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Primer on Condition Curves for Water Mains

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Primer on Condition Curves for Water Mains

by

James Thomson

and

Stephanie Flamberg and Wendy Condit
Battelle
Columbus, OH 43201

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for

Michael Royer
Task Order Manager

Water Supply and Water Resources Division
Urban Watershed Management Branch
2890 Woodbridge Avenue (MS-104)
Edison, NJ 08837

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, OH 45268

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ABSTRACT

The development of economical tools to prioritize pipe renewal based upon structural condition and remaining asset life is essential to effectively manage water infrastructure assets for both large and small diameter pipes. One tool that may facilitate asset management is a condition curve. A condition curve is a graphical representation of the condition of a pipeline versus time. This report provides a review of the state-of-the-technology for structural/physical condition curves for water mains. Various models are summarized such as break frequency curves, deterioration/decay/survival curves, condition rating curves and condition rating indices, and serviceability/performance curves. This report also provides new case study information on how condition curves are used by utilities for managing their water infrastructure based upon a survey of nine utilities. The utilities that were surveyed for these case studies used methods that ranged from very detailed asset management programs that combine inspection, monitoring, and test data with their pipeline condition assessment program to simple analyses of pipe break history to prioritize pipeline renewal activities. The review also discusses short-term and long-term research needs for further development of a performance-based buried infrastructure asset management approach to improve the quality and quantity of data used by all utilities.

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EXECUTIVE SUMMARY

A key requirement for asset management is to understand the condition of pipelines in a system. The development of economical tools to prioritize pipe renewal based upon structural condition and remaining asset life is essential to effectively manage water infrastructure assets for both large and small diameter pipes. One tool that may facilitate asset management is a condition curve. A condition curve is a graphical representation of the condition of a pipeline versus time. If the appropriate curve can be matched to the pipe system of interest, then condition curves can be used to estimate the current condition, remaining asset life, and failure rate of a pipeline. These estimates can be very useful for both short-term and long-term maintenance and capital improvement planning.

The term "condition" can take on many different meanings for water utilities. To some it means the structural condition of the pipe, and to others it may mean pipe serviceability (i.e., the ability of the pipe to provide the type of service expected by its customers). For most utilities, the term "condition" often involves several different factors such as structural condition, water quality, hydraulic capacity, serviceability, location, and economics. Therefore, to develop condition curves, utilities must first start by defining what "condition" means for their particular concern, and what constitutes unacceptable conditions that require action (e.g., inspection, repair, rehabilitation, or replacement).

"Structural condition" of the pipeline is narrowly defined in this review as the presence/absence of holes, cracks, breaks, or circumstances leading to their formation, in the transmission or distribution pipe wall, lining, coating, and joints. Structural condition does not, as defined here, generally include occlusion of the pipe bore by tuberculation, scale, or other deposits.

The term "condition curve" can be defined in several ways. To avoid confusion, it is important to specify the particular definition in use. The general definition for condition curve is a graphical representation of condition versus time. The condition of a pipeline can refer to its hydraulic, water quality, economic, or structural condition. However, in this report, the focus is on the structural/physical condition curves of pipelines or cohorts of pipes. Condition curves are most often generated for a pipeline (e.g., a contiguous section of pipes) or pipe cohorts (e.g., a relatively homogenous population of pipes expected to have similar physical, environmental, and operational characteristics and therefore similar performance).

This report provides a review of the state-of-the-technology for structural/physical condition curves for water mains. Various classes of models are summarized such as break frequency curves, deterioration/decay/survival curves, condition rating curves and condition rating indices, and serviceability/performance curves. In order to define and document the use of condition curves and deterioration models, a comprehensive literature review was performed including an examination of research efforts undertaken by organizations such as the Water Research Foundation (WaterRF), Water Environment Research Foundation (WERF), National Research Council Canada (NRC), Commonwealth Scientific and Industrial Research Organization (CSIRO), U.S. EPA, and others. The information on condition curves obtained from this state-of-the-technology review is summarized, along with selection factors, advantages, and limitations for the use of condition curves.

This report also provides new case study information on how condition curves are used by utilities for managing their water infrastructure based upon a survey of nine utilities (along with three additional case studies presented in the literature). The nine utilities surveyed operate a total of over 32,000 mi. of water pipe. The pipe networks were overwhelmingly less than 21 in. in diameter. There was considerable variance in the pipe types used, but cast iron and ductile iron have the greatest length for most utilities. The utilities that were surveyed for these case studies used methods that ranged from very detailed asset management programs that combine inspection, monitoring, and test data with their pipeline condition assessment program to simple analyses of pipe break history to prioritize pipeline renewal activities.

It was found that the most widely used approach was the break frequency curve. In the literature, over 20 models based on break frequency have been developed in the last 30 yr. Out of the twelve utilities examined, nine of them made use of break frequency approaches within their condition assessment programs. The next most common practice was the use of a condition rating curve and/or condition rating index with five utilities reporting use of this approach. Because of the difficulties and cost of modeling, some utilities use these rating systems that are based largely upon judgment, expert opinion and/or performance indicator data to determine criticality and assign priorities. Although this approach is reliant upon expert opinion, the condition rating curve or index approach does provide a logical and documented framework for determining pipeline renewal priorities. Four examples were identified of utilities that have reported using some form of deterioration, decay, or survival curves.

Any asset management program must start with a thorough review of available historical data about pipe performance and failure. Once the necessary data are gathered, condition curves and/or deterioration models can go a long way in providing insight into the condition of these assets. In general, empirical/statistical models are an economically viable approach for smaller distribution water mains. Currently, only large water mains with costly consequences of failure may justify the cost of accumulation of data that are required for physical model application. For these high risk pipelines, where failures are catastrophic and unacceptable at any time, more extensive and complex approaches may be warranted and cost effective. Condition curves for larger diameter pipes should generally be generated from hard data based on non destructive testing inspections, investigations, and/or laboratory testing to define pipe condition and obtain more accurate predictions of remaining life.

There are several short-term and long-term needs for the development of a performance-based buried infrastructure asset management approach that could yield major improvements in the quality and quantity of data used by all utilities.

A general consensus is that any condition curve should be simple to understand, transparent to the users, and easy to implement. There is need for the development of standardized methodologies for data collection and standardized protocols to generate and calibrate condition curves for the site-specific data collected. There is also very little subsequent validation of the condition curves and/or deterioration models with “real-world” case studies, which is also an important need. Piloting existing and/or new models at various utilities could be conducted to define their practical use and ease of adoption by utilities.

Additional research is needed on how to design more efficient and cost-effective data collection strategies, how to extract information from existing datasets, and how to standardize names and definitions for water utility assets, which subsequently will allow the data to be shared and compared across utilities. The lack of data for many utilities is a major limitation in using anything, but the most basic approaches to condition assessment. However, in many cases, the reality is that only partial data exist. A robust model or condition curve should be able to deal with partial data, but it should be clear that in general the results will be less accurate and less precise compared to those results obtained with a more complete dataset.

Further research can help to continue to refine critical inferential parameters that affect water pipe performance based on pipe material, diameter, joint type, external and internal environmental factors, and more. A longer-term goal should be to develop a national database of assets and failures with common terminology and methods of data collection and analysis for assets and breaks. WaterRF, in partnership with UKWIR, is currently assessing the feasibility of such a national database. Ultimately, this will allow identification of the most vulnerable pipes, reduce failures, and improve understanding of the type and distribution of failure modes and indicators.

Additional guidance should also be developed for identifying and quantifying the high risk scenarios, which requires characterizing both the likelihood and consequence of failure. With limited funds, it is necessary for utilities to focus on the highest risk situations to limit the impact of failures on consumers and the public.

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ACRONYMS AND ABBREVIATIONS

AC	asbestos cement
ANN	artificial neural networks
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation
CARE-W	Computer Aided Rehabilitation of Water Networks
CIP	capital improvement program
CP	cathodic protection
CSIRO	Commonwealth Scientific and Industrial Research Organization
DIPRA	Ductile Iron Pipe Research Association
D-WARP	Distribution – Water Mains Renewal Planner
GIS	geographic information system
I-WARP	Individual Water Main Renewal Planner
LADWP	Los Angeles Department of Water and Power
LEFM	linear elastic fracture mechanics
LEYP	Linearly Extended Yule Process
LVVWD	Las Vegas Valley Water District
LWC	Louisville Water Company
NDT	nondestructive testing
NPV	net present value
NRC	National Research Council - Canada
PCCP	prestressed concrete cylinder pipe
PE	polyethylene
PEM	Pipe Evaluation Model
ppm	parts per million
PV	present value
PVC	polyvinyl chloride
PWD	Philadelphia Water Department
RPV	replacement priority value
SIF	stress intensity factor
SPU	Seattle Public Utilities
T-WARP	Transmission - Water Mains Renewal Planner
UKWIR	U.K. Water Industry Research
UMP	Utility Master Plan
U.S. EPA	United States Environmental Protection Agency
WaterRF	Water Research Foundation (formerly known as AwwaRF)
WERF	Water Environment Research Foundation
WRc	Water Research Center
WSSC	Washington Suburban Sanitary Commission

1.0: INTRODUCTION

1.1 Background

Effective management of water supply networks is a major challenge for all water utilities. It is complex not only because of the vast array of components, pipe sizes, vintages, and pipe types that exist, but also because most pipelines are installed underground (i.e., out of sight), in variable soil conditions, and subject to various environmental factors.

A key requirement for asset management is to understand the condition of pipelines in a system. Although on-site, real-time inspection of a pipeline is the ideal method to analyze and understand its condition, this approach can be expensive and usually cannot be cost effectively applied to smaller diameter distribution lines, which make up the majority of water systems. Therefore, the development of economical tools to prioritize pipe renewal is essential to effectively manage water infrastructure assets for both large and small diameter pipes.

One tool that may facilitate asset management is a condition curve. A condition curve is a graphical representation of the condition of a pipeline versus time. If the curve is accurate, and if the appropriate curve can be matched to the pipe system of interest, then condition curves can be used to estimate the condition, remaining asset life, and failure rate of a pipeline. These estimates can be very useful for both short-term and long-term maintenance and capital improvement planning. Although the pipe condition curve concept is fairly straightforward, the state-of-the-technology is not so obvious.

1.2 Project Objective and Scope

The objective of this project was to review the state-of-the-technology for structural/physical condition curves for water mains and to produce a document that consolidates, analyzes, and clearly presents this information as a guideline for utilities. This report documents the review of various classes of models such as break frequency curves, deterioration/decay/survival curves, condition rating curves and condition rating indices, and serviceability/performance curves. The report does not provide an exhaustive list of models in each category, but rather provides a few examples to illustrate the concept of each type of curve.

The scope of this report is limited to structural/physical condition curves as they have the greatest potential for prediction/management of water main breaks and serve as a tool for pipe renewal planning. Pipe investment and renewal decisions are also based on other considerations (e.g., hydraulics, water quality, economics, and related infrastructure), but these factors are not the focus of this report.

1.3 Target Audience

This report is aimed at relatively new practitioners and utility managers of medium (3,300 to 10,000 customers) to large (10,000 to 100,000 customers) community water systems. The report is intended to provide a basic definition for structural/physical condition curves and to present a brief overview of the components of a condition curve, condition curve variations, and how condition curves are used as tools for making asset management decisions. Experienced asset management practitioners looking for more in-depth information should refer to detailed reports published by the Water Environment Research Foundation (WERF) and the Water Research Foundation (WaterRF).

1.4 Basic Terminology

The term "condition" can take on many different meanings for water utilities. To some it means the structural condition of the pipe, and to others it may mean pipe serviceability (i.e., the ability of the pipe to provide the type of service expected by its customers). For most utilities, the term "condition" often involves several different factors such as structural condition, water quality, hydraulic capacity, serviceability, location, and economics. Therefore, to develop condition curves, utilities must first start by defining what "condition" means for their particular concern, and what constitutes unacceptable conditions that require action (e.g., inspection, repair, rehabilitation, or replacement).

"Structural condition" of the pipeline is narrowly defined here as the presence/absence of holes, cracks, breaks, or circumstances leading to their formation, in the transmission or distribution pipe wall, lining, coating, and joints. Structural condition does not, as defined here, generally include occlusion of the pipe bore by tuberculation, scale, or other deposits.

"Structural condition assessment" involves: (1) development of a formal or informal structural condition-rating approach that links pipeline parameter data to the likelihood of structural failure (i.e., holes, cracks, and breaks) for the time period of interest; (2) collection of data (e.g., physical, environmental, and operational characteristics; failure history, processes, and associated indicators) by applicable direct and/or indirect methods; and (3) analysis of the pipeline data and information to categorize the pipe's current and future structural condition as input for pipe renewal decisions. This analysis could be based upon empirically derived statistical models or physical/mechanistic modeling, which is based on pipe-intrinsic properties, internal/external loading, and other factors (United States Environmental Protection Agency [U.S. EPA], 2011a).

The term "condition curve" can be defined in several ways. To avoid confusion, it is important to specify the particular definition in use. The generic definition for condition curve is a graphical representation of condition versus time. In general, the condition of a pipeline can refer to its hydraulic, water quality, economic, or structural condition. However, in this report, the focus is on the structural/physical condition curves of pipelines or cohorts of pipes. Condition curves are most often generated for a pipeline (e.g., a contiguous section of pipes) or pipe cohorts (e.g., a relatively homogenous population of pipes expected to have similar physical, environmental, and operational characteristics and therefore similar performance). Unless it is a high consequence scenario, it is not cost effective to generate a condition curve for a single pipe (e.g., a pipe segment from bell to spigot).

Structural condition can be determined by various approaches (e.g., by historical data, by inspection, by a point system, by a model, or some combination of these approaches). The time axis on the structural condition curve does not necessarily have to be the age of the pipe. It could, for example, be pressure cycles or temperature cycles, but one must be able to convert the independent variable into a time measurement to use the condition curve to support decisions about when to take corrective action.

1.5 Use of Condition Curves and Reasons for Using Condition Curves

The main reason for using condition curves is to plan and prioritize renewal projects. Condition curves can be used as a tool to predict the remaining asset life of a pipe and therefore to plan for the overall timing of renewal activities. Condition curves can also be useful tools in rating or scoring the pipeline condition and therefore assist in quantifying the probability of failure. Ultimately, this information, when combined with other considerations (such as hydraulics, water quality, economics, and related infrastructure), can be used to prioritize renewal activities for more efficient expenditure of utilities' annual capital improvement budget.

The different techniques and methods currently used by utilities to develop condition curves include break frequency curves, deterioration, decay, and survival curves, condition rating curves and condition rating indices, and serviceability curves. These curves are discussed in greater detail in Sections 2.0 and 3.0 of this report with examples of their application by utilities presented in Section 4.0.

There are also economic-based curves, such as Nessie curves, that are developed and used to plan for the future cost of network replacement. These curves are not based on structural condition, but strictly on the time of installation and design life. These types of curves are not covered in great detail in this report; however, references are provided should the reader want to seek additional information on the development and use of Nessie curves.

1.6 Project Approach

This report was developed based upon a comprehensive literature review including an examination of extensive research undertaken by organizations such as the WaterRF, WERF, National Research Council Canada (NRC), Commonwealth Scientific and Industrial Research Organization (CSIRO), and U.S. EPA. In addition to a literature review, this report summarizes new case study information on how condition curves are used by utilities for managing their water infrastructure based upon a survey of nine utilities conducted by Virginia Tech.

In its basic form, this report is meant to serve as a primer to provide utilities or new practitioners of asset management with a concise overview of the various types of condition curves available. The key feature of this report distinguishing it from previous research efforts is that it offers a concise overview within a single document that covers the types of condition curves, their benefits and limitations, who is using them, and for what purpose. It enables readers to understand the general nature and various classes of condition curves with reference to more detailed documents for the specifics on data requirements and model/curve development. A comprehensive list of references is provided as a valuable resource for those interested in finding out more details on how to implement condition curves and their associated data requirements. The report also highlights gaps between the state-of-the-art in the literature and state-of-practice in the field.

1.7 Report Organization

This report is organized into five sections that include introductory material (Section 1.0), the role of conditions curves in asset management and issues in their development (Section 2.0), review of methods used to generate condition curves and types of condition curves (Section 3.0), current use of condition curves (Section 4.0), and findings and recommendations on condition curve gaps and research needs (Section 5.0).

2.0: ROLE OF CONDITION CURVES IN ASSET MANAGEMENT AND ISSUES IN THEIR DEVELOPMENT

The main goal for determining pipeline condition is to gain a better understanding of remaining asset life. By understanding the remaining asset life, utilities will be able to better prioritize and optimize operations, maintenance, and capital improvement decisions. This will help to reduce pipeline failures and their adverse effects and minimize life-cycle costs.

One tool for predicting remaining asset life is the condition curve. This section sets up the role of condition curves in asset management by first providing basic definitions of asset life, end of asset life, and remaining asset life as defined in the WERF report "Remaining Asset Life: A State of the Art Review" (Marlow et al., 2009). This is followed by a discussion of how condition curves can be used as a tool for predicting remaining asset life, along with an overview of distress indicators for the predominant pipe types (ferrous, asbestos cement [AC], prestressed concrete cylinder pipes [PCCP], and plastic). Lastly, key issues are discussed related to the development and use of condition curves.

2.1 Defining Asset Life

Asset life could be defined as the time between installation and reaching an "end of life" criterion (defined in Section 2.2). Additional terminology related to the life of an asset from Marlow et al. (2009) is presented below with some modification to focus on water pipelines as follows:

- ***Design life***: the period of time over which the pipeline is designed to be available for use and able to provide the required level of service at an acceptable risk of failure (e.g., the product of failure likelihood and failure consequence).
- ***Service life***: the period of time over which the pipeline is actually available for use and able to provide the required level of service at an acceptable risk of failure (e.g., without unforeseen costs of disruption for maintenance and repair).
- ***Operational life***: some pipeline assets may be operated past the point where they provide the required level of service at an acceptable risk of failure. As such, the operational life is taken to be the time over which the asset remains operational irrespective of its serviceability or performance. This situation tends to occur where the expected cost of a failure is lower than the cost of mitigating or preventing the failure via renovation or replacement.

2.2 Defining End of Asset Life

Ultimately, the end of asset life occurs when the asset has to be replaced or is taken out of service. However, given the maintenance options available, predicting when this event will occur is a complex issue. Various definitions relevant to the end of asset life were compiled from Marlow et al. (2009) as follows:

- ***End of physical asset life***: when the pipe is physically derelict and non-functioning.
- ***End of technical service life***: when the pipe is failing to provide required functionality, service levels and/or reliability.
- ***End of economic asset life***: when the pipe is physically able to provide a service, but ceases to be the lowest cost alternative to satisfy a particular level of service (Institute of Public

Works Engineering Australia, 2006). In practice, this often reduces the time when the risk/cost associated with retaining an asset exceeds the cost of rehabilitating the asset.

- ***End of financial life***: when the pipeline's initial capital value is fully depreciated.
- ***Obsolescence***: when the pipeline is obsolete because of changes in technology, regulatory requirements, or performance criteria.

2.3 Defining Remaining Asset Life

The remaining asset life could then be defined as the time remaining until one of the "end of life" criterion described above is reached. A more detailed assessment of remaining asset life could include the following considerations from Marlow et al. (2009):

> "*Since an asset passes through a range of condition and/or performance states as it deteriorates, condition and performance assessment can be used to understand remaining asset life. In particular, acceptable asset condition states can be defined that characterize the threshold above which risk is deemed to be unacceptable. Condition assessment can then be used to determine whether the current state of an asset, expressed in terms of failure likelihood, is acceptable. Acceptability criteria for assessing degraded condition can be obtained from a number of sources including the use of expert opinion, condition grading, detection of critical defects and performance monitoring.*"

Based upon the condition of the pipeline, whether or not the asset can be renovated also has a significant influence on the concept of remaining asset life. Loss of function does not necessarily imply the end of asset life as pipelines are repairable or can be rehabilitated. Maintenance activities such as repair, cleaning, and relining can remedy defects and restore condition, which will slow the overall deterioration of an asset and extend its remaining asset life.

2.4 Assessing Asset Condition

A key consideration in asset management of water distribution and transmission systems is determining current condition and predicting future condition. Condition can be assessed in terms of a number of functions including:

1. Leakage
2. Hydraulic capacity
3. Water quality
4. Serviceability (e.g., defined as the capability of a system of assets to deliver a reference level of service to customers and to the environment now and into the future)
5. Structural/physical integrity
6. Economic

In reality, these conditions are interrelated. For example, leakage can be an important contributor to physical failure by eroding the pipeline bedding. While on the other hand, structural deterioration by corrosion, such as a through-the-pipe-wall hole, can be a cause of leakage.

In the most basic of terms, the aim of condition assessment is to provide insight into the nature of possible root causes of pipeline failure, the pattern of the pipeline deterioration curve, and the timing of possible failure, which will determine its remaining asset life.

2.5 Pipeline Functional Life

The functional life of a pipeline is illustrated in Figure 2-1 and takes into account the pipeline design, construction, operation, maintenance, and ultimately the end of the pipeline's functional or service life. The concept of a pipeline functional life is presented by Rose (2008) and is a similar concept to the "service life" terminology presented by Marlow et al. (2009) and summarized in Section 2.1.

