can extend pipe life if structural integrity is present or restored.

Joints

The type of joint used for ductile iron in trenches is predominantly bell and spigot push fit with an elastomeric seal. These allow some flexibility for soil movement.

Spun-cast iron pipes also used this form of joint although earlier versions of cast iron pipes (i.e., pit-cast) can have lead and leadite joints. Steel pipes have flanged and welded joints. Welded, lead, and leadite joints cannot accommodate movement; any movement causes stresses in the pipe.

Joint leaks occur due to improper installation and soil movement, so the indicator is not the joint but the installation. The exception is leadite joints, as bell splitting has found to be associated with this type of joints. Leadite is a plasticized sulfur cement compound that was used as an alternative to lead. It was found to be an inferior product to lead for two reasons. First, leadite has a different coefficient of thermal expansion than cast iron and results in additional internal stresses that can ultimately lead to longitudinal splits in the pipe bell. Secondly, sulfur in leadite can facilitate pitting corrosion, resulting in circumferential breaks on the spigot end of the pipe near the leadite joint. The failure rate for a leadite joint pipe is significantly higher than that for a lead joint pipe even though the pipe may not be as old. Therefore, for a leadite joint pipe, the indicator is the joint in conjunction with soil movement.

Location

Location and depth of cover can identify external loadings on a pipe. This information should be readily available. It should include key features such as crossings of roads, rail tracks, waterways, depth of cover, and other situations. A U.K. study showed that pipes laid under heavily trafficked roads had a very high rate of failure, particularly in the colder months of November through February, although these are thought to be circumferential fractures and mainly in smaller diameters (UKWIR, 2001).

Loading on a pipeline in practice is a combination of external loadings and internal pressure.

Installation Defects

A remarkably large number of defects in pipelines originate from the time of installation. Improper bedding and badly made joints are examples. Some failures appear shortly after installation but often show up many years later as a structural failure. External corrosion resulting from improperly installed polyethylene wrapping may not show for many years. Experience and records will show up patterns that build a picture on the good and the bad.

Potential Soil Instabilities

Soil instabilities can arise from various causes, including the soil type. A UKWIR study found that for pipes in clay soils the annual rate of bursts was nearly twice that of pipes laid in chalk areas (UKWIR, 2001). The study also concluded that the most likely cause of enhanced seasonal failures was the change in clay soil volume caused by variations in moisture.

Examples of more extreme causes are seismic movements and locations where a pipeline is on or adjacent to a slope.

An AwwaRF study of grey cast iron pipes found that changes in soil support were a major contributory factor to circumferential failures (Makar, 2005).

Soil Temperature

Changing soil temperature is of particular concern in Northern regions where ground frost and the freeze/thaw cycle can cause movement. Since high temperature can accelerate corrosion rates, it needs to be considered in conjunction with soil aggressivity. It should be noted that soil temperature is used as a surrogate measure of water temperature which may be the actual cause of most breaks (see below).

A UKWIR study showed that circumferential fractures in pipe of smaller diameters (4 to 6 in.) significantly increased in the months of November through January (UKWIR, 2001). No similar pattern was present for longitudinal fractures. NRC published a paper on the influence of weather and burial conditions on break rates and developed an empirical model for correlating break rates with climatic changes (Kleiner and Rajani, 2002; 2004; 2008).

Groundwater Levels

Seasonal changes of groundwater level and those caused, for example, by tidal variations can contribute to both soil instability and corrosive conditions. In sensitive clays, seasonal changes can cause heave and shrinkage, resulting in significant pipe movement.

Pressure Changes

Transient pressure can be a significant cause of failures. Some authorities consider that this can be the most important cause of induced stress failures. The original design would be based on an operating pressure with a maximum test pressure that would allow for surges and other intermittent pressure variations. In the normal operating life, the pipe should be quite capable of working within this design range. However if there are surges or increases in operating pressures beyond those allowed in the design, or that occur when the pipe has deteriorated, then there is a likelihood of failure.

Water Temperature Changes

Thermal stress due to changes in water temperature in the pipe has been found to be a contributory factor to failure in some regions. When the water in the pipe becomes colder, especially near the maximum density of water, it seems that pipes tend to break. This occurs when the water in a reservoir turns over in the fall, and although soil temperature may still be well above freezing, pipes tend to break. Also, rapid temperature changes seem to possibly be another secondary factor.

An overall summary of failure modes and indicators is given in Table 2-5, as an initial attempt to provide a set of indicators and ranking.

Table 2-5. Failure Modes and Indicators

Mode:	Causes of Structural Failures			Causes of Leak	
	Internal Corrosion (a Direct Form of Failure)	**External Corrosion (a Direct Form of Failure)**	**Induced Stresses (Often in Combination with Internal and External Corrosion)**	**Wall Perforations (Can be a Subset of Internal and External Corrosion)**	**Joint Failure (a Defect)**
Key Indicators					
Break Failures	VC	VC	VC	NC	NC
Leak Failures	NC	NC	NC	VC	C
Pipe Wall Corrosion (Investigation Data)	VC	VC	VC	VC	NA
Pipe Wall Corrosion (Environmental Conditions)	C	C	VC	VC	NA
Secondary Indicators					
Pipe Age	C	C	C	C	C
Pipe Diameter	NC	NC	NC	NC	NC
Pipe Thickness	C	C	NC	NC	NA
Type of Internal Lining	VC	NA	NA	C	NA
External Protection	NA	C[(a)]	NC	C[(a)]	NA
Joints	NA	NA	C	NA	VC
Location	NC	NC	C	NC	C
Installation Defects	C[(b)]	C[(b)]	C[(c)]	C[(b)]	VC
Soil Instabilities	NC	NC	VC	NC	VC
Soil Temperature	NC	C	C	NC	C
Groundwater Levels	NC	C	C	C	C
Pressure Changes	NC	NC	VC	NC	C
Water Temperature Changes[(d)]	NC	NC	C	NC	C

VC = very critical; C = critical; NC = not critical; NA = not applicable

(a) Can be a positive indicator and reduce failure potential.
(b) Damaged linings and external protection.
(c) Defective installation.
(d) Applying to cold regions only.

3.0 TECHNOLOGIES FOR CONDITION ASSESSMENT

Condition assessment methods can be classified as direct and/or indirect methods. Direct assessment usually requires access to the inside or the outside of the pipe, including visual inspection, destructive testing, and non-destructive testing (NDT). Indirect methods include the analysis of failure history, leakage level, hydraulics, and soil properties. Several AwwaRF reports provide a description of a number of NDT with trials of prototypes (Dingus et al., 2002; Reed et al., 2004; Lillie et al., 2004). The WERF/ AwwaRF study "Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets" lists 85 individual condition assessment tools and techniques (WERF, 2007). The report "Non-Destructive Testing of Water Mains for Physical Integrity" (AwwaRF, 1992) is outdated, and thus is less relevant in view of the developments over the last 30 years.

This section provides the basic technologies and their applications together with observations on their limitations and potential application to ferrous water mains. Examples of commercial technologies are listed in Appendix A.

3.1 Visual Investigations

3.1.1 External Condition Inspection. The visual judgment of an experienced utility engineer or operator can have considerable value. Where pipelines are laid above ground, visual surveys play a more important role in that the pipeline can be directly observed for evidence of coating damage, leaks, or other defects. For buried pipelines, these can range from walk-over inspection of the surface along the line to various forms of aerial surveys. Aerial surveys are rare in the water industry but have been used in times of drought to look for water leaks by noting unexpected areas of green vegetation.

The monitoring of a line by walk-over surveys is relatively common practice for many pipelines. It is valuable in that it can give a warning of some defect or problem such as leakage or ground movement. However, as no direct observations of the pipeline can be made, it has limitations.

Opportunistic visual inspections when a pipe is exposed for maintenance or repairs can provide a great deal of valuable information to an experienced engineer or technician. Deb (2002a) offered a standard data form that can be used for opportunistic visual inspection of a pipe when it is exposed for maintenance or repairs.

3.1.2 Internal Condition Inspection Using CCTV. Closed circuit television (CCTV) is a well known technique employed in gravity sewer mains. The current generation of CCTV systems has features that enable an operator to obtain useful information on the internal condition of a pressure main. Key components include:

- Pan and tilt head
- Zoom lens
- Sonde
- Crawlers/tractors.

A CCTV inspection does not provide any quantitative information on the structural condition of the pipe. The main purpose of such a survey would be to provide some visual indicators to possible defect locations. Where a pipe has an internal lining, it will provide some qualitative information on the condition of the lining. It may also be possible to identify leaks from inward groundwater infiltration when the pipe is empty.

In common with many other “internal” technologies, the main barrier in undertaking such inspections is the need to gain access to the line, which may require temporary by-passing, shut down, dewatering, cleaning and removal of pipe sections or fittings to allow a camera to be put into the line. The costs associated with these support requirements will be many times the cost of the CCTV survey. Where a line has to be closed down and emptied for maintenance or repairs, then the opportunity to carry out a CCTV survey can be taken.

The Water Research Centre (WRc) in the U.K. has developed a CCTV capability based on the same kind of launch system used for Sahara® leak detection, which is described in A.3.1 in Appendix A. The camera is attached to a calibrated umbilical cable through which it transmits data in real time. In water mains a drogue is attached which propels the camera through the line. The cable also controls the speed of movement of the tool and allows its retrieval. Color surveys of live water mains up to 2,500 ft from the entry point are possible. The location of the camera can be detected from the surface using a walkover tool so that the operator can mark the surface with the exact location. The operation of a camera may be incorporated as a supplement to the Sahara® leak detection system

3.2 Pit Depth Measurements

A manual technique is widely used as a basis for obtaining a rate of corrosion by measuring pit depth. Tools are widely available, portable, and simple to use.

Although pit depth often is used as a key factor in calculating the remaining life of a water main, there appears to be no standard method of measurement. At least five different measurement methods can be used, ranging from mechanical calipers and depth gauges to ultrasonic and electromagnetic techniques.

In field investigation a section of buried pipe is exposed in an excavation and a selection of pits that are observed is measured. The number chosen for measurement varies among investigation companies. For mechanical measurement methods, cleaning and preparation of pipe are required, which may be done in different ways.

For laboratory testing of samples, the pipe is shot-blasted; in some cases the laboratory may take up to 10 random measurements. Other laboratories will take a given number of the largest pits that can be seen. It is therefore difficult to interpret and compare utility databases on pit depth measurements, and it is normal to find a large variation in results.

3.3 Destructive Testing

The most common practice is to retain, inspect, and test coupons of pipe wall in a laboratory; however this is not routinely done in the U.S. and is highly variable among utilities. Core and coupons can be taken from a ferrous pipe wall using drilling techniques, including pipes in service using pipe tapping techniques. Some utilities performing non-structural rehabilitation will collect samples to confirm the structural integrity of the newly lined pipe.

In addition, sections or length of pipe (cut outs) are removed for laboratory analysis. Gas distribution and potable water utilities commonly undertake laboratory tests on samples.

The mechanical tests carried out include:

- Burst test
- Tensile test
- Ring test

- Fracture toughness test
- Four-point bending test.

The metallurgical tests include:

- Examination of the metal structure and properties
- Examination of fracture surfaces, inclusions and fracture pits
- Analysis of fracture surfaces and corrosion pits.

A full description of these mechanical and metallurgical tests can be found in Chapters 2 and 4 respectively of the AwwaRF study "Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life" (Rajani, 2000).

3.4 Non-Destructive Testing

3.4.1 Sonic/Seismic Technologies. Sonic and seismic technologies generate mechanical waves in a medium and measure the time taken for a reflected wave to reach a transceiver. This time can be correlated to material thickness if the elastic response characteristics of the medium are known.

Ultrasonics measure the propagation time of high-frequency, short-wavelength mechanical waves through a ferrous pipe wall, and correlate this with the nominal thickness of the material. The detection of flaws is based on the reflection of the wave from the interface between materials of different properties, for instance graphite or a cement mortar lining. The resolution is such that small areas of wall loss can be identified, allowing the creation of a map of the wall thickness of a pipe. Ultrasonic waves are at frequencies greater than 100 kHz, but accurate thickness measurements use frequencies in the order of 10 MHz.

External Applications of Ultrasonics

Ultrasonic measurements are among some of the best-established methods for simple external testing of points along a ferrous pipeline wall. The equipment is in the form of hand-held instruments where a probe is positioned on the metal (see Figure A-1, Appendix A). The tool is calibrated to provide a direct thickness reading, which can then be compared with the original wall thickness. These measurements are point readings of the depth, and there can be substantial variations that are not detected between the chosen points.

Ultrasonics performs best on steel and ductile iron, and less well on thicker grey iron. Most ultrasonic devices require direct contact with clean metal, which involves removal of coatings, linings, and corrosion products.

Because ultrasonic tools are inexpensive, they have become popular in-house inspection tools with some utilities. However, operators still need to be properly trained and understand how the tools work, including their limitations, to avoid generating misleading data.

In-Line Investigation Ultrasonic Pigs

The ultrasonic principle is used in intelligent pigs that have been developed for in-line inspection (ILI) of oil and gas pipelines. The tools directly measure the wall thickness as they travel through the line. They are equipped with transducers that emit ultrasonic signals perpendicular to the surface of the pipe. These transducers are located in a carrier that covers the internal circumference. Typically the spacing will be every 8 mm circumferentially and 3 mm longitudinally. An echo is received from the internal and external pipe surfaces. By timing these return signals and comparing them to the speed of ultrasound in steel pipe, the wall thickness can be calculated.

Using ultrasonics in-line requires good contact with the pipe wall to obtain an accurate response. Typically the contact medium is a liquid. This contact, or coupling, is usually sufficient for liquid-carrying pipelines. This method may be impractical in tuberculated mains and potentially compromised in lined pipes.

It should be noted that the tools used in the oil and gas industry are not suited technically or economically to the inspection of water mains. Various laboratory developments have been reported and prototypes have been built. However, a commercial proven tool is not thought to be available.

3.4.2 Guided Wave Ultrasonic Testing. Guided wave ultrasonic testing (GWUT) has the potential to inspect portions of pipes with continuity from accessible locations. GWUT uses the pipe wall as a conduit for the ultrasonic energy.

Guided wave pipe inspection technology was developed for external remote detection. The concept is to generate ultrasonic Lamb waves and send them along a pipe using one of several transducer types. Discontinuities such as corrosion give a differing reflection back to the transducer, which is able to measure and determine the size of the defect. A guided wave propagation and reception collar is mounted on the outer surface of the pipe. This transmits and receives ultrasonic pulses around the full circumference of the pipe. Losses of wall thickness can be identified and mapped. To date tools that are commercially available have been used in the process, oil, and gas industries on pipes with welded steel joints that provide the continuity. The diameter ranges from 2 to 48 in. Typically, the length of pipe that can be scanned depends on pipe condition, coating, and type of soil with maximum distance in the order of 100 ft. It works for pipes that are insulated or coated. It is particularly useful for buried steel pipelines and road crossings.

Trials of guided wave systems on steel mains are described in an AwwaRF report, “Techniques for Monitoring Structural Behavior of Pipeline Systems” (Reed et al., 2004).

3.4.3 Electromagnetic Methods. Several technologies are based on electromagnetic principles, but all are variations on two: magnetic flux leakage (MFL) and eddy currents. They are applicable to ferrous pipes, or pipes with a ferrous component.

Magnetic Flux Leakage

When a magnet is placed next to a pipe wall, most of the flux lines pass through the pipe wall. That is, the pipe wall is a preferred path for the flux. While most of the flux lines concentrate in the pipe wall, a few pass through the surrounding media. Flux leakage at a metal-loss region is caused by a local decrease in the thickness of the pipe wall. At a metal-loss region, the flux carried by the thin section is less than that carried in the full wall. Flux leaks from both surfaces of the pipe.

A sensor positioned on the inside (magnet side) of the pipe is typically used to measure the magnetic field adjacent to the pipe wall. At a metal-loss region, a sensor records a higher flux density or magnetic field, which indicates the presence of an anomaly. In this manner, an MFL tool detects an anomaly that causes flux to leak. The measured leakage field depends on the radial depth, axial length, circumferential width, and shape of the anomaly, as well as the magnetic properties of the nearby material. To characterize the anomaly, the measured leakage field must be analyzed.

MFL is the most commonly used inspection technology for oil and gas pipeline inspection. Numerous inspection companies provide services, but these tools are not suited to "pigging" of water mains.

MFL tools detect and characterize metal loss from corrosion, one of the most common causes of ferrous pipeline failures. As currently used, though, MFL tools cannot detect all metal loss or reliably detect other defects such as axial cracking. High resolution and extra high resolution tools can provide improved detection capabilities.

Eddy Currents

When an energized coil is brought near the surface of a metal component, eddy currents are induced in the specimen. These currents create a magnetic field that tends to oppose the original magnetic field. The impedance of a coil in close proximity to the specimen is affected by the presence of the induced eddy currents in the specimen. When the eddy currents in the specimen are distorted by the presence of flaws or material variations, the impedance in the coil is altered. In effect, the eddy currents act as a shield, and defects reduce the eddy current shield.

These induced eddy currents are the key to defect detection. Defects block and distort their preferred flow patterns. This change is measured and displayed in a manner that indicates the type of flaw or material condition. Cracks at right angles to the current path interrupt the surface eddy current flow and are detected. Cracks lying parallel to the current path will not cause any significant interruption and may not be detected.

Skin effects limit conventional eddy current inspection techniques to inspection of only the surface nearest to the probe.

One eddy current technique, the remote field eddy current (RFEC), is capable of inspecting the entire wall thickness without the need to use ultra low frequency. An exciter that is sized to nearly the same diameter as the inside diameter of the pipe, is driven with a low-frequency sinusoidal current. A small, magnetic field sensor is positioned some distance away. One portion of the magnetic field generated by the exciter travels down the inside of the pipe, with the field directly coupled to the sensor. A second portion of the alternating magnetic field propagates through the material of the pipe, inducing eddy currents as it goes. Once the magnetic field penetrates the outside wall of the pipe, it spreads along the surface of the pipe and re-enters the pipe, again inducing eddy currents to flow in the pipe material. This second path is referred to as the remote path. The total magnetic field and eddy current flow at any point is the combination of directly coupled and remotely coupled fields.

Several RFEC tools are in commercial use for ferrous pipeline inspection.

Eddy current technologies have some inherent limitations:

- Frequency – most systems are frequency dependent or have a limited number of frequencies in their operating range. This limits the detectability of material thickness variations
- Size and shape of sensors – the transmitter and receiver size and shape affect the operational frequency, so antenna configuration is not easily altered to suit survey configurations.

3.4.4 Radiographic Testing. Radiography is a non-destructive test method that can be used on ferrous pipes. Radiography shows changes in thickness and density that are associated with corrosion. It has been used widely in petrochemical processing plants and outside the U.S. on water mains. It has technical limitations in that pipes of 15 in. inner diameter and greater must be emptied. It also has considerable health and safety issues. Radiographic testing is expensive and requires specialist operators.

3.5 Environmental Testing

The soil, water table, and pollutants can create conditions leading to corrosion of unprotected ferrous pipe. Soil environments are not all corrosive to ferrous pipes, and even in moderately corrosive soils the rate of corrosion may be such that the pipe will have a service life of more than 100 years. All types of ferrous pipes can suffer potential damage from contaminated soils.

Due to the lack of better indicators of corrosion, the soil environment evaluation is currently the best approach to evaluating external corrosion for unprotected pipe. Table 3-1 provides a summary of indicators and criticality ratings for soil environment data.