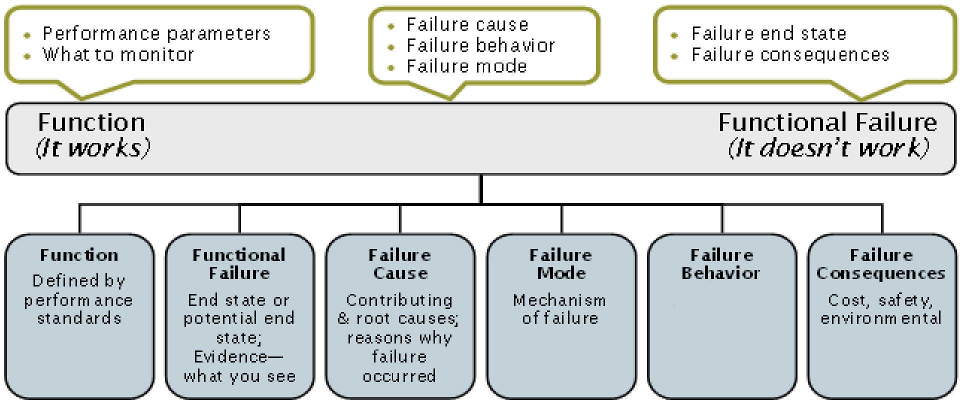

Figure 2-1. Functional Life of a Pipeline (after Rose, 2008)

A "bathtub" curve can also be used to illustrate this concept of the pipeline functional life. The bathtub theory is a function of the probability of failure over time. The name "bathtub" comes from the shape of the line commonly produced by the conditional failure probability curve over time. The bathtub curve generally consists of three periods: 1) a premature failure period with a decreasing failure rate, 2) followed by a normal service life period with a low, relatively constant failure rate, and 3) concluding with a wear-out period that exhibits an increasing failure rate. A graphical representation of the "bathtub" process is illustrated in Figure 2-2.

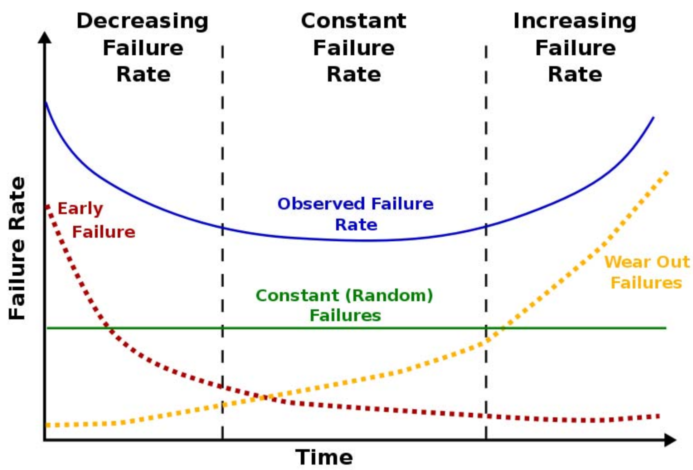

Figure 2-2. The "Bathtub" Curve (Source: Wikipedia)

2.6 Condition Assessment Tool

Condition curves are tools to graphically represent a pipeline's condition versus time. If the curve is developed with sufficient data for the particular pipe type under consideration, then the pipeline's functional life can be projected to predict its remaining life or when intervention will be required. The condition curve will not be precise to the month or even year as too many factors are involved. However, it is a useful tool to provide a priority rating based on likelihood of failure. There is a demonstrated need for such tools to aid utilities in prioritizing and allocating their limited capital improvement funding and to provide a technically defensible and repeatable process to evaluate pipeline structural condition and the likelihood of failure over time.

Condition curves usually are based on a horizontal axis representing the age of the pipeline starting with the installation date and finishing at some estimated maximum life beyond the "design life." The vertical axis represents the state, or sometimes the performance, of the pipe ranging from 100% when newly installed to 0% when the asset reaches the end of its service life. Figure 2-3 illustrates the concept with and without appropriate rehabilitation that can increase a pipeline's functional life.

The likelihood of failure increases as the pipeline ages and deteriorates. Given sufficient data, it is possible to estimate the likelihood of failure for a given pipeline. However, in some cases, acquiring sufficient data will be impractical or not cost effective; therefore, alternative approaches for asset condition assessment should be employed. All of these alternative approaches involve defining condition states based on beliefs about the types and levels of distress indicators that characterize increasing and finally unacceptable levels of failure risk.

It is important to stress that condition curves are tools that come in a number of types and varying degrees of sophistication. As such, the chosen tool must match the problem or the need. For example, the problem may be a lack of data due to cost constraints for acquiring the data (e.g., asset not worth the expense to employ inspection tools or to develop detailed data sets). In this case, more simplistic condition curves should be chosen that can be applied using a minimum amount of data and resources to construct. Section 3 provides a more detailed review of the types of condition curves, their development, and applications.

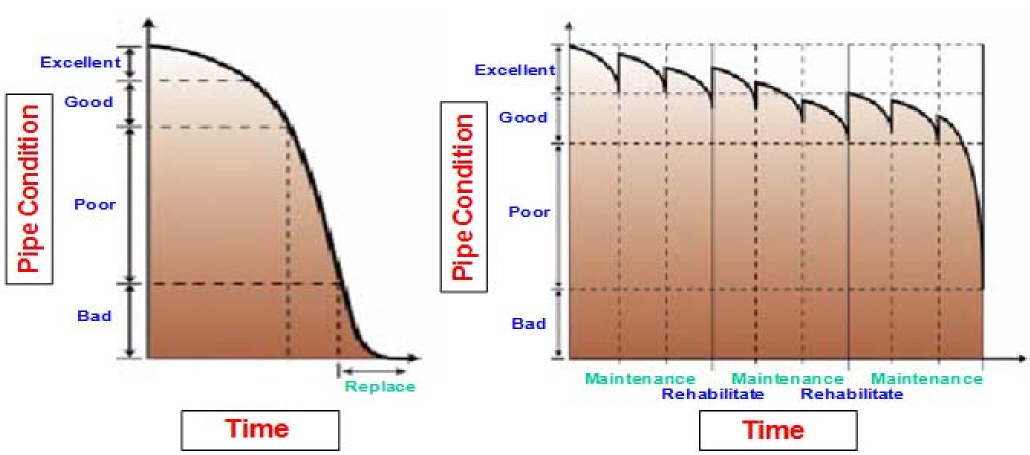

Figure 2-3. Condition Curves for a Pipeline with and without Rehabilitation

2.7 Pipe Networks, Characteristics, and Behavior

To determine pipe condition, utilities need to have a good understanding of the pipe materials of construction and their behavior over time under the anticipated environmental and operational conditions. This basic understanding of pipe behavior provides the focus on key issues in the development and use of condition curves.

2.7.1 The Distribution and Transmission Water Network. Estimates of the total current length of water distribution and transmission pipelines in the U.S. exceed one million miles. In round figures, as best as can be estimated, this mileage breaks down into the percentages shown in Table 2-1 (Stone et al., 2002):

Table 2-1. U.S. Pipeline Mileage by Pipe Material and Pipe Diameter

Classifying by Pipe Material	
Cast/spun Iron	38%
Ductile Iron	23%
Steel	4%
Asbestos Cement	15%
PVC	15%
PCCP	3%
Other	2%
Classifying by Pipe Diameter	
Diameters of 10 in. and less	73%
Diameters 12 to 24 in.	20%
Diameters greater than 24 in.	7%

Research indicates that between 250,000 and 300,000 breaks occur every year in the U.S., which corresponds to a rate of 25 to 30 breaks/100/miles/year (Grigg, 2007; Deb et al., 2002).

In undertaking condition assessment and remaining life prediction for all forms of pipe, it is important to understand the initial form of failure (distress indicators), the pattern of their development (failure causes and distribution), and the ultimate form of the failure (failure mode).

- ***Distress indicators***: the indicators that can be used to infer that a pipe is degrading or will degrade.
- ***Failure causes***: the factors that contribute to the failure mode. There can be multiple paths leading to a particular failure mode.
- ***Failure mode***: the ultimate form of the failure.

2.7.2 Ferrous Pipe. Ferrous type pipe materials account for around 65% of the U.S. water network and consist of some of the oldest pipes in the network. By 1930, vertically cast iron pipe was superseded by spun cast iron pipe. Since the mid-1960s, spun cast iron pipe began to be replaced in the U.S. by ductile iron pipe. Spun cast iron use decreases substantially after the early 1970s, and production ceased in the 1980s (US. EPA, 2002). The approximately 38% of the network that is pit cast and spun cast iron pipe (Stone et al., 2002) is therefore at least 30 years old and most of it is much older. This percentage is gradually decreasing due to pipe replacement. The oldest cast iron pipes, dating to the late

1800s, have an average functional life of about 120 years. The average life of these older cast iron pipes ranged from 90 to 150 years before they needed to be replaced. There is some evidence that pipes laid in the post World War II boom have a reduced life averaging 75 years, which could be due to factors like the reduced wall thickness compared to earlier specifications and/or to sub-standard site installation (AWWA, 2001).

Forms, Causes, and Modes of Failures

The causes of failure in ferrous pipes are often complex and due to a combination of factors. Corrosion causing pipe wall loss is a primary factor that is often combined with external and internal loadings, which ultimately lead to pipe failure. Table 2-2 provides a summary of the main factors that lead to pipeline failure for ferrous pipes.

Table 2-2. Summary of Factors Leading to Failure for Ferrous Pipes

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 fluctuations 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 – the 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

Extensive literature provides a comprehensive review of forms, causes and modes of failure of steel, cast, spun, and ductile iron water mains. The WaterRF report "Main Break Prediction, Prevention and Control" (Grigg, 2007) devotes an entire chapter to reviewing this research. Additional sources of literature for failure modes and mechanisms for ferrous pipe types include: "Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life" (Rajani, 2000), "Long-Term Performance of Ductile-Iron Pipe" (Project #3036; WaterRF, in progress a), "Fracture Failure of Large Diameter Cast Iron Water Mains"(Project #4035; WaterRF, in progress b), and "Long-Term Performance Prediction of Steel Pipe" (Project # 4318; WaterRF, in progress c).

In considering failure modes of ferrous pipe, they should be allocated into groups by material, diameter, and age.

- By far the greatest number of failures due to perforation or fracture occurs in pipe diameters less than 10 inches. A U.K. survey of failures by pipe size and failure type showed that 77% of failures were due to pipe fractures and 97% of these were circumferential for pipes with diameters less than 10 inches. Some 14.3% of failures were due to pipe perforations with 94% of the failures in pipe diameters of less than 10 inches (U.K. Water Industry Research [UKWIR], 2001).

- The main mechanism for smaller diameter failures is circumferential cracking.
- Random and localized corrosion occurs in cast iron pipes and the failure of one pipe is no indication as to the condition of adjacent pipes.
- In terms of break frequency, Table 2-3 shows that the majority of pipe breaks occur in cast iron pipes which, based on their manufacturing history, are usually much older.

Table 2-3. Ferrous Pipe Break Frequency/100 mi/yr

Source	Cast Iron	Ductile Iron	Steel
NRC (1995)	58	15.5	n/a
Pelletier et al. (2003)	93	32.5	n/a
Weimer (2001)	44	5	53.5

n/a = not available

- Vintage and pipe class determine the wall thickness. There has been a substantial reduction in wall thickness over the years due to improvements in manufacture and material strength. It is also common to find that in times past the cheapest, lowest class pipe available with the thinnest wall would be installed. The corrosion rate for all ferrous pipes is considered to be similar so that a thinner pipe will corrode and perforate quicker when subjected to the same conditions.
- The majority of water pipes are internally protected with cement mortar lining. It is estimated by Ductile Iron Pipe Research Association ([DIPRA]) that 30% to 40% of ductile iron pipe has been protected externally by polythene wrap. DIPRA has investigated the current condition of some of the oldest installations, which were installed in the 1960s and found no evidence of significant corrosion in corrosive soils (Horn, 2010). In addition, some larger utilities have fitted or retrofitted ferrous transmission pipe with cathodic protection (CP) systems. If installed correctly and maintained, these systems will greatly inhibit corrosion.

The forms, causes and indicators of distress of cast and ductile iron are summarized in Table 2-4.

Table 2-4. Cast, Spun, and Ductile Iron – Forms, Causes, and Indicators of Failure

Form of Failure	Cause of Failure	Indicators of Distress	Comments
Burst failure	External pitting and graphitization corrosion weakening the pipe wall; often combined with induced strains.	Damaged protection – wall loss from external pitting, graphitization (hard to detect), leaks. External loads, pressure variations. Aggressive/polluted soils. Galvanic/electrolytic conditions.	Corrosion is principal contributor to failure. Specific vintages; unprotected pipe and diameters <8 in. are more vulnerable. Cathodic and external protection mitigates.
Burst failure	Internal pitting and graphitization corrosion weakening the pipe wall; often combined with induced strains.	Damaged lining – wall loss from internal pitting, graphitization (hard to detect), leaks. External loads, pressure variations.	Low pH water. Unlined pipe mainly cast and some spun. Ductile iron pipe mainly cement mortar lined.
Burst failure	Third party damage.	Construction activity – impact	Unpredictable.

Table 2-4. Cast, Spun, and Ductile Iron – Forms, Causes, and Indicators of Failure (Continued)

Form of Failure	Cause of Failure	Indicators of Distress	Comments
		damage to pipe or protection.	
Structural failure – circumferential cracking	Thermal stresses, poor support leading to bending, internal pressure, excess external loads.	Circumferential cracks, loss of bedding, joint movement, high traffic loads, frost regions.	Most common cause of failure in small diameters. Often combination of loss of wall through corrosion and internal/external loads.
Structural failure – longitudinal cracking	Internal transient pressures, high external loadings.	Longitudinal cracks, increasing external/internal loads, frost regions.	Mostly in diameters >12 in. Often combination of loss of wall through corrosion and internal/external loads.
Structural failure – joint split and sheared bells	Excessive stress at joint, fatigue, loss of support.	Leadite joints (cast iron), joint rotation, leakage.	Can be due to manufacturing and installation defects.
Leaks	Wall perforations, cracks and defective joints.	Wet areas, leak noise.	Many small leaks not detected. Leaks contributory cause due to loss of bedding.

2.7.3 Asbestos Cement Pipes. The bulk of AC pipes were installed for water mains initially in the 1930s and extensively in the 1950s and 1960s. The recognition of the health hazards in manufacture and use of asbestos products led to a reduction in use and phasing out of their manufacture in 1983. It is therefore likely that most AC pipe was installed 50 or more years ago. The degradation of AC pipe can release asbestos fibers into the water supply and limits have been set on the amount of these free fibers (U.S. EPA, 2011b).

Forms, Causes, and Modes of Failures

Failures can be classified into:

- *Corrosion failures:* AC pipe corrosion failures are the result of the degradation by leaching resulting in wall thinning, loss of strength, and through-the-wall holes. The process of deterioration is through decomposition of hydrated silicates in the cement mortar brought about by the leaching of calcium hydroxide. AC pipe is vulnerable to this form of attack internally and externally.
- *Mechanical failures:* AC pipe is classified as being rigid and susceptible to mechanical failure. Poor handling and installation can damage the pipe. In service, higher external and internal loads can lead to breaks. Pipes of diameters less than 8 in. have low beam strength and are prone to circumferential failure. An NRC study showed that circumferential breaks accounted for nearly 67% of all recorded AC pipe failures and longitudinal cracking some 10% of failures (Huy et al., 2010).

A New Zealand study based on 400 samples indicated that the average asset life for AC pipe increases with diameter (Opus Consultants, 2001). AC pipes with diameters of 15 in. had an average life twice that of AC pipes 4 in. in diameter (i.e., 80 to 85 yr. versus 35 to 40 yr.). Table 2-5 summarizes the forms, causes, and distress indicators for AC pipe. Additional information on AC pipe will be reported in "Long-Term Performance of Asbestos Cement Pipe" (Project # 4093; WaterRF, in progress d) ongoing WaterRF project).

Table 2-5. Asbestos Cement – Forms, Causes, and Indicators of Failure

Form of Failure	Cause of Failure	Indicators of Distress	Comments
Burst failure	External leaching corrosion with loss of wall strength.	Aggressive soil/groundwater. Damage to external coating. Reduced wall thickness. Softening of wall. Circumferential cracks. Longitudinal cracks. Inadequate or excessive depth of cover.	Circumferential breaks common in small diameters. Inadequate design, manufacture, or installation. Bending due to loss of support or high operational loads. Often a combination of loss of wall strength with other defects
Burst failure	Internal leaching corrosion with loss of wall strength. Excessive operating and transient pressures. Fatigue.	Low pH water. Operational records.	Longitudinal cracks due to low hoop resistance or high operational loads often combined with reduced wall strength.
Burst failure	Third party damage.	Construction activity - impact damage to pipe or protection.	Unpredictable.
Structural failure - Joint	Excessive stress at joint, fatigue, leakage causing loss of bedding.	Change in pipe alignment, joint rotation, crack in external diaper.	Can be due to manufacturing and installation defects.
Leaks	Defective joints or through wall corrosion.	Wet areas, leak noise.	Many small leaks not detected. Leaks contributory cause to failure due to loss of bedding.

2.7.4 Prestressed Concrete Cylinder Pipes. PCCP is used for transmission mains with diameters of 16 in. and larger and includes some of the largest transmission mains. Although PCCP is only around 3% of the total network length, it plays a critical role due to its large diameters and therefore greater consequences of failure. There are two forms of PCCP:

- Lined cylinder pipe manufactured in diameters from 16 in. to 60 in..
- Embedded cylinder pipe manufactured in diameters from 48 in. and upwards.

Both forms use a steel internal cylinder wrapped with high strength stressed steel wire and then are coated with a protective mortar coating.

Forms, Causes, and Modes of Failures

Wire Breaks: The most common defect for PCCP is wire breaks due to corrosion and/or hydrogen embrittlement. Breaks release the core compression and give rise to a number of distress indicators which can be identified by investigation. PCCP is designed to have a factor of safety against failure so some wire breakage can be tolerated. In some cases, it takes more than 50% wire loss to result in a failure. The early 1970s saw pipes manufactured with a Class IV wire, which has proved to be very prone to early failure.

It has been found that the extent and speed of corrosion of the underlying steel wire is a direct function of the quality of mortar and its application (Price et al., 1990). The extent and rapidity of corrosion of the mortar are a function of:

- The quality of the mortar
- Volume of permeable voids
- Aggressiveness of the environment

Operational Factors: One of the major causes of PCCP failure, second to wire corrosion, is operating conditions that greatly exceed the pipes' original design. Water hammer or surge pressure is one of the more commonly encountered problems. It has been shown that total submersion of PCCP does not necessarily increase the risk of corrosion, but that cycling from a wet to dry environment does significantly increase corrosion risks.

Soil Considerations: Bianchetti (1993) reports the following as being favorable environments for corrosion:

- Soil acidity, pH less than 5
- Sulfate >6,000 parts per million (ppm) or >2000 mg/L of sulfate ions
- Magnesium >50,000 ppm
- Groundwater with a negative Langelier Index

Table 2-6 summarizes the forms, causes, and distress indicators for PCCP. Additional information on PCCP can be found in "Performance of Prestressed Concrete Pipe" (American Water Works Association Research Foundation [AwwaRF], 1993), "Failure of Pre-Stressed Concrete Cylinder Pipe" (Romer et al., 2008), and several U.S. Bureau of Reclamation reports on PCCP failures (Travers, 1994; Hartwell, 1994; Von Fay and Peabody, 1994; Uyeda et al., 1994).

Table 2-6. PCCP – Forms, Causes and Indicators of Failure

Form of Failure	Cause of Failure	Indicators of Distress	Comments
Burst Failure	Wire breaks beyond critical number.	Class III and IV wire. Mortar coating - spalling, damage, aggressive soil conditions, external circumferential cracks. Circumferential cracks to inner core. Out of roundness. Delamination and hollow areas. Galvanic/electrolytic conditions.	Class III and IV wire susceptible to hydrogen embrittlement. Mortar exposure to wet/dry ground water conditions. Frost loads. Pre 1970 cast coating used which has greater tendency to spall. Shorting straps mitigate corrosion.
Burst failure	Excessive operating or transient pressures. Greater cover depths than design. Fatigue.	Low pH water. Operational records.	None.
Burst failure	Third party damage.	Construction activity - impact damage to mortar coating and pipe.	Unpredictable.
Structural failure - Joint	Excessive stress at joint, fatigue, leakage causing loss of bedding.	Change in pipe alignment, joint rotation, crack in external diaper.	Can also be due to manufacturing and installation defects.
Leaks	Defective joints.	Wet areas, leak noise.	Many small leaks not detected. Leaks contributory cause due to loss of bedding and possible catalyst for chemical attack in dry soils.

2.7.5 Polyvinyl Chloride Pipes. Since their introduction in the 1950s, polyvinyl chloride (PVC) pipes have established a major market share for new installations of small diameter mains (although diameters up to 36 inches are available). The technically correct designation is PVC-U (unplasticized), as there are other modified forms including PVC-M (manufactured by mass polymerization) and PVC-O (molecularly oriented).

Forms, Causes and Modes of Failures

Failures in plastic pipelines take the following forms:

- Leaks
- Physical failure
  - Chemical breakdown of the physical structure
  - Crack growth mechanism
  - Fatigue
  - Buckling

Leaks: The evidence suggests that the majority of leaks in PVC pressure mains arise at joints and fittings and is predominantly caused by improper or poor installation.

Physical failure: The cause of a physical failure is often not immediately clear from observation and thus field descriptions can be misleading. As plastic pipes are not subject to aging by corrosion, modes of failures are frequently related to inherent defects in the pipe, damage during installation, and impingement damage. Closer examination and laboratory investigation indicate that, for many failures, there is a combination of factors. Physical failure can also occur due to a chemical breakdown of the polymer structure or by structural breakdown.

Most failures in the field are attributed to slow crack growth followed by brittle fracture rather than ductile mechanisms. Cracks are initiated from concentrations in the pipe wall. These concentrations can be defects built in during manufacture such as air bubbles, dust or particles or they can be created by impingement on the wall from stones or sharp objects in the backfill surround.

Buckling (e.g., instability causing excessive deformations) is created by static and dynamic compressive forces. Buckling behavior is affected by the interaction of the pipe and its surrounding soil. The relative stiffness of the pipe and the surrounding soil and the external loading determine the deformation mode of the pipe.

Although failure probability is related to age for PVC, the statistical evidence may not provide a sound basis for extrapolating likelihood of failure. PVC was first used some 50 years ago and has been upgraded and improved since.

Failure of PVC pipes is a complex subject and for a more in-depth understanding reference should be made to “Plastic Pipe Systems: Failure Investigation and Diagnosis” (Farshad, 2006), “Long-Term Performance Prediction of Polyethylene (PE) Pipe” (Davis et al., 2007), “Long-Term Performance Prediction for PVC Pipe” (Burn et al., 2006), and “Evaluation of PVC Pipe Performance” (Moser and Kellogg, 1994).

Table 2-7 summarizes the forms, causes and distress indicators for PVC pipe.

Table 2-7. PVC Pipes – Forms, Causes, and Indicators of Failure

Form of Failure	Cause of Failure	Indicators of Distress	Comments
Burst failure	Pipe splitting by slow crack growth.	Manufacturing defect. Scratch >10% wall thickness. Stones in backfill.	PVC not subject to corrosion. Manufacturing defects such as air bubbles and inclusions can initiate crack growth. Scratch resulting from transport or installation mishandling. Impingement from stones in backfill. The vulnerability to failure due to these defects increases due to creep as the pipe ages. The indicators of stress are not identifiable by current site investigation. Tapping can initiate and lead to splits.
Burst failure	High pressure, pressure changes, frequency and external loadings in excess of design.	Operational records.	PVC not suitable for frost loads.
Burst failure	Third party damage.	Construction activity - impact damage to pipe or protection.	Unpredictable.
Structural failure - Joint	Excess stress at joint.	Change in pipe alignment, joint rotation.	Initial leak may create bedding loss.
Leaks	Defective joints.	Wet areas, leak noise.	Poor workmanship a frequent cause. Many small leaks not detected. Leaks contributory cause to failure due to loss of bedding.

2.8 Key Issues for Condition Curves

It is important to understand the types of decisions that condition curves can be used to support and the circumstances under which they are best applied. Some of the key issues that need to be considered in the development and use of condition curves are as follows:

- Condition curves have greater potential application in the prediction of condition and failure for smaller diameter pipelines.
  - For many pipelines with a relatively low replacement cost, it is not cost effective to obtain direct condition data by investigation or laboratory testing.
  - Smaller diameter pipelines account for the majority of the total length of the network and also for the majority of failures.
  - There is a much greater body of historical experience of failures and defects that can be used in the development of condition curves and management of these parts of the network.
  - The direct and indirect consequences of failure are much less for small diameters.
  - For small diameter pipelines (with low consequences of failure), condition curves can be used as a means to monitor and keep the annual breakage rate below an acceptable threshold through proactive renewal.

- Larger diameter pipelines represent a much smaller percentage of the network and failures are much less frequent.
  - The direct and indirect consequences of failure are much greater.
  - The forms of failure and distress indicators tend to differ from smaller diameters.
  - There are often insufficient historical data to develop the trend or shape of condition curves for large diameter pipelines.
  - Condition curves for larger diameter pipelines generally need to be generated based on hard data from inspection and investigation or laboratory testing. This is due to the fact that there is often minimal historical data for large diameter pipelines on which to base models or curves and therefore field data are needed to verify the rate of deterioration.
  - For large diameter pipelines (with high consequences of failure), condition curves can be used to monitor trends in pre-failure indicators over time in order to provide a warning of either an impending failure or an increased probability of failure. This enables a response to be implemented in order to prevent a catastrophic failure.

- It is important to understand how to develop condition curves for a given network.
  - Condition curves are very site specific and a clear understanding is needed of the basic assumptions that form the basis of the curve.
  - Various pipeline assets may have differing rates of deterioration. Developing a single condition curve that works for an entire network is unlikely. A condition curve scenario should be generated for each pipe cohort of interest. The accuracy will be determined by how well the pipe cohorts are grouped in terms of common factors.
  - Curves will need to be generated for various scenarios and to take into account the appropriate factors (e.g., environmental conditions, operational and maintenance practices, pipe types, diameters, vintages, installation practices, etc.).

- It is important to understand how to apply condition curves for improved decision-making.
  - Condition curves can be used to evaluate and quantify current asset condition and to predict future condition and remaining asset life.
  - Condition curves can be used to support the development of short-term and long-term maintenance program priorities and schedules. With sufficient data and understanding of failure modes and causes of distress, a utility can effectively use condition curves to support rehabilitation or replacement decisions.
  - Condition curves can be used for long-term economic planning. For a utility just starting an asset management program, the primary benefit of the use of condition curves is to create a repeatable and technically defensible process for prioritizing and allocating funding for capital improvement plans based upon remaining asset life.

3.0: REVIEW OF METHODS USED TO GENERATE CONDITION CURVES AND TYPES OF CONDITION CURVES

This section presents an overview of available literature on the methods used to generate condition curves and the types of curves being used by utilities. The intent of this section is to provide guidance to utilities on available condition assessment tools and where to find more detailed information for specific applications.

3.1 Development of Condition Models

A great deal of work has been undertaken by researchers to understand the distress indicators and mechanisms for the various types of pipe used in the water system. There is a large amount of information on the numerous combinations of mechanisms leading to failure and in some cases conflicting findings across research projects. This makes it difficult to synthesize this research into a single methodology that has broad and practical application to the industry. It can be defined as a multivariate statistical problem with uncertainty because of lack and variability of data on pipe condition, operating conditions, and environmental conditions.

It is not possible to develop a universal, reliable condition/performance prediction model for use with all types of pipes and conditions. Instead, various prediction models have been developed for specific implementations of decision type, pipe material, diameter, vintage, structural design, environmental, and operational factors. Such models are constrained by data availability and other factors.

As defined in the WERF report on “Remaining Asset Life: A State of the Art Review” (Marlow et al., 2009), existing condition/performance prediction models can be classified under the following approaches:

1. **Deterministic models** – where relationships between external factors and asset performance are assumed to be certain. Deterministic models are relatively simple to develop and apply. However, they usually rely on a number of simplifying assumptions. Furthermore, deterministic models do not account for the uncertainty that is associated with asset deterioration and failure.
2. **Statistical models** – based on analysis of historical failure rate or service lifetime and other data. Statistical models attempt to capture this inherent uncertainty and use historical data describing failure rates or service lifetimes in asset cohorts. Statistical models work for assets where historical data are readily available for analysis. Bayesian analysis is a robust way of supplementing historical data with beliefs (or opinions) concerning asset failure rates or lifetimes, which are based on engineering knowledge or related observations.
3. **Physical probabilistic models** – based on an understanding of the physical processes that lead to asset failure, while accounting for realistic uncertainty. These models are underpinned by a robust understanding of the degradation and failure processes that occur for an asset in service (corrosion, fracture, etc.). They also attempt to account for realistic uncertainty by using appropriate probability distributions for model variables. However, they can be data intensive and, in the event that insufficient data exist to adequately describe model variables, simplifying assumptions are required.
4. **Soft computing or artificial intelligence models** – There are a number of approaches such as neural networks where model structure is determined by the data and no prior relationships

are assumed. Other models use complex mathematics, but are otherwise transparent and the underlying methodologies and assumptions are fully published (e.g., fuzzy-based models).

In addition, Kleiner and Rajani have developed a comprehensive review of structural deterioration models to predict the probability of water main failures that were presented in two papers, one on physical (mechanistic) models (Rajani and Kleiner, 2001) and the other on statistical (empirical) models (Kleiner and Rajani, 2001).

A key objective in asset management is to balance system performance and cost. The balance differs for small distribution mains compared to large transmission mains, and this difference leads to different forms of management for the two classes of assets. Figure 3-1 illustrates these differences qualitatively.

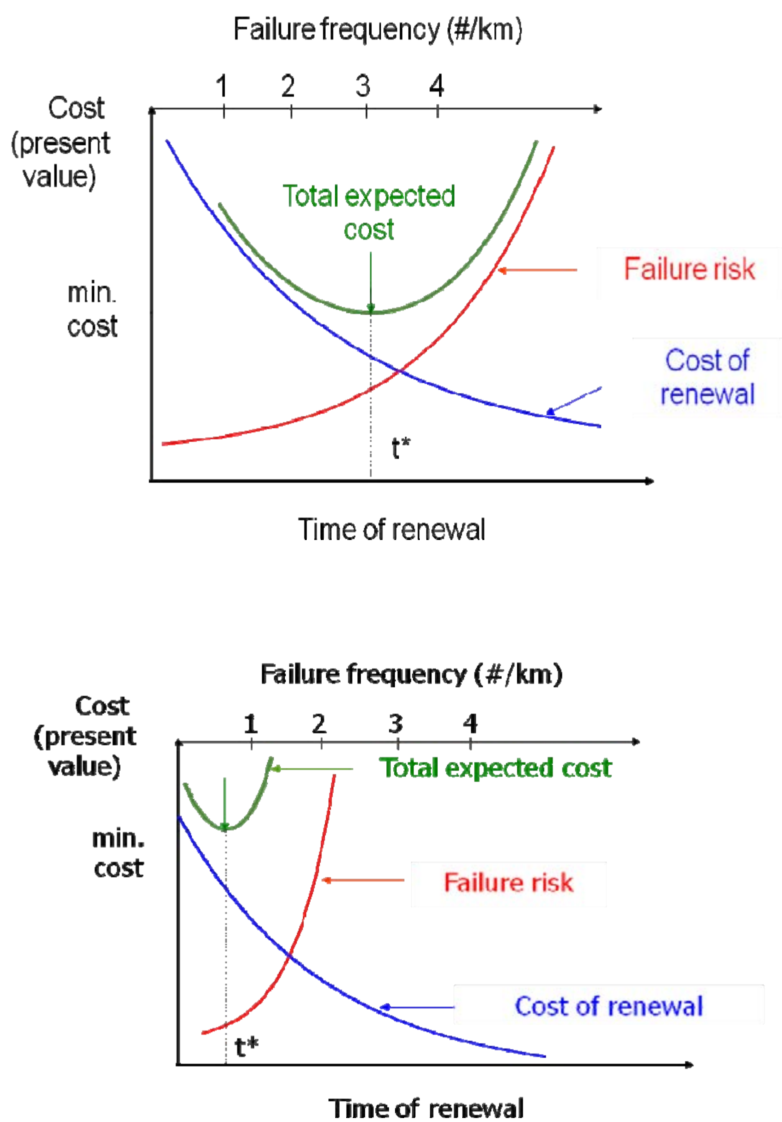

Figure 3-1. Optimal Renewal Frequency for Distribution Mains (Top) versus Transmission Mains (bottom) (Rajani and Kleiner, 2002)

As a pipe ages and deteriorates (without renewal), the likelihood of failure increases along with the risk. The risk can be expressed as the present value (PV) of expected cost (or consequences) of failure. At the same time, the discounted (or PV) renewal cost declines as pipe renewal is deferred. The total expected life-cycle cost typically forms a convex shape, where the minimum point depicts the optimal time of renewal (t*). The top part of Figure 3-1 illustrates this situation for small distribution mains, where the cost of failure is relatively low. Therefore, the optimal time of renewal strategy allows a relatively higher failure frequency. In contrast, the bottom part of Figure 3-1 illustrates this concept for large transmission mains, where the cost of failure is typically high. Therefore, the optimal strategy is to avoid failure altogether (i.e., failure prevention rather than failure frequency management). The time of renewal scales are not the same for the two cases.

Currently, most nondestructive testing (NDT) technologies that can identify distress indicators are not cost effective for small diameter water distribution mains (the exception being where the consequences of failure are high). The predominant approach for assessing condition of small diameter distribution mains is based on the observation of historical failure frequency. On the other hand, condition assessment of transmission mains frequently requires the use of NDT to identify distress indicators due to the lack of inferential indicators and the high consequences of failure. Some of the technologies intended to identify inferential indicators (e.g., those related to soil properties) are used for both small and large pipes.

It is possible to balance maintenance expenditure against risk-cost such that the overall cost of asset ownership is minimized. Importantly, increased reliability can be achieved through higher maintenance expenditure with reduced capital expenditure. In financial terms, the increase in expenditure to achieve this level of asset performance needs to be justified. While in practice it may be difficult to undertake analysis to develop the type of curve shown in Figure 3-2, reducing risk to an economic/acceptable level through a judicious combination of maintenance and renewal activity is still a viable approach to asset management.

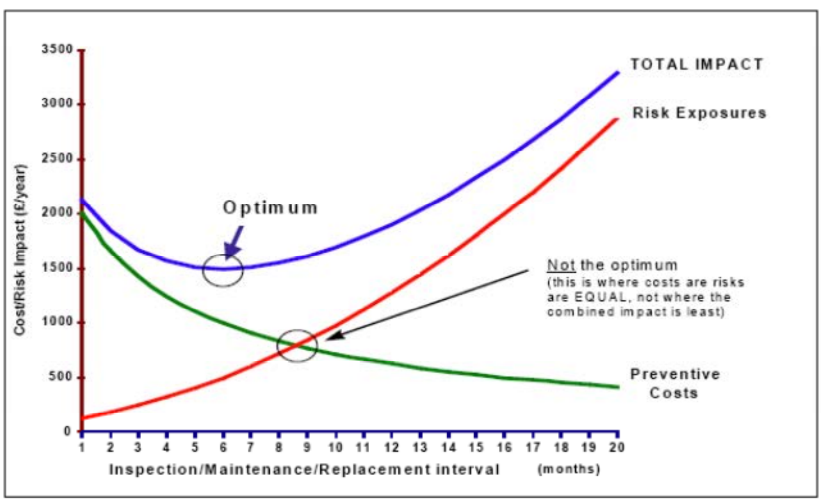

Figure 3-2. Optimal Timing of Intervention (Woodhouse, 1999)

The above is a limited overview of condition assessment tools. A comprehensive review and evaluation of tools can be found in "Remaining Asset Life: A State of the Art Review" (Marlow et al., 2009), "Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models" (Rajani and Kleiner, 2001), "Comprehensive Review of Structural Deterioration of Water Mains: Statistical

Models (Kleiner and Rajani, 2001), and a U.S. EPA report prepared by NRC "Condition Assessment Technologies for Water Transmission and Distribution Systems" (U.S. EPA, 2011a).

3.2 Types of Condition Curves

Developing condition-based and performance-based deterioration curves appropriate to the risk of failure, benchmarking of deterioration curves to real-life asset failures, and the examination of the underlying factors has generated a large body of literature. This subsection attempts to provide an overview with references where more detailed information can be found.

Condition curves are of particular interest because of their usefulness for long-term water asset planning. This subsection focuses on structural/physical condition curves rather than investment and renewal curves, which are based on other considerations. For condition curves to be useful to a utility, they must recognize the following:

- *Trend or shape* of the failure or decay (or deterioration) curve,
- *Where* on the curve is an asset's current condition, and
- Asset's remaining useful life.

Moreover, condition curve predictions need to recognize that the original pipes may have been modified by repair, rehabilitation, or replacement.

Types of condition curves that have been developed and applied by various utilities include:

- Break frequency curve
- Deterioration, decay, and survival curves
- Condition rating curve and condition rating index
- Serviceability curve

In addition, other types of curves are available, but are not the focus of this report:

- *Structural P-F curve*: These to date have not been used by utilities for predicting failure of pipelines. They find greatest use in situations where the time between where failure indicators are noted (P) and failure (F) are short such as electric motors, tires, and other applications.
- *Nessie curve*: The prediction of annual replacement curves are also known as Nessie curves. Nessie curves find significant use by utilities for forecasting capital expenditure needs, but are based on the design life of the pipelines and not on structural condition or failure considerations.

3.2.1 Break Frequency Curves. The most widely used statistical approach is the break frequency curve. Most utilities keep records of pipe breaks, so that the basic data to populate a curve are available and it can be applied to all types of pipes. The application of these data can range from simple direct analysis of break rates (e.g., breaks per mile per year) to sophisticated mathematical models incorporating a variety of factors (i.e., soil condition, operating conditions, pipe types, location, etc.) to predict remaining life. This method is best suited to applications where there is an adequate amount of historic break data over a sufficient time period on which to develop the curve(s). After the break frequency curves have been developed, the results of the analysis can be used to facilitate proactive renewal by replacing pipelines based on projected breakage rates that exceed an acceptable threshold.

Break rates can be calculated for different pipe cohorts and used to prioritize replacement or rehabilitation. Typically, a utility will determine a level of break where it becomes unacceptable on cost or serviceability grounds. A WaterRF study of 20 cities found that 0.1 to 0.2 breaks per mile per year was considered to be an "acceptable benchmark" (American Water Works Association [AWWA], 2001).

The most common method for generating break frequency curves is to allocate pipelines into relatively homogenous groups or pipe cohorts based upon specific pipe characteristics (e.g., pipe type, pipe diameter, age). The next step is to generate curves based on these characteristics. Several utilities also collect valuable information on the nature of the pipe failure, which allows them to identify possible systemic issues.

With this information, a utility can undertake a location or spatial analysis by plotting the location of the breaks on a map to discern the patterns and the potential causes of breaks. If break data are collected over a sufficiently long period of time, the information can be used as a temporal analysis to determine if there are any factors other than age (such as weather conditions, soil conditions, loading factors, etc.) that are impacting the break rate. The same approaches can be used to evaluate leak frequency.

An NRC review of condition assessment technologies for the U.S. EPA lists approximately 20 models based on break frequency that have been developed over the last 30 years (U.S. EPA, 2011a). Out of the 12 utilities described in Section 4.0, nine of them made use of break frequency approaches within their condition assessment programs. The discussion below provides several examples of the use of break frequency curves as discussed in the literature.

Main Break Modeling

Grigg (2007) discussed the link between main break models and contributing risk factors (predictor variables) in a WaterRF project. Examples of these predictor variables include pipe age (minor factor in later stages of failure), material, diameter, soil corrosivity, and operational pressures that vary by utility. It was found that different coefficients were required to model different scenarios and pipe variables to estimate break frequency for each utility.

Grigg describes an approach to develop break predictions and prioritized segments for replacement where, if the PV of a future break cost (consequence) is greater than the current cost of pipe replacement, the pipe should be replaced. The model was applied and customized for two water utilities. The inputs required are:

- At least six years of coded data on all past breaks showing location, diameter, installation year, material, type of break, and some other break qualifiers.
- Categorical descriptions of mains mileage by diameter, installation year, and material.
- Unit costs of several break consequences and replacement by diameter.

Grigg was not able to develop coefficients for variables that can be transferred from one utility to another because of too much variation in data. Grigg found that main break modeling is complex and requires trained modelers to develop and run models. In addition, internal data are used to calibrate the models that require statistical expertise and data quality checks (Grigg, 2007).

__Pipe Class Analysis to Predict Main Breaks__

Another example of the use of breakage rates and pipe categorization into groups is described by Sekuler and Banciulescu (2009). This work was undertaken for the Metropolitan District in Hartford, CT. The stages of development were:

- Data management by developing a structured database
- Pipe class analysis: 21 pipe classes were identified by pipe material, soil type, and pipe diameter (breakage rates were plotted for each class)
- Field sampling and testing (to obtain extent of corrosion and wall thickness for coupons)
- Asset modeling and development of deterioration curves

Figure 3-3 illustrates six different break frequency curves for 4 to 6 in. cast iron pipes of different ages, materials, and soil types. The graph also shows the condition index and the breakage rate level where replacement is deemed to be cost effective. What is significant is that although 4 to 6 in. cast iron could be considered as one class of pipe, the curves predict a range of replacement times from 63 to 133 yr. depending on the soil type and date of installation for the pipe. This wide variation is attributed to the fact that some of the older pipes had greater wall thicknesses at the time of installation compared to the newer pipes.