Table 3-1. Indicators and Criticality from Environmental Data

Indicator	Criticality	Comments
Soil Resistivity	High	A function of soil moisture, temperature, and concentrations of ionic soluble salts
Soil Moisture Content	Low	Soils with moisture content greater than 20% considered more corrosive
Soil pH	High	Likelihood of corrosion increases in acid soils with pH values of 4.5 and less
Chloride Ion Content	Medium	Use of de-icing salts on paved surfaces can lead to high concentrations of chloride ions in trench. Where concentrations are in the range of 10 to 1,000 ppm there is an increasing potential for corrosion
Sulfate and sulfide	Medium	Presence of sulfide in waterlogged soils indicates that bacteria have been promoting reduction of sulfate ions and indicates MIC activity
Redox Potential	High	Redox potential is an indicator of degree of aeration in soil. A high level is an indicator of aerobic soil and increase potential for corrosion. A low negative redox potential is an indicator of anaerobic conditions and potential for SRB and MIC forms of corrosion
Known Corrosive Environments	High	Experience indicates that some soils and site conditions are corrosive regardless of testing. These include polluted sites, cinders, landfills, and peat bogs
Soil Temperature	Low	Changing soil temperature is of particular concern in northern climates where ground frost can cause movement. High temperatures can accelerate corrosion rates
Groundwater Levels	Medium	Groundwater levels need to be recorded including seasonal changes. Those caused for example by tidal variations can contribute to both soil instability and corrosive conditions. Constant high groundwater level can create anaerobic conditions
Potential Soil Instabilities	Medium	Soil instabilities can arise from various causes including, for example, seismic movements and locations where a pipeline is on or adjacent to a slope or subject to man-made vibration, such as subway, rail line, heavy vehicle traffic

Various researchers have tried to establish a direct correlation between soil properties and corrosion measurements. The aim is to predict the size of a corrosion pit over time from the estimated corrosion rate, the known soil properties, and the size of the pit as measured at inspection. However, this work has not been conclusive. Although external corrosion is influenced by soil environment, the particular properties and how they govern this behavior are debatable.

For example, it has been shown that the “average corrosion rate” does not reflect the process as the maximum pitting rate is high and then falls, so it is not a constant. Another problem lies in changing environmental conditions that can change the soil properties.

Although internal water quality has no bearing on external corrosion, there is some evidence that the treatment of water by chlorination and oxygenation is a potential cause of internal corrosion in unlined cast iron pipes.

The National Association of Corrosion Engineers (NACE) Corrosion Basics provides a table for soil resistivity vs. degree of corrosion (NACE, 1984).

American National Standards Institute **(**ANSI)/AWWA C-105/A21.5 provides a 10-point system for evaluating the likelihood of corrosion deterioration.

DIPRA has a Design Decision Model (DDM) (DIPRA, 2005), which uses a 10-point system for likelihood of corrosion and uses the same basis of environmental factors as the ANSI/AWWA Appendix A. It is intended for new design, but the same considerations can be applied to evaluation of existing installations.

A discussion of soil tests and corrosion is presented in “Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life” (Rajani, 2000).

Some key points that arise from this research are of importance in evaluating likelihood of failure.

- The growth of corrosion pits is time dependent and depends to a large degree on the surrounding soil and its properties
- The rate of pitting is higher early in the life of a pipe and then falls
- There is no single dominant soil property that appears to govern corrosion
- Low values of saturated soil resistivity appear to be directly related to high rates of corrosion.

The conclusion was that the predicted pit depth was a function of

- Time (exposure period)
- Pipe diameter
- Chloride content
- Soil sulfide content
- Soil redox potential
- Saturated soil resistivity
- Liquid limit for soil.

The correlation between pH and pitting corrosion was shown to be weak and is not included in the analysis. A mathematical analysis using these factors showed a moderate correlation (mean error 45 percent) between predicted and actual pit depths. However, American Water observed external corrosion on polywrapping ductile iron pipes in areas affected by acid mine drainage (causing low pH soil) and employed polyethylene pipe instead (Hughes, 2008).

3.6 Leakage Management

3.6.1 Overview of Leak Management. The International Water Association (IWA) has suggested that there are four key tasks in leakage management:

- Pressure Management
- Leak Detection
- Leak Repair
- Pipeline Replacement.

The focus of the Forum was on the first two tasks.

Leakage management in North America has been mainly reactive by responding to identified leaks and from information obtained from water loss audits. To date there has been no regulatory pressure, but drought and limited water resources are increasing political, economic, and environmental concern to reduce leakage. In some countries, such as the U.K., water utilities are subject to government regulation. This has provided the incentive to develop pro-active approaches such as leak management and improved leak detection methods. Leak management based on District Metering Area (DMA) has been used by the U.K. water utilities as a basic approach for over 10 years and covered most of the national network. A DMA is an area of between 500 to 3,000 connections into which water can be measured and analyzed to determine the level of leakage.

A recently published AwwaRF report titled "Leakage Management Technologies" addresses the use of leakage management methods (Fanner et al., 2007). This report has three objectives:

- Review proactive management techniques used internationally
- Assess the applicability of these techniques to North America
- Provide guidance on how to practically and cost effectively apply these techniques.

The report highlights the importance of understanding the nature and extent of their water losses in order to develop the best water loss management strategy. The study found that a water audit can provide the necessary information on the level of losses. DMAs are recommended to facilitate the identification of areas of probable leakage and focus leak detection surveys. Pressure management was identified as being important in reducing the flow rate of hidden breaks and short term break frequency.

A more detailed description of flow metering, logging, and analysis of the data is presented in "Technology and Equipment for Water Loss Management" (Farley, 2007).

Pressure management has been identified as an important measure for the long-term reduction of real losses. The principle behind pressure management is quite simple – lower system pressures during periods of lower demands (when system pressures normally rise) and reduce the flowrate from the existing background leakage (those small weeping leaks from fittings and joints). An additional benefit of pressure management is the potential reduction in water main break frequencies, which in turn helps to extend the life of the pipeline.

3.6.2 Leak Detection Technologies. Leak detection uses a variety of methods including acoustic, acoustic with correlation, infrared thermography, chemical (using a tracer gas), and mechanical (Smith et al., 2000). Acoustic leak detection is the most widely used method. Since the beginning of the 21^{st} century, a number of new leak detection technologies have been developed, including ground penetrating radar (GPR), combined acoustic logger and leak noise correlator, digital correlator, and radio-frequency interferometer (Pilcher, 2003). One of the recent advances is in-line leak detection systems, such as the Sahara® and SmartBall® acoustic systems. Selected leak detection technologies are described below.

External Leak Detection

External technologies fall into two groups: acoustic and correlators. The former works on the basis of directly locating the noise of a leak; in its most effective form, it entails the use of a monitor brought in contact with the main to listen for leakage noise. Other monitors, called hydrophones, do not come into direct contact with the pipe, valves, or hydrants but are placed over the location of the pipe. There have been numerous acoustic and electronic advances to improve the capability of "stick sounding."

Correlators are based on the velocity of sound made by a leak as it travels along the pipe wall between two hydrophones or similar sensors. The sensors are situated at convenient locations on the pipe some distance away from, and on either side of, the leak point. The difference in time taken for the sound to travel to each sensor allows the difference in path length to be calculated, from which the leak position can be identified. It has long been recognized that correlators are not as effective on large-diameter transmission mains.

A recent advance in external technology is the deployment of monitoring units designed to monitor acoustic noise over extended time periods including permanent installations. There are several variations in these systems. Some units provide data by downloading to mobile receivers that stop or pass nearby the monitors. Others are linked to automatic meter reading (AMR) networks that transmit data to a base station or website. Some systems are connected to water service lines while others are connected to the top of valves.

In-Line Leak Detection

One of the most recent valuable leak detection developments has been "In-Pipe Technology." Leaks can be detected by passing a hydrophone through the interior of the pipe to the point where the leak noise signal is detected. As the hydrophone travels through the pipe it can only be a maximum of one pipe diameter away from the leak, so even small leaks can be detected.

Commercially available tools include Sahara® and SmartBall®. Sahara® is a single hydrophone attached to a calibrated umbilical cable that can detect and locate leaks, in real time, as it travels through the interior of the pipe. SmartBall® is a free-swimming foam ball with an instrument-filled aluminum alloy core that records acoustic activity to identify leaks as it moves along the pipeline. Both are described in Appendix A.

Ground Penetrating Radar

GPR technology has been adapted for leak location. GPR uses electromagnetic wave propagation and scattering to locate and identify changes in the electrical and magnetic properties in the ground. It is the ability to detect differences in the density and water content of soils that allows GPR to be used as a leak detector.

It is used in South Africa on a daily basis for leak detection. It is used frequently as a rapid reconnaissance survey tool by attaching an array of antennae to a vehicle and driving the pipeline route. This kind of survey can cost around $500 per mile for a long transmission line.

However, as with all GPR investigations there are limitations depending on soil conditions, surface pavement, and other underground structures in urban areas, and the use and data interpretation require a high level of skill and experience.

Radio Frequency Interferometry

This technology uses a radio-frequency interferometer that transmits low power, ultra high frequency (UHF) radio waves into the ground. The signal is reflected from the leaking water back to the antenna. The signal is amplified and processed by a sensitive interferometer system, which ignores signals that do not change with time but identifies rapidly changing signals that can be displayed to show strength and character.

Infra-Red Thermography

Infra-red thermography is used to detect leaks in pipelines and the voids around them. High-resolution temperature measurements made by infra-red cameras show variations in temperature in a pipe wall. The method is frequently used from aircraft over-flying long and remote pipelines; it is fast and provides instant feedback on-site. The pressure drop at a leak point and the plume of leaking fluid in the surrounding soil both show measurable temperature changes. It has been used for leak surveys on less accessible water mains.

3.7 Summary of Inspection Methods and Applications

Tables 3-2 through 3-4 present summaries of the current inspection methods and applications discussed above. More information on the technologies is provided in Appendix A.

For external technologies, if the pipe is not exposed, it will be necessary to excavate inspection pits.

Table 3-2. Tools and Technologies for Inspecting Structural Integrity Externally

Application	Pit Depth Measurement	Ultrasonics	Guided Wave Ultrasonics	MFL (ECAT)	BEM
Grey Cast Iron	Yes	Yes	No	Yes	Yes
Ductile Iron	Yes	Yes	No	Yes	Yes
Steel	Yes	Yes	Yes	Yes	Yes
Diameters	Any	Any	2–48 in.	6 in. and up	2 in. and up
Typical Length Scanned	3–6 ft	3–6 ft	300 ft	3–12 ft	3–12 ft
Line in Operation	Yes	Yes	Yes	Yes	Yes
Scan through Coatings/Wrappings	No	No	Yes	Yes	Yes
Loss of Metal	No	Yes	Yes	Yes	Yes
Pit Depth	Yes	No	No	No	N
Graphitization	No	No	N/A	Yes	Yes
Cracks	No	No	Yes	Yes	Yes
Mobilization Costs	Minimal	Low	Medium	Medium	Low
Scanning/Processing Cost	Low	Medium	High	Medium	Low/Medium[(a)]
Suitable for Water Main Investigations	Yes	Yes	No	Yes	Yes

BEM = Broadband Electromagnetic; ECAT = External Condition Assessment Tool; MFL = magnetic flux leakage

See Appendix A for more detailed information.

(a) Real time provides immediate structural condition without further processing. Full data processing is an additional cost.

Table 3-3. Tools and Technologies for Inspecting Structural Integrity Internally

Application	In-Line Ultrasonics	In-Line MFL	RFT "See Snake"	BEM In-Line Pig
Grey Cast Iron	No	No	Yes	Yes
Ductile Iron	No	No	Yes	Yes
Steel	Yes	Yes	Yes	Yes
Diameters	Most	Most	Up to 14 in.	6 in. and up
Typical Length Scanned	Miles	Miles	10,000 ft	3,000 ft
Line in Operation	Yes[(a)]	Yes[(a)]	Possibly	No
Scan through Linings	No	No	Possibly	Yes
Loss of Metal	Yes	Yes	Yes	Yes
Pit Depth	No	No	No	No
Graphitization	Yes	No	Yes	Yes
Cracks	Yes	No	Yes	Yes
Mobilization Costs	Very high	Very high	Medium	Medium
Scanning /Processing Cost	High	High	Medium	Medium/high
Suitable for Water Main Investigations	No	No	Yes	Yes

BEM = broadband electromagnetic; MFL = magnetic flux leakage; RFT = remote field technology

See Appendix A for more detailed information.

(a) For oil and gas pipeline.

Table 3-4. Tools and Technologies for Leak Inspection

Application	Leak Correlators	Listening Sticks	Continuous Acoustic Monitoring	Sahara®	SmartBall®
External/Internal	External	External	External	Internal	Internal
Grey Cast Iron	Yes	Yes	Yes	Yes	Yes
Ductile Iron	Yes	Yes	Yes	Yes	Yes
Steel	Yes	Yes	Yes	Yes	Yes
Diameters	Most	Most	16 in. and less	from 12 in.	24 in. and up
Typical Length Scanned	300 ft	3 ft	300–500 ft	up to 6,000 ft	Several miles
Line in Operation	Yes	Yes	Yes	Yes	Yes
Joint Leaks	Yes	Yes	Yes	Yes	Yes
Wall Perforation Leaks	Yes	Yes	Yes	Yes	Yes
Accuracy for Locating Small Leaks	Good	Fair (supplement with correlator)	Fair (supplement with correlator)	Excellent	Excellent
Insertion into Line	N/A	N/A	N/A	via 2-in tapping	via valve or tapping
Mobilization Costs	Low	Low	Low	Medium	Low
Scanning/Processing Cost	Low	N/A	Medium	Low/Medium	Low/Medium
Suitable for Water Main Investigations	Yes	Possible	Yes	Yes	Yes

See Appendix A for more detailed information.

4.0 APPROACHES TO CONDITION ASSESSMENT

4.1 Condition Assessment Basics

In condition assessment it is necessary to have a logical and robust basis for estimation of the likelihood of failure for the range of assets in the network. Where there is a significant amount of data, in particular break data, the likelihood of failure can be assessed using statistical techniques. Where there is no failure history, the approach needs to be modified.

Historical, environmental, and operational data can be used to:

- Provide an overall screening tool for an evaluation of a water main and focus field investigation activities
- Predict failure without use of structural integrity investigation.

The key to screening for likelihood of failure is to have a structured database or inventory that is constantly updated, can be interrogated, and records the full data on the pipeline, its surroundings, and its operation. There are programs of condition assessment developed for water utilities that provide guidance on developing and operating an appropriate database. If the database can be based on a Geographic Information System (GIS), it becomes more useful and effective.

Equally important, a likelihood of failure analysis should provide a sound basis on which to develop a cost-effective investigation program. This allows a utility to focus its site investigation not only in terms of where but also of how, when, and what to investigate. Such an investigation program needs to supplement and fill the gaps in the information available from historical, environmental, and operational data. Thus, data gaps need to be identified before embarking on an investigation program so that the investigation is focused on the data required.

In the American Petroleum Institute (API) Recommended Practice for Risk Based Inspection (API, 2002), an important point is made that is relevant to the development of any program. The document explains that a risk-based inspection (RBI) can be based on qualitative data, quantitative data, or a mixture of the two. Quantitative risk analysis requires hard data that can be used to calculate, for example, the anticipated remaining life of a pipe. The data set needs to be comprehensive for the line under consideration and the methods used in the calculation need to provide answers that conform closely to actual performance. For much of the water network, utilities do not have either the comprehensive data or performance records that allow them to use quantitative risk approaches.

Therefore, it is necessary to rely heavily on qualitative data, which involves inputs based on engineering observation, judgment, and experience as the basis for determining likelihood of failure. Where it is possible to obtain measurable data such as pitting depth or metal loss in the wall of a pipe, such data will be a major contributor to that judgment. Likelihood judgments and criticality rating are not given as mathematical answers, but rather in qualitative terms such as high, moderate, or low or some comparative numerical value.

A consensus has emerged that RBI that considers the consequences and likelihood of failure is the preferred approach. Figure 2-1 from Section 2 illustrates this approach. The Global Water Research Coalition (GWRC) is leading an international project “Tools for Risk Management” that uses this approach. This project is one element of Track 4 of the Strategic Asset Management (SAM) initiative, as described below.

There is a multitude of papers and programs on the subject of condition assessment, including the following studies published by AwwaRF that cover ferrous pipes:

- Risk Management of Large-Diameter Water Transmission Mains (Kleiner et al., 2005)
- Assessment and Renewal of Water Distribution Systems (Grigg, 2004)
- Prioritizing Water Main Replacement and Rehabilitation (Deb, 2002a)
- Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life (Rajani, 2000)
- Quantifying Future Rehabilitation and Replacement Needs of Water Mains (Deb, 1998).

A specific and very comprehensive study running to several hundred pages is the WERF/AwwaRF "Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets" (WERF, 2007). This study has now been incorporated along with others into an overall SAM Challenge program involving WERF, Water Research Foundation, and several international associations and agencies. Three of the tracks being pursued are of relevance here:

- Track 2: SAM Benchmarking and case studies
- Track 3: Decision support tools
- Track 4: Prediction of remaining asset life.

Each track has several embedded research projects.

4.2 Condition Assessment and Likelihood of Failure

The whole purpose of collecting data from inventories, records, observations, and inspections is to use the information to make an assessment of the current condition of the asset. The second aspect based on this assessment is to determine the likelihood of failure and predict the future structural condition and life expectancy. A third use is to prioritize inspection where additional data are needed.

A key element of effective asset management is a cost-effective approach for assessing condition assessment and performance. The demand will differ greatly between utilities according to size and outcome required. Many programs have been developed in order to meet regulatory requirements.

The uses and needs of utilities for condition assessment vary, and approaches can range from simple in-house evaluations to sophisticated programs operated by specialists.

4.2.1 Relative Criticality. Determination of the relative criticality of mains and a priority ranking is undertaken using experienced judgment or some more structured approach. Criticality should begin with water customer considerations such as interruptions of water supply that are life threatening (e.g., kidney dialysis), impact on a large number of customers, industrial or commercial commerce, or disruption of transportation. Other ranking considerations can include:

- Ranking of sections for inspection
- Ranking of structural concern
- Ranking of operational concern
- Ranking of critical concern sections.

4.2.2 "Belief Networks". Bayesian theory defines probabilities as "reasonable degrees of belief." Probabilities are assigned to propositions based on beliefs gained from observations. The probabilities are conditional based on the state of the variables.

In reality, it is a structured application of expert knowledge and experience to the available information and observation. Many engineers and operators use this approach instinctively in making their assessments.

A sophisticated version of Bayesian "Belief Networks" is "Sewer Cataloguing, Retrieval and Prioritization System" developed for WERF (WERF, 2004). This is a computer-based expert system for identifying pipelines at risk of operational and structural failure, and takes into account consequences of failure. Although developed for wastewater, it is relevant and adaptable to potable water and many other assets.

A simpler version has been developed by Jason Consultants, which is aimed at small to medium utilities that have need for a tool that can be used by their own staff. A "Relative Criticality Ranking" of large diameter water transmission mains was developed for a major U.S. city using this technique.

The technique is used to provide a rating both for likelihood and consequences of failure. Supporting detailed "Belief Networks" are developed to provide the information for this overall network (see Figure 4-1).

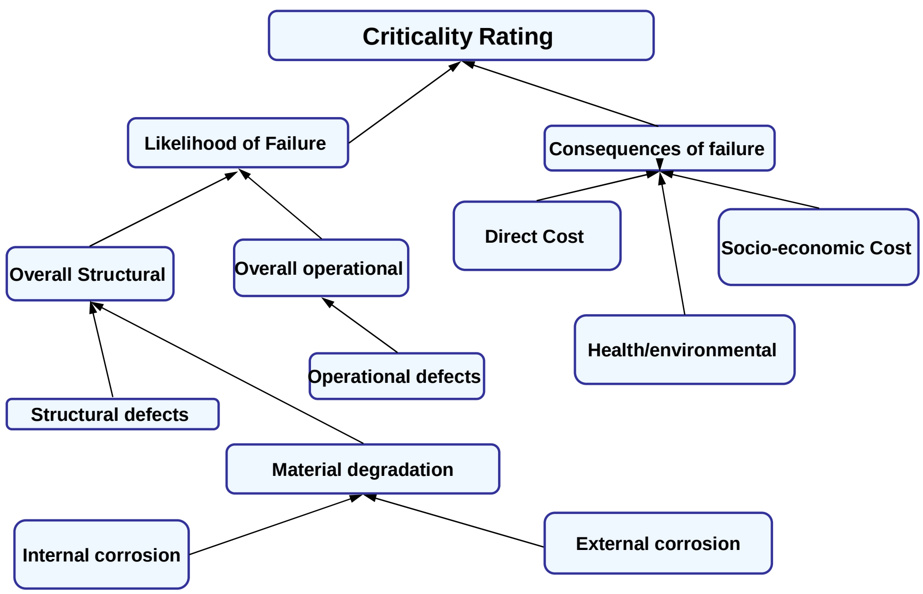
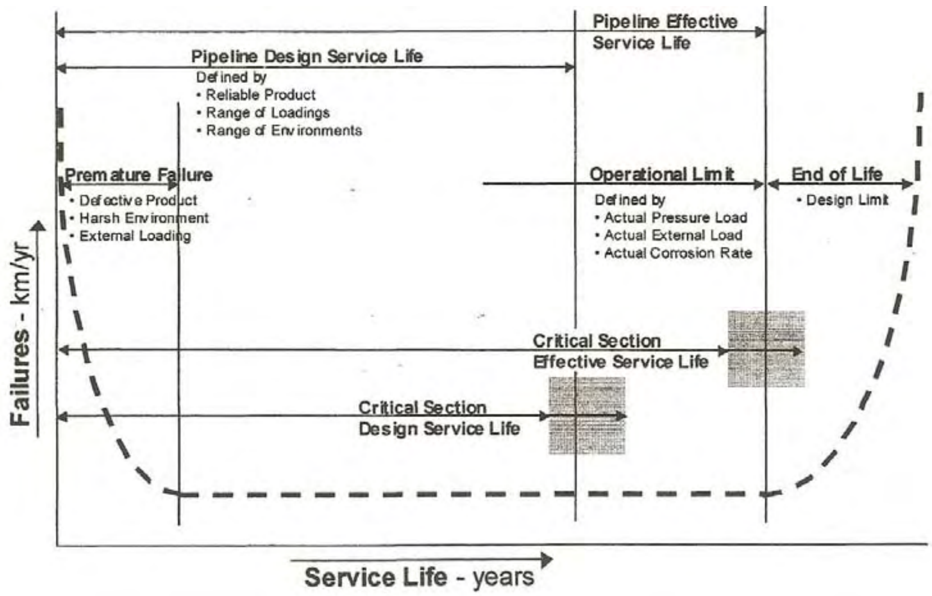


Figure 4-1. Overall Belief Network – Likelihood and Consequences

4.3 Life Cycle Curves

The "Bathtub Curve" is a widely accepted conceptual representation of a pipeline life cycle.

Figure 4-2 shows such a curve. There is an early high premature failure due to defective design, material or workmanship. This is followed by a long period of low failures and moves into a higher rate of failures as the pipe reaches its effective service life.



Source: Wayman, 2003.

Figure 4-2. Life Cycle of Typical Pipeline

What is of interest is the **effective service life**, which can be much greater or sometimes less than the **design life**. It is worth noting the factors that determine the effective service life by operational limit, which are:

- Actual pressure load
- Actual external load and other pipe stresses such as thermal stresses
- Actual corrosion rate.

4.4 Residual Life – Life Predictions, Modeling, and Life Expectancy Curves

It has long been the aim to find a means to accurately predict when a pipe will fail. The determination of residual life depends on many factors; interpreting these to reach a residual life that corresponds with operational experience is challenging. Predicting future performance is based on past performance and there are considerable variations in experience between utilities due to different local conditions.

4.4.1 Life Predictions. Pit depth measurement is a widely used method for inferring the residual life of a ferrous water main. The rate of corrosion is based on combining maximum external and internal pit depths together with the pipe age and original thickness. A linear rate of corrosion is assumed when the pit or pits will fully penetrate the pipe wall and this is then taken to be the time of failure. ASME B31 code provides guidance on determining the remaining strength, but not on pit depth measurement (ASME, 1991).

This approach has several weaknesses:

- It can be difficult to determine the true age of the pipeline
- It can be difficult to determine the original pipe wall thickness
- The way pit depths are measured is not a standard procedure
- Pit depth sampling is very random and pitting is very variable along a pipeline so that it is an act of faith to assume the pit depths recorded represent the worst case
- Internal pitting is very difficult to identify and measure in a pressure main
- Pitting in coated pipelines may start after failure of the coating
- It has been observed that the rate of pit corrosion is not uniform and tends to slow down over time.

Utility experience has shown that such predictions can significantly underestimate or overestimate the service life. The reality is that isolated pit penetration which can lead to leakage is not a major cause of pipe burst failure (UKWIR, 2001). Only if an area becomes weakened by a group of pits is it likely to be an important contribution to failure. It has been noted earlier that grey cast iron pipes continue to function even when full wall penetration has occurred. However, in ductile iron it becomes a more frequent cause of failure.

Various attempts to improve the reliability of life predictions have been developed. For example, when the extent and depth of pitting can be compared with a database of various types of pitting in pipes of a similar age and type, then it becomes more meaningful. CSIRO developed a failure model that takes into account variations in corrosion rate, the resistance as the pipe corrodes, and the applied service loads.

New York City Department of Environmental Protection (NYCDEP) is currently undertaking non-destructive evaluation and development of an asset management system for wastewater force mains. They developed an asset inventory database first, including a standardized reporting tool. In order to develop a structural rating, a detailed finite element analysis was conducted on typical mains. This has resulted in Table 4-1, which defines the level of defect and action.

Table 4-1. Structural Condition Ratings for Force Mains (after NYCDEP)

Defects	Condition	Ra
Cracks, breaks, significant change in cross section, bending deflection > 4 mm for CI, > 0.06D for DI and 0.1D for lined DI	Failed; immediate action required	5
Greater than 75% loss of wall thickness at any cross section, noticeable sag or change in cross section	Severe damage; preventive action required	4
Wall thickness loss between 50–75%	Moderate damage; preventive repair planned	3
Wall thickness loss between 25–50%	Small damage; preventive repair on basis of remaining service life	2
0–25% wall thickness loss	Minimal damage; no immediate action required	1

CI = cast iron; D = diameter; DI = ductile iron

Although this analysis was for force mains, it has a relevance to ferrous pipes in the water network.

4.4.2 Modeling. Modeling is used to assist utilities in a wide range of infrastructure situations. Models can be used to provide indications of the overall network picture as well as detailed structural evaluations at a zonal level (McKellar, 2006). A specific example of this approach is the "Burst Consequence" model developed by Thames Water. This identifies where flooding would occur if there were a burst and the financial consequences (Blakey, 2001).

A paper "Comprehensive Review of Structural Deterioration of Water Mains: Statistical Models" provides an overview of work carried out in the past 20 years to quantify the structural deterioration of water mains by analyzing historical performance data (Kleiner and Rajani, 2001). The authors consider the physical mechanisms that lead to pipe failure often require data that are not readily available and are costly to obtain. Physical models may currently be justified only for major transmission water mains, where the cost of failure is significant, whereas statistical models, which can be applied with various levels of input data, are useful for distribution water mains. The statistical methods are classified into two classes, deterministic and probabilistic models. Subclasses are probabilistic multi-variate and probabilistic single-variate group processing models. The review provides descriptions of the various models including their governing equations, as well as critiques, comparisons and identification of the types of data that are required for implementation.

A current project undertaken by NRC in conjunction with Water Research Foundation is "Dynamic Influences on the Deterioration Rates of Individual Water Mains" (Project #3052). The objective is to develop a model that considers both the static and dynamic factors of individual water mains. The deterioration process is complex with many static factors like soil, pipe material, size, and age as well as dynamic factors like climate, operation, and protection. It is expected that the outcome will be a model and analytical tool that covers dynamic factors for an individual main.

A model to prioritize the replacement of cast iron distribution mains was developed for AwwaRF and AWWA titled "Decision Support System for Distribution System Piping Renewal" (Deb, 2002b). It is based on the relationship between remaining wall thickness and residual strength. External and internal loads are used to model the stresses on the pipe, fed into a model and compare them to the current strength and the current Safety Factor (SF) is calculated.

A partnership between AwwaRF and NRC has produced a report titled "Risk Management of Large-Diameter Water Transmission Mains" that provides a method to translate distress indicators obtained visually or from non-destructive evaluation techniques on large water mains into condition ratings (Kleiner et al., 2005). The process involves "fuzzy logic", a method for combining scarce condition data with modeling that predicts the statistical likelihood of deterioration and failure of a given pipe.

4.4.3 Life Expectancy Curves. The concept of determining the economic life of an asset using statistically developed life expectancy curves has been developed by a number of researchers and authorities. There is some disagreement about the value of this approach.

Any pipe material laid in a given year will have an average life, but may not require replacement at the same time due to a multitude of factors. The basis is that the mains will have a probability of needing replacement spread on either side of the average. Typically, a life expectancy model combines a series of normal distribution curves for types of pipes and the year laid. The simplest approach is to decide the life of the asset and then using standard deviations (10 to 20 percent) to produce a series of replacement cost curves.

Some fundamental assumptions like "average life" and standard deviations are made, but they should correspond with experience to match real life.

4.4.4 Software Programs. Many programs have been developed for residual life prediction as part of condition assessment strategic planning. These programs range widely in degree of sophistication. Many of them are developed as planning models, but all are concerned with making an evaluation of the life of an asset.

"Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets" (WERF, 2007) has an extensive table in Chapter 7 that summarizes the tools and techniques available for condition assessment of both water and wastewater systems that have been developed worldwide. Table 4-2 was modified based on this work for condition assessment strategic planning of water systems.

Table 4-2. Tools and Techniques for Condition Assessment Strategic Planning

Tool or Technique	Assessment Focus	Data Needs	Skills Required	Degree of Sophistication	Commercially Available
FailNet-Stat	Failure forecasting	High – asset and failure data	High	High	No (only research application in Europe)
WRc Trunk Main Structural Condition	Current condition/ remaining life	Moderate	High	Basic generic approach	Available as manual
CARE -W	Strategic planning with rehab planning	Dependant on tools used	High	Basic generic approach	No (trials in Europe)
KANEW	Strategic tool for replacing	High – comprehensive data	High	High	Available from CH2M Hill
MRP	Decision support tool for main renewal	Very High – asset, performance and failure	High	High	Yes
PARMS-PLANNING	Decision support for asset renewal	High – asset and failure	High	High	Yes (in Australia)
PIREP	Decision support system for rehab planning	High – asset and failure	High	High	No (under development)
UtilNets	Reliability support system	Very high – asset and failure	High	High	No (prototype stage)
WARP	Long term planning using asset failure curves	High – asset and failure	High	High	Yes

Note: many of these programs cover more than pipeline assets.
Updated based on Table 7-6 in WERF, 2007.

The tools and techniques listed in Table 4-2 have the following in common:

- All are computer-based
- Very high data needs – assets and failures

- High professional engineering skills required.

This list is by no means comprehensive and there are a number of other programs and developments currently under way. It would require an extensive effort to evaluate these programs for their comparative merits.

An example of one of these programs is "UtilNets." European funding invested a significant sum in this forecasting model, which is a decision-support system (DSS) for rehabilitation planning and optimization of the maintenance of underground pipe network of water utilities. The DSS performs reliability-based life predictions of the pipes and determines the consequences of maintenance and neglect over time in order to optimize rehabilitation policy. While admirable in its aims and logic, it was found that the model requires more data than currently available to make its use worthwhile.

4.5 Current Barriers to Effective Use of Condition Assessment

There are a number of barriers to effective use of condition assessment. The following is not meant to serve as a comprehensive list.

4.5.1 Database Quality. In the previous section it was noted that all condition assessment programs are based on high quality asset and failure databases. The lack of robust databases for many water utilities is a major barrier to condition assessment in building a picture of the failure patterns for different ages and types of pipe in a range of locations.

The UKWIR's "Nationally Agreed Failure Data Base and Analysis Methodology for Water Mains" has provided statistically robust information on mains failure together with basic data on the assets for more than 95 percent of the U.K. water network (UKWIR, 2004). It has more than 500,000 records and is increasing the number and quality of records in a staged development. The data from the utilities was taken and reformatted to be consistent and comparable. This has provided valuable insights into both national and regional patterns of failure for all types of pipe material.

Currently, Water Research Foundation is pursuing a project (Project #4195) to try to make use of the architecture, definitions and structure of the UKWIR database for data on main breaks in the U.S. This is being done in parallel with Australian water utilities. At present, Water Research Foundation is identifying a handful of utilities that have interest in the topic of main breaks and condition assessment to work on this project and provide some feedback on adaptation of this model to the situation in the U.S., while the Water Services Association of Australia (WSAA) follows a similar path in Australia.

In many cases, the existing U.S. utility databases are incomplete and/or inaccurate. Failure databases are not standardized when kept, and failures are normally not recorded or attributed in a uniform manner that could allow any sensible comparison.

The fragmentation and diversity of water utilities in the U.S. would make the development of a national database a difficult, but valuable task. The U.S. electrical utilities have the North American Electric Reliability Corporation (NERC) database. It is maintained by the electrical utilities and contains information on reliability and failure of electrical power systems supplied by vendors.

An AwwaRF paper supports the concept of National Water Main Failure Database and believes that it would be of great value to water utilities (Gaewski and Blaha, 2007).

4.5.2 Regional and Local Variations. In an attempt to provide all-purpose condition and management assessment tools applicable to a wide range of clients, the importance of local variations that can arise from a number of reasons, not just environmental, has not been given sufficient consideration in the past. This is now better recognized, and several organizations including NRC, WRc, and UKWIR are building frameworks that allow individual utilities to model around their own experience and data.

4.5.3 Inspection Data Set Requirements. Although a great deal has been written on both the asset and failure data, there is not a good consensus on what key data sets are needed or can be obtained from an inspection to make a reliable condition assessment and life prediction. This lack of consensus is likely due to the fact that it is difficult to define the exact and reliable pre-failure conditions leading to structural failures because of multiple types and magnitudes of loadings and pipe strengths. Furthermore, for technical and economic reasons, it is often difficult to measure the pipe and loading parameters with adequate spatial, temporal, and failure mode coverage even though the feasibility of measuring critical parameters may change as technologies improve and costs decline. For structural condition assessment, a typical aim is to try to determine the loss of metal by general corrosion, graphitization, and pitting. Detecting cracks and flaws is also needed, though.

However, external investigations, which can only cover a small percentage of the main, may not represent the maximum loss of metal or be typical of the line. Internal investigations are costly and disruptive to the utility operation, and are rarely undertaken. The quality of the data in terms of identifying pitting is often poor. General areas of metal loss are more easily identifiable than graphitization or pitting.

At best, inspection can only provide a snapshot of the current condition. To make predictions, the basic information on the pipe (type, age, and original wall thickness) is needed. Additional information such as how long corrosion has been taking place and if it has been uniform is also needed.

The use of soil characteristics to determine the likelihood of corrosion and particularly pitting has relevance when the pipe is unprotected, but a large part of the ferrous network has been laid with some sort of protection. Polyethylene encasements became common, but not universal, in the U.S. in the 1970s and now installation of ductile iron pipe with polyethylene encasement is considered routine by most utilities. However, many unprotected pipes have been and continue to be installed. Cathodic protection installed during initial work, retroactively or opportunistically, is another protection method.

In earlier sections of this report some anomalies are highlighted both in the forms of failure and the relevance of the statistical and inspection data.

Many vendors' reports are prefaced with a wide range of disclaimers as to their accuracy.

4.5.4 Current Condition Assessment Methodologies. All models and predictions must determine what key factors leading to failure will be used in a model. It is apparent that there is no consensus among researchers on what these factors are and what their comparative weighting should be. Differing pipe manufacturers, vintages, and local environmental conditions make it difficult to develop a model to fit all.

Many programs require a high level of technical input, which is probably only available in larger organizations or by the consultants promoting the method. The multiplicity of approaches and level of sophistication of these programs can be daunting to managers and engineers in the small to medium size utilities. There is a need for improving the situation for utilities to operate in-house condition assessment.

4.5.5 Current Inspection Technologies. The technologies currently available are described in Section 3 and Appendix A. Undoubtedly, progress has been made and there have been valuable developments that will continue.

However, the reality is that there is a long way to go for an inspection tools for structural condition that will fully meet the needs of the water utilities. The typical "wish list" is set out below:

- Inspect without disruption of service
- Inspect unlined pipe without disturbing tuberculation
- Access live mains
- No obstruction to flow
- Negotiate multiple bends, restrictions and appurtenances
- Determine presence of linings and coatings and their condition
- Inspect without removal of linings and coatings
- Provide comprehensive structural data, including loss of metal through general corrosion, graphitization and pitting to an accuracy of 10 percent of the original wall thickness
- Provide both internal and external loss of metal
- Identify longitudinal and circumferential cracks and flaws
- Low mobilization cost
- Inspection cost of 3 to 5 percent of the asset value.

Internal Inspection

No commercial internal inspection tools currently available can meet all of the criteria either technically or economically. Recently, tools have been developed that claim to work in pipe diameters up to 14 in. with the main in operation. These are recent innovations and little field experience is available.

Major shortfalls lie in the tool's ability to identify pitting and the high cost of mobilization and inspection.

External Inspection

In terms of the "wish list" above, external investigation comes closer to meeting the criteria. There are tools that will closely identify the structural condition for the section of pipe exposed and inspected.

The downside of external inspection lies in the cost of exposing a section of pipe and the reliability of such investigations as being representative of the whole line. This point is discussed elsewhere.

In undertaking limited external sampling, locations and conditions need to be chosen so as to be fairly uniform in the section being investigated.

Leak Detection

The developments in in-line leak detection have brought us closer to meeting most of the utilities' "wish list" for leak investigation. However, mobilization and setting up launch and/or retrieval points can be a significant cost. Current in-line leak detection is a snapshot of the current leaks. It is possible for a leak to develop immediately after examination and remain undetected until being inspected again.

4.5.6 Physical Difficulties and Costs of Inspection. Major barriers to inspection by utilities are the physical difficulties and the costs involved in gaining access to the pipe.

For an internal investigation the tools that can be used in an operational main are currently limited by diameter and quality of the data collected. To gain access for such tools, some form of launch and/or retrieval facility needs to be retrofitted. Any tuberculation would need to be removed prior to inspection. Several of the technologies can inspect the ferrous pipe through lining. Other internal technologies can only operate with the main out of service, emptied and cleaned.

Many utilities have reservations about introducing inspection tools into operational water mains. The possibility of contaminating the water supply is a major concern.

For an external investigation of a main in the road, the costs of excavations can easily be several times the cost of the inspection. If these are located in roads, then traffic control, pavement removal, reinstatement, and dealing with existing utilities add to the cost.

4.5.7 Relationship between Information Needed and What Current Technologies Provide. The quality of the information that is obtained by external and internal inspection technologies is not well defined. Currently, a utility has to adjudge any technology or method on the sales pitch and cost. There is no independent testing and evaluation information to compare competing methods for their ability to give the information needed.

A number of inspection technologies produce a great deal of data that after processing is presented to the client in relatively simplistic plots. However, the interpretation of the data lays in the hands of the vendor whose understanding of electronics and data processing may be greater than his understanding of pipes. There have been a number of inspections that have not identified or quantified key defects.

4.5.8 Relationship between Performance and Cost. A paper “Economic Assessment of Inspection – The Inspection Value Method” sets out the concept of a performance-based economic model of inspection based on cash values (Wall and Wedgewood, 1998). It defines value of inspection as the benefit less the cost of inspection (Value = Benefit – Cost). For cost, it uses three elements:

- Fixed cost
- Time and speed-dependent cost
- Cost depending on reliability.

These can be readily expressed in cash terms.

To estimate the benefit in cash terms is more subjective. Avoidance of costs associated with breaks might be considered to be a major benefit. It could also be considered as the benefit gained from avoiding renewal for a longer period.

Grand Central Model (GCM) was developed as a standard Microsoft® Excel spreadsheet to assist utilities to calculate the cost of failure (Cromwell et al., 2002). The AwwaRF paper “Analysis of Total Cost of Large Diameter Pipe Failures” continued this work (Gaewski and Blaha, 2007). It was recognized in the later work that it was unlikely that water utility managers would use the original model to develop the extensive data inputs as needed. A simplified data collection sheet was developed that made certain assumptions on behalf of the utility. The approach and assumptions are detailed in the paper.

Direct costs of the majority of failures are relatively low. A recent AwwaRF paper estimated that for diameters of 20 in. and less, there are 300,000 breaks per year, with the average direct cost of a break being $5,000 and with societal cost accounting for another $5,000 (Grigg, 2007). The paper estimated that for diameters over 20 in. there was approximately 500 breaks a year and from a range of records calculated that the geometric mean of all costs was $500,000. Again the breakdown is 50 percent direct cost and 50 percent societal cost. Societal costs are paid by the utility sometimes or only partially.