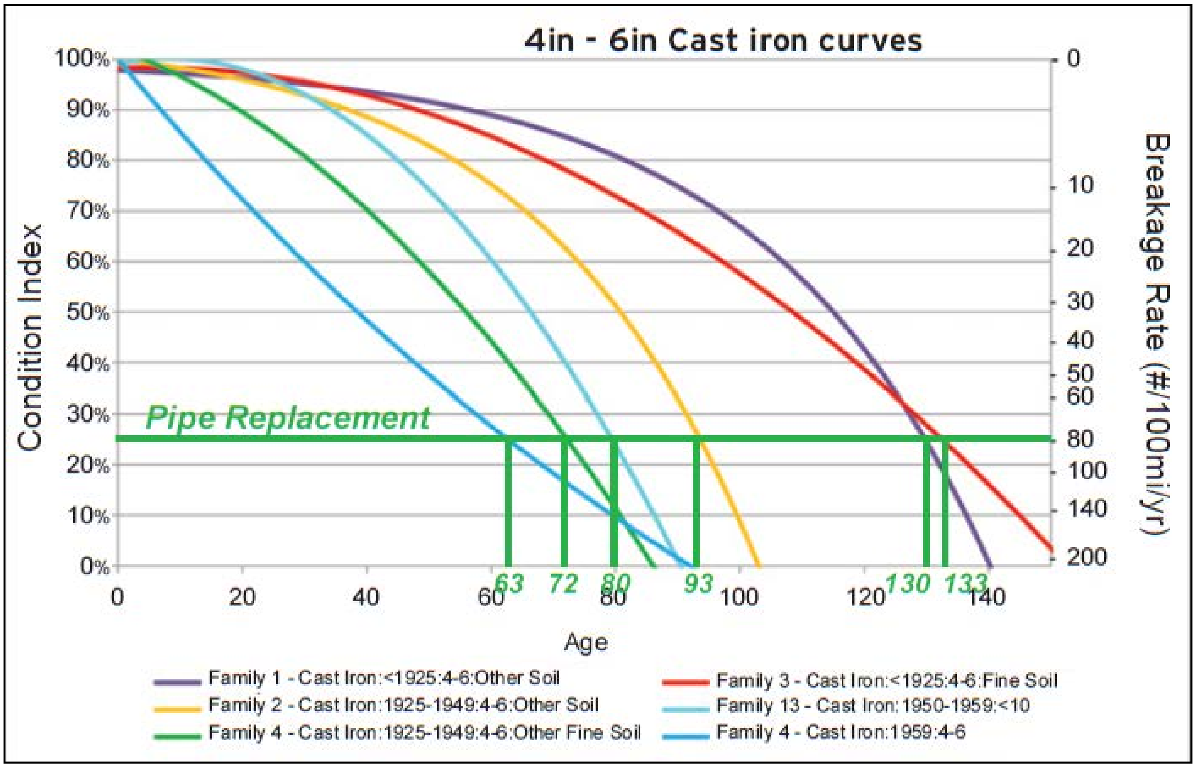

Figure 3-3. Example of Break Frequency Curves by Pipe Class (Sekuler and Banciulescu, 2009)

Regression Models

Regression models have proved to be a popular approach with modelers. They identify relationships between cumulative historical breakage patterns in space and time. The assumption is that the patterns will continue into the future, which allows for the forecasting of break rates (breaks per distance at some year). Researchers applied linear and exponential regression techniques to obtain a relationship for the breakage rate of a pipe as a function of time. Based on the costs associated with pipe repairs and forecasted breakage rates, an economic break-even analysis can be developed to determine the optimal year of pipe replacement.

Distribution – Water Mains Renewal Planner (D-WARP)

A development has been the NRC's D-WARP model, which analyzes the deterioration of water distribution pipe cohorts (in terms of the increase of their breakage rates) as an exponential function of age. The analysis of water main breakage patterns takes into consideration time-dependent factors such as temperature, soil moisture and rainfall deficit, and CP strategies. D-WARP allows the user to see the "optimal" time of pipe replacement, as well as to generate, examine, and compare complex scenarios that include combinations of replacement and CP strategies. D-WARP is currently a standalone program, available for free download at the NRC Web site (Kleiner and Rajani, 2004).

Individual Water Main Renewal Planner (I-WARP) Model

The most recent development from NRC is I-WARP, which uses a statistical method to provide an effective way to estimate deterioration for individual pipelines or pipe cohorts. The model takes into account both dynamic and static factors. I-WARP requires inventory and breakage data about individual pipes. Pipes are divided into homogenous groups - material, diameter, vintage - or any other grouping for which data are available. The model is calibrated to discern historical breakage patterns for each group providing group-specific parameters, which can be used to forecast future breaks. A minimum of 5 years of break data are required. The model allows the consideration of time-dependent factors such as temperature, soil moisture and rainfall deficit, CP strategies, as well as user defined qualitative and quantitative factors (e.g., changes in operational conditions, leak-detection campaigns, etc.). I-WARP is currently a software prototype, available through WaterRF (Kleiner and Rajani, 2009).

3.2.2 Deterioration, Decay and Survival Curves. Deterioration, decay, and survival are different names for curves that mirror the decay process and the deterioration of the pipe. These curves are primarily used for ferrous pipe, PCCP, and AC pipe where a time-dependent factor, such as corrosion, is a primary cause of failure. These types of curves are not typically appropriate for polymer pipes, which are more vulnerable to failures from inclusions, scratches, or impingements.

Such curves are developed in a number of ways using a range of information and levels of acceptability. These types of curves are designed to provide estimates of:

- Trend and/or pattern of the deterioration
- The current condition of the pipeline on the curve
- A prediction of the remaining life of the pipeline.

Direct inspection of the pipeline with measurement of defects will provide data on the progress of the deterioration and allow a curve to be plotted. Alternatively, laboratory testing and analysis of test specimens taken from the pipeline will provide condition data. As the pipe diameter increases and the consequences of failure increase, the use of inspection to provide data becomes more cost effective.

The last 30 years has seen the development of many models although not many have become established as everyday tools used by the water industry. Section 4.0 provides four examples of utilities (Las Vegas Valley Water District [LVVWD], Sydney Water, PWD, and the Hartford Metropolitan District) that have reported using some form of deterioration, decay, and survival curves. The discussion below provides several examples of the use of deterioration, decay, or survival curves as discussed in the literature.

Deterministic Models

Deterministic models aim to predict corrosion rates and to estimate the remaining wall thickness and, consequently, the service life of the pipe. The deterministic models typically use two or three parameter equations to model pipe breakage patterns. These models are best applied to pipe cohorts or groups of water mains that are relatively homogeneous with respect to factors that might influence their breakage patterns. These models are relatively simple to apply, but require careful consideration of water main grouping schemes.

For ferrous pipe, the type of data that are required for different methods is similar, including pipe age, soil parameters, wall thickness, and current extent of corrosion.

The corrosion pit measurement can be acquired using NDT techniques or by examining exhumed pipe samples. Assessment based on pit depth measurement has limitations. It requires an assumption that measurement or number of pits at one location will be representative of the whole pipeline. For structural failure, it requires a significant grouping of pits to reduce the wall strength. The widely used assumption that failure occurs when through wall penetration occurs is overly conservative in terms of ongoing service life particularly with cast iron pipes.

Probabilistic Models

Probabilistic models are designed to calculate the probability of the survival of the pipeline over a certain period of time, predict the remaining life time, or estimate the probability of failure. The main difference between the probabilistic and deterministic models is that probabilistic models incorporate an uncertainty component, which is ignored in the deterministic models. Probabilistic models are used where direct data on condition are not available, limited or not cost effective to obtain. Probabilistic models use explicit assumptions about the probability distribution of the modeled event.

The probabilistic "multi-variate" models can consider many of the factors that influence breakage patterns, thus reducing the need for the model operator to partition the water mains into homogeneous groups. The advantage is that the model can incorporate multiple factors such as environmental conditions (e.g., soil corrosivity), operational stress factors, pipe age at certain breakage rates, number of previous breaks in pipe, period of installation, and other relevant covariates. These models provide outputs such as the instantaneous rate of failure (e.g., hazard function) or estimates of the probability of the time duration between consecutive breaks. These models require significant technical expertise and sufficient data available that cover multiple variables (Ugarelli and Bruaset, 2010).

The probabilistic "single-variate" group-processing models include models that use probabilistic processes on grouped data to derive probabilities of pipeline life expectancy, probability of breakage, and probabilistic analysis of break frequency.

T-WARP

Transmission - Water Mains Renewal Planner (T-WARP) models the deterioration of larger diameter mains using a so-called fuzzy rule based on the Markov deterioration process. It requires that the pipe be investigated at least once to establish the current condition rating, while future pipe deterioration is predicted through the analysis of failure likelihood. The owner is required to rate the consequences of failure on a fuzzy scale. Given likelihood and consequences of failure, a fuzzy risk of failure is computed and a rehabilitation strategy formulated. This program developed by Kleiner et al. (2006) is available through WaterRF.

CARE-W

Computer Aided Rehabilitation of Water Networks (CARE-W) is a suite of tools developed in Europe by a collaborative research effort. It contains several independent decision support tools, including CARE-W Fail, which has five different modules to forecast pipe failure. These five modules predict failures based upon statistical, probabilistic, or physical means. The tools include the: (1) Markov model, based on Asset-map1 (Malandain et al., 1999); (2) Poisson model, based on Asset-map2 (Malandain et al., 1999); (3) Proportional Hazard Model (PHM), based on Failnet-Stat (Le Gat and Eisenbeis, 2000); (4) UTILNETS (Hadzilacos et al., 2000); and (5) Non-Homogeneous Poisson Process (NHPP) model, based on Winroc (Rostum, 2000; Eisenbeis et al., 2002). LVVWD uses CARE-W software combined with the Casses software to evaluate its water pipe condition for renewal planning as discussed in Section 4.0.

Safety Factor Curves

The safety factor concept allows for a quantitative comparison of the anticipated stresses on a pipe and its residual strength. One approach is the safety factor curve, which allows for an assessment of the residual strength as the wall thins from deterioration over time. A safety factor of “1” indicates that the pipe is likely to fail. For large PCCP transmission mains, this approach has been successfully used to prioritize which individual pipes need to be replaced or rehabilitated. As discussed in Section 2, the main distress indicator for PCCP is wire breaks that can be determined from inspection techniques and from these the safety factor curve can be developed.

An example of the safety factor approach is provided in Deb et al. (2002) where a mechanistic model for cast iron pipe was developed involving four modules:

- Pipe Load Module - the loads to which the pipe is subjected
- Pipe Deterioration Module - the corrosion process and loss of strength
- Statistical Correlation Module - calculates the residual strength based upon the reduced wall strength
- Pipe Break Module - compares the stresses on the pipe and the residual strength. The ratio between these represents a safety factor.

3.2.3 Condition Rating Curves and Condition Rating Indices. Because of the difficulties and cost of modeling, some utilities use systems based on judgment, expert opinion, and/or performance indicator data to determine criticality and assign priorities. Although it is reliant upon expert opinion, the condition rating curve or condition rating index approach does provide a logical and documented framework for determining pipeline renewal priorities. This approach is best applied when the deterioration can be classified into discrete states to define a structural condition rating or score (such as the ratings from excellent to very poor shown in Figure 3-4). This rating or score can then be assigned to corresponding action levels such as no action, increased frequency of inspection, repair, rehabilitate, or replace).

This approach is also well suited to incorporating consequence of failure ratings, as well as likelihood of failure ratings, to give an estimate of the overall failure risk. Another advantage of such an approach is that local conditions can easily be incorporated. Figure 3-4 graphically shows an example of the condition rating curve approach. It should be noted that the condition rating output does not have to be developed into a curve, but can be implemented on a score or rating index basis only.

This type of curve is widely used for wastewater and stormwater gravity systems, but is less common for water networks. WERF has a project "Best Practices in Water Infrastructure Asset Management" based on condition ratings for all types of utility assets including pipelines (Bhagwan, 2009)

Using a formalized approach, it is possible to develop relative criticality based on expert judgment combined with weightings of defects to arrive at a condition rating. This approach is used in prioritizing gravity pipelines using mainly information from closed-circuit television inspections, historical, and environmental data. Methodologies developed by the Water Research Center (WRc) and National Association of Sewer Service Companies provide the ratings for evaluating the condition (WRc, 2003).

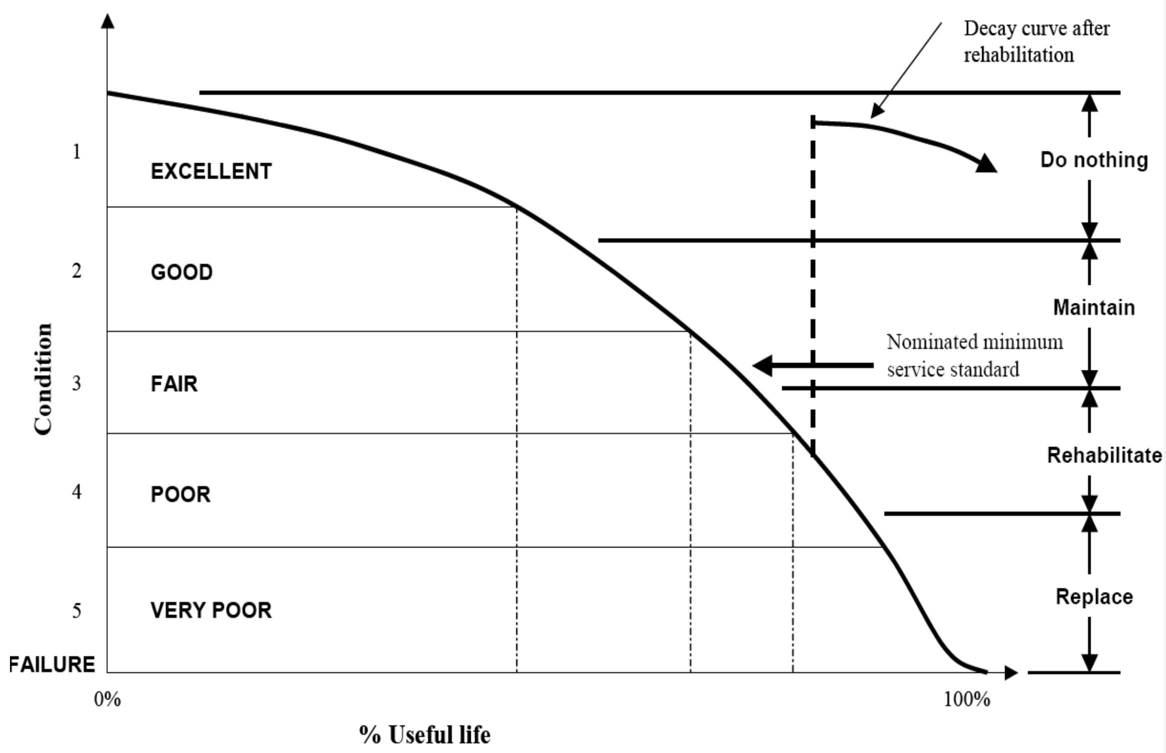

Figure 3-4. Typical Condition Curve Based on Broad Performance Indicators (DERM, 2001)

A few examples of this approach as applied to water mains and/or pressure mains are provided below. As discussed in Section 4.0, several utilities employ a condition rating curve or condition rating index approach including EPCOR Water Services, Seattle Public Utilities (SPU), Sydney Water, Washington Suburban Sanitary Commission (WSSC), and Louisville Water Company (LWC).

Bayesian Belief Networks

The application of this approach to pressure mains is more complex because of the wide range of variables. One approach for pressure mains is to use what have been termed "Tendency Trees" or "Belief Networks" (Thomson, 2010). This method can be used when failure or investigation data are limited. They use physical, operational and environmental factors that have a bearing on the likelihood of failure. Each factor is assessed on a given scale indicating its condition. Each factor is given a relative weighting relating to its importance in the failure process. Weightings are based on observation, data analysis, and expert opinion and are usually specific to a particular utility.

This approach is a structured application of expert knowledge and experience using available information and observation. Many engineers and operators use this approach instinctively in making their assessments. A basic version of this approach has been developed for small to medium utilities that have need for a tool that can be used by their own staff. The technique is used to provide a rating both for likelihood and consequence of failure and an example of the overall rating approach is shown in Figure 3-5. For both likelihood and consequences of failure detailed "Belief Networks" are developed to provide the inputs for this summary network to reach a criticality rating.

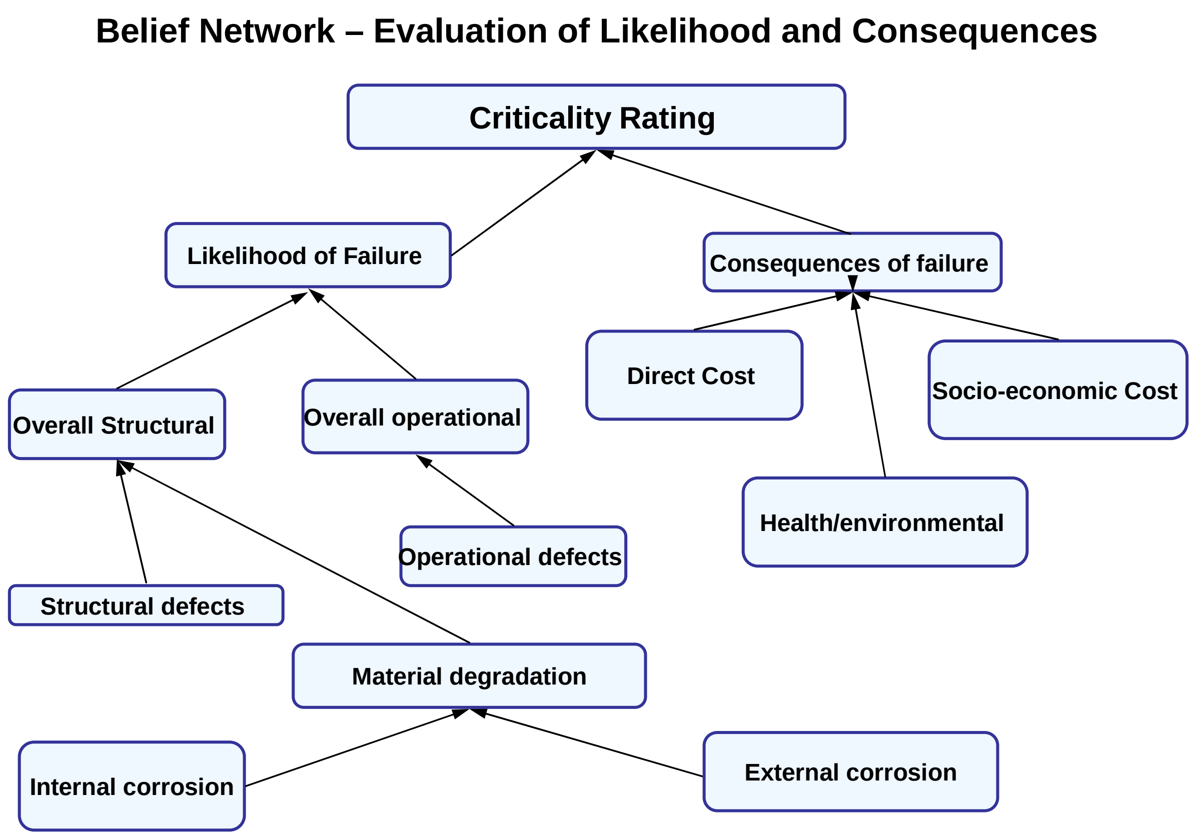

Figure 3-5. Overall Belief Network - Likelihood and Consequences (Thomson, 2010)

PARMS-PRIORITY

PARMS is a suite of computer applications based on models that have been developed by CSIRO of Australia. PARMS-PRIORITY is a commercially available decision support system designed to prioritize pipeline renewal, mainly for low to medium cost failures. The software uses asset and failure data to develop deterioration curves through statistical analysis and the use of physical/probabilistic models. The curves take into consideration factors such as the pipe age, material type, pipe diameter, operating pressure, length of pipe, pipe failure history, and soil conditions. The PARMS-PRIORITY model is primarily based on five key tasks: risk calculation, failure prediction, cost assessment, data exploration (asset and failure records), and scenario evaluation. In Section 4.0, the use of a risk score or matrix along with the PARMS model by Sydney Water is described. This risk matrix assigns a rating based on the consequence of failure defined in monetary terms (cost of pipe renewal, customers affected by the loss of water supply, etc.), and the probability of a failure as calculated using the PARMS model output. More information on model parameters for PARMS can be found in Moglia et al. (2006).

Condition Rating Approaches for AC Water Mains

Failures for AC water mains can be broadly divided into corrosion and mechanical failures. Corrosion failures are the result of the deterioration of the pipe wall resulting in wall thinning and through holes. AC degradation can occur at both the internal and external surfaces of a pipe and if sufficiently rapid, can decrease residual strength to a level where structural integrity is lost before the design life of a pipe is reached.

One method of approximately representing degradation and creating a condition curve is to empirically determine the rate of decrease in tensile strength (e.g., assuming the rate of decrease in tensile strength is constant over time). Since NDT technologies for assessing the condition of AC pipes are currently unavailable, degradation rates are measured using small coupons extracted from the pipe wall. A second approach to measuring the amount of wall degradation is treating core samples with phenolphthalein, which gives rise to a marked change in color between the degraded and non-degraded portions that can be measured.

"Condition Assessment of an Asbestos Cement Pipeline" (Ojdrovic et al., 2007) describes a condition study of 16.5 mi. of 12 and 14 in. diameter AC transmission line to determine if the pipeline could continue to provide service under proposed higher flow conditions. The work involved analysis of available data, structural evaluation, determination of corrosivity of soil/groundwater and internal water. Samples of the pipe were laboratory tested by three methods: (1) edge bearing test, (2) flexural test and (3) petrographic examination.

Condition Rating Approaches for Plastic Water Mains

A number of researchers have developed approaches for predicting failure in plastic water mains. Some of this work is set out below. However, to date no viable cost-effective approach has been adopted by utilities.

For plastic materials such as PVC, only limited failure data are available. Lifetime prediction for brittle polymers is largely based on the linear elastic fracture mechanics (LEFM) theory. LEFM uses the concept of a single parameter known as the applied stress intensity factor (SIF), which characterizes the stress field at the tip of a crack in a plastic material. The dependence of crack growth rate on the applied SIF can be determined using small laboratory scale tests on coupon samples, which can then be applied to the geometry of a flawed asset in service via a geometrical correction factor.

A WaterRF study (Burn et al., 2005) provides an in-depth review on the causes of failure and concludes that manufacturing and installation practices may be the largest factor in determining the likelihood of failure. The report sets out tests which concentrated on brittle and ductile failure and from this develops a fracture mechanics failure model to predict time of failure under combined internal pressure and deflection loads. This is then further developed with the use of Monte Carlo simulation models to predict the performance of PVC pipelines.

Farshad (2006) developed a methodology based on an expert system for failure diagnosis of plastic pipe. His system uses communication between the user and a software system. The system has two levels: a core program that is a knowledge base and a user interaction level where the user can apply his/her own experience and know how.

There is no literature describing use of these approaches by utilities.

3.2.4 Serviceability/Performance Methods. An NRC study "Measuring and Improving Performance" (NRC, 1995) states "performance was the degree to which infrastructure provided the services that the community expects of the infrastructure and can be defined as a function of effectiveness, reliability, and cost." The primary function of a distribution system is to reliably deliver a sufficient quantity of good quality water under adequate pressures to its customers (Deb, 1994). Deb suggests that there is no single performance indicator that will define the performance of a distribution system and proposes four performance indicators that should be analyzed over time: adequacy, dependability, efficiency, and quality. These four indicators essentially define pipeline "serviceability."

There is a need to address deterioration modeling in terms of service, and not just asset deterioration. Aging water pipes present other problems including decreasing hydraulic capacity, degradation of water quality, increasing customer complaints, and increased liability resulting from direct and indirect economic consequences of service disruption. The concept of serviceability rather than failure is gaining favor in a number of countries and particularly in the U.K. where serviceability methods have operated successfully for several years covering water and wastewater services for around 53 million people.

"Serviceability" is defined as the capability of a system of assets to deliver a reference level of service to customers and to the environment now and into the future. It is on this basis that the utilities are judged by the U.K. Water Services Regulation Authority (Office of Water [OFWAT], 2000). The basic assumption underlying the approach is that a water network's life can be extended infinitely if properly maintained (including replacement).

OFWAT requires that water mains and sewers be maintained in perpetuity. In practice, this means that network (pipe) assets are not depreciated in the same way as discrete assets (such as pumps, tanks or treatment works). Instead, an infrastructure renewal charge that reflects the level of investment needed to maintain the network of assets is calculated.

One consequence of this approach is that the concept of "remaining life" is not explicitly used for network assets. Furthermore, OFWAT does not accept investment planning approaches that are based solely on estimations of remaining asset life. For example, a recent OFWAT ruling was that a particular utility should reduce its replacement proposal of 1% mains replacement with only 0.3% mains replacement per year.

The key performance indicators that OFWAT uses to decide if a utility is maintaining serviceability to its customers and which are used as the basis of curves are:

- Number of bursts
- Assessment of extent of unacceptably low pressure
- Scale of interruptions
- Water quality compliance

Although break frequency as described earlier is a widely used basis for pipe replacement, in this case, it is also a measure of the scale of interruptions.

The utilities' charges to the consumer are regulated by OFWAT so gaining approval is fundamental to management and provides every incentive to maintain and improve the key indicators. OFWAT collects standardized data from all companies on an annual basis and for 5-year license reviews in order to assess the structural condition and performance of the networks over time. OFWAT examines overall trends for the performance indicators to determine whether the renewal activities carried out by the utility have resulted in stable, improving, or deteriorating services to customers. It assigns each company a combined performance score based upon the performance indicators summarized above. Collecting these data on an annual basis allows OFWAT to track the overall structural condition of the U.K. network over time and to determine the percentage of the network that remains in poor condition. It is important to assess trends in structural condition over time to determine if operation/maintenance and rehabilitation practices are having a positive impact on system costs and overall serviceability in meeting customer expectations. Interestingly, all of these performance indicators have shown an improving trend over the last 15 years since the serviceability concept has been applied and tracked (Stone et al., 2002).

The OFWAT serviceability approach is a unique model that has been in wide use for a number of years. It has been successfully used by a number of different utilities serving large populations over many years. It is worth noting that it also takes a less pessimistic approach to remaining service life, which has resulted in a reduction in replacement capital expenditures. The U.S. EPA report "Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems" (Stone et al., 2002) provides a fuller review of the OFWAT approach. This report also provides a large amount of useful information on the use of performance indicators in Europe.

The CARE-W suite of software has already been noted. One of the modules CARE-W PI is used to estimate the current and future condition of a water network against a range of key performance indicators. It is based on the International Water Association list of performance indicators. There are a total of 49 performance indicators in five groups, including operational, quality of service, financial, water resources, and physical indicators. It is noted that 153 single pieces of utility information are required to assess the 49 performance indicators. In addition, 29 external indicators, not under utility control, such as climate, soil, and topography, are considered in the evaluation (Batista and Alegre, 2002).

3.2.5 Economic Models - Prediction of Annual Replacement Curves. Economic models to predict annual pipe replacement are not condition curves as they are based on theoretical life expectancy or design life and not on structural condition. Therefore, the details on how these curves are generated are outside the scope of this review. However, as economic models that are often closely allied with condition curves in asset management, a brief overview is provided.

Economic models are used to determine the present worth of future pipe repair and eventual replacement costs. An example of such a model is the Nessie curve, which is an aggregate prediction of replacement capital needs projected over time to forecast reinvestment needs. The humps in the cumulative reinvestment shown in a Nessie curve are due to the echo effect where pipe reinvestment needs mirror, at a projected future date, the original installation date of pipes. The name comes from the belief that the curve with its humps and troughs resembles the legendary Loch Ness monster. A typical curve showing the echo effect of pipe construction is shown in Figure 3-6.

The decision-making process for determining the end of economic life is developed with varying degrees of complexity in a paper by Buckland and Hastings (2001). Some researchers have attempted to incorporate condition predictions into the decision-making process. To forecast the number of breaks in future years these models are augmented with either a regression or probability-based predictive model. This information is then used to perform a break-even analysis in which a total cost curve is derived as the sum of the pipe repair and replacement curves. The low point of the total cost curve represents the optimal replacement time (Grablutz and Hanneken, 2000).

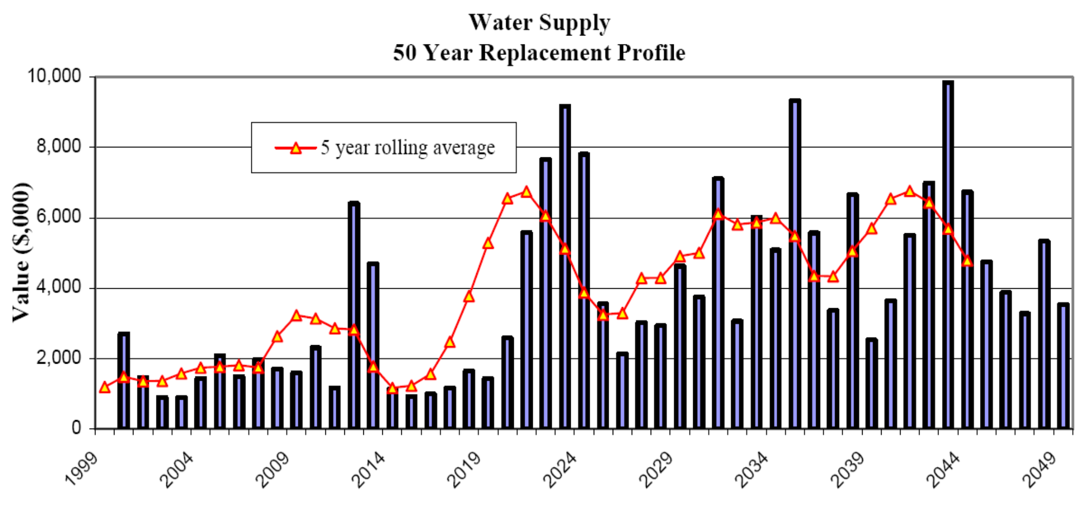

Figure 3-6. Asset Replacement Cost Profile (DERM, 2001)

3.3 Structural Condition Curve Selection Factors, Benefits, and Limitations

The intended use of a condition curve should be to develop a repeatable and technically defensible process for prioritizing the renewal of water mains based upon an evaluation of the structural condition/performance of the pipeline or pipe cohorts in a given network. Any structural condition/performance evaluation process should ideally possess the following characteristics:

- **Applicability** — the model is technically feasible and applies to the decision(s) and pipe scenarios of interest;
- **Repeatability** — the same condition rating will be determined if a different person performs the rating;
- **Objectivity** — the rating can be measured on the basis of some physical characteristics such as cracking;
- **Simplicity** — simple systems are easier to understand and use; and
- **Cost effectiveness** — it is economically feasible to gather the data and the value of the information provided (in terms of improved decision-making) exceeds the cost to the utility to gather the data.

The selection of tools for developing structural condition curves will depend upon the level of asset management sophistication particularly in relation to data, as well as the capacity of the tools themselves. Additional considerations in tool selection are listed below:

1. **Data requirements**: Are there high levels of data requirements?
2. **Inclusion of expert opinion**: Does the tool allow expert opinion to be utilized?
3. **Treatment of uncertainty**: Does the tool explicitly consider uncertainty?
4. **Treatment of economic risk factors**: Does the tool consider economic risk factors, or does it simply consider physical asset life?
5. **Blackbox**: Does the tool provide a framework within which to understand the problem or is it more of a blackbox approach, providing answers with no specific insights into the mechanisms of the decision-making?
6. **Availability**: Is the tool available packaged and off the shelf, while allowing for customization to meet utility needs and site-specific conditions?
7. **Population or single asset**: Does the tool apply to a single asset, population, or both?
8. **Scenario testing**: Does the tool provide the capacity to test different scenarios and thus understand the results of different strategies?

The approach of utilities can be guided by the stages of network development. Utilities with relatively young networks need to develop good practices in the early life-cycle stages of asset management and specifically in data collection. Utilities with aging networks will be more concerned with rehabilitation planning and delivery. This is likely to call for more comprehensive approaches for determining remaining asset life.

3.3.1 Benefits of Condition Curves

- Condition curves can contribute to better prioritization, scheduling, and funding of inspection and renewal activities, which in turn helps to meet service goals and reduces failures. Ultimately, this could lead to an improved asset management program to help to reduce premature replacement, to enable better financial planning and rate determinations, and to avoid large maintenance backlogs.
- Condition curves provide a systematic and repeatable process to improve the decision-making process for water main renewal based upon remaining asset life. The process should be transparent and technically defensible, so that utility stakeholders are confident in the usefulness of the results.
- Improving the understanding of risk can help utilities to anticipate main breaks and reduce their direct costs, as well as those suffered by the public. Utilities need to have this information to build reliable cases for renewal and obtain the required funding. By using condition curves appropriate to the situation, utilities become more aware of risk factors and any information from new breaks adds to their understanding. In-house employees can be trained to use this information in main break programs.
- The selection of the appropriate rehabilitation/proactive failure management technique depends on the cost-benefit ratio. The cost is represented by the cost of inspection, assessment, and renewal, and the benefit is proportional to the losses avoided by prevention of failure. The AWWA 2002 Water Utility Distribution Survey (AWWA, 2004) found that the average reported cost per main break was $1,320, although other studies indicate this

figure may be higher. Assuming this average cost is reasonably accurate, this would favor – especially for small diameter, low risk pipes where the cost of inspection may not be justified – less expensive statistical or expert-opinion -based approaches for predicting pipe failures and developing renewal prioritization mechanisms.

- The cost of investigation and building physical models is more easily justified for the large transmission pipelines where the consequences of the failure can be large. Gaewski and Blaha (2007) determined the cost of failure for larger diameter pipes (20 inches and greater) is much greater in direct and indirect costs than it is for distribution network pipelines. The average mean cost for 30 large diameter failures was $500,000 split about evenly between direct and indirect costs.
- The Governmental Accounting Standards Board requires reporting of all major capital assets in the utility's financial statement using the historical cost approach or the approved modified approach. Certain benefits to a utility are available by using the modified approach. Because the modified approach defines the level of service to be maintained and maintains the value of assets on the utilities' balance sheets, there is an improvement in the standing of the utility with the customers, regulators and financial community. The utility can expect to have a better bond rating and get more favorable bond rates for its capital improvement projects if the modified approach is used. For the modified approach, condition assessment of assets must be performed every three years. Statistical approaches, such as structural condition curves, can be used to fulfill this requirement. The modified approach also requires development of a complete inventory of existing assets. In addition, the condition of the assets should be documented and a program established to maintain the condition of the assets at the desired or specified performance level (Nelson, 2005).

3.3.2 Limitations of Condition Curves

- Value is often the limiting factor when it comes to selection of failure management strategies. Water supply utilities do not usually have a budget that would allow large investment and therefore less advanced techniques are chosen. Utilities need to have a clear understanding of the investment and effort required to implement the various methods described in this report. Information on the cost to develop and implement these curves/models is limited and not widely available in the literature as it resides with individual utilities and/or consultants. Although the information exists, it is difficult to document as noted in the survey work discussed later in Section 4.0.
- Without an adequate level of data, models cannot operate successfully. It can be very costly to collect and manage the level of data that are required.
- The cost of acquiring pipe condition information that is necessary for some models must be balanced against the critical nature of the pipeline. Proactive failure management is approached in different ways for transmission and distribution systems.
- For distribution systems, the need is for less expensive options that are likely to have a lower performance standard. The relatively low cost associated with "fail and fix" for small diameter pipes in low risk situations make it difficult to justify significant investment in data collection and more sophisticated modeling. The greater volume of basic data for breaks in small diameters makes simpler break frequency approaches the most feasible.
- For some models, the underlying assumptions in terms of factors and their weighting are not clear and may not be applicable to all utilities. One size does not fit all. Validity of methods

depends on validity of data. Even with valid data there is a need for the right objectives, criteria, alternatives and the cost benefit in what is being proposed.

- It is recognized that many models are mathematically complex and will require special skills to operate. Reluctance on the part of utilities to use “black box” models is acknowledged and even understandable. However, the complexity that underlies more transparent models is not (and should not be) a deterrent for its use. Further efforts are needed for utilities to become familiar with and confident in the output of these models.
- Some may consider these approaches as an imprecise science, which miss some failures and replace some pipe that still has an economic life. Despite modeling advances, the application of models is constrained by limited below-ground data and the complexity caused by the interaction between factors that contribute to water pipe failure (Grigg, 2004).

4.0: CURRENT USE OF CONDITION CURVES

This section provides an overview of current utility practices related to condition curves for water mains through examination of published case studies and results from a survey of nine major utilities conducted by Virginia Tech.

4.1 Who is Using Condition Curves?

As discussed in the previous sections, numerous methods, including various forms of condition curves, are used by water utilities to assess the condition of their water transmission and distribution systems. The utilities that were surveyed for these case studies used methods that ranged from very detailed asset management programs that combine inspection, monitoring, and test data with their pipeline condition assessment program to simple analyses of pipe break history to prioritize pipeline renewal activities. Few utilities surveyed are using deterioration, decay, and survival curves likely due to the more extensive data required to generate meaningful curves for the range of pipe types and diameters. In addition, there is a need to clearly demonstrate a net benefit for the utility in order to warrant the extra cost of the data collection efforts. However, there has been increasing recognition that development of quality data is a major element in managing water networks. Such data have to be structured using a standard system for naming and defining water utility assets, which subsequently allows the data to be shared and compared across utilities. The WaterRF and WERF have a project underway related to standardizing terminology which could be a major advance specifically for improving condition curve implementation (WaterRF Project #4187).

4.1.1 Types of Condition Curves Being Used by Utilities. Each utility has developed its own methodology for tracking and analyzing the condition of its network over time based on available data, resources, and ultimate goals of the utility. Condition curve methods that were found to be in use include pipe break frequency curves, condition rating curves or condition rating indices, and economic forecasting models, such as Nessie curves. The only commonality found was that many utilities use pipe break frequency as a main indicator for pipe renewal decisions. This finding is supported by a U.S. EPA report (Stone et al., 2002) and a WaterRF report (Grigg, 2007), which indicated that the number of pipe breaks is one of the most commonly used indicators of water pipe effectiveness and that the break rate is the most important factor for prioritizing renewal activities.

4.1.2 Primary Pipe Types and Sizes for Condition Curves. The "condition curves" generated by each utility focus on the pipe types that represent a majority in their water network. For those utilities that participated in the survey, the focus of their condition assessment programs was primarily on ductile iron and cast iron with slightly less focus on AC, PCCP, and plastic pipe types. Development of condition curves for these pipe types (especially ductile iron, cast iron, and PCCP) can be somewhat easier because utilities have a fairly good understanding of the failure modes and mechanisms and can collect data on failure indicators. Plastic pipes, on the other hand, have very different failure mechanisms that are far more difficult to detect, making it complex to develop accurate condition curves and failure predictions.

Focus is also placed on smaller diameter distribution mains as these dominate both the total water pipeline mileage and the number of failures. Because of the significant quantity of pipeline mileage, utilities need methods to prioritize their renewal activities so that the most critical infrastructure is replaced in a timely and cost-effective manner. Therefore, break frequency curves combined with economic models appear to be the most common type of analysis conducted. These methods are easier and less costly to develop, yet provide sufficient information to do a fair job at prioritizing renewal of distribution pipes.

4.2 Case Studies from Various Utilities

To better understand who is using condition curves and how they are being used, utilities with significant activities in water pipe infrastructure management in the U.S., Australia, and Canada were contacted by Virginia Tech to participate in a survey. Only nine utilities were selected due to restrictions of the Paperwork Reduction Act. All participating utilities provided detailed information related to current practices/programs for pipe inspection, condition assessment, and renewal planning. In addition, several papers were reviewed that detailed case studies of how utilities are managing water pipe assets with specific emphasis on the use of condition curves. All sources of data have been combined into this section to provide a general overview of who is using condition curves and for what purpose in an effort to provide guidance to users of this document and to highlight potential gaps and research needs.

4.2.1 Development of Survey. A survey of the nine utilities was conducted by Virginia Tech to identify the factors that influence water main deterioration and state-of-the-art in condition curves/deterioration modeling. Focus was placed on each utility's practices related to the use of pipe deterioration models for generating pipe condition curves. The type of information requested included:

- Types of inspection and condition assessment techniques used;
- Prioritization of inspection, maintenance, and renewal;
- Methods used for condition deterioration prediction;
- Methods used to generate condition curves;
- Factors included within the condition curves;
- Software used;
- Associated costs in generating condition curves; and
- Type of pipe condition and/or performance index.

4.2.2 Participating Utilities. A total of nine utilities across U.S., Canada, and Australia participated in the survey, providing an overview of the current best practices available (see Table 4-1 for the list of utilities). These utilities were selected because they are fairly sizeable utilities representing a range of pipe types and diameters and they expressed a willingness to provide information for this research. To supplement the information obtained from the nine utility surveys, additional case studies were reviewed, including:

- The Metropolitan District – Hartford, CT (Sekuler and Banciulescu, 2009)
- The Los Angeles Department of Water and Power (LADWP, 2010)
- U.K. Water Services Regulation Authority OFWAT (discussed in Section 3.2.4)

4.2.3 Water Pipe Inventories for Case Study Utilities. The nine case study utilities operate a total of over 32,000 miles of water pipe. The largest of these utilities is Sydney Water, operating nearly 13,000 miles of water pipe. The pipe is overwhelmingly <21 inches in diameter. There is considerable variance in the pipe types used, but cast iron and ductile iron have the greatest length for most utilities. A summary of the water pipe inventories for each utility is provided in Table 4-1.

4.2.4 Inspection, Monitoring and Condition Assessment Programs. Each of the utilities that participated in the survey indicated varying degrees of inspection, monitoring, and condition evaluations for their water transmission and distribution systems. Some utilities, such as EPCOR in Edmonton, Alberta, Canada and LWC, responded to the survey with greater detail on their condition assessment programs. These two utilities have comprehensive programs that generate a large amount of data for managing the condition of their assets, including techniques such as CP, hydraulic modeling, geographic information system (GIS) integration, soil and/or pipe sampling and testing, and non-invasive inspection.

Table 4-1. Water Pipe Inventories for Case Study Utilities

Utility	Pipe Diameter (inches)	Percentage of Pipe Miles: Asbestos Cement (AC)	Concrete Cylinder[1]	Concrete[2]	Cast Iron (CI)[3]	Ductile Iron (DI)[4]	Galvanized Iron	PVC[5]	Steel[6]	Other[7]	Total (miles)
EPCOR Water Services Inc.	<21	33%	0%		22%	0.1%		43%	2%	0.1%	2,044
	21 to 36	1%	40%		1%			18%	35%	5%	110
	>36		70%						30%		33
Las Vegas Valley Water District (LVVWD)	<21	40%			2%	2%		55%	0.4%	0%	4,190
	21 to 36	6%			1%	12%		5%	75%	0%	293
	>36	0.4%				0.4%			99%		227
Newport News Waterworks	<21	0.5%		0.3%	33%	55%	7%	4%		1%	1,680
	21 to 36			46%	31%	22%					89
	>36			93%		6%			1%		81
Seattle Public Utilities (SPU)	<21		0%		83%	14%	2%	0%	1%	0%	1,600
	21 to 36		27%	4%	31%	8%			28%	1%	95
	>36		13%	6%	1%	2%			77%	1%	159
Sydney Water	<6	1%		0.0%	66%	22%	0.0%	10%	0.2%	1%	9,658
	6 to 12	0.4%		0.1%	64%	24%		7%	2%	2%	1,871
	12 to 24	0.0%		0.4%	67%	23%			8%	1%	1,054
	>24			0.3%	17%	6%			74%	3%	413
Washington Suburban Sanitary Commission (WSSC)	<16				51%	49%	1%				3,899
	≥16		25%		43%	28%			3%		821
City of Hamilton Public Works Department	<18				-%[8]	-%[(8)]					1,079
	>18				-%[8]	-%[(8)]					96

Table 4-1. Water Pipe Inventories for Case Study Utilities (Continued)

Utility	Pipe Diameter (inches)	Percentage of Pipe Miles									Total (miles)
		Asbestos Cement (AC)	Concrete Cylinder[(1)]	Concrete[(2)]	Cast Iron (CI)[(3)]	Ductile Iron (DI)[(4)]	Galvanized Iron	PVC[(5)]	Steel[(6)]	Other[(7)]	
Louisville Water Company (LWC)[(9)]	Unknown			0.1%	5%	1%		58%		36%	3
	<6	4%			9%	5%	0.4%	75%		7%	200
	6 to 12	2%			42%	27%		28%		1%	3,503
	12 to 20	0.9%			21%	72%		1%		5%	213
	24 to 30			73%	17%	10%				0.1%	89
	36 to 48		0.9%	49%	40%	8%				2%	45
	60		0.4%	99%	0.1%				0.2%	0.1%	37
Philadelphia Water Department (PWD)	3 to 93			0.2%	81%	16%			3%		3,278

(1) The concrete cylinder category can include concrete cylinder and PCCP.
(2) The concrete category can include concrete and reinforced concrete pipe.
(3) The cast iron category can include cast iron, cement lined cast iron pipe, and unlined cast iron.
(4) The ductile iron category can include ductile iron and cement lined ductile iron pipe.
(5) The PVC category can include plastic, mPolyvinyl chloride, oPolyvinyl chloride, and uPolyvinyl chloride pipe
(6) The steel category can include steel, mortar lined and coated steel pipe, galvanized steel, lock bar steel, riveted steel, stainless steel, welded steel, wrapped steel, cement lined steel.
(7) The other category can include fiberglass, high-density polyethylene (PE), copper, Kalamein, iron, wood stave, FL Bar, glass reinforced pipe, PE, vitrified clay, wrought iron.
(8) Actual percentages were not provided. The information that was received indicated that pipe types owned and operated by the City of Hamilton Public Works Department are predominately cast iron and ductile iron.
(9) LWC has approximately 105 miles of PCCP; however the GIS system on which the numbers in Table 4-1 are based did not note whether or not it was PCCP.