It cannot be assumed that inspection will directly identify a pending structural failure. This reality is well understood by many utility managers who find it more cost-effective to fix breaks than anticipating them.

In terms of the benefit, it will be difficult to show value for smaller diameters taking into account all of the costs of inspection.

An AwwaRF study "Performance and Cost Targets for Water Pipeline Inspection Technologies" (Project #3065), still to be published, addresses the issue of value of inspection. The interim findings state that for many situations neither the performance nor the cost of many water inspection technologies is acceptable. It proposes that quantitative cost and performance targets for technologies be identified. The point is made that value of pipeline inspection information is not well quantified, thereby making cost/benefit decisions about assessment difficult or impossible.

It is noted that the cost of inspecting just 0.2 percent of a line externally will involve pits every 3,000 ft (this is based on exposing a 6-ft length). Statistically this is a small sample. The cost of pits in a highway can easily be in the range of $20,000 to $50,000. The actual cost of the inspection element and reporting could be in the order of $3,000 to $5,000 at each excavation. Improving the quality of the data by conducting more inspections in excavations will add significant cost.

Internal inspection should be able to provide more comprehensive information, but has a significant cost in gaining access to the line. Therefore, the inspection company's high cost associated with equipment mobilization, data collection, and data processing can be a significant percentage of the asset value.

There is a strong economic case for not inspecting smaller diameters as the cost of any inspection will be a significant percentage of the replacement or rehabilitation cost.

The AwwaRF study also discussed the "acceptable" costs to utilities of collecting investigation information. Generally, utilities considered the cost too high, even for large mains. For cases in which they were prepared to offer a percentage relationship, there were two schools. One considered something between 2 and 5 percent of the pipeline value; the other was willing to pay less than 1 percent. For a comprehensive survey even the upper levels will be difficult to achieve because, based on the costs of the current technologies, it is likely to be 10 percent or even higher.

Undoubtedly, cost of investigation is a major barrier to greater use of inspection devices. For many in-line technologies the scope for reducing cost appears to be limited because of the following factors:

- High development and production cost of intelligent pigs
- High cost of mobilization
- Significant cost in providing launch and recovery facilities
- Large amount of data collected which has to be processed.

5.0 KEY PERFORMANCE AND COST IMPROVEMENT AREAS

The Technology Forum brought the experience and expertise of a wide range of people to bear on the issue of improving performance and cost of structural condition assessment for ferrous water transmission and distribution pipes. The following subsections provide brief descriptions of six key, potential research products that the authors recommended for consideration and discussion by the Forum attendees. The products fall into two main categories: (1) improving the consolidation, organization, analysis, and use of data that already have been, or are being, collected by utilities, and (2) improving the capability and cost-effectiveness of inspection technologies.

5.1 National Asset and Failure Database Guidelines

The adoption of a national standardized asset and failure database would be a major step in improving condition assessment.

AWWA has recognized that such a database would provide considerable benefit and they could make a valuable contribution by pursuing this initiative. In keeping with this sentiment, Water Research Foundation is currently pursuing a project (Project #4195) to try to make use of the architecture, definitions, and structure of the UKWIR database for main breaks in the U.S. This is being done in parallel with Australian water utilities. At present, Water Research Foundation is identifying a handful of utilities that have interest in participating in this project and providing feedback on adaptation of this model to the situation in the U.S., while the WSAA follows a similar path in Australia.

5.2 Guidelines for Interpreting Defects and Distress Indicators and Developing Condition Ratings

Progressive utility managers and operators have a significant body of knowledge and experience in interpreting defects and distress indicators for their own networks. Less experienced managers and operators could benefit if guidelines are developed, based on input from leading utilities, on interpreting distress indicators and defects and determining their significance. In addition, guidance on rating pipe condition and on specific investigation or monitoring techniques would be of great help to utilities in interpreting and allocating defects and distress indicators to the correct cause. This in turn will mean more accurate inputs into condition rating and life expectancy predictions.

This guidance will also assist utilities to implement the suggestion in Subsection 5.4 that, for models and life prediction curves to be useful, they need to be modified to take into account local experience.

A great deal of literature addresses this subject, and it should be possible to synthesize it to develop user friendly guidelines for utilities and their operators.

5.3 Guidelines for Utilities on Undertaking Condition Assessment

These guidelines would address actions to be taken after a decision has been made to do condition assessment, and the goals of the condition assessment have been established. The guidelines should present condition assessment as a two-stage process. The first stage is an initial assessment based on asset and failure databases. This will in some cases be sufficient for a decision to be made without investigation. In other cases it will define and prioritize the second stage, which is a more detailed, specific investigation that will typically involve inspection.

The initial condition assessment should define what additional information, if any, is required from an inspection to complete the assessment. A feature of the initial assessment should be a definition of type, quality, and quantity of additional data needed, which in turn defines the inspection approach.

The guidelines should emphasize actions and approaches to ensure that the information obtained through inspection is not an end in itself, which is not an uncommon approach. Rather, it should be emphasized that database and inspection information needs is a complementary and integral part of a final condition assessment and life prediction.

5.4 Developing User-Friendly Models to Predict Residual Life and Deterioration

The current approaches are discussed in Section 4. A good deal of work has been undertaken on the prediction of residual life. Some form of evaluation of the effectiveness of these models, and their extent of use by utilities, would be valuable.

The need is to develop user-friendly techniques that can be used by a wide range of utilities to assist them in their asset management planning and expenditure forecasting. Some earlier prediction and life cycle tools did not correspond well with utility experience, which created some distrust.

The prediction models for individual water mains need to be tailored to the local characteristics and experience. However, the process to customize these models to local conditions and provide reliable results could be complex. Some programs are building in this facility but the more complex and structured the model, the more difficult and costly they are to support data requirements and operate.

5.5 Developing Cost-Effective Inspection Tools and Methodologies

Development of cost-effective inspection tools and/or methodologies to provide data on existing structural condition and prediction of future deterioration is the most challenging task of all.

A consensus is required on what data need to be collected, over what percentage of a pipeline, to what accuracy, and at what cost so that the utilities are willing to pay. Questions that should be considered include the following:

- Can external inspection of a small percentage of the pipeline provide sufficient data to be able to draw conclusions on the whole line?
- Can limited external inspection be combined with other condition assessment techniques to reach conclusions on the whole line? This appears to be possible, for instance, for an unprotected cast iron pipe where external corrosion is a key factor and soil aggressivity can be defined.
- Can the circumstances be determined under which a full internal inspection is needed for metal loss or for leakage?
- Can tools be developed that can be used with a main in operation? Leakage tools like Sahara® and SmartBall® using appropriate launch and retrieval measures are able to do this. For structural investigation diameters above 14 in. require the main to be taken out of service, cleaned and emptied. It may be possible for some technologies to work in mains that are out of service but not emptied.
- Can acoustic or other technologies be developed for internal investigation that can provide the required level of information on structural condition? For example, can the Sahara® or

SmartBall® technologies be developed to carry sensors which collect data on the structural condition?

- Can the method of installing a wire or fiber optic cable in a pipe to collect acoustic emissions or other data on leaks and wire breaks in PCCP be adopted to collect information on structural condition of ferrous pipes?
- Are “Smart Pipes” a viable option? The concept of “Smart Pipes” has been promoted for many years and has never made many inroads although technically possible. The cost and practical difficulties have all discouraged utilities.
- How much are utilities willing to pay for inspection to prevent failures for critical high risk or high interest scenarios?

5.6 Determining an Acceptable Relationship between Cost of Inspection and Value of Asset

For any vendor or developer of inspection tools to achieve success, they need to understand the potential market and the cost that the market will bear.

The potential market is very large, but in reality the current market is very small because of the barriers discussed. Even basic, relatively inexpensive technologies like ultrasonic tools find few applications. Several vendors have withdrawn from the market. Currently, the cost that the market will apparently bear may discourage commercial companies in investing substantial sums in development. In addition, the data collection and processing require a good deal of manual input and is a significant cost element of inspection.

This can be compared to the oil and gas transmission industries where there is a wide array of available tools to serve a very large market that will pay for inspection. The even greater volume of data collected is analyzed automatically using specially developed software. It is often suggested that some of these tools might be adapted to use in ferrous water transmission pipes, but there are considerable differences that will make the transition difficult:

- The value of oil and gas is high. A large transmission line can easily be carrying a million dollars of product a day.

  The value of water is low.

- Leaks from oil and gas lines are highly dangerous to life and property.

  Leaks from water lines occur all the time and are rarely dangerous.

- Federal regulations impose a strict set of rules for oil and gas inspection performance and frequency.

  There are no similar requirements for the water industry.

- Most oil and gas transmission lines investigations are on very long and straight lines.

  Most water transmission mains are relatively short and have linings, bends, tees, valves which create obstructions and limit the use of intelligent pigs.

- The very high cost of mobilization becomes acceptable when spread over an inspection of many miles.

Water utilities do not have the funds or the need to carry out very large inspection programs.

- Oil and gas transmission lines use steel pipe with welded joints giving continuity.

  Most water pipes are bell and spigot jointed.

- Oil and gas transmission lines are externally wrapped for corrosion protection and methods are available to check discontinuities of coatings and potential corrosion spots.

  Where water pipes are externally protected it is with polyethylene baggies and no method is available for checking condition. Cathodic protection indicators (accessible sacrificial anodes) are available but seldom employed.

- Oil and gas transmission lines do not have internal coatings so that inspection methods can be in direct contact with the metal.

  A large percentage of water lines are lined internally with cement mortar linings or other materials. Where no linings have been installed then many older water lines are tuberculated.

- Oil and gas transmission lines are constructed with launch and recovery facilities for intelligent pigs.

  Most water lines would require retrofitting with launch and recovery traps to use intelligent pigs.

For the inspection of prestressed concrete water pipes, the water industry has accepted that inspection is required to determine the structural condition of pipes. PCCP has been used mainly for large transmission lines where there have been a number of catastrophic failures. It is possible to identify the mains at most risk, but without inspection, it is not possible to determine the structural condition.

Utilities seem prepared to pay the relatively high cost of inspection as the consequences of failure can be very high in terms of damage, loss of service, and repair cost, especially after a utility has experienced a catastrophic failure or knows someone with a similar system who has. This squares with the report on the costs associated with failures of large mains. There is value, after cost of investigation is deducted from the benefit, in avoiding a failure.

6.0 PROSPECTS FOR SHORT- AND LONG-TERM IMPROVEMENTS TO CONDITION ASSESSMENT FOR FERROUS WATER MAINS

The objective of this Forum was to bring the experience and expertise of a wide range of people to discuss how both short- and long-term improvements can be made to condition assessment for ferrous transmission and distribution mains. The following potential improvements were set out to stimulate discussion and identify additional improvements.

6.1 Starting Points for Evaluating and Improving Short- and Long-Term Advances in Condition Assessment

The "EPA Water Infrastructure Research Plan" (EPA, 2007) spelled out the following questions that, if addressed, will lead to a better understanding of the capabilities and limitations of condition assessment for ferrous transmission and distribution mains, and a clear recognition of opportunities for short- and long-term improvements of condition assessment.

- What is water main condition assessment?
- What are the goals?
- What outputs are required?
- What is the minimum precision and accuracy needed to meet the goals?
- What data, calculations and criteria are required to produce the outputs?
- What conceptual, preliminary and physical tasks are involved in obtaining the data?
- Do suitable methods exist to collect the data?
- How does one determine the value of condition assessment?
- What are the limits of condition assessment?

6.2 Short-Term Improvements to Condition Assessment

6.2.1 Short-Term Improvements to Use of Existing Information. Within the short-term, the use of existing information for condition assessment could offer the best opportunity to improve the asset management performance of the water industry.

There is a wealth of environmental, historical, and operational information that has been or can be developed into an asset database. Operational records should provide information on failures and repairs.

A great deal of literature has been published on asset management and condition assessment programs. Many of the programs require very good quality data and high levels of expertise to operate. Some of these programs have been developed to meet the needs of very large water companies to satisfy regulator demands for data and expenditure justification. Because of their size they are able to have specialists allocated to operate such tools. Such specialized expertise is not normally available except in a few large U.S. utilities and/or through consultants.

The knowledge and understanding of the network of the management, engineers, and operators should be harnessed, because they are in the best position to understand local conditions, defects, and failures.

Providing a logical framework on recording the assets and the failures, using this information along with developed life expectancy curves or models, and then applying their own observations and local knowledge could lead to significant improvements in condition assessment. It would enable practitioners to prioritize both investigation and planned investment.

Some guidance should be developed for identifying the high risk scenarios, which requires characterizing both likelihood and consequences of failure. With limited funds, it is necessary for utilities to focus on the highest risk situations.

The role of government in this area should be through coordination with and support of organizations such as Water Research Foundation and WERF.

6.2.2 Short-Term Advances in Inspection Technologies. The various barriers to short-term advances in inspection technologies were discussed earlier in this State of Technology Review Report.

Regarding internal inspection technologies and tools, because the current technologies cannot meet technical and economic requirements and because there is no regulatory driver for utilities to inspect water mains, the limited current market for inspection becomes a major deterrent to potential vendors, particularly for smaller diameter ferrous pipes.

However, progress has been made in developments of in-line leak detection/location/characterization and pressure management to reduce water loss and prevent small water main breaks. Adopting novel approaches for proactive maintenance of low-risk mains may have the potential to be economically viable for some applications.

Sahara® and SmartBall® also offer platforms for carrying sensors to assess the pipe wall conditions in a live main. For example, the Sahara® Video carries a camera for CCTV inspection of in-service water mains, such as the overall condition of the internal cement mortal lining. The Sahara®- and SmartBall®-based tools are being developed to assess the changes in the pipe wall thickness by measuring either the speed of sound or the pipe stiffness at certain intervals along the pipe as the tool travels through the pipe.

External inspection, if, as suggested earlier, used in conjunction with other tools, can provide the level of information needed to support water infrastructure managers, then there are opportunities for short-term improvements to current external inspection methods. For example, Gas Technology Institute (GTI) has a program of developing inspection tools that will work from keyhole excavations. A combination of open and keyhole excavations/inspections could provide a better level of inspection while keeping the cost of pipe exposure to a reasonable level.

6.3 Long-Term Improvements to Condition Assessment

6.3.1 Long-Term Improvements to Use of Existing Information. There is considerable potential for utilities to be provided with a better understanding of the behavior of different forms of ferrous pipes in the water network. There is a wealth of information available from a large body of research and reports. However, the various research generated can be abstract, sometimes offer information contradictory to each other, and may have limited applicability. Where contradictions and anomalies occur, they need to be understood and resolved. The information should be synthesized into practical guidelines for operators. For instance, it would be possible to develop a range of more specific life expectancy curves and models that relate not just to a pipe material but to various periods in the pipe manufacture that have different failure expectancies. It is commonly accepted that some ferrous pipes of later vintage have a reduced life expectancy compared to earlier vintage.

Such curves and models need to be changed to reflect local conditions such as soil parameters and support. For example, the relationship of local soil conditions and the corrosion of unprotected cast iron should be taken into account. Lack of soil support, often coupled with increased external loadings, may be another local factor that can modify life expectancy curves.

Taking a wider range of historical factors and experience into account along with specific local conditions for a utility could provide more realistic life expectancy predictions. This should help identify the most vulnerable pipes and reduce failures. It will also allow improved asset management and allocation of funds in a long-term program of replacement or rehabilitation.

If a national database of assets and failures were available relating breaks and leaks to specific materials and environment, this would support the decision-making process of utilities, allowing them to benchmark their own experience.

6.3.2 Long-Term Advances in Inspection Technologies. A staged approach is needed for long-term advances in inspection technologies. Initially the objective should be to reach agreement and define technical and cost performance targets for both internal and external tools.

One means of obtaining inputs from all sides would be to organize workshops with attendees from utilities, consultants, developers, and manufacturers. The objective would be to determine if there is consensus on effective approaches and ideas on how the objectives can be achieved cost-effectively.

For **internal investigations** a number of prototypes and trials are under way that could lead to longer-term improvements. Fundamental characteristics and limitations to the basic technologies employed in in-line tools need to be understood, along with their cost implications, for any development of internal inspection in operational water mains.

The New York trials with non-contact ultrasonic tools, the Super-Pig, and Russell Technologies' new tools, "See Snake", are described in Appendix A. Technically they appear to have potentials for effective internal inspection of water networks. However, the tools will require launch and recovery features to be retrofitted. These tools are sophisticated and likely to be costly to produce, mobilize, and operate.

In the case of the Super-Pig, its diameter range is limited so that a series of tools will be required to cover the size spectrum. Although the prototype performed well, this tool remains at the developmental stage. The cost of development compared to the potential market and the rates the market would bear is likely to limit its use to the larger diameters.

One apparently easy approach is to undertake **continuous monitoring of pipes** for indicators of deterioration, such as corrosion, wall loss, acoustic emissions (e.g., from leakage, cracking, or impingement), or strain. An embedded sensor system would be required for continuous monitoring. The initial cost of an embedded sensor system is potentially offset by reduction in mobilization and demobilization costs, and better spatial and temporal coverage of the pipe network. Continuous monitoring is already done for corrosion in some industries, and some of the current commercial tools can be adapted relatively easily. For example, fiber optic sensors are developed to measure pipe wall thickness directly by measuring the change of strain on the pipe outside surface. However, it seems to have limitations for monitoring corrosion in the water network. Only a small number of locations can be monitored, and the rate of deterioration is slow and would require years of data collection to yield any useful data.

The advances in electronics, sensor technology, information science, electrical and computer engineering promote the emergence of new technologies that can be applied to the inspection, monitoring, and assessment of the conditions of water mains. Some technologies are initially developed for non-water applications. The opportunities of technology transfer to the water main condition assessment should be evaluated.

A major need is to have some **independent test facilities where tools can be tested** for their abilities to identify and quantify defects in varying types of pipes. Tools could then be given an initial classification based on the results from the test bed. It should include evaluation of mobilization, launch, parameter measurement capability (e.g., type and number of parameters measured, precision, accuracy, speed, effects of interferences), and operational and reporting costs. Such independent tests would allow engineers and utilities to have some basis for choosing an inspection vendor. Currently, there are no benchmarks or comparisons among different methods and tools.

6.4 Measuring Success

Measuring success will take a number of forms. By the nature of the utility structure and the measures needed it will take time for the full benefits to flow. Initially it would require the following activities:

- Adoption by utilities of a standardized form of asset database and reporting together with a standardized failure database and reporting
- Adoption of guidelines with a standard approach to interpreting data and carrying out condition assessments to allow comparisons and benchmarking
- Getting utilities to use life prediction charts tailored to their type of pipes and local conditions
- Using risk-based assessment approaches in determining priorities for renewal and inspection
- Encouraging utilities to allocate funds to investigation of critical lines.

Over a period of time, these activities should result in reduced unforeseen failures and catastrophic events. This will reduce direct and indirect costs associated with unforeseen failures. Improved life prediction curves will provide a sound basis for budgeting for renewals and allow a running program to be developed.

If inspection methods and technologies can be developed that improve the quality of the information collected and reduce the current high cost, this in itself will be a significant success, as it will lay the foundation for better temporal, spatial, and failure mode inspection coverage of the pipe network, which will enable better assessment of pipe condition, and more appropriate, timely, and economical inspection, repair, rehabilitation, and replacement programs.

6.5 Accelerating Development – Potential Government Roles

The potential government roles cited below are understood to be undertaken in cooperation and collaboration with relevant stakeholders.

6.5.1 Guaranteed Minimum Work Programs for Internal Inspection. Currently the development of cost-effective inspection tools, with the exception of in-line leak detection, faces a “chicken and egg” situation, where the lack of market discourages developers from developing better and more economical technologies, and the lack of cost effective inspection methods discourages utilities from inspecting. Also, some of the more sophisticated and expensive technologies may only be cost-effective for larger diameter, high risk lines.

If some form of guaranteed minimum work program for inspection of ferrous pipes were established with a number of utilities, this could be attractive for vendors to spend money on developing tools to meet the program’s technical goals and cost targets. This approach could apply to both external and internal inspection, and should initially focus on the larger diameters, for which the value and willingness to pay for inspection will be greater. Vendors would have to meet performance specifications. In the case of external inspection, they would need to set out what other support methods would be used to ensure that the external inspections were representative of the whole line.

6.5.2 Support for Database Development. Transmission and distribution systems are "laboratories" that produce large amounts of valuable data. However, it can be difficult and costly to collect, organize, analyze, and disseminate the results. Government support, in cooperation with the user/expert communities, can help accelerate and expand collection and use of valuable data, e.g., failure statistics, deterioration rates, failure cause analysis, failure consequences, inspection technology performance, decision support system performance, etc. that will help improve asset management decision-making.

6.5.3 Defining Next-Generation Inspection Technology Needs. If target performance and cost specifications can be developed for "next-generation", as opposed to ideal inspection technologies, this could be invaluable for focusing intellect, energy and resources toward developing the desired inspection capability.

6.5.4 Funding Technology Innovation Research. Although full government funding of advanced inspection technologies for ferrous water mains is unlikely, the U.S. government does have programs in place that can accelerate improvement of technology at various points in the development process. For example, The National Institute of Standards and Technology (NIST) Technology Innovation Program (TIP) issued a large solicitation in July 2008 for advanced sensing technologies for infrastructure, including roads, highways, bridges, and water systems. The EPA National Risk Management Research Laboratory (NRMRL) recently (2007) initiated an Aging Water Infrastructure applied research program that includes evaluation, improvement, controlled-condition testing, demonstration, verification, and decision-support for condition assessment technology research. The program will be conducted by a combination of in-house, contractor, and assistance agreement efforts. The EPA National Center for Environmental Research's (NCER) Small Business Innovation Research (SBIR) program, included water infrastructure inspection in their recent call for proposals. NCER's Science to Achieve Results (STAR) Program issued a large solicitation to non-profit research organizations for innovation and research for water infrastructure and water infrastructure sustainability. Also, the oil and gas sector and the U.S. government place a high value on inspection of oil and gas infrastructure, and the U.S. government supports this research through the Department of Transportation. So, even though there are many technical and economic obstacles to transferring technology from oil and gas pipe inspection to water pipe inspection, this is an area of research activity that must be periodically examined for potential technology transfer opportunities.

6.5.5 Development and Support of Condition Assessment Technology Facilities. Providing test facilities for conducting independent testing and evaluations would be of considerable value. This could include laboratory testing of "breadboard" developments. Establishing a dedicated test site would be most useful for evaluating existing and prototype tools for their ability to detect, identify, and accurately characterize various forms of defects that typically occur in various types of water pipe.

There should also be some evaluation of the support work required and costs associated with an inspection. It will be very important to plan the test pipe and flaws carefully. Inputs from utilities and specialists will be needed as to what are considered to be the benchmarks laid down. The test facility should focus on structural defects and not leakage.

It will be important to assess the capabilities of existing test facilities as part of the planning process. For example, Battelle has a pipeline facility that was designed for testing and evaluating inspection tools for the oil and gas industry. Organizations like the Electric Power Research Institute (EPRI) also operate a similar test bed for evaluating investigation tools. One of the advantages these controlled-condition simulation/test sites offer the vendor is helping to define the strengths and weaknesses of a tool under various conditions, and/or in comparisons with other tools, giving direction for making necessary improvements. Other advantages of a test site include the reduced cost, complexity, time, risk, and variability from field conditions, and the ability to characterize, control, vary, and repeat conditions of interest. An advantage for both the utility and the industry is that they can obtain a basic independent evaluation of tools as well as guidance on which tools might cost effectively meet specific needs.

EPA also has experience operating test facilities, including Test and Evaluation Facility, Cincinnati, OH; Leaking Underground Storage Tank Test Apparatus, Edison, NJ; Pipeline Test Apparatus (PTA), Edison, NJ; Oil and Hazardous Materials Simulated Environmental Test Tank, Leonardo, NJ. Upgrades of the PTA in Edison, NJ are being planned. These research programs expect to generate products that can reduce cost and increase benefits to utilities in the condition assessment process and condition inspection. An EPA-developed test apparatus can be utilized by EPA and its contractors or by others under an outside user agreement. Usage costs for non-profits may be waived or substantially reduced.

6.5.6 Support of Field Demonstrations. The government can also support proper field trials of various types of tools. These should be real life situations – monitored, recorded, and reported. They do not serve just as vendors' demonstrations. Competing vendors could inspect the same pipeline where practical to allow a direct comparison to be made.

Some utilities may be prepared to pay or make a contribution for high-quality inspection information that has direct use in their condition assessment work. Recent experience indicates that utilities are cutting back on inspection because of lack of funds. Some technology vendors may be prepared to subsidize the costs of investigations but may not be able to cover everything, and would expect to be paid for good quality data.

Bringing both clients and vendors together on relatively unproven technologies can be difficult. Federal support would facilitate this work. It could take the form of a partnership with a group of utilities, vendors, and research organizations with the aim of developing a structured program. Some funding would be required for the work involved in developing the program, monitoring, recording, and reporting the trials. It may be necessary to provide some subsidy, for instance, when two technologies are tested on the same line.

Federal support in these areas will:

- Provide the potential users and the developers with understanding of the advantages and limitations of the technologies and the tools
- Accelerate acceptance and use of inspection tools and methods.

6.6 Getting Utilities to Buy-In

Several studies have shown that the benefits of condition assessment and the techniques used in inspection, assessment, and prediction are not well understood in the industry. Some predictions from earlier models and curves were costly to produce and did not tie in well with operational experience, resulting in a loss of credibility.

After credible analysis of the cost-benefit trade-offs, it will be equally necessary to communicate the benefits through various channels, including workshops, teleconferences, papers, and articles. By raising awareness and interest, the benefits of adopting the methods and technologies will become apparent to the utilities. They will adopt these techniques only if such an action helps them save money, make their work easier, and make their customers happier.

As suggested in Section 6.5.5 and 6.5.6, field trials will be a key way to show utilities what can be done and at what cost.

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APPENDIX A
CURRENT AND DEVELOPING INSPECTION TECHNOLOGIES

It should be noted that much of the information in this appendix was obtained from the vendors or developers and is provided on that basis. A critical evaluation would require extensive testing under controlled and field conditions.

A.1 Overview of Fielded and Demonstrated Inspection Technologies

A.1.1 Hand Held Ultrasonics

Many similar hand held tools are available for purchase. Figure A-1 shows views of two tools being used in the field. The following are some examples.

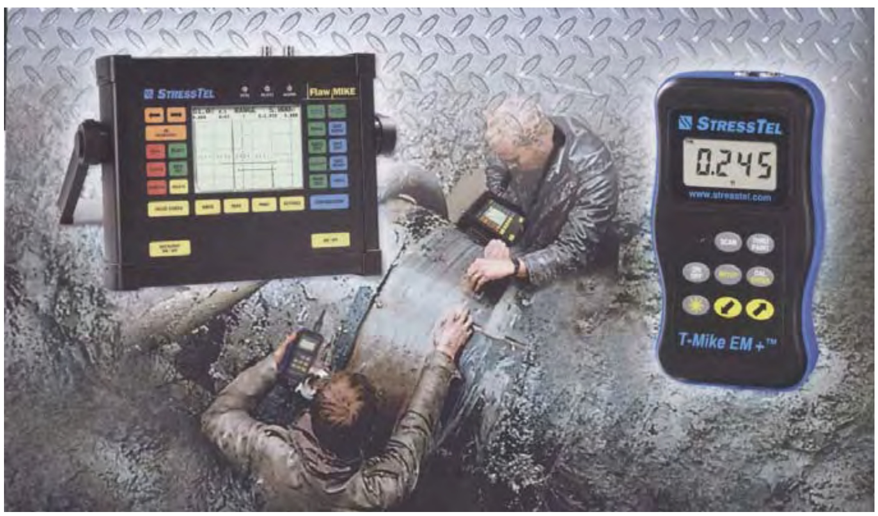


Figure A-1. Hand Held Ultrasonic Testing Tool

A more sophisticated tool that can scan the wall of a pipeline has been developed by GE Inspection Technologies (GEI), a leading inspection group. The IAS50 consists of a high performance, five-channel ultrasonic test kit coupled with a two-axis motion controller and data acquisition system. It can scan on flat or curved surfaces and has the capability to map flaws and thickness, and internal and external corrosion loss. It contains built-in remaining strength analysis software. The IAS tool scanning the external wall of a pipe is shown at Figure A-2.

Ultrasonics is also the basis for a range of intelligent pigs developed for the oil and gas industry. Such tools are based on direct contact with the pipe wall.

Reprinted with permission of GE Inspection Technologies.

Figure A-2. IAS50 Ultrasonic Scanning Tool (GEI)

A.1.2 Automated Ultrasonic Testing

The ultrasonic thickness measurement process has been automated to increase inspection speed and repeatability. Fully automated, turnkey ultrasonic inspection systems are available to perform high-speed ultrasonic thickness imaging, referred to as automated ultrasonic testing (AUT), of large structures such as plate stock, pressure vessels, storage tanks, pipelines, and ship hulls.

Figure A-3 shows a typical system configured to inspect a 12-in. diameter pipe for internal corrosion. The sensor moves back and forth along the axis of the pipe. A water source provides the necessary coupling fluid to transmit the ultrasound into the pipe to obtain the thickness measurements.

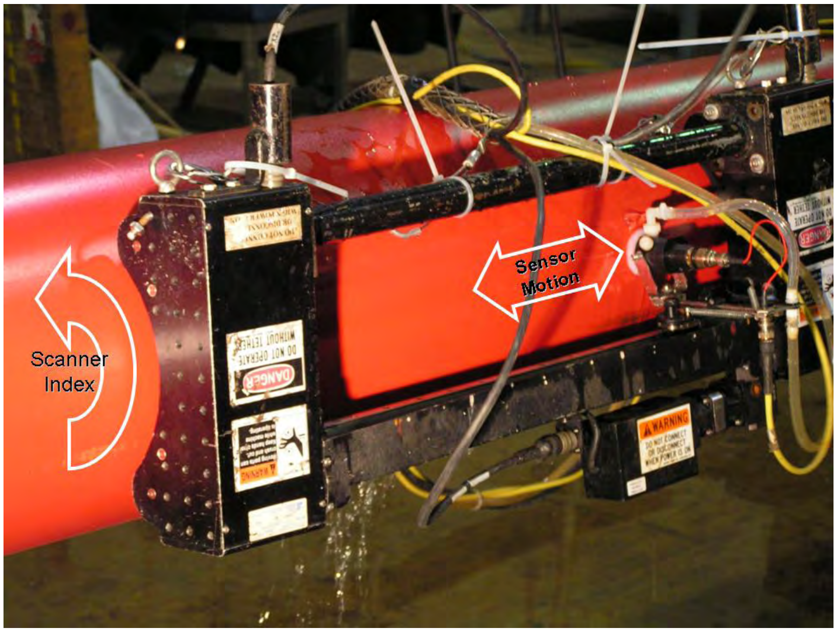
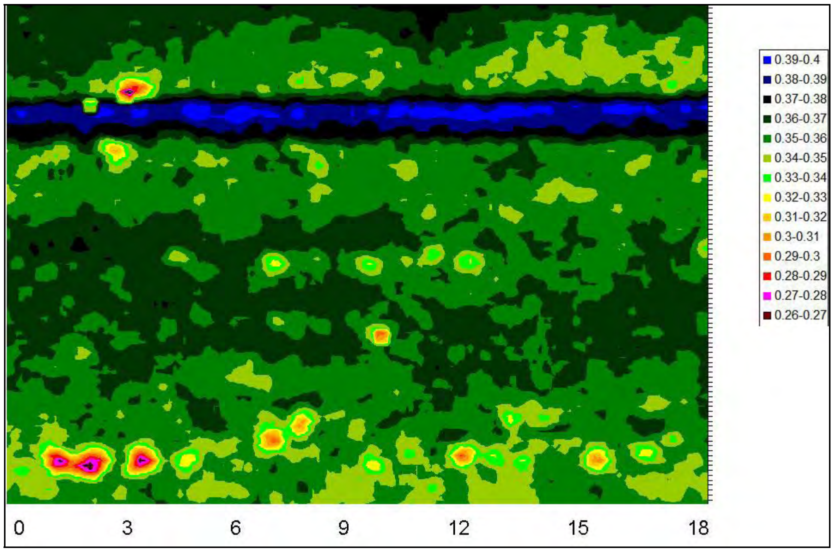


Figure A-3. Water Column-Based Automated Ultrasonic (AUT) Scanner for Measuring Wall Thickness

Magnetic wheels hold the unit to the pipe and are indexed to attain measurements in successive scan lines around the pipe circumference. About 10 min is required to cover a swath 18 in. wide around the full pipe circumference. These systems produce maps of wall thickness, shown in Figure A-4, which are easy to interpret using standard personal computers. Local inspection service providers have ultrasonic inspection equipment readily available and typically provide a complete inspection service for about $2,400 per day. This fee includes the cost of operating the equipment, the personnel to perform the inspection, and an inspection report.



The nominal thickness is 0.365 (green), the weld is added material (blue), and the corrosion pits appear in yellow, red, and magenta.

Figure A-4. AUT Output of Pipe Wall Thickness

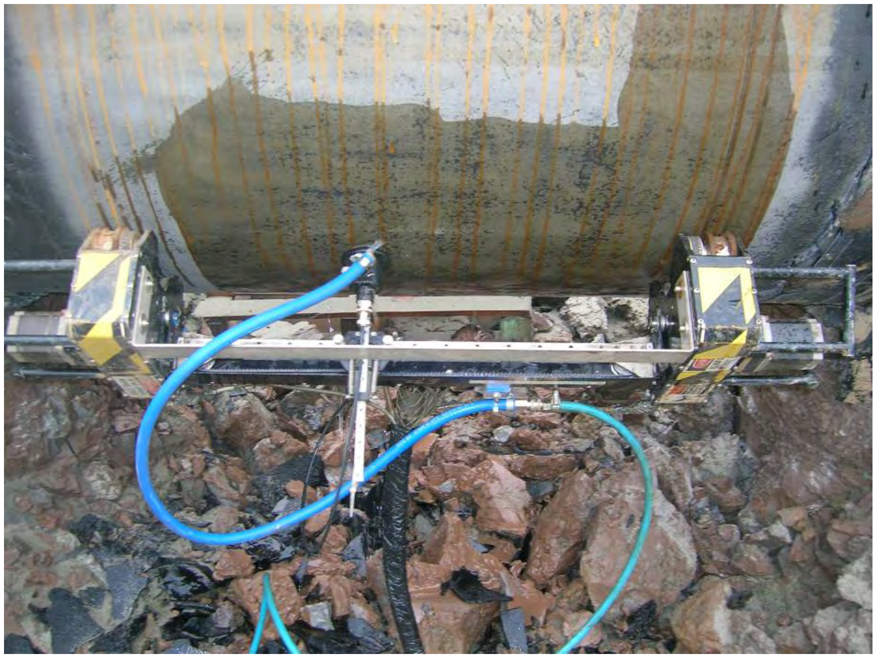
A.1.3 C-Scan

This tool shown in Figure A-5, developed by Bodycote UK, maps an area of pipe wall and identifies external and internal pits. It requires the pipe to be exposed externally and external coatings to be removed from a minimum strip of 300 mm around the circumference. It takes thousands of readings on a 2 to 3 mm grid. The close grid setting and number of readings should provide an accurate definition of metal loss. This tool is not currently available in North America but similar tools are available from U.S. vendors.

A.1.4 Guided Wave Ultrasonic Systems

Teletest is an example of a tool available commercially. It is used on steel pipe with welded joints that provide the continuity (Figure A-6). The diameter range is from 2 to 48 in. The transducer is mounted on an exposed section of pipe about 18 in. long. Typically the length of pipe that can be scanned is approximately 100 ft. It works for pipes that are insulated or coated and it is particularly useful for buried pipelines and road crossings.

Another example, based on the guided wave principle, is the Long Range Ultrasonic Testing tool, which claims to be able to inspect insulated welded steel pipelines over long lengths while the line remains in service. It can detect both internal and external corrosion.



Reprinted with permission of Bodycote PDL.

Figure A-5. C-Scan from Bodycote

Reprinted with permission of TWI Technology Centre.

Figure A-6. The Teletest Remote Detection Tool Showing Transducer

A.1.5 Magnetic Flux Leakage Tool for External Investigation

A tool based on this principle has been developed by a U.K. company (AES Ltd.) for water, wastewater and gas ferrous pipes investigation. The AES 519 has been extensively used in the U.K. and also in Europe and Australia. One version used for pipe diameters of 3 to 12 in. is an external full circumferential wall inspection tool (Figure A-7). For diameters up to 6 in., the exciter and sensor ring wrap around the pipe and the tool moves along the pipe. For diameters of 8 in. or more, pipe inspection is by segments.

ECAT (External Condition Assessment Tool) is designed for non-intrusive assessment of larger diameter ferrous pipe wall conditions. This tool, which uses the same basic technology, carries out a series (Figure A-7) of inspection sweeps using a carrier mounted on guide rails. It is designed to work in diameters of 12 in. and greater. The data can be displayed in both 3-D graphical and numeric form.

Reprinted with permission of AES Ltd.

Figure A-7. AES S19 and AES ECAT Pipe Wall Inspection Tools

Magnetic flux leakage (MFL) is the most commonly used inspection technology for ferrous pipelines today, holding over 80 percent of the oil and gas inspection market. Numerous inspection companies provide the service. Figure A-8 illustrates an MFL type of pig.

A.1.6 Remote Field Eddy Current

A number of remote field technology (RFT) tools are in commercial use for ferrous pipeline inspection. A major advantage is that RFT does not require close contact with the pipe wall and tools are designed with a minimum clearance of 0.25 in. This allows the tool to pass local diameter reductions and deposits. It also allows scanning of ferrous pipes with internal linings including cement mortar, epoxy and PE. RFT technologies have some inherent limitations:

- Frequency: most systems are frequency dependent or have a limited number of frequencies to operate at. This limits the material thickness variations that are detectable.
- Size and shape of sensors: the transmitter and receiver size and shape affect the operational frequency, so antenna configuration is not easily altered to suit survey configurations.

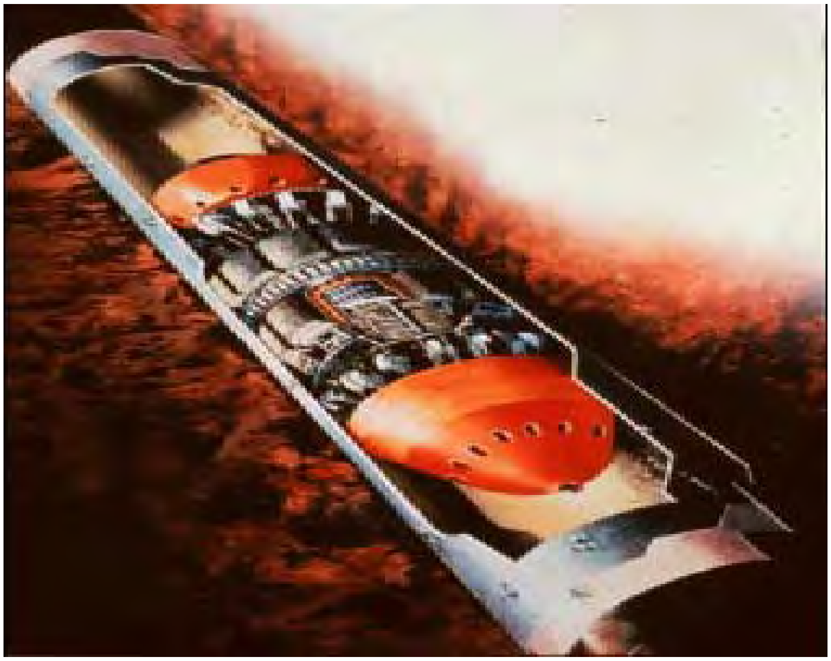


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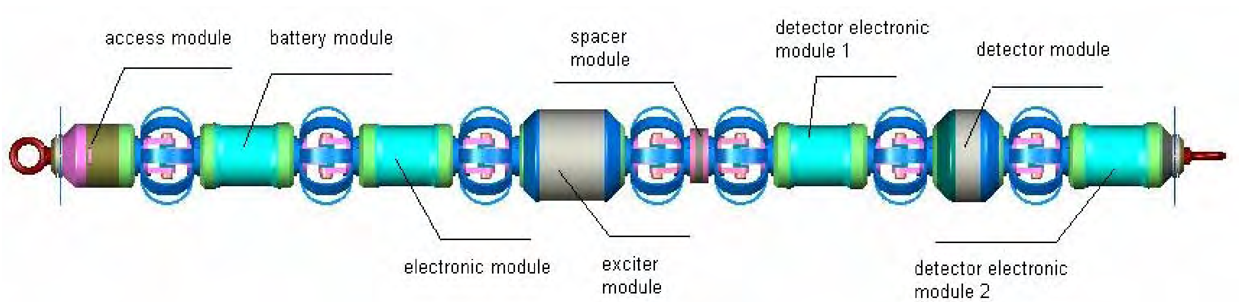
Figure A-8. An MFL In-Line Inspection Pig

Russell Technologies of Canada has been involved in the development of a number of RFT tools mainly for oil and gas applications. They were closely associated with the development of the Hydroscope tool. The Hydroscope Company is currently no longer offering inspection services.