Several utilities use some of the same techniques as EPCOR and LWC, but reported their condition assessment activities on a more limited scale in their survey response. For example, the LVVWD primarily assesses AC pipes greater than 4 inches and steel pipes greater than 12 inches in diameter using non-invasive leak and condition assessment technologies, CP for steel pipes, and forensic analyses of failed pipes. Newport News also varies its condition assessment techniques based on pipe diameter.

Sydney Water prioritizes inspection and condition assessment of critical water mains using a quantified risk-based prioritization tool. Sydney Water mainly focuses on the condition assessment of cast iron water mains using non-invasive inspection techniques such as linear polarization resistance, magnetic flux leakage, and ultrasonics.

Similarly, WSSC selects transmission main condition assessment methods based on pipe material type and diameter. The techniques used include internal visual/sounding inspection (PCCP only), NDT techniques (remote field eddy current, sonic/ultrasonic pulse echo), acoustic fiber optics (PCCP only), and electrochemical potential surveys. It does not actively inspect distribution mains with the use of NDT tools, but prioritizes renewal activities by analyzing work order histories, pipe physical properties, defect types, and soil corrosivity.

Some utilities surveyed, such as SPU, do not conduct routine inspections of transmission and distribution water mains. Rather, SPU uses a combination of CP and spot checks during maintenance to assess the condition of its transmission mains in combination with leak and break data as indicators of structural condition. During the spot checks, they record data for several variables including physical pipe properties (material, joint type, wall thickness, diameter, etc.), soil properties, and pipe condition. The only time internal inspections are performed is when the pipe is out of service. SPU did have a condition assessment program (primarily consisting of pipe sample collection during tapping or repairs) for several years in the 1990s; however, it was discontinued because costs exceeded the value of the information obtained.

4.3 Survey Results: State-of-the-Practice in Pipe Condition Curves for Renewal Prioritization

4.3.1 EPCOR Water Services Inc. EPCOR Water Services Inc. is a corporatized public utility located in Edmonton, Alberta, Canada. EPCOR prioritizes its water main renewal activities through both a reactive and proactive renewal program. EPCOR's reactive and proactive renewal programs primarily use break frequency and a condition rating index using a GIS platform to prioritize renewal activities. EPCOR has also experimented using other deterioration models including the development of pipe failure prediction curves to allocate capital funds and artificial neural networks (ANN) to predict upcoming spikes in main breaks, which was intended as a tool to assist in arranging staff schedules and minimizing overtime. However, EPCOR found that efficiently modeling failure prediction curves to allocate capital funds was largely unsuccessful and it was unable to utilize the ANN to predict main breaks with ample notice. In the end, EPCOR plans to continue using its reactive and proactive renewal programs rather than further pursue the development of deterioration type condition curves.

4.3.1.1 Reactive Water Pipe Renewal Program (Break Frequency Curves). EPCOR's reactive renewal program began in 1985. The "reactive" terminology used here refers to the fact that EPCOR is reacting to the increasing frequency of breaks along a given pipeline (this is the utility's own terminology and somewhat different than the traditional "reactive" approach of only repairing a main after it is unserviceable and replacing it). The pipeline sections for replacement are identified using a GIS application designed to calculate break frequencies for candidate pipeline sections between valves. The break frequency is classified by the replacement priority value (RPV), which is calculated by the total number of main breaks over five years divided by the total length of the pipe section between the valves. Pipeline candidates with frequencies of five or more breaks/km/year are identified for replacement. Used in conjunction with the main criteria, alternate criteria that were evaluated by EPCOR for pipe replacement decision-making included replacement at a minimum of at least two breaks in five years, more than six breaks in five years, and 12 or more breaks since 1982. In general, the deteriorating pipelines requiring replacement are replaced with PVC pipe.

4.3.1.2 Proactive Water Pipe Renewal Program (Condition Rating Index). The proactive renewal program started in 2002 and was designed to target water mains that do not qualify for reactive renewal based on break frequencies, but are performing below EPCOR's design standards (e.g., fire flow, water quality, etc.). The first part of the proactive renewal program consists of area prioritization through evaluation of pipe condition, hydraulic deficiencies, and water quality from several different data sources all imported into the GIS database. Specific data used to rank areas include pipe material, pipe length, flow, unidirectional flushing frequency, leak and/or break history, available flow, and hydrant data (i.e., hydrants with long flushing times and total number of hydrants). Current conditions, standards, and/or common industry practices influence the threshold values for each criterion. An example of EPCOR's area prioritization system for cast iron pipe is shown in Figure 4-1 in which 45% of the pipe renewal score is based on structural factors, 30% is based on hydraulic factors, and 25% is based on water quality.

The total score for a particular pipe type is compared against threshold values set by EPCOR to prioritize renewal of specific areas. An example of the area ranking threshold values for CI pipe and a graphical representation of the area prioritization is shown in Figure 4-2. Using this information, EPCOR engineers pinpoint critical areas for more detailed evaluation.

Candidate prioritization is then used to down-select areas to one pipeline section. EPCOR establishes candidate criteria rankings for pipeline sections by evaluating condition/break history, demographics, hydraulics, water quality, and economies of scale. EPCOR uses sensitivity analysis to determine the candidate weightings for the various pipe types.

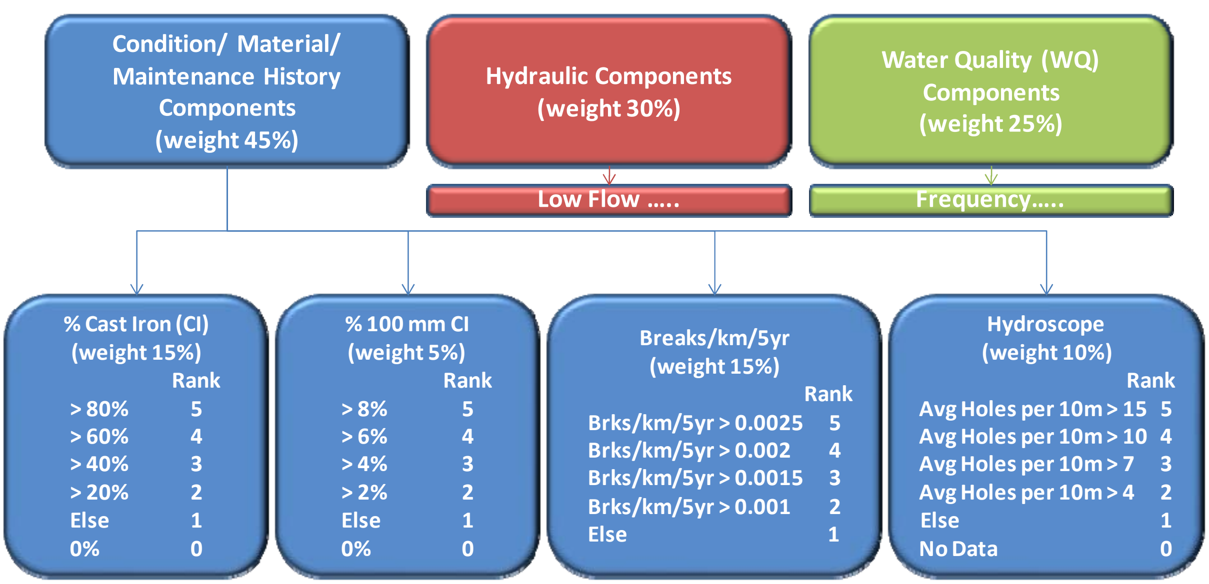

Figure 4-1. Example of Area Criteria Ranking and Weights for Cast Iron Water Pipe

Area CI Total Score	Rank
> 60 points	5
> 45 points	4
> 30 points	3
> 15 points	2
Else	1

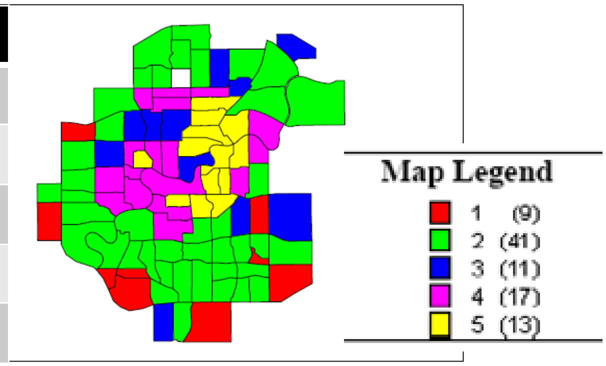

Figure 4-2. Area Ranking Threshold Values and Graphical Prioritization for Cast Iron Water Pipe

4.3.1.3 Validation of Condition Assessment Models and Associated Costs for Generating Models. EPCOR's main focus is minimizing the impacts and response times to breaks, improving tools for selecting candidate pipes for renewal, and reducing the construction impact during renewal. Even though validation of its program with respect to predictive effectiveness has not been a main focus, EPCOR did evaluate the RPV renewal qualification criteria and found that if a pipe was not renewed once the renewal criteria were reached, its break rate would increase.

EPCOR estimated that it spends approximately $50,000 to $100,000 per year on pipe inspections, data collection, data management, modeling software, and interpreting results to identify pipes at risk.

4.3.2 Las Vegas Valley Water District. The LVVWD is a public utility located in Las Vegas, Nevada. LVVWD uses CARE-W and Casses software modules to analyze and prioritize renewal of its water infrastructure system.

4.3.2.1 CARE-W and Casses Software (Break Frequency, Deterioration, and Economic Models). LVVWD uses the CARE-W software combined with the Casses software to evaluate its water pipe condition for renewal planning (see Figure 4-3). CARE-W contains modules for estimating the current and future condition of water networks and includes routines for estimating long-term planning and investment needs as well as selection and ranking of annual rehabilitation projects (using the CARE-W ARP tool). These tools are integrated and operated jointly in the CARE-W software.

The Casses software (based on the LEYP model) is then used to analyze pipe physical and environmental data together with break history to predict pipe break rates. LEYP can assign a probability of failure to a pipe based on time (Weibul module), failure factors (Cox module), and past breaks (Yule module). LVVWD only uses the Casses model for predicting break failure rates for AC pipes since there is an insufficient amount of break data for steel pipes to obtain reasonable results. Instead, LVVWD uses corrosion data and the potential consequence of failure (e.g., business disruption) to prioritize renewal activities for steel water mains.

More information on the CARE-W[1] and Casses[2] software packages are provided on their Web sites.

[1] SINTEF project Web site: http://www.sintef.no/Projectweb/CARE-W/Project-Results/ARP-Multicriteria-decision-of-rehab-projects--/.
[2] Cemagref Casses Web site: https://casses.cemagref.fr/.

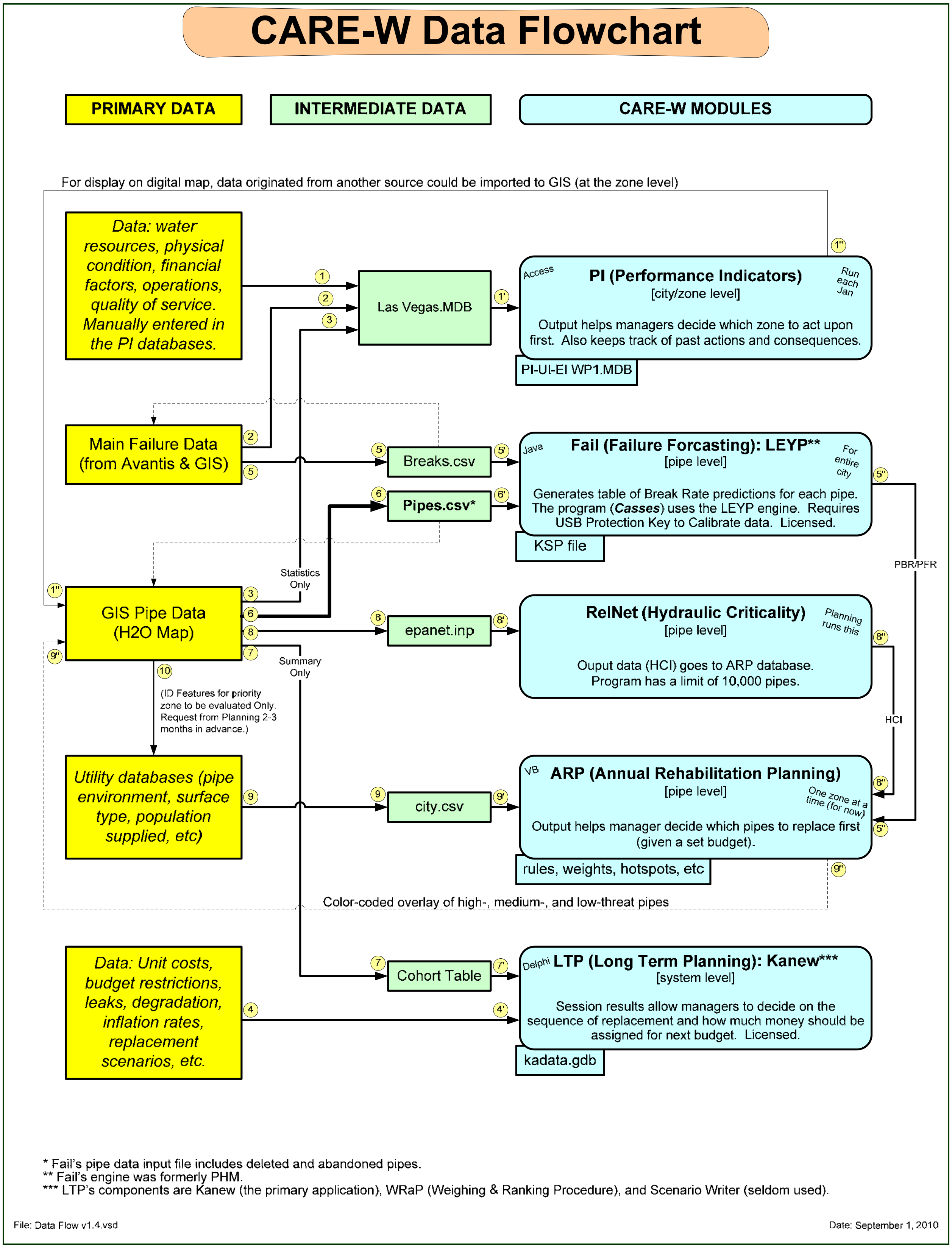

Figure 4-3. CARE-W Data Flowchart for LVVWD

4.3.2.2 Validation of Condition Assessment Models and Associated Costs for Generating Models. The LVVWD has not performed an evaluation of the CARE-W software results primarily because there is not sufficient pipe break data to be statistically valid; however, LVVWD is confident that the models are practical. LVVWD has performed back-casting on the Casses break prediction model that indicated the software produces reasonable results. Some limitations of these models identified by the LVVWD include the need to acquire reliable data and costly in-house analyses.

Data collection and management, modeling, and identifying pipes at risk are done in house by LVVWD personnel while some assessment work is performed by specialized consultants as needed. LVVWD did incur the one-time cost for implementing the CARE-W program; however, there are no annual fees for continued use of the software. If any software/programs are needed in the future, these costs would be included or accounted for as part of LVVWD's operating budget.

4.3.3 Newport News Waterworks. Newport News Waterworks is a public utility located in Newport News, Virginia. Prioritization of renewal activities at Newport News Waterworks varies based on pipe diameter. Small diameter pipes (2 to 4 inches) are replaced based on failure rates using a prioritization program focused on the economics of repair versus replacement. For pipes 6 to 12 inches in diameter, replacement is based primarily on their failure rate, as well as experience with similar pipe materials. Large diameter pipes (>12 inches) are replaced when there is a known propensity for manufacturing and/or installation issues (e.g., pre-1985 unwrapped ductile iron pipe is often recommended for early replacement in areas of corrosive soil). To date, Newport News has not experienced a significant number of failures in large diameter pipes since most have been installed within the last 40 years.

Historically, Newport News used a point system (condition rating index) in combination with economic models (Nessie curves) to analyze water pipe condition and prioritize renewal activities. However, the point system has evolved over time to primarily account for break frequency as described below. The focus of the discussion below is on Newport News' pipe replacement prioritization program, which assigns points based on pipe breaks and their potential costs.

4.3.3.1 Pipe Replacement Prioritization Program (Break Frequency). Newport News' pipe replacement prioritization program was established in the 1980s and has been updated and revised over time. The initial program was a point system. A score was assigned to pipe sections based on evaluations of 10 different pipe criteria: break history, pipe size, pipe depth, grid pattern in area, pipe material, soil corrosiveness, system pressure, available fire flow, work in area by others, and cost comparison between repair and replace/rehabilitation.

Over time, Newport News found that many of these pipe categories did not affect the priority ranking. After several iterations, the replacement prioritization program evolved into what it is today, which involves prioritizing pipe replacement based only on the number of pipe breaks, pipe life expectancy (based on Nessie curves), and maintenance costs. In particular, up to five points are assigned for each pipe break. Points assigned for life expectancy are based on the equation: % of life reached/25. Points assigned for cost are based on the formula: (100 * cost of breaks)/(cost to replace). The ArcView GIS program stores this information and is used to identify projects and to update the priority rankings.

4.3.3.2 Validation of Condition Assessment Models and Associated Costs for Generating Models. Newport News has not performed statistical analyses of its models. The Nessie curve analysis was performed by an outside consultant for an estimated cost of $20,000 to $40,000. However, Newport News reports spending in the magnitude of millions of dollars to create and maintain its customized geodatabase for asset management, which supplies the pipe data upon which their prioritization program/point system is based. All associated costs have been included within Newport News' annual budget.

4.3.4 Seattle Public Utilities. The SPU is a private utility located in Seattle, Washington. The SPU prioritizes water transmission main renewal based on failure probabilities for critical pipes generated by a Water Main Replacement model combined with economic forecasts from the Wave Rider model. The definition of "critical" pipes is still being refined by SPU but includes factors that lead to increased risk (e.g., transmission mains under body of water, railroad track, hospital, pipe material, soil corrosivity, leak history, etc.). The methods used to generate the models for critical pipe failure probability and economic forecasting are statistical and empirical and were developed in house based on industry accepted best practices for infrastructure asset management.

For distribution pipes, a prioritization process is used that compares the expected future cost of repair to the life-cycle cost of replacement to determine whether distribution pipe leaks/breaks should be repaired or replaced. This method is the same for all distribution pipes regardless of the type of material, size, and/or location.

4.3.4.1 Wave Rider (Economic Model). The SPU's economic model, Wave Rider, is used for long-term capital planning. Wave Rider forecasts renewal expenditures by year for nine pipe classes (ductile iron, cast iron divided into four subcategories by size and vintage, steel, concrete, galvanized, and other) and is based on Weibull distribution curves for each class. The model results have been compared and calibrated to the actual break history/repair rate data (collected since 1990). Although Wave Rider helps SPU forecast renewal expenditures for groups of water pipes, it does not address individual pipes.

4.3.4.2 Water Main Replacement Model (Condition Rating Index). The SPU also uses a Water Main Replacement Model for individual transmission pipe renewal decisions. It is primarily a cost-benefit model that compares the net present value (NPV) of the replacement cost to the potential economic and social disruption costs of a failure event. The analytical framework for the model is the same across pipe materials, sizes, locations, and other parameters and is based primarily on a Weibull distribution curve generated from the leak history data of a given pipe.

The model is used to determine whether or not the water pipe is at the end of its economic life and should be replaced. The pipe has reached the end of its economic life when the replacement cost of a new pipe is lower than the "marginal risk cost" of the pipe failure. The marginal risk cost is defined as the product of the probability of failure and the total repair cost. The probability of failure is determined by leakage rate data collected by SPU for the individual pipe. As shown in Table 4-2, the total repair cost consists of construction costs plus various social costs associated with service loss, traffic disruption, lost water, property damage, fire risk, and water quality issues. The output of the model, shown in Table 4-3, includes the NPV of a replacement, total leaks per year over time, and a break-out of costs for repair and replacement options.