A.1.6.1 "See Snake". The current main range of tools is based around the name "See Snake" which operates in diameters from 2 to 14 in., although the company states they intend building larger versions. The "See Snake" tool modules, illustrated in Figure A-9, allow for a large degree of flexibility with a capability of negotiating 90 degree bends. The spacers center the tool and direct contact with the pipe wall is not required. 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. The free swimming version can inspect lengths up to 15,000 ft from the launch point. A "T" or "Y" piece needs to be retrofitted into the line to provide a launch trap. The tool is propelled through the line by the product flow or compressed air while the line is in operation.



Reprinted with permission of Russell Technologies

Figure A-9. "See Snake" Modules and Spacers

To date the tool has been used in lengths up to about two miles from the launch point. Russell Technologies claim that they can identify and measure internal and external pitting and remaining wall thickness to an accuracy of 20 percent. The “See Snake” cannot distinguish between internal and external defects. The “See Snake” is powered by internal batteries and the collected data are stored onboard and downloaded by USB or Bluetooth connections.

Reported “See Snake” specifications are:

- Run time: minimum 5 hr
- Speed: approx. 10 ft/min
- Pipe thickness: up to 0.5 in. steel; 1 in. for cast iron
- Pipe diameters: 2 to 14 in.
- Clearance is 0.25 to 1 in. around tool
- Tool length is approximately 20 times diameter
- Can negotiate some bends.

The limitations on thickness of 0.5 in. for steel and 1 in. for cast and ductile iron should not be a problem for diameters up to 14 in.

Russell Technologies has also adapted a tool used for inspection of well casings and ferrous pipelines with or without internal linings and of diameters greater than 24 in. The line needs to be closed down and dewatered to allow an operator to “walk” the tool through the line collect data. The tool is shown in Figure A-10.

Figure A-10. Russell Technology Internal RFET Tool

A.1.6.2 Mainscan. This is an RFT tool that has been developed in Australia by Earth Tech Engineering. It uses the response of a single frequency in the remote field region to determine the thickness of remaining metal. The equipment consists of a 16 channel CPU unit, a laptop computer and a scanning head. The probe module houses two differential and two absolute coils. The differential coils used with an X-Y display detect and display absolute defects such as pits. The absolute coils are used to detect and quantify general wall loss. Data are gathered and saved for analysis as the scanning head is moved across the pipe surface (Vickridge et al., 2006).

A.1.6.3 Broadband Electromagnetic. A series of tools have been developed and patented by Rock Solid Pty. Ltd., an Australian company. BEM is one application of electromagnetic or eddy current systems. The technique works by inducing eddy currents to flow in close proximity to a transmitter. In a ferrous pipe these eddy currents migrate with time allowing a complete profile of the ferrous pipe to be obtained.

By assessing the primary and secondary induced currents it is possible to gauge the thickness of the metal and to evaluate the metallurgical changes such as graphitization.

If a fracture exists, the scanned area of the fracture acts as a short circuit for the primary induced current and perturbs the shape of the possible primary induced current. This perturbation is easily detected.

Typically, eddy current (EC) tools have either one or a limited number of signal frequencies at which they can operate. BEM differs from other EC tools by being frequency independent. This means that the frequency at which it operates can be altered or modified to suit the material and site conditions.

Various sizes of sensors are used, with the standard having a 2-in^2 footprint. The sensor measures the thickness of metal under the footprint and provides an average thickness over that area. Thus individual pits will not be identified except as a general loss of material. It is claimed that metal loss can be identified to 10% of the wall thickness in the area under the sensor. Any wall thickness can be scanned.

An available 1-in^2. sensor provides a higher degree of accuracy when needed as the footprint is only 1 in^2 rather than 4 in^2. Sensors are made up into antennae with anywhere between 1 and 6 sensors.

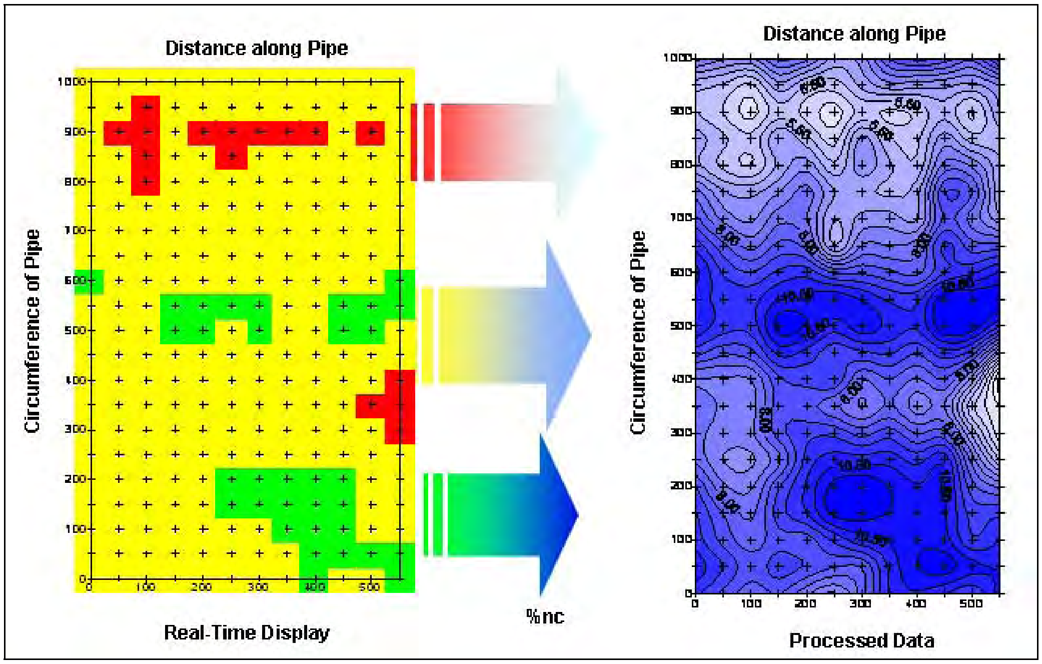
The data are seen in real time on the computer screen as a traffic light display but can be fully processed by the vendor and displayed as a contour plot although this adds to the cost. See Figure A-11 which shows the comparison between the real time results and the same data analyzed and processed.

A major advantage is that BEM does not require close contact with the metal as the depth of penetration of the magnetic flux is around 2.5 times the transmitter diameter. This capability allows BEM to scan through coatings, linings and insulation.

One disadvantage when scanning pipelines internally, compared to other technologies, is that the process is not continuous and therefore it takes more time to survey a pipeline.

A typical external scanning operation is shown in Figure A-12.

The costs of external scans are comparable to ultrasonic costs with the cost of exposing the pipe under roads being the major cost.



Reprinted with permission of Rock Solid Pty

Figure A-11. Post-Survey Data Processing, Analysis, and Plotting

Reprinted with permission of Rock Solid Pty.

Figure A-12. A BEM Hand Held Tool Being Used to Scan a Gray Iron Pipe

For internal scanning the antennae are made up into an in-line inspection pig. Pipes of 4 in. in diameter and more can be scanned with an internal tool. Access to the line is required and it must be out of service, emptied and cleaned of loose deposits.

The pig can be moved by hydraulics or by push or pull rod devices. Normally, the pig is designed to fire off each 6-sensor antenna successively so that the pig travels for 12 in., takes a reading, and moves on. This is relatively slow and means that a line has to be out of service for several days as well as being

dewatered and a section removed to gain entry. A BEM pig for a 24-in. diameter internal scan is shown in Figure A-13. Because of the large number of readings, the cost becomes significant.

Other tools have been developed using the same basic EM principals. These include a hand held tool that takes corrosion pit readings without the need for cleaning and measuring required with traditional approaches.

The company also has a modification that will operate an antenna on a rod attachment to take scans on top of pipes exposed in keyhole (vacuum) excavations. This has the potential to provide information about pipe condition (wall thickness) without disrupting service or involving the heavy cost of full access excavations.

A.1.7 Soil Investigation Technologies

Some tools for field testing provide a direct approach to capturing the data.

A.1.7.1 NovaProbe. Russell Technologies of Canada has developed the NovaProbe which simultaneously acquires soil related properties at the pipe depth and surrounds (Figure A-14). The properties that it acquires are:

- Resistivity
- Pipe to soil potential
- Soil redox potential
- Soil temperature
- pH.

It does not collect data on chlorides and sulfides.

A.1.7.2 Linear Polarization Resistance. This technology is available from Earth Technology, Australia. Essentially this evaluates external corrosion in the form of pitting based on soil aggressivity. This is not a new concept but Earth Tech has refined the approach. LPR soil testing is an electrochemical soil testing technique using soil samples taken from pipe depth to obtain a quantitative measure of soil corrosivity (see Figure A-15). This approach provides a corrosion rate that can be applied for extrapolation to quantitative time to failure calculate.

The process involves the use of a specially developed cell that provides a measure of the combined effects of several soil parameters. The assessment and time to failure calculation takes into account the pipe class, age, length of main and type and life of coating.

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Figure A-13. A 24-in. BEM In-Line Intelligent Pig

Figure A-14. The NovaProbe from Russell Technologies

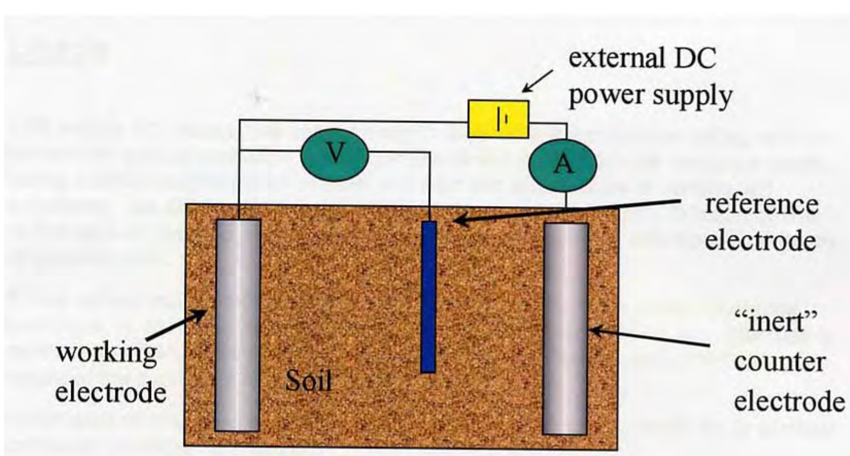


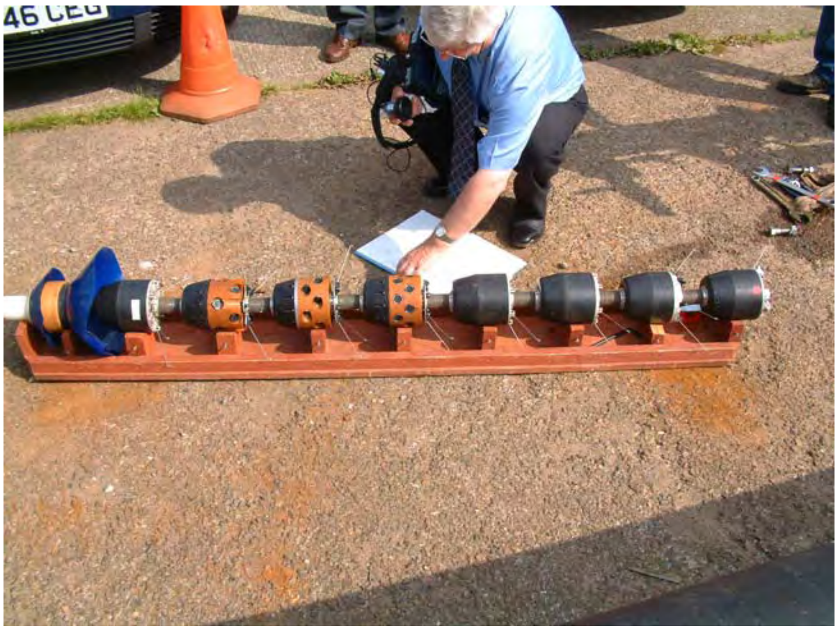
Figure A-15. LPR Ferguson-Nicholas Cell

A.2 Overview of Developing Technologies for Ferrous Pipe Investigation

For the sake of completeness a number of technologies that are under development or being tested are noted. At this time it is not thought that any are commercially available.

A.2.1 Super-Pig

Three UK water utilities developed the Super-Pig, the field testing being undertaken by Thames Water. This tool is designed to provide a comprehensive condition assessment of a water line. The prototype was developed for mains in the range of 200 to 300 mm (8 to 12 in.) and will identify wall thickness loss to 1 mm, longitudinal and circumferential cracks, damage to linings, and leaks (Figure A-16).



Reprinted with permission of Thames Water plc.

Figure A-16. Ultrasonic Super-pig Modules

The pig is based on an electronic transducer array. These arrays are battery powered and miniaturized and designed to collect and store data over several miles of inspection. For example, it generates 30 GB of data for three miles of survey. It uses water as the contact medium and transducers are not in direct contact with the pipe wall. It can see through thin internal linings that are fully bonded to the pipe wall,

but it is reported that close fit polyethylene linings and thicker linings such as cement mortar present difficulties. The pig can operate with a water main in service but needs special launch and recovery facilities which need to be retrofitted to the line.

To date it has been used on proving trials and is stated to have performed well.

A.2.2 EMAT - Electro Magnetic Acoustic Transducer

EMAT is based on a coil in a magnetic field at the surface of the pipe internal wall. Alternating current through the coil induces a current in the pipe wall causing Lorentz forces which in turn generate ultrasound. Lorentz forces are forces acting on moving charges in magnetic field. The type and configuration of the transducer defines the types and modes of generated ultrasound and the characteristics of propagation through the pipe wall.

The advantage of such a tool is that it does not need a couplant. EMAT is dry coupled and suited to gas pipelines. It is capable of identifying a wide range of defects including internal and external metal loss and cracking. The disadvantage is that it needs to be very close (1 mm) to the pipe surface. The transmitted low frequency ultrasonic energy is a limitation on resolution.

A.2.3 "No Pig"

This is another tool that was developed for non-piggable oil and gas lines. The above-ground tool detects and measures corrosion in lines that are not suited to in-line inspection. It uses an applied signal of various frequencies at two points along the pipeline up to 1 km apart. The magnetic field at these frequencies is measured at inspection points along the line.

Calculations are made to determine a cross-sectional position of an equivalent current line. Due to the skin effect, a variation of this position with frequency indicates a local wall thickness reduction. This dependence is evaluated quantitatively to give the percentage of the metal wall loss.
This technique has not been commercialized.

A.2.4 Non-Contact Ultrasonics

The New York City Department of Environmental Protection (NYCDEP) commissioned research on non-destructive investigation of force mains. The cumulative effort of all the research into available technologies concluded that in 2006 an ultrasonic based crawler developed jointly by Inspector Systems GmbH (Rödermark, Germany) and the RTD Group (Rotterdam, NL), was the most fitting technology for internal inspection of force mains (see Figure A-17). The technology has been verified for internal inspection of pipes and is commercially available.

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Figure A-17. The Ultrasonic Crawler

The ultrasonic crawler system consists of a video inspection system robot with a ring of ultrasonic transducers at the back of the crawler. Main features of this system are highlighted below.

Crawler System: The Video Inspection crawler has the ability to climb/descent vertically while moving both forwards and backwards and to negotiate all standard bends >1.5 D.

RCCTV**:** The pan and tilt camera allows to rotate 360° and to sweep 135° up and down. Together with the integrated zoom, focus and high intensity light source, it is possible to have a direct view to each point inside the pipe. The accuracy of the video inspection crawler including the high resolution camera is better than 1 mm (length and width) in a pipe with diameter < approximately 23.6 in. (600 mm).

Non-contact Ultrasonics: The ring of ultrasonic sensors can be seen in Figure A-18. They scan the pipe continuously and transmit data to the control which analyzes the data and generates a profile of the pipe wall.

Crawler Connectivity: The crawler is connected to a special fiber optic cable for remote control and video transmission.

Inspection/Scan Length*:* The crawler can travel at the speed of 200 m/h (660 ft/hr) and can inspect pipes up to 500 m (1,650 ft in length).

Pilot Testing*:* A pilot testing of a steel pipe of 18 in. in diameter and 100 ft in length was carried out in Rotterdam by RTD. The pipe had hidden damages that were to be detected by the crawler. It was demonstrated during the pilot testing that the crawler could detect loss in pipe thickness of steel pipes successfully.

Information is awaited on full-scale trials that the NYCDEP is proposing to undertake later in 2008 in the field on force mains.

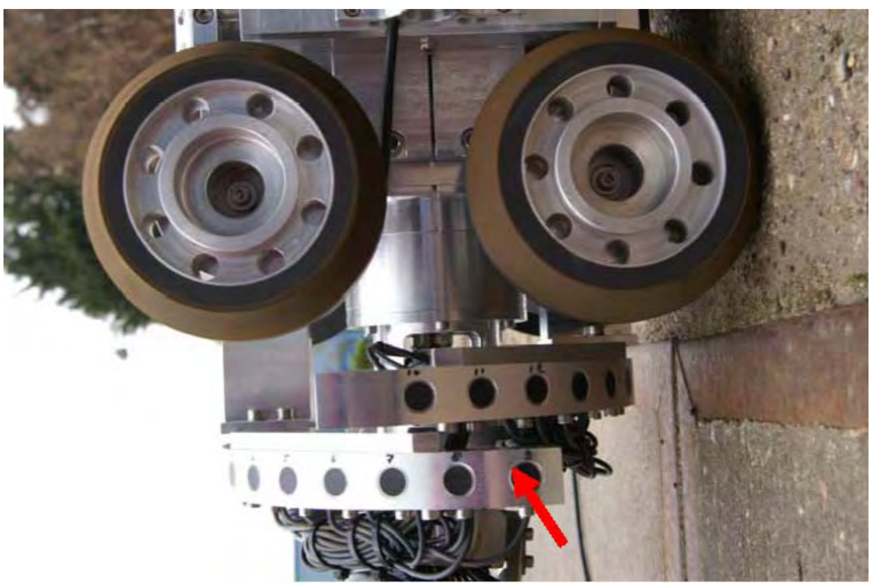

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Figure A-18. Ring of Ultrasonic Sensors Marked by Arrow

A.2.5 Acoustic Based Technology for Non-Destructive Testing Condition

A Canadian company based in Toronto, Echologics Engineering Inc., has entered into a collaborative research agreement with NRC of Canada to develop and commercialize this technology. It is based on utilizing the propagation and characteristics of acoustic signals (Hunaidi, 2006).

The technology works by measuring how quickly acoustic signals are transmitted along a section of pipe. Acoustic signals are induced in pipes by releasing water at fire hydrants in a controlled manner. Then, they are measured using acoustic sensors positioned at two longitudinally separated points on a pipe. The sensors are attached at easy-to-access points, such as fire hydrants and control valves, or directly on pipes in existing access manholes. A schematic of the measurement setup is shown in Figure A-19. The acoustic propagation velocity is calculated based on the sensor spacing and time delay between the measured acoustic signals. Average wall thickness of the pipe section between the acoustic sensors is then back calculated from a theoretical model of its relationship with the acoustic velocity, the pipe's internal diameter and Young's modulus of its wall, and the bulk modulus of elasticity of water, all of which are usually known or easily determined.