4.3.4.3 Validation of Condition Assessment Models and Associated Costs for Generating Models. No statistical analysis has been completed to evaluate the validity of the Water Main Replacement Model. It has been difficult for SPU to validate the predictive effectiveness of the failure curves since the majority of its pipes have remained in the flat part of the curve. If and when SPU's break rates begin to rise, it may need to re-assess its current pipe replacement program. SPU does not document or keep track of the costs of these activities. In a 2008 estimate, SPU spent approximately $43,000 on asset data, decision models, and related support. In general, most of the work in generating the failure curves is conducted in house, with the occasional use of consultants. SPU also did not incur the costs for purchasing specialized software because the analysis relies upon software applications already in place such as Microsoft® Excel and ArcView GIS.

Table 4-2. SPU Input Parameters Included in the Water Main Replacement Model

Option	Data Class	Input Variables	Input Values
Leak Repair	Pipe	Pipe Length Miles	0.088
		Leaks per Mile per Year in Year 1	11.4
		Pipe Age	60.0
	Construction	Leak Repair Hours	5
		Persons per Repair	3
		Cost per Person per Hour	$ 50
		Equipment Pieces per Repair	3
		Cost per Equipment Piece per Hour	$ 75
		Material Cost	$ 625
		Total Cost per Leak	$ 2,500
	Service	Hours Service Interruption per Leak	3
		Customers Impacted per Leak	15
		% Leak Repairs w/ Water Shutoff	50%
		Cost per Customer per Hour	$5
	Traffic	Hours Traffic Interruption	5
		Traffic Flow Cars per Hour	40
		Cost per Car	$2
	Lost Water	Hours of Water Loss per Leak	168
		Gallons Lost per Hour	25
		Cost per Gallon Lost	$ 0.002
	Damage	Number of Damage Claims per Leak	0.167
		Settlement Cost per Claim	$ 2,000
	Fire Risk	Customers Impacted Fire Flow	15
		Property Value per Customer	$500,000
		Probability each Year Fire w/ Inadequate Fire Flow	0.00001
		Damage % Property Value	100%
	Water Quality	Customers Impacted Low Water Quality	15
		Cost per Customer per Leak Low Water Quality	$25
Replacement	Pipe	New Pipe Economic Life Years	175
	Construction	Replacement Construction Cost per Foot	$300
	Service	Hours Service Interruption During Construction	5
		Customers Impacted Construction	15
		Cost per Customer per Hour	$ 5
	Traffic	Hours/Project Traffic Interrupt During Construction	72
		Feet per Project	300
		Traffic Flow Cars per Hour	40
		Cost per Car	$ 2
	Water Quality	Customers Impacted Water Quality Construction	15
		Cost per Customer Low Water Quality	$ 10
	Benefits	Customers Gain Improved Service Levels	15
		Annual Benefit per Customer Improved Service	$ -

Table 4-3. Outputs of the Water Main Replacement Model

Outputs	Value
Net Present Value of Replacement @ 3%	$48,298
Net Present Value of Replacement @ 5%	$276
Net Present Value of Replacement @ 7%	$34,570
Total Leaks per Year in Year 1	1.00
Total Leaks per Year in Year 20	4.00
Construction % of Leak Repair Option Cost	66%
Service % of Leak Repair Option Cost	3%
Traffic % of Leak Repair Option Cost	11%
Lost Water % of Leak Repair Option Cost	0%
Damage % of Leak Repair Option Cost	9%
Fire Risk % of Leak Repair Option Cost	1%
Water Quality % of Leak Repair Option Cost	10%
Construction % of Replacement Cost	94%
Service % of Replacement Cost	0%
Traffic % of Replacement Cost	6%
Water Quality % of Replacement Cost	0%

4.3.5 Sydney Water. Sydney Water is a public utility located in Sydney, Australia. Sydney Water has used KANEW and is currently implementing the PARMS model in cooperation with the Water Service Association of Australia as described below.

4.3.5.1 KANEW (Deterioration, Decay, and Survival Curves). KANEW is a cohort survival model for infrastructure assets. KANEW predicts when selected pipe sections will reach the end of their service lives, differentiated by date of installation and by type of pipe sections with distinctive life spans. The current version of the KANEW software includes a module to manage pipe inventory, a module to perform the cohort survival calculations, a failure and break forecasting module, a module to perform cost calculations, a module to support decision-making by running and comparing various scenarios, an economic data module, and a strategy comparison module. Sydney Water uses KANEW to analyze its long-term capital investments. KANEW analyzes data according to the year of pipe installation or rehabilitation against the pipes' aging behavior. KANEW is limited in that the failure curves produced represent a cohort of pipes and not an individual pipeline asset. Furthermore, Sydney Water feels that there is no explicit relationship between the assets' performance versus the deterioration curve. Sydney Water has concluded that KANEW is not suitable by itself for its critical water mains because it does not take risk into account.

4.3.5.2 Pipeline Asset and Risk Management System (Deterioration, Decay, and Survival Curves and Condition Rating Index). Working with the Water Service Association of Australia, Sydney Water is currently implementing the PARMS[3] software to manage its water assets. PARMS is a suite of computer applications based on models that have been developed by CSIRO of Australia. Currently, two PARMS applications are publicly available as commercial products (Marlow et al., 2007). PARMS-Planning forecasts the number of pipe failures and assesses cost implications of various high-level, long-term pipe renewal scenarios. PARMS-Priority allows prioritization of individual pipes for renewal and facilitates low-level planning of pipe replacement and some aspects of network operations (Moglia et al.,

[3] For more information on PARMS-PRIORITY, refer to http://www.csiro.au/files/files/pt41.pdf.

2006). The PARMS-Priority software uses asset and failure data from Sydney Water to develop deterioration curves through rigorous statistical analysis and the use of physical/probabilistic models. The PARMS-Priority model is primarily based on five key tasks: risk calculation, failure prediction (using a statistical non-homogeneous Poisson model and a physical/probabilistic model based on fracture mechanics), cost assessment, data exploration (asset and failure records), and scenario evaluation.

Sydney Water then generates a risk score or matrix with the output from the PARMS model, which considers the consequence of failure defined in monetary terms (cost of pipe renewal, customers affected by the loss of water supply, etc.) and probability of a failure. Figure 4-4 illustrates the risk matrix used by Sydney Water where pipelines that fall into the red area have the highest risk and those that fall in the green area have the lowest risk.

Probability of failure			**4**	**3**	**2**	**1**
			>50%	**20% - 50%**	**5% - 20%**	**0% - 5%**
Consequence of Failure	5	>$2M				
	4	$1M - $2M				
	3	$0.75M - $1M				
	2	$0.35M - $0.75M				
	1	$0 - $0.35M				

Figure 4-4. Sydney Water's Risk Ranking Matrix

4.3.5.3 Validation of Condition Assessment Models and Associated Costs for Generating Models. Sydney Water continually validates and calibrates the deterioration curves based on analyses and failure history. It is currently working on refining the statistical model basis within PARMS-PRIORITY that estimates the likelihood of failure based upon functions of pipe length, time, and other covariates. It is also looking into how to measure the likelihood of failure (i.e., using either an annual versus a cumulative probability). Because the PARMS model is developed and calibrated for each participant utility based on its failure data, forecasted performance tends to mirror the actual asset performance. Sydney Water has funded the Water Services Association of Australia for $100,000 to redevelop the PARMS model to a new language and customize it for its use.

4.3.6 Washington Suburban Sanitary Commission. The WSSC is a public utility located in Maryland. The WSSC prioritizes the inspection, maintenance, and renewal of water pipes using methods that vary for different pipe types and diameters.

Currently, the WSSC prioritizes renewal activities (i.e., inspection, maintenance, repair, rehabilitation, and replacement) for distribution water pipes (diameter < 16 inch) based on break frequency through an analysis of work order history, pipe physical property, defect type, and soil corrosivity. In the future, the WSSC plans to implement a water pipe condition rating system based on these parameters (see Section 4.3.6.1). A pipeline is typically replaced if it has experienced three or more breaks within a five-year period.

Condition assessment and renewal activities for transmission mains (diameter ≥16 inch) are dependent upon pipe material. WSSC prioritizes condition assessment for cast iron and ductile iron pipes with diameters ranging from 16 to 48 inches by data mining. Replacement decisions for ferrous pipes are primarily based on the analysis of the work order history, the age or class of pipe, and the presence of lead or leadite joints. Alternatively, WSSC has developed a specific program for condition assessment activities for PCCP transmission pipe (48 inch diameter or greater), which is based on pipe design, pipe materials, size, manufacturer, reliability, and consequence of pipe failure. The program generates a risk rating that WSSC uses to make decisions regarding inspection, repair, rehabilitation, or replacement. Replacement decisions for PCCP are based on findings from pipe inspections.

4.3.6.1 Water Pipe Condition Rating System (Condition Rating Index). WSSC's Utility Master Plan (UMP) is aimed at establishing a baseline condition rating for WSSC's transmission and distribution water pipes. The UMP rating system consists of six risk factors that aid WSSC in prioritizing pipe inspection needs: Land Use Factor (LF), Repair History (RH), Operational Needs (ON), Known Manufacturing Defects (KD), Last Inspected (LI), and Pipe Diameter (DI). Each risk factor is further subdivided into several rating factors to generate a score. For example, the last inspected risk factor is subdivided into less than 5 years ago, 5 to 8 years ago, 9 to 12 years ago, 13 to 15 years ago, and 16 to never giving scores of one, two, three, four, and five, respectively. Similar scoring is used for the other risk factors. Overall, the empirical formula defining risk is given by:

$$Risk = (RH + DI + KD) * (ON * 4 + LI)(LF)$$

The use of the risk terminology here by WSSC does not follow the traditional definition of risk equal to the likelihood of failure times the consequence of failure, although factors related to likelihood and consequences of failure are included. The combined risk factor formula does not have an upper limit; however, the WSSC considers a risk value of approximately 80 to be at risk and above 100 to be at greater risk as illustrated in Figure 4-5. At the time this report was written, the rating system did not yet include hydrology or hydraulic factors.

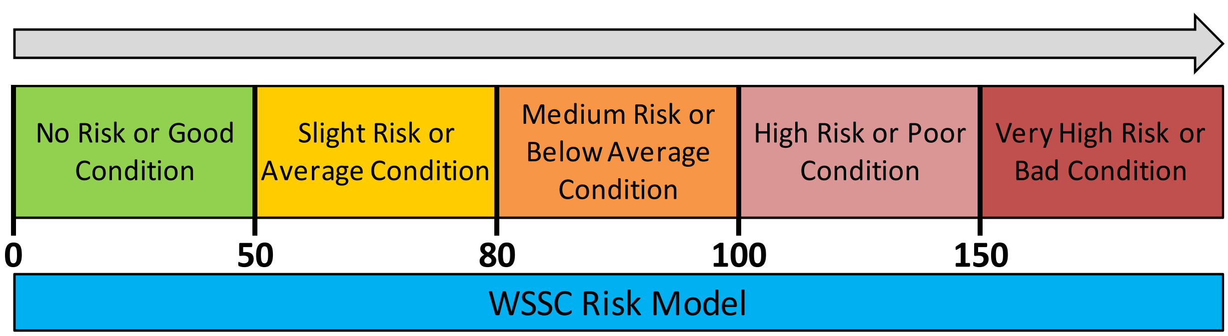

Figure 4-5. WSSC Risk Model Range

4.3.6.2 Validation of Condition Assessment Models and Associated Costs for Generating Models. The water pipe condition rating system was developed in house, however cost details were not provided.

4.3.7 City of Hamilton Public Works Department. The City of Hamilton Public Works Department Water and Wastewater Division is a public utility located in Hamilton, Ontario, Canada. The City of Hamilton has been working towards a goal of the development of a GIS-based Enterprise Asset Management Plan across its transportation, water, and wastewater assets.

4.3.7.1 Infor Hansen Asset Management System (Economic Model). Hamilton has developed a replacement profile for water mains utilizing the Infor Hansen asset management system,[4] which is a key component for estimating the timing of renewal activities. The replacement profile for water mains is primarily based on the age of the asset and is allocated by year (either presented as km of pipe to be replaced per year or revenue requirements per year). The average annual revenue requirements to sustain the City's water network are derived through analysis of capital and operating revenues; however, the exact calculation methods were not presented. This type of analysis appears to be similar to a Nessie curve approach, which is used primarily for long-term capital planning and is not applicable for the annual prioritization of pipeline renewal projects.

4.3.8 Louisville Water Company. LWC has a number of programs in place for managing its water infrastructure assets. In particular, LWC has developed a Pipe Evaluation Model (PEM) for prioritizing water pipe renewal. Additionally, in 1992, LWC established a $150 million, 15-year program designed to replace and rehabilitate approximately 500 miles of unlined cast iron pipe installed between 1860 and 1935, numerous hydrants and valves, and 40,000 lead service lines.

The LWC pipe assessment and replacement decisions have been featured in WaterRF reports (O'Day et al., 1986) and its pipe work has been the subject of an asset management case study as part of the larger Global Water Research Coalition (Bhagwan, 2009).

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

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

The renewal projects are scored according to all of these criteria and then the projects are ranked based upon their degree of importance. LWC uses a criterion of two breaks per mile per year as the threshold for replacement. Additional information about LWC's PEM approach can be found in Bhagwan (2009). An example of LWC's PEM criteria and scoring for physical pipe aspects is shown in Figure 4-6.

[4] For more information, refer to http://www.infor.com/hansen/solutions/asset-management/.

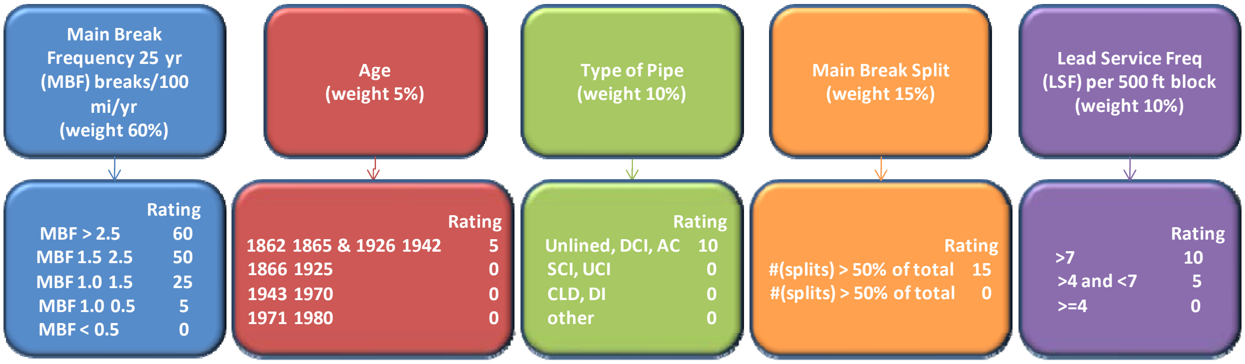

Figure 4-6. Example of LWC's 2007 PEM Criteria and Scoring

4.3.9 Philadelphia Water Department. The PWD serves approximately 1.5 million residents in the Philadelphia, Pennsylvania area. PWD has a long track record of monitoring and recording water main failures. This historical information has served as a useful basis for its asset management decision-making over the years. Since the 1960s, PWD has used a point-score system on a full-scale basis to screen and prioritize water mains for renewal work, as presented in O'Day et al. (1986). This point-score system is still in use today in a modified form as described below, but PWD is researching a more comprehensive approach to asset management.

PWD has taken several steps to advance its overall asset management approach. To date, PWD has established a GIS system to track its network assets and also developed a new hydraulic model that assists in scenario testing to determine the criticality and failure consequence for specific water mains. It is also currently deploying CityWorks®, which has improved maintenance recordkeeping to document more detailed information from the field on each water main break experienced. It is researching the use of the LEYP model to assign a likelihood of failure to a pipeline based on past breaks and other failure factors. PWD has funded the trial of LEYP for approximately $100,000 and the trial is expected to last for a one-year period. Its overall goal is to integrate the resulting information on failure likelihood and failure consequence into a single asset management software program that also takes into account scheduling considerations from street paving schedules in order to optimize the timing of renewal projects.

4.3.9.1 Structural Condition Model (Safety Factor and Deterioration, Decay, and Survival Curves). PWD tested a structural condition model on a research basis as described in Deb et al. (2002), but these models were not deployed on a long-term basis. At the time, PWD undertook a sampling program to assess the physical condition of its water mains. For this sampling program, PWD conducted testing to document the pipe's structural deterioration, inspected water mains that had failed, conducted a pipe-wall analysis of the mains, and classified the surrounding soils. PWD then developed a computer-based model to assess the structural condition of cast iron water mains using inputs such as pipe characteristics, structural properties (tensile strengths), internal and external forces acting on the pipe, age factors (manufacturing techniques, construction practices, etc.), corrosion rates, and soil characteristics. This model was designed to generate a "structural condition rating" where values greater than 1.0 were classified as satisfactory and values less than 1.0 were classified as questionable. The model was found to be sensitive to several factors such as beam span space, corrosion rates, diameter, temperature range, and working pressure and thus concluded that the success of the model depended on accurately determining these difficult to quantify factors.

4.3.9.2 Point System (Break Frequency). PWD has developed a point system for prioritization of water main renewal activities. This point system comprises a combination of the age of the water main and its break frequency. Overall, the goal of the PWD is to replace mains with seven or more points. While this system is currently in use, PWD is testing a more comprehensive approach as described above and expects its use of the point-score system to be phased out over the next few years. Limitations cited were that the point system is heavily weighted toward the age of the pipe, it does not allow for quantification of failure likelihood or consequence in a systematic manner, and it does not allow the City to track trends in breaks from ambient temperature changes, increased road traffic, or other failure factors.

The PWD point system is a series of integrated databases. The PWD evaluates the maintenance history, date and location of main breaks, installation year, size of main, and other information compiled in a database. Each break is tagged with a status code and contract number of the replacement. Status codes include active, on hold, planning, design, etc. Breaks entered each month are printed out and contain all of the break information and the status code of each break. The points assigned for the year of installation and break frequency can be seen in Table 4-4. The points are assigned on a block-by-block basis (which is typically about 500 ft in length for the City of Philadelphia).

Table 4-4. The PWD Points Assigned for Year of Installation and Break Frequency

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

There are some exceptions when assessing the assigned points. For example, cast iron water mains constructed between 1946 and 1954 were installed using leadite joint compound, which has been found to become brittle with age, causing premature joint failures. For the areas with leadite joints, replacement is scheduled after the third break on a block.

Using the point system, PWD has witnessed a decreasing break trend and the target point total for scheduling replacement has decreased from 10 to 7 over time.

4.3.10 The Metropolitan District. The Metropolitan Water District provides water and sewer service to 12 communities, and more than 400,000 people in the Hartford, CT area. Its water distribution system includes 1,600 miles of water mains and 100,000 customer connections. Over 92% of the water mains are cast iron and ductile iron pipes with 67% of the pipes 10 in. diameter or less. The District worked with Malcolm Pirnie to develop its capital improvement program (CIP), which utilizes a combination of break frequency and deterioration curves to ascertain pipe condition and prioritize capital improvement projects (Sekuler and Banciulescu, 2009).

4.3.10.1 Break Frequency and Deterioration, Decay, Survival Curves. According to Sekuler and Banciulescu (2009), the Metropolitan District set out to accomplish three goals for its CIP:

- Create a process for prioritizing and allocating funds for water infrastructure needs on an annual basis;
- Employ a computer model to simulate water main deterioration and its impact on CIP expenditures;
- Establish a defensible, repeatable CIP process.

To achieve these goals, the consultant first compiled an asset inventory to ensure the District had a complete listing of all of its assets and used this data as input into Harfan's Integrated Decision Support System (IDSS) model to simulate asset deterioration and calculate anticipated CIP needs. The District's database already included information on pipe installation year, material, and diameter. Additional data that was added included soil type and operating pressure extrapolated from the District's hydraulic model corresponding to the maximum daily demand. A statistical evaluation was then performed using historical data on water main breaks to develop pipe classes and deterioration curves for use in the computer model. Through this effort, deterioration curves were generated for 21 pipe classes that were identified as having different breakage rate patterns. Each pipe class included a different combination of material, age, soil type, and pipe diameter. Figure 3-3 in Section 3 shows the deterioration curves for 4-in. to 6-in. diameter cast iron. Figure 4-7 below shows an example deterioration curve for cast iron pipes greater than 10-in. diameter, along with the historic break data and end of life for that pipe class predicted by a field sampling program. The pipe replacement threshold was set at a breakage frequency of 80 breaks/100 miles/year and defined as equivalent to a condition index of 0.25 (or 25%).

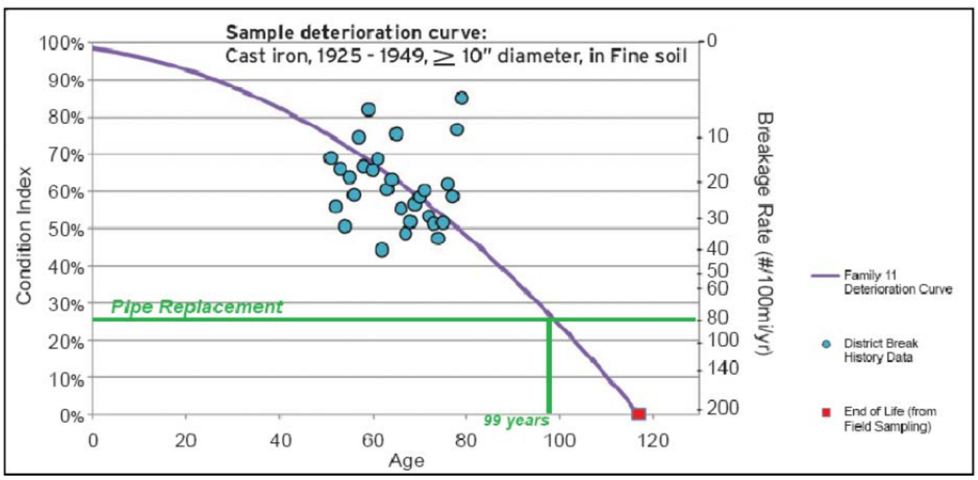

Figure 4-7. Deterioration Curve for Cast Iron Pipe Greater than 10-in. Diameter

Field testing was performed to ascertain in-situ pipe conditions and further refine the pipe deterioration curves to improve model accuracy. The primary goal of the field effort was to assist in the determination of remaining asset life to predict when the water distribution system would need major capital funding investments. The cost for the field testing program was approximately $400,000, which included selecting the sample locations, excavation, pipe coupon and soil sample collection, corrosion studies on the pipe samples, laboratory analysis of the soil samples for corrosivity parameters, and other related work. Half of the 46 pipe coupons collected were from main breaks already exhumed by the utility and the other half were specifically collected for the study from targeted pipe classes of interest. Samples were analyzed by corrosion specialists using metallographic and stereomicroscopic (high magnification) methods. Data was recorded on the extent of corrosion, remaining wall thickness, types(s) of corrosion, failure mechanisms, and then used to estimate remaining asset life. The remaining asset life was incorporated into the deterioration curve as the age at which the condition index was expected to reach 0% (see Figure 4-7). The remaining asset life that was determined for the various pipe classes based on this effort are shown in Table 4-5.

Table 4-5. Pipe Class Replacement Ages

Class #	Pipe Class	Replacement Age (yrs)*
1	Cast Iron:<1925:4-6:<>Fine	130
2	Cast Iron:1925-1949:4-6:<>Fine	93
3	Cast Iron:<1925:4-6:Fine	133
4	Cast Iron:1925-1949:4-6:Fine	72
5	Cast Iron:<1925:8:<>Fine	135
6	Cast Iron:1925-1929:8:<>Fine	94
7	Cast Iron:1930-1949:8:<>Fine	91
8	Cast Iron:<1925:8:Fine	126
9	Cast Iron:1925-1949:8:Fine	87
10	Cast Iron:<1925:>=10:Fine	139
11	Cast Iron:1925-1949:>=10:Fine	99
12	Cast Iron:<1950:>=10:<>Fine	115
13	Cast Iron:1950-1959:<10	80
14	Cast Iron:1950-1959:>=10	102
15	Cast Iron:>1959:4-6	63
16	Cast Iron:>1959:8	74
17	Cast Iron:>1959:>=10	90
18	Ductile Iron	87
19	Other	73
20	Reinforced Concrete	140
21	Concrete	130

The consultant configured the asset model, performed various model scenarios, and worked with the District to develop a 45-year capital improvement program for water mains, valves, pump stations, and storage tanks. The timing for the water main replacement was based upon a pipeline's physical condition falling below the 25% condition index (e.g., 80 breaks/100 miles/year). A pipeline would not be placed onto the CIP schedule until this criteria was met. Each year, the highest priority projects can be identified based upon physical condition (via break history and field condition assessment), functional condition (pressure, fire flow, capacity), and socio-economic (criticality, flow, traffic, critical customers, and access problems) factors. Ultimately, the project benefitted the District by allowing it to identify the highest priority projects that would fit within each year's annual capital improvement budget. The City has the capability to continue to update the model input and output based upon the latest information stored in its GIS and maintenance records (e.g., pipe repairs and break history). The City was able to save funding resources by using the process to optimize the timing of renewal projects to coincide with the town's paving schedules and combined sewer overflow separation plan (Sekuler and Banciulescu, 2009).

4.3.11 The Los Angeles Department of Water and Power. In the summer of 2009, LADWP conducted an investigation of its water main leaks to determine the cause(s) for the increase in distribution main breaks on cast iron pipe (LADWP, 2010). In its preliminary investigative report, plans for transitioning to a more formalized and proactive pipe replacement program were presented as detailed below.

4.3.11.1 Break Frequency Curves. Prior to 2007, the LADWP primarily used a reactive strategy for water main replacement with the primary drivers being failure modes of repeated leaks or insufficient capacity. However, according to a 2009 water main preliminary leak investigation report (LADWP, 2010), LADWP is transitioning to a more proactive replacement program to better prioritize and target the appropriate water mains for renewal. LADWP is working to develop a predictive model that uses existing data for factors that contribute to water main deterioration (pipe material, soil corrosivity, construction methods, and other internal/external conditions) to determine replacement priority for all pipe segments in the system. The results of the model, combined with pipe criticality assessments and leak history, will be used to focus resources on pipe segments that are more likely to fail and disrupt service.

4.4 Summary of State-of-the-Practice Review

The municipalities and utilities that participated in the survey have very different inspection, condition assessment, and renewal prioritization techniques. Most utilities apply some form of break frequency curve often combined with an economic model to prioritize pipeline renewal activities. Some utilities use more sophisticated deterioration curves; however, they typically required the assistance of external consultants and/or computerized modeling programs. A table illustrating the utilities condition and/or economic models can be seen in Table 4-5.

Based on the survey results and review of other case studies in the literature, a select number of medium to large size utilities are using a formal condition assessment process involving either break frequency and/or condition rating curve/index. This approach is often combined with an economic model in order to both prioritize pipe renewal in the short term and capital improvement budgets over the long term. Input for these models is generated from a number of different inspection, monitoring, and condition assessment techniques. In general:

- Inspection, monitoring and condition assessment techniques are dependent on the pipe properties and differ significantly across utilities.
- The types of "condition curves" and the factors used to generate the curves vary significantly across utilities and are dependent on the utility's asset management objectives. These objectives included using the condition curves to drive renewal timing decisions for pipelines and/or for long-term capital investment planning.
- Based on the survey results, break frequency and condition rating curve/index (with threshold values) are the most common approaches used by the utilities to prioritize water pipe renewal.
- Condition curve development is dependent on site-specific factors such as pipe material; pipe diameter; maintenance practices; leakage and main break history; operational conditions; pipe criticality; environmental conditions, etc. which vary significantly across utilities.
- Six of the nine utilities surveyed are combining the results of long-term economic forecasting models with their "condition curve" models to facilitate asset management decision-making.
- Validation of condition curves is not a priority for most utilities surveyed and the validation process could take years or even decades. Therefore, few utilities have validated their models; however, most of the utilities surveyed felt confident about the results generated from their models.
- Utilities incur exceptionally different costs for their condition assessment programs which are dependent on the extent of inspections, monitoring, testing, software development, data

management, resources, etc. The software and programs utilized by each utility vary based on their needs and budget.

- All of the utilities surveyed use some form of GIS platform to integrate their water infrastructure and condition assessment data.

Table 4-6. Summary of Utility Inspection, Condition Index/Performance Measures, and Models

Utility	Types of Condition Curves: Break Freq.	Deter., Decay, Survival	Cond. Rating /Index	Service -ability	Econ.	Models
EPCOR Water Services Inc. (Canada)	X		X			Reactive Renewal Program Proactive Renewal Program
Las Vegas Valley Water District (LVVWD) (Nevada)	X	X			X	Computer Aided Rehabilitation of Water Networks (CARE-W) Casses Linearly Extended Yule Process (LEYP)
Newport News Waterworks (Virginia)	X				X	Pipe Prioritization Replacement Model Nessie Curve Economic Model[1]
Seattle Public Utilities (SPU) (Washington)			X		X	Water Main Replacement Model Wave Rider Economic Model
Sydney Water (Australia)		X	X		X	PARMS-PRIORITY (Water Main Prediction Model) KANEW Economic Model
Washington Suburban Sanitary Commission (WSSC) (Maryland)	X		X		X	UMP Condition Rating System Nessie Curve Economic Model[1]
City of Hamilton Public Works Department (Canada)					X	Hansen Asset Management System Economic Model
Louisville Water Company (LWC) (Kentucky)	X		X			Pipe Evaluation Model (PEM)
Philadelphia Water Department (PWD) (Pennsylvania)	X	X				Structural Condition Rating System Point System
The Metropolitan District Hartford, Connecticut)	X	X				Break Frequency and Deterioration Curves
Los Angeles Department of Water and Power (LADWP) (California)	X					Reactive Renewal Program Proactive Renewal Program
United Kingdom Office of Water (OFWAT) (United Kingdom)	X			X		Serviceability based on Performance Indicators (Break Frequency)

(1) The use of Nessie curves by these utilities is not discussed in the text because the scope of the report does not include this type of curve, which is primarily an economic forecasting model.

As evidenced by the above summary, a number of different approaches are being implemented by utilities, yet validation of the approaches is limited or non-existent. The various users indicated that they were satisfied with their particular mix of tools, but reported large differences in the costs for developing and implementing such tools. Without data on the accuracy and value of the various pipe condition curves, there is a limited basis for the selection of one approach over another.

No one curve or index will meet all utility needs. The approaches described here are flexible enough to be customized to meet the site-specific conditions and needs of other utilities. The approximately 52,000 community water systems in the U.S. might benefit from recommendations, guidance, and training on the best practices related to asset management tools, models, curves, and indices currently available as they move toward adopting more formalized asset management programs.

5.0: FINDINGS AND RECOMMENDATIONS

5.1 Selecting the Approach

Condition curves are very site specific and a clear understanding is needed of the basic assumptions built into the curves. With sufficient data and an understanding of failure modes and causes of distress, a utility can effectively use condition curves to make replacement decisions; however, it is unlikely that a single condition curve will work for an entire network. Curves will need to be generated for various pipe classes and take into account the appropriate factors (e.g., environmental conditions, operational and maintenance practices, pipe types, diameters, vintages, installation practices, etc.).

Like all tools, condition curves need to be appropriate to the task and the conditions being evaluated. It is important to accept that like any tool they don't provide the answer, but assist the user in reaching one. Curves and the methods used to develop the curves range from simplistic to complex. The more extensive the factors that are taken into consideration, the more data hungry and complex the analysis becomes for utilities.

The current short-term approach to condition assessment is to use readily available data, rather than collect and/or integrate the appropriate data for making predictions and setting priorities. Every utility has a wealth of environmental, historical, and operational information that has been or can be developed into an asset database.

Those utilities that use condition curves tend to focus on the majority of pipe types in their systems, divided into specific pipe classes. For those utilities that participated in the survey, the focus of their condition assessment programs was primarily on ductile iron and cast iron, with slightly less focus on AC, PCCP, and plastic pipe types. Development of condition curves for ductile iron, cast iron, and PCCP can be somewhat easier because utilities have a fairly good understanding of the failure modes and mechanisms and can collect data on failure indicators. Plastic pipes, on the other hand, have very different failure mechanisms that are far more difficult to detect, making it more complex to develop accurate condition curves and failure predictions.

Condition curves have greater potential application for smaller diameter distribution mains, which dominate both the total water pipe mileage and the number of failures. There is a much greater body of historical experience of failures and defects for smaller diameter pipes that can be used in the development of condition curves and management of the network. For many smaller diameter pipes with a relatively low replacement cost, it is not cost effective to obtain direct condition data by investigation or laboratory testing, particularly because the consequence of failure from small diameter pipes is much less. For these reasons, utilities need simple methods to prioritize their renewal activities for small diameter pipes. For small diameter pipes break frequency curves combined with economic models appear to be the most common approach. These methods are easier and less costly to develop, yet provide sufficient information to do a fair job at supporting renewal scheduling of smaller distribution pipes. Utilities prefer to set limits on the number of breaks where it becomes more cost effective to replace or rehabilitate than to repair low risk pipelines. Break frequency curves are not meant to identify the date when the next failure will occur; rather, they are used to forecast future trends in breakage rates.

Although larger diameter pipes represent a small percentage of the network and failures are much less frequent, the consequences of failure are much greater. In addition, the forms of defects and modes of failure for large diameter pipes also tend to differ from smaller diameters and there is relatively sparse historical data on which to develop the condition curves. For these high risk pipelines, where failures are catastrophic and unacceptable at any time, more extensive and complex approaches may be warranted and cost effective. Condition curves for larger diameter pipes should generally be generated from hard data based on NDT inspections, investigations, and/or laboratory testing to define pipe condition and obtain more accurate predictions of remaining life.

5.2 Application of Condition Assessment Models

Many different condition assessment approaches, some of which were described in Section 3, have been developed by researchers and consultants. Many models have yet to be validated or verified because of a shortfall in the quantity and quality of available data. In addition, the level of training and expertise in statistics required to operate some of the techniques are not always available within a utility. There is a gap in enthusiasm between those who develop condition assessment models and those who need to use them. The model developers need to show how they use the data in their models and prove the business case to utility employees and managers.

A general consensus is that any condition curve should be simple to understand, transparent to the users, and easy to implement. Validation of the model with “real-world” case studies is also important. While the model should be transparent and easy to use, the person implementing the model should be an engineer or technical staff member with sufficient experience to understand the inherent complexities and the correctness of assumptions used in the model.

- A number of mathematical models have been proposed, yet few utilities have translated these models and/or methods into a practical asset management tool. It is recognized that many models are mathematically complex and will require special skills to operate. Most utilities are uncomfortable with inputting data and leaving the model to provide the answer.
- Limitations of model capabilities are not in mathematics, but in lack of fundamental understanding of pipe performance based on environmental factors combined with failure modes and mechanisms.
- For some models, the underlying assumptions for factors and their weighting are not clear and may not be applicable to all utilities.
- Without adequate data, models cannot make informed predictions and it can be very costly to collect and manage the level of data that are required. The cost of acquiring the necessary data must be balanced against the pipe criticality.

What is not readily available and is needed by utilities contemplating the use of models to construct condition curves is information on the varying approaches. For example:

- How proven is a particular piece of software in providing the required level of performance and decision-making help?
- What is the basis for deciding which of the competing approaches is the most suitable for a utility and its particular conditions?
- How well do predictions correspond with actual events for a range of pipe types and conditions?
- Can the utility operate the model using its own staff? Does it require specialists or consultants to undertake the work?
- What level of data and in what format is needed to operate these methods? Is the model capable of dealing with partial data when complete data are not available?

- What kind of costs will a utility incur in setting up and effectively operating any particular approach?
- How transparent is the method in terms of the assumptions used and their relevance to a particular need of a utility? Has the underlying model been published and received peer-acceptance?
- Can the model be modified to take into account differing conditions and their relative importance?
- How much calibration of the model is required to make it work with a utility's data?

5.3 Short-Term Needs and Improvements

Overall, significant challenges still remain in predicting the remaining asset life of water mains using condition curves including:

- A range of factors influence the condition and performance of water pipe infrastructure, which makes it nearly impossible to develop universally applicable condition curves.
- There is a lack of historical databases, standard data collection and analysis protocols for the development of robust condition curves capable of accurately predicting asset life.
- There is no clear definition of pipe 'failure'— some utilities consider a water pipe leak as a failure, while other utilities consider water pipe burst/rupture as a failure.
- Development costs are often the limiting factor when it comes to selection of condition assessment strategies. Utilities generally do not have a budget that would allow large investment and therefore less advanced techniques are usually chosen.
- For distribution systems, the need is for less expensive options to estimate remaining life that are likely to have a lower performance standard.

Based on the above gaps, several recommendations are provided for improving condition curve methods for predicting the condition/performance of water pipes.

- Development of condition curve methodologies that use standardized data collection and reporting and can then be calibrated to site-specific data and conditions and then tested for a range of utilities.
- Continue to refine critical inferential parameters that affect water pipe performance based on pipe material, diameter, joint type, external and internal environmental factors, etc.
- Develop methods to improve the quality, quantity, and accessibility of condition/performance assessment data. Additional research is needed on how to design more efficient and cost-effective data collection strategies, how to extract information from existing datasets, and how to standardize names and definitions for water utility assets, which subsequently will allow the data to be shared and compared across utilities.
- Due to restrictions imposed by the Paperwork Reduction Act, only surveys from nine utilities are reported. It may be of value to conduct a larger scale utility survey to develop a more extensive database on who is using condition curves/deterioration models and for what purposes.

- Pilot existing and/or new models at various utilities to define their practical use and ease of adoption by utilities.
- New technologies with the potential for improving the pipe condition/performance assessment process continue to emerge, and utilities need help in their technical and economic evaluation.

5.4 Long-Term Needs and Improvements

Beyond the short-term needs, there is a fundamental long-term need to develop a performance-based buried infrastructure asset management approach that involves a major improvement in the quality and quantity of data used by all utilities.

The lack of data for many utilities is a major limitation in using anything, but the most basic approaches to condition assessment. Ideally, pipe material, size, age, type of bedding, soil characteristics, operating pressures, water temperatures, time, place and type of historical breaks should be available. However, in many cases, only partial sets of data exist. A robust model or condition curve should be able to deal with partial data, but it should be clear that in general the results will be less accurate and less precise compared to those results obtained with a more complete dataset.

A second serious limitation is the lack of consistency or thoroughness in terminology and data collection, which inhibits comparison of data amongst utilities or for research. For example, identifying critical trends in main failures is complicated with different definitions of "water main break." Some consider any leak, big or small, from a joint or a small perforation, to be a "water main break," while others consider only large breaks where the line is no longer functioning to be classified as a "water main break."

WaterRF and WERF have suggested data sets for asset management, both at the higher level (strategic) and lower levels (operational or tactical). WaterRF projects have especially considered lower level data related to condition assessment, pipeline renewal, optimizing the distribution system, and performance of pipe materials. A broad overview of data obtained during condition assessment is included in a WERF-WaterRF report titled "Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets" (WERF, 2007). Examples of lower level data are the field data that may be collected after a pipe is exposed for repair or maintenance work (Grigg, 2004; Matichich et al., 2006).

Some guidance should also be developed for identifying and quantifying the high risk scenarios, which requires characterizing both the likelihood and consequence of failure. With limited funds, it is necessary for utilities to focus on the highest risk situations to limit the impact of failures on consumers and the public.

The longer-term goal should be to develop a national database of assets and failures with common terminology and methods of data collection and analysis for assets and breaks. Relating breaks and leaks to specific pipe materials and environments would support the decision-making processes of utilities and allow them to benchmark their own experience against other utilities to provide more realistic life expectancy predictions. Ultimately, this will allow identification of the most vulnerable pipes, reduce failures, and improve understanding of the type and distribution of failure modes and mechanisms. It will also facilitate improved allocation of funds in long-term replacement or rehabilitation programs.

An example of the successful implementation of a national asset and failure database is the UKWIR mains break and asset databases in the U.K. 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 % 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. This database has provided valuable insights into both national and regional patterns of failure for all types of pipe material (Trew and Mills, 2011). WaterRF Project #4195, in partnership with UKWIR, is currently assessing the adaptability of the UKWIR database to the U.S.

Further understanding is needed on the distress factors and their combination that lead to failure. A great deal of valuable research has been undertaken and further projects are currently underway. What is apparent is that the combinations of distress factors vary in their importance according to location and local conditions. For example, the role of freezing soils and low temperatures is not a concern in Florida. Understanding and guidance are needed not just on the distress indicators, but their combinations that become critical in differing situations.

Design life is often stated as some definitive number of years under normal operating conditions. The reality is that the operational life of pipes is highly variable in relation to the calculated design life. Many pipes have already doubled their design lives and others have failed in less than half that time. Design life needs to go further than just specifying a pipe that meets the capacity and pressure requirements by looking it up in the manufacturer's design guide and then developing layouts covering alignment, grade and depth with appropriate appurtenances. To obtain longer service lives and reduce premature failures, other factors that lead to failure need to be taken into account. Investigation of failures indicates that many problems arise from improper handling, installation and operation. In addition, pipe performance depends on a number of local factors such as soil conditions, temperature, and installation practices. Current design guides for water mains make no reference to corrosion.

An example of this wider approach is AltPipe, a Web-based tool that can be used to assist designers in the appropriate selection of pipe materials for culvert and storm drain applications. The AltPipe tool was developed by the California Department of Transportation and takes into account various combinations of pipe materials, dimensions, fluid compositions, operating conditions, liners, and coatings in the design of culverts. The AltPipe experience, although not directly applicable to pressure pipes, provides a useful example for developing a more realistic approach to design life. The AltPipe tool is available at http://dap1.dot.ca.gov/design/altpipe/.

5.5 Conclusions

Any asset management program must start with a thorough review of available historical data about pipe performance and failure. Once the necessary data are gathered, condition curves and/or deterioration models can go a long way in providing insight into the condition of these assets. Currently, only large water mains with costly consequences of failure may justify the cost of accumulation of data that are required for physical model application, whereas the empirical/statistical models are an economically viable approach for the smaller distribution water mains. For both large and small diameter pipes, condition curves and deterioration models can help to evaluate current asset condition, assess the rate of deterioration, and help to predict future condition and remaining asset life. This information can benefit utilities by creating a repeatable and technically defensible process for prioritizing and allocating funding for capital improvement plans. With sufficient data and understanding of failure modes and causes of distress, a utility can also use condition curves to make renewal decisions based upon remaining asset life.

6.0: REFERENCES

American Water Works Association (AWWA). 2004. *Water://Stats 2002 Distribution Survey*. American Water Works Association, Denver, CO.

American Water Works Association (AWWA). 2001. *Dawn of the Replacement Era, Reinvesting in Drinking Water Infrastructure,* American Water Works Association, Denver, CO.

AwwaRF. 1993. *Performance of Prestressed Concrete Pipe,* AwwaRF Project No. 724 (unpublished; see references for U.S. Bureau of Reclamation reports).

Batista, J., and H. Alegre. 2002. "CARE-W WP1 D2 - Validation of the Rehabilitation Performance Indicators System." National Civil Engineering Laboratory, Lisbon, Portugal.

Bhagwan, J.N. 2009. "Compendium of Best Practices in Water Infrastructure Asset