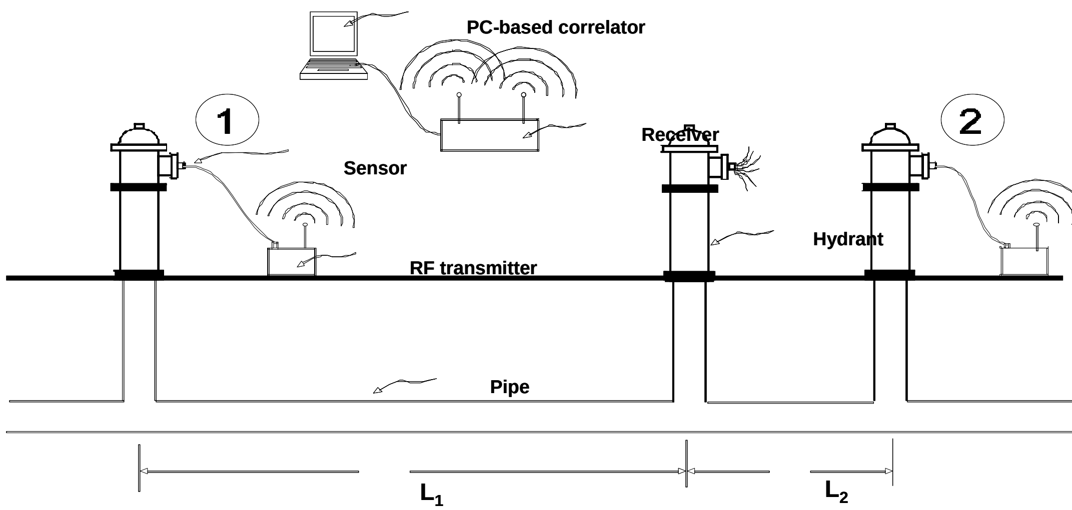

Figure A-19. Measurement of Acoustical Propagation Velocity Using: (a) an Out-of-Bracket Noise Source; (b) an In-Bracket Noise Source

(a) Wave propagation velocity (v) = D / ΔT, where ΔT is time delay between signals 1 and 2
(b) Arrival time of signal 1 = $T_1 = L_1 / v$, where v is sound propagation velocity in pipe
Arrival time of signal 2 = $T_2 = L_2 / v$
Time lag between signals 1 and 2 = $\Delta T = T_2 - T_1 = (L_2 - L_1) / v$
$v = (L_2 - L_1) / \Delta T$

The length of the pipe section over which the acoustic velocity is measured can be arbitrarily chosen. Initially, a section 100 to 200 meters long, which is the usual distance between fire hydrants or valves in urban areas, may be chosen. Subsequently, if a higher resolution is needed where there are concerns about a particular section, the resolution can be increased by moving the acoustic sensors closer together.

Velocity measurement can be performed with hardware normally used for locating pipe leaks using the cross-correlation equipment, as shown in Figure A-20. However, measurement of the velocity tends to be more technical than the usually straightforward leak correlation. Velocity measurement and wall thickness calculations are made in real time using specially developed software, trademarked as "ThicknessfinderRT". Recent research and development have led to a refined theoretical model for non-uniform pipe sections, an optimal procedure for acoustic velocity measurement, and a method for inspecting the quality of the measurements.

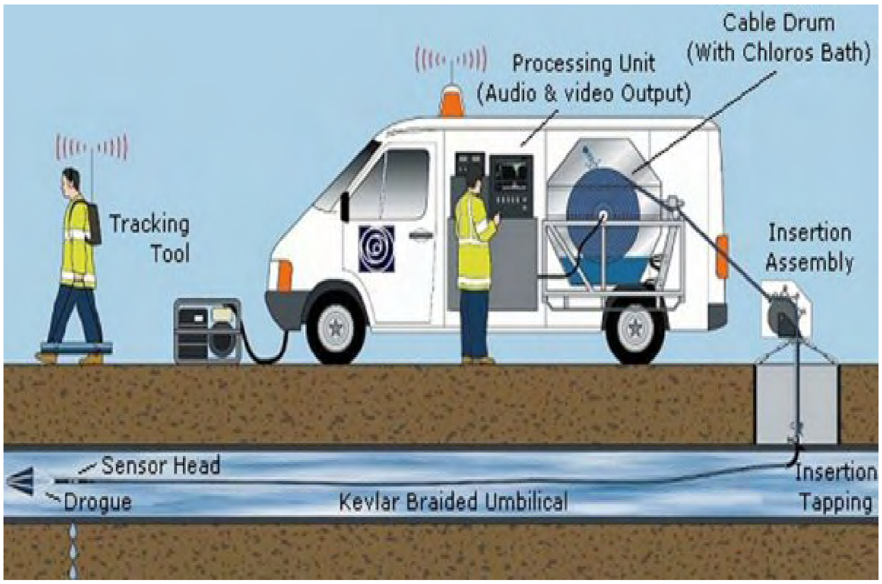

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Figure A-20. Schematic View of Sahara® in Operation

Remaining pipe wall thickness predicted by NRC's acoustic technology represents an "effective" value from a mechanics of materials point of view and subsequently it reflects general structural deterioration of the pipe. Therefore, ferrous pipes in corroded condition may be significantly worse condition locally than the average thickness indicates. This is not a limiting aspect for some pipe types such as asbestos cement (AC) as generally such pipes will have a more-or-less uniform thickness profile. The developers acknowledge that this is a limiting factor for ferrous pipes as average thickness between two sensors is not the key concern. Echologics is conducting further research and development on this issue.

Pilot tests have been undertaken on 10 sites on the water distribution system of the City of Toronto. Pipes were all pit- or spun-cast iron with diameters up to 20 in. The results coincided with independent testing of samples for average thickness loss. Echologics has undertaken condition assessment in a number of other sites. At Maple Ridge, British Columbia, 21 sections were surveyed. Pipes were ductile iron, cast iron, and AC in diameters from 100 mm to 200 mm (4 to 8 in.). In Las Vegas, two sections of 150 mm (6-in.) AC pipe were assessed and found to be in good condition with thickness greater than the records (probably due to a higher class of pipe being installed than recorded).

A.2.6 Robotic Arm with Sensors

A current project of NRC and the University of Regina is to develop a robotic arm capable of manipulating sensors in water mains. A robotic articulated arm would be mounted on an inspection robot that would travel through a pipeline. Sensors mounted on the arm would be moved into position to take readings on the pipe wall. Sensors could be of various types including ultrasonic.

A.2.7 Autonomous Underwater Vehicle

NRC also has an ongoing project to develop a torpedo like vehicle to inspect large water mains. It is envisaged that a number of NDT techniques could be mounted and manipulated from such a platform. These could include ultrasonic testing, laser profiling and a multi-camera vision system.

A.3 Leak Detection Technologies

A.3.1 Sahara®

The Sahara® tool is a single, 1-in. diameter hydrophone attached to a calibrated umbilical cable through which data is transmitted in real time (Figure A-20). In water mains a drogue is attached which propels the tool through the line. The cable also controls the tool's speed and allows its retrieval. Sahara® can be inserted into a line through any standard 2-in. tapping, such as an air valve in a water main, and can survey up to 6,000 ft from the insertion point. The location of the sensor can be detected from the surface, using a walkover tool, so that the operator can mark the surface with the exact location of any leak. It operates on the principle that leaks cause turbulence, which in turn causes noise, and it detects this noise.

Sahara® operates in any pipe material, in pipes 300 mm (12 in.) or greater diameter. Operating pressures between 0.5 and 16 bar (7 to 230 psi) and flow velocities between 0.3 and 1.5 m/s (1 to 5 ft/s) define the operating range of Sahara®. It has proven capable of locating leaks as small as 0.25 gal/hr with a high degree of accuracy.

The cost of setting up an insertion point can be significant but the survey costs vary, depending on amount to be surveyed, but range from $2/ft for several miles to $4/ft for shorter runs.

The Pressure Pipe Inspection Co., Mississauga, Ontario, is the licensee of Sahara® from WRc for North America and offers a leak inspection service.

A.3.2 SmartBall®

SmartBall®, developed by Pure Technologies Ltd, is another example of an in-line detector. This is an acoustic acquisition device complete with power supply contained within an aluminum casing and then placed inside a foam ball. The system can operate for up to 15 hr and is free swimming and capable of investigating pipes of diameter greater than 10 in. although it operates most effectively in diameters of 24 in. and greater. SmartBall® can be inserted and retrieved from an operational pipeline. It can be inserted through a 4-in. open port valve or 3.5-in. air valve.

Prior to insertion a number of transponders will be connected to existing appurtenances. These generate a pulse that is detected by the SmartBall® providing synchronization with known points.

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Figure A-21. SmartBall® Inspection Method – Insertion, Travelling, and Removal

APPENDIX B
FORUM SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Approximately 34 technical experts and representatives from utilities, technology and service providers, academia, research organizations, consultants, and EPA attended the two-day Technology Forum held in Edison, NJ on September 9 and 10, 2008. The Forum consisted of a State of Technology Review Report feedback session followed by six breakout sessions. A companion EPA report titled "Draft Forum Report on Condition Assessment of Ferrous Water Transmission and Distribution Systems" has been prepared to fully document the Forum presentations and discussions (Thomson and Wang, 2008). Presentations and discussions from each session and major conclusions and recommendations are summarized below.

B.1 State of Technology Review Report Review

The Forum attendees suggested some changes/corrections to the draft State of Technology Review Report, but there were no major disagreements with the overall sense of the State of Technology Review Report. The key points which arose from the open discussion are highlighted below.

One attendee suggested that more emphasis should be given to potential technology transfer from other federal agency research developments. Some attendees expressed reservations because of the economic and technical difficulties of transfer.

The relative benefits of inspection in terms of cost to asset value for small and large pipes were raised by several attendees. There were two counter views. One considered that the total cost of the larger number of small-diameter pipe failures was higher; therefore, reducing these failures would be more cost effective than reducing the smaller number of large-diameter pipe failures. The counter view was that it was not cost effective to inspect small diameter pipes. The "fail and fix" approach or condition assessment based on pipeline asset and failure data was cost effective for small-diameter pipes.

The definition of condition assessment was raised and its role in asset management. Current condition assessment is based on individual pipe sections rather than a cohort approach. The current approach is needed because of the lack of homogeneity and the wide variations that occur in a set of pipes.

The lack of agreed rigorous definitions used commonly in the water industry was a key issue. One example was the definition of failure. Some attendees considered that any event that would require remedial action, including repairing a leaking joint, constituted a failure. The counter view was that failure should be defined as when the pipe no longer was operating and serviceable. Leaks should be defined as defects that needed to be fixed but did not stop a pipe from being serviceable. The term "Pipe Life" was another term that was not rigorously defined. The "Design life" was not thought to be a useful concept and an alternative of "Economic Life" was suggested where the cost of maintaining the line in service became excessive.

Written comments were received from the project stakeholders and have been incorporated into the Final State of the Technology.

B.2 Large-Diameter Cast Iron Pipes

Presentations included an overview by Yehuda Kleiner, NRC of failure modes and mechanisms of ferrous pipes and case studies on large-diameter cast iron pipe failures experienced by the City of Cleveland and Washington Suburban Sanitary Commission (WSSC).

The overview of failure modes for cast iron pipes emphasized the need to understand failure modes and mechanisms. Some key points that have arisen out of NRC work were:

- Pipe age is generally not a good indicator of pipe condition
- For small-diameter distribution water mains, the strategy should be to manage failure frequency. For large-diameter transmission mains, the strategy should be to prevent failures because of the potential of high consequences
- There are highly variable properties in cast iron pipes
- Variable delivery and installation practices could lead to built-in defects.

Large-diameter CIP and DIP are identified as high-risk and high-interest pipe scenarios for which better, cost-effective condition assessment capabilities are recognized by the user community as valuable, but not attainable with available condition assessment tools (e.g., databases, inspection technologies, and deterioration and failure models). Many different mechanisms and parameters are involved in corrosion and failure of ferrous pipes. CIP can fail due to the rigid nature of joints, the lack of tensile strength, and weakening due to graphitization.

An ongoing Water Research Foundation/NRC study revealed that the large-diameter CIP failures experienced at Cleveland were likely caused by longitudinal and bell cracks, which may originate from defects or damages caused by manufacturing, delivery, or installation practices. The low rate of failure (0.07%) did not justify any replacement program and inspection of the bells to find growing cracks is technically difficult because of the complex geometry. This case study generated a lot of interest and discussions as to whether potential technologies, such as the RFT and BEM, might be possible to detect the bell cracks, whether similar failures were occurring elsewhere, and whether this high-risk scenario would offer an opportunity to improve condition assessment capabilities.

Potential difficulties in internal inspection due to fittings, tuberculation, etc. were reported. Utilities like WSSC placed emphasis and value on data mining using extensive field records, GIS, and "Google Earth" to help survey the pipeline and assess the condition of their large-diameter CIP. Field records should be consistently updated when the opportunity occurs during excavations and new installations.

B.3 Large-Diameter Ductile Iron Pipes

This session focused on the corrosion issues with DIP and case studies provided by WSSC and Louisville Water Company (LWC).

Mike Woodcock of WSCC emphasized that like all materials DI had limitations and it was important that users understood these. He did not agree with the State of Technology Review Report where it was stated that most DI was polyethylene wrapped. Much of WSSC's DIPs were not wrapped but laid bare. However, larger diameters were protected cathodically. He considered that a typical life for DIP in WSSC was 30 years. He pointed out that the thinner wall for DIP meant failure earlier when corrosion was present.

He discussed and illustrated the changes in DIP and coatings over the years. Originally DI was produced from nearly pure iron, but the much greater use of scrap metal has resulted in a differing metallurgical structure that has the same strength properties, but may not have the same corrosion resistance. He also had concerns that some manufacturers were not heat treating pipe to the same extent because of high energy costs.

Greg Horne of DIPRA presented on “Ductile Iron Pipe Failure Modes and Condition Assessment Practices”. He accepted that deterioration can occur but the problem lay in how to decide which pipes need to be fixed. He did not consider that current inspection tools could provide this information cost effectively. He recommended that condition assessment based on records was needed. He showed a series of slides to illustrate this approach which included asset databases, customer complaints, and break and leak records. He reiterated that CIP could fail due to its rigid nature and that DIP fails usually due to corrosion. As corrosion was the potential problem for DIP he recommended that areas of potential soil corrosion be identified by soil testing and use of the DIPRA “Design Decision Model” using consequences and likelihood of failure ratings.

Dale Lindemuth of CORRPRO presented on “External Corrosion Condition Assessment Procedures”. The thrust of the presentation was the possible application of External Corrosion Direct Assessment (ECDA) methods, which were developed for the oil and gas industry, to the water industry. These methods are used for the condition assessment of pipelines that cannot be inspected by direct inspection technologies. There are four stages involved in the ECDA:

- Stage 1. Pre-assessment data gathering and planning
- Stage 2. Indirect inspection with a number of different approaches. The outcome of this stage is to integrate and analyze all data and develop rankings to select the most likely sites for direct examination
- Stage 3. Direct examination involving excavations to expose the pipe and taking direct readings and measurements
- Stage 4. Post assessment with the main activity being to calculate remaining life by different methods.

Cathodic protection was recommended as being a viable method.

The final presentation was by Keith Coombs of the LWC “Case Studies from Louisville Water Company”. The overall goals of the company were the reduction of breaks to 600 per year, the elimination of unlined CIP and the replacement of two vintages of CI mains showing a much higher break frequency. Vintages of 1862 to 1865 and 1926 to 1931 had high break frequency and would be replaced and upsized where necessary. Pipes of the 1866 to 1925 vintage had minimal maintenance history and were adequately sized so they could be rehabilitated.

The discussion that followed on Sessions 1 and 2 emphasized a number of key issues. Several speakers expanded on the multiplicity of defects and their causes in ferrous pipe and the need to understand “What you were looking for,” and then use the appropriate technology to find it.

In responding to a question about whether possible limitations to condition assessment arose from the hardware or the signal processing, one of the leading technology developers pointed out that the real limitations lay in the basic physics, which cannot be changed.

One university delegate suggested that in view of the costs and disruption involved in internal investigations, multisensory platforms should be used to collect all possible data at one pass. The response from a utility delegate was that this resulted in data overload and delays in getting key results which needed to be immediately available to determine remedial works while the pipe was out of service.

The problems of access and disruption that are involved in internal inspection suggested that greater consideration be given to developing external non-intrusive inspection and combining limited direct inspection with asset, soil and coating data. Some inspection companies were developing this approach.

A broader issue was the utilities' approach to the value of inspection. A leading inspection vendor of ferrous pipes said that direct inspection costs were around 4 to 5% of the asset value but with a further 4 to 5% of indirect support cost. This was well above the highest figure of 5% of asset value that utilities felt that they were prepared to pay according to an AwwaRF study. A leading utility representative stated that he felt that utilities were aware of the technologies but needed to understand the value of inspection in reducing failures before they would begin using them. Another speaker felt that, as with PCCP, the critical need that condition assessment should address is to reduce catastrophic failures where the consequential cost is high.

In conclusion a speaker pointed out that a utility inspection only told you that you had a problem. However, it did not solve the problem.

B.4 Leakage Management

Mark LeChevallier of American Water opened with "American Water Leak Detection Technology Update". He described their experience with AMR and how it became cost effective by coupling with water leak detection. A number of permanent and semi-permanent water leak devices based on acoustic monitoring tools were described. The data could also be mined to relate leaks to temperature changes and patterns that repeat annually and revealed that the maximum number of leaks seemed to occur in the fall. Conclusions to date include:

- Acoustic monitoring works and may reduce leakage about 30 to 50% mainly on low-medium leaks
- Early detection and repair reduces operational cost
- Leaks increase with water temperature drop. Large temperature drop trigger larger main failure
- Many leaks start in the fall
- Acoustic monitoring does not find all leaks because of background noise
- Acoustic monitoring and area metering can work effectively together
- Acoustic monitoring and area metering analysis and decoders can identify metered leaks.

The second presentation "Optimizing Water Pressure Management to Sustain Distribution Infrastructure" was presented by George Kunkel of Philadelphia Department of Water. In opening, he emphasized the need to find ways to activate utilities to take action on water leakage as most utilities do not have any pro-active approach. He described three components of leakage – reported, unreported, and background leakage. Philadelphia had reduced leakage by about one third. He then described appropriate approaches to intervention. This was followed by a representation of the four components of managing real loss to an economic level:

- Active leakage control
- Pressure management
- Improved system maintenance, replacement and rehabilitation
- Improved response time to leak repair.

The second part of his presentation described Philadelphia's DMA project.

Brian Mergelas of Pressure Pipe Inspection Company (PPIC) presented "Recent Advances in Leak Detection Technologies" based on the Sahara® system licensed internationally from WRc the developer. Sahara® in-line leak detection is able to identify small leaks of less than 1 gal/hr in operational lines due to the proximity of the acoustic sensor as it passes a leak. It is suitable for diameters of 12 in. and greater. Up to 6,000 ft can be surveyed from one insertion point and one to two miles of line can be surveyed in a day. It is inserted by means of a 2-in. tap. All leaks were not created equal, and many leaks were found that had not appeared at the surface.

The returns from a Sahara program were illustrated by reference to five projects. The client cost per mile in line preparation was about $25,000 and the Sahara® survey cost $25,000 per mile. Using the number of leaks detected and the cost of repair a total cost was determined. The savings from break avoidance in terms of value of water recovered at 50% of retail price was calculated and the comparison of net benefits against cost showed rates of return on the investment all in excess of 1,000%.

PPIC have recently introduced a video camera which can be inserted into an operational main through the launch point. He showed examples of the pictures obtained of the inside condition of the pipe including air pockets.

The final presentation was by Michael Higgins of Pure Technologies "Leak Detection Ball for Large Diameter Pipes and Future Leak Detection Technologies"

He set out the following goals of inspection:

- Reliability of detecting defects
- Pipe remains in service
- Non-intrusive
- Direct test for long pipelines
- Inexpensive to deploy.

To his knowledge, currently there were no tools that met all these criteria. One of the tools that Pure has developed is Smartball®. The ball is free swimming and propelled through the line at near flow velocity. An acoustic ping is emitted every three seconds which allows tracking equipment to follow the ball. It follows the dominant water flow and passes around bends and fittings. It can record data up to 12 hr so is able to monitor many miles from one insertion. The tool requires a 4-in. port for insertion and removal.

A future approach to permanent leak detection was based on the use of acoustically sensitive fiber optic cable which could be up to 25 miles long. This was seen as being a tool that would be installed in key trunk mains and provide continuous permanent monitoring.

The key points which arose from the open discussion on leakage management are highlighted below.

On the question of how to convince utilities of the technical and economic feasibility and value of reducing leakage, there was a variety of responses. It was pointed out that unlike countries, which had achieved significant leakage reduction, there were no real drivers in the U.S. One vendor said his experience was that there were a whole range of clients from pro-active to reactive. So some utilities did not need convincing.

The representative from Philadelphia Water pointed out that there were many low tech utilities doing nothing and using low tech designs. He cited utilities who could not isolate areas because they either did not have valves that were operational or, in some cases, did not know where the valves were.

Another speaker pointed out that he had problems of convincing utilities and particularly operators of the value of inspection because they did not wish to have anything which might disturb the day-to-day operations.

Steve McKellar referenced the U.K. experience with DMAs and suggested that it would be insane not to use this approach. He pointed out that all the major U.K. water utilities had been using DMAs now for 10 years and there is 75 to 90% coverage of the network. It is almost mandatory now that UK utilities use DMAs because of the leakage reduction that could be achieved.

It was questioned if leak monitoring combined with other data could provide information on condition and if additional tools could be added to provide information on structural condition.

WSSC believed from their experience that the data collected by Sahara® and SmartBall® contained a great deal of additional information which could be extracted by improved signal analysis. For example, the individual key pipelines could have each pipe tagged so that as the tool passed it could be identified. It was thought that more could be done to closely identify defects and their locations.

A suggestion was made that a common system was needed to describe the different forms of leaks that were found and repaired. As illustrated in the literature, a wide range of leaks occur. Leaks could be from joints, fittings, perforation, and breaks. These failure data would be invaluable in understanding the nature and causes of leaks and the collection of the data should be undertaken by utilities in conjunction with the vendors.

B.5 Prediction Models and Databases

The session opened by Yehuda Kleiner of NRC who presented "Small Distribution Mains Breakage Frequency Modelling".

His understanding of what utilities wanted to know included:

- Remaining service life
- Criteria for replace or rehabilitate
- Optimal timing for renewal/inspection
- Allocations for future budgets.

Rather than demonstrating the models, he discussed the development and results of the models. He showed derived curves for small and large diameter pipes taking into account cost of renewal and failure risk giving a total expected cost. He showed how the bottom of this curve was the most cost effective time of renewal. The time to renewal for large mains was much shorter on this basis because the failure risk curve was much steeper. He believed that this was the basis for managing small mains which was to accept a higher failure frequency than for large mains where it is much more important to identify impending failures.

Yehuda Kleiner commented on the pros and cons of modelling based on statistical and physical information. Statistical models are simpler and data are more readily available. He listed the data requirements and the trade off between group size and homogeneity. The benefits of opportunistic fitting of CP anodes and retroactive systematic fitting were graphically illustrated. His final comments were recommendations directed towards the need for robustness and simplicity in modelling.

This presentation was followed by Steve McKellar who outlined the "UKWIR Sewers and Water Mains National Failure Database". Steve Mackellar pointed out that there were a number of differences between the U.K. and the U.S. practices that needed to be taken into account. Operating pressures were higher in the U.S; there was much greater use of PE for potable water in U.K. Probably the biggest difference was the smaller number of large utilities in U.K. who were responsible for over 90% of the system and were monitored for performance by a government appointed regulator. The regulator determined, from the capital spending budgets and plans, the rate increases that would be allowed.

The initiative for development of National Failure Database was from UKWIR who wanted to:

- Create a repository for failure data
- Make data provision easy
- Make data use easy
- Manage data and keep secure
- Respond to changing needs.

Participation in the database is voluntary and the operation is financed by subscription. Currently participation is greater than 90%. The water database has now been operational for some years and is proving to be highly beneficial to utilities in that they are able to compare their own experience with failures and pipe materials against national experience. The sewer database will come on line shortly.

In conclusion he showed a wide range of analysis that was possible. A range of data sets were shown of different pipe types, failures, leakage and assets and how they could be used to undertake forecast modelling and mains replacement.

Sunil Sinha of Virginia Tech presented "Condition Curves State-of-the-Technology" and "Predictability/Preventability Indices" and his role in TO 62. Prediction deterioration models can be grouped into five major categories:

- Deterministic
- Statistical
- Probabilistic
- Advanced mathematical
- Heuristic.

Water Research Foundation has identified six concepts for modelling. Five of these were listed below:

- Main age of failure
- Total failures over time
- Breaks as functions of single causative factors
- Break probability in next time period
- Aggregate data.

Sunil Sinha emphasized that sound data had to be the basis of all modelling. It was not just taking data from utilities which came in many forms. Virginia Tech on their other projects were taking the data from utilities and interpreting it into their own format, which is termed "data cleansing". He emphasized that they were not developing curves but looking into what might be possible.

He continued with his work on exploring the feasibility and value of developing procedures for calculating predictability and preventability indices.

- The predictability index will indicate the inherent, theoretical predictability of various types of pipe failure
- The preventability index will indicate the technical and economic feasibility of preventing pipe failure.

The predictability index was graphically shown in terms of five stages:

- Type of failure
- Failure mode and mechanism
- Variables that predict failure
- Develop scoring system for variables
- Pipe failure preventability index.

The development of a preventability index was shown in five stages:

- Identify water pipe technologies
- Evaluate technical feasibility
- Evaluate economic feasibility
- Develop rating system
- Preventability index.

The presentations in this session created significant comments and suggestions throughout the discussion.

One university delegate pointed out that in statistical modelling the stability of the model is essential. In this type of modelling it is necessary to create a population of individuals which remain stable. However in real life the "pipe" individuals change because of new works, repairs, and replacements. No longer is it possible to accurately assign failures. This was illustrated by another speaker who provided an example where a utility had replaced a lot of failing PVC with PE but the model attributed the earlier PVC failures to PE.

She also commented that the data cleansing that Virginia Tech was proposing required a great deal of effort. The representative from NRC emphasized this point and pointed out the difficulties of obtaining data to populate models. He also sounded a warning note on data cleansing and the momentous task involved. One set of 140,000 pipe records from one utility had proved to be unusable because of the way they had been recorded. He considered that data recording had to be at utility level and involve operators who had in-depth knowledge of the system.

Steve McKellar explained that the UKWIR database was based on two separate records. A higher level geospatial database presented a picture of long term requirements and investment in the system. The second was an asset database which provided the information at the operational level on pipe behaviour and which to replace. This removed some of the difficulties discussed. It was essential to have a snapshot of changes and in U.K. the changes were recorded every year. Since only 1% of the system was replaced annually it was thought to an acceptable compromise.

On the use of curves or models, Mike Woodcock said that WSSC did not use such methods. He felt that the modellers were making things complicated. Using a GIS system, WSSC knew where their assets were, the maintenance records, and where failures had occurred. There was no need to model; from this information they could analyze to prioritize their selection of where to replace or inspect. Models don't take into account extraneous considerations, which can be most important. It was suggested that Mike Woodcock was actually modelling.

A speaker pointed out that the description of the parameters in Sunil's model did not include leakage, which could be a valuable indicator of pipe condition. This was accepted as being a valid comment. It was pointed out that the factors used for predictability and preventability were the same. The value of the preventability index was questioned. Another comment was that the predictability of failure seemed to be the same as the current models which used the term "the likelihood of failure".
One university delegate said that his concern in modelling was "Garbage In and Garbage Out". There are so many parameters in a model that you can make a model produce any desirable output. His advice was to keep it simple.

B.6 Emerging Technologies

The session was opened by Marc Bracken of Echologics with "Condition Assessment of Water Pipes". The basic concept of using acoustic technology to calculate the remaining wall thickness was developed by NRC and is being further developed and commercialized by Echologics.

The method is based on how quickly low frequency acoustic signals are transmitted along a section of pipe. Using this relationship between velocity of signal and pipe wall thickness it is possible to back calculate thickness. Varying pipe thickness around the circumference can be calculated as being uniform or linearly variable. The calculated pipe thickness was the average along the section being inspected, which was typically 100 meters long. Examples of inspections and findings on pilot tests on CI and AC pipe were presented. The results of the inspections and the exhumed pipes were provided.

Krish Ramalingham of CCNY presented "Non-destructive Evaluation of Force Mains in New York". The technologies being proposed for the evaluation of New York ferrous force mains has direct application to the evaluation of ferrous water main condition. Initially asset information was collected and a comprehensive database, standards for structural rating, and condition assessment framework were developed. The tool that has been chosen for trialling is the Ultrasonic Crawler developed by Inspection Systems GMBH. The tool is capable of meeting the criteria and can also provide high resolution digital video of internal condition. It can be applied to different diameters and work through 1.5 diameter bends and climb and ascend vertically. It can scan lengths up to 3,300 ft. The intention is to undertake field trials in New York in early 2009.

Dave Russell of Russell Technologies presented "In-Line Inspection Tools (Intelligent Pigging) for Water Mains". Russell Technologies have a range of in-line inspection tools based on RFT, including wire line, free swimming, walk through and collapsible tools. He estimated, based on replacement cost of $150/ft, the inspection cost was 10% of replacement. This included the clients cost with the investigation portion accounting for 40% of the ILI cost which equated to 4% of replacement. The tool averaged some 1,800 ft a day of inspection with access to the operating mains through hydrants.

Some of the concerns and the solutions were:

- Internal pipe scale – solved by use of a soft foam pig
- Red water – solved by a 20 min flush after using tool
- Plugged customers filters – not a problem if customers did not use water during inspection
- Lost/stuck tools – very occasional and had to be dug up to recover.

Some unexpected findings were:

- Pipelines with graphitized through-holes that had not leaked
- DIP had commonly a band of corrosion 3 ft back from bell end which was traced to poor coating adherence during manufacture
- Corrosion hot spots were found near un-insulated copper services
- Long lengths of CI and DI scheduled for replacement with almost no visible corrosion.

Dave Russell wound up by confirming that tools and technologies were available for ILI. The "See Snake" is a remote RFT tool for diameters up to 14" with potential for larger diameters if there is a demand.

The final presentation was by Edgar Smith of USACE Engineering Research Development Center "Sensor Enabled Water Quality and Corrosion Degradation Assessment Systems for Water Distribution Networks". His presentation focussed on detection of water quality and corrosion monitoring by the use of wireless sensors. These included corrosion rate sensors, HACH Pipe-Sonde water quality sensors. The use of dynamic modelling and the integration of sensors and models in support of water distribution networks were discussed. The use of permanently installed leak detection systems was illustrated. The vision was that tying these tools together could provide a "smart" utility network.

Discussion on emerging technologies brought a variety of points.

One speaker believed that there were plenty of tools that a utility can use in inspecting its mains. However the increase in use is very small compared to what it should be. The limitations are not due to the lack of technology but the lack of incentive for utilities. He suggested that the barriers were institutional because of the way utilities are organized, operated, and regulated. The utilities needed to look at the rates they are setting as the income is insufficient to cover the basic level of service.

One vendor continued the theme from his experience working in two different markets – U.S. and U.K. In U.K. he had found great interest from utilities who he termed "technology adaptors" as they were seeking technical solutions in their work. In the U.S., the level of interest is very specific to individual utilities. His company found that utilities will carry out leak detection so by coupling condition assessment they are carrying out projects where almost the condition information is seen as an add-on thrown in.

One speaker considered that one potentially exciting development was the use of fibre optics in the pipe and the potential to provide both the condition of the pipe and the stress in the pipe.

There are fundamental characteristics and limitations to the basic technologies employed in in-line tools which need to be understood for any development together with cost implications for internal inspection in operational water mains. It was also recognized that there were both economic and technical barriers to inspection, not only in the ability of tools to detect cracks and corrosion but also the cost and difficulties associated with both internal and external inspections.

The group discussed ideas for motivating the utilities to improve their inspection practices, including possibly bringing together a group of utilities to develop a guaranteed minimum work program for condition assessment and condition inspection. One of the problems of U.S. water utilities is the fragmentation so that very few have the length of pipeline to justify the high mobilization cost for condition inspection. Such a minimum program of inspection would be attractive to the vendors due to a steady flow of work over an extended period and would offer cost-benefit to the participating utilities.

The point was made that inspection technologies are most effective on pipelines with good records on construction, maintenance, failure and repair. This information will focus inspection and lead to the greatest cost-benefit.

The cost of an inspection must be kept low, an acceptable fraction of the replacement cost. Otherwise, utilities will consider it to be more cost effective to execute a scheduled replacement program. Utilities that do not keep detailed records often find this to be the most effective approach.

B.7 Technology Demonstration

Bruce Nestleroth of Battelle opened the session with "EPA Technology Field Demonstrations: Protocols/Metrics/Site Selection." He laid out a framework with possible types and goals of the EPA technology demonstrations, including both controlled-condition and field demonstrations of established and new technologies. He highlighted the pros and cons of controlled demonstrations and field demonstrations. Controlled demonstrations assess performance of inspection technologies on a full range of anomaly types and sizes. Field demonstrations assess implementation variables and evaluate a few anomalies that happen to be present. He then talked about the needs which included input and contribution from stakeholder groups, water utilities, and inspection vendors.

The final paper was by Rob Pennington of CDM with "Controlled Condition Assessment Needs." Under Task Order 64 CDM had the task of looking at "Controlled – Condition Research on Wastewater Collection and Drinking Water Distribution Systems." The scope included evaluating EPA's Edison Pipeline Test Apparatus (EPTA) facility in Edison, New Jersey, and preparing a design basis and preliminary designs of controlled-condition testing needs. This was to cover all types of gravity and pressure pipe assessment and also pipe rehabilitation. Eleven pipe assessment situations along with four pipe rehabilitation needs for both pressure and gravity pipe were identified.

During the discussion, comments came from all sides of the floor and particularly vendors that it was important to simulate real life defects. Experience was that simulated defects in test facilities were not representative of real life defects and would not be found by technologies which were structured to find actual defects.

There was concern on the range of defects, conditions, and inspection technologies. It would be very difficult to cover the whole range in a control testing facility or at best would be exorbitantly expensive. It was pointed out that a loop format was not suitable for leak detecting technologies.

It was also pointed out that vendors already have substantial experience and validation of inspection findings. They didn't feel that they had to prove their technologies by doing tests in a simulated facility. They felt that it would be more beneficial to find ways to validate their technologies on real pipes.

Utility representatives were lukewarm on the value of controlled testing. They suggested that it would not make much difference to utilities in changing their demand for inspection. In their view, demonstrations that are conducted on real pipes that have similarities to their own are more likely to stimulate interest and provide more benefit.

The involvement of utilities is a key to the success of technology demonstration. A survey should be conducted to determine the level of interest of the utilities. One suggestion was for EPA to subsidize utilities' pilot studies by collecting supplementary data.

LWC offered a 2,450-ft long, 24-in. 1933 cast iron main for use by the EPA technology demonstration. Competing vendors could inspect the same pipeline where practical to allow a direct comparison to be made.

B.8 Recommendations – "Top 10 Findings" from TO 62 Forum

1. **Leakage management.** Leak detection and mitigation provides the biggest bang for the buck. With the reported six billion gallons of water loss out of 40 billion gallons extracted daily, even a 20 percent reduction would achieve massive environmental benefits and cost savings. Recent advances in leak detection and location technologies provide utilities with tools and methods to reduce leakage. However, without regulatory pressure, there is little incentive for many utilities to implement leak reduction programs. EPA should consider: (a) if there is any existing requirement that can be utilized to audit utility performance; and (b) setting rules with specific leakage targets. For example, Washington's Water Use Efficiency Rule requires all municipal water suppliers to maintain their distribution system leakage at or below 10 percent of their production (http://www.doh.wa.gov/ehp/dw/Programs/wue.htm). EPA could also undertake programs to demonstrate the technical and economic feasibility and value of reducing leakage.

2. **Data collection and management**. A general consensus among the participants is that there is insufficient data collection and management by utilities. For example, few water utilities collect data on main breaks/burst/failure/repair events and there are no standardized protocols for documenting, storing, and managing the data. Since the UKWIR mains break database has been proven useful and workable in the U.K., the adoption of this database by the U.S. will provide considerable value to water utilities and the researchers by improving understanding of the type and distribution of failure modes and mechanisms, and this information can be used to support better decisions regarding pipe selection, installation, inspection, service-life prediction, and technology development. Water Research Foundation is currently assessing the adaptability of the UKWIR database to the U.S. utilities. EPA should consider supporting this initiative.

3. **Barriers to effective condition assessment.** From the utilities' perspective, there are plenty of effective tools in providing the level of information required. It is not unusual to find that a utility will use an ineffective method because it is low cost. There is some slight increase of interest and usage for condition assessment. However, the real incentives are not there for the utilities to conduct condition assessment. The limitations are not due to lack of technologies. The limitations are institutional, which is the real barrier. Water rates need to reflect cost of production and delivery.

4. **Technology demonstration.** There is a strong desire for EPA to subsidize field trials of inspection technologies. LWC offers an immediate opportunity: a 2,450-ft long, 24-in. 1933 vintage cast iron main will be removed and replaced in August 2009. This section of main can be used for testing of multiple leak detection and inspection technologies. At the time of finalizing this State of Technology Review Report, EPA has provided funding to plan, setup, monitoring, verifying, and reporting such field tests. For large-scale demonstrations at multiple locations, a questionnaire should be sent to major cities to solicit their interest in participation. The survey should be developed to reflect utility concerns and reasons why they should participate and any potential benefits from participation.

5. **Controlled-condition testing.** Water utilities and vendors were generally unconvinced that a controlled-condition testing facility for condition assessment technologies would provide

substantial benefits. A key limitation is that controlled-condition testing is not equivalent to real-world, field demonstration. Field demonstrations also have limitations, e.g., cost, risk, complexity, and repeatability. However, should a controlled-condition test facility be determined viable, utilities are willing to provide pipe samples for testing. Further evaluation of potential controlled-condition testing needs was recommended. Another function for the EPA PTA facility in Edison, NJ would be to keep an inventory of pipe samples, perform forensic examinations of various pipe failures for all pipe types, and maintain a database of forensic analysis.

6. **Predictive models.** Much work has been done on the prediction of residual life. An extensive evaluation of the effectiveness of these models and their extent of use by utilities, engineers, and consultants, would be valuable. Some existing curves and models need to be changed to reflect local conditions such as soil parameters and support. For example, the relationship of local soil conditions and the corrosion of unprotected CIP should be taken into account. Lack of soil support, often coupled with increased external loadings, may be another local factor that can modify life expectancy curves. A general consensus is that any index or model development should be simple to understand, transparent to the users, and easy to implement.

7. **Definition of terms.** There is lack of proper definitions in the water industry for terms like leak, break, failure, condition curves, condition assessment, etc. A consensus needs to be reached among research organizations such as Water Research Foundation, WERF, EPA, NRC, UKWIR and others so that there is a common vocabulary and understanding of alternative terms for the same thing.

8. **Emerging technologies.** Condition assessment and inspection technologies for existing pipe are important, but emerging technologies should also be considered for enabling condition assessment for future pipe design and installation (for example, embedded sensor, micro-chip, wireless technologies, etc.).

9. **Value of inspection**. More in-depth studies should be conducted on the value of inspection in relation to asset value for different diameter and types of pipes. This could go hand in hand with alternative ways of condition assessment for smaller diameter pipes and justify the use of NDT inspection tools.

10. **Need for condition assessment guidance**. Provide utilities a basic synthesis of the extensive knowledge on pipe failures – cause and symptoms, the means to detect them, and basic information about leak detection, condition inspection, and prediction methods. Some efforts (e.g., WERF et al., SAM Challenge program) are underway to address this need. It will be necessary to update the guidance as improvements occur in micro- and macro- level understanding of pipe failure; pipe materials, liners, and coatings; and data collection and analysis methods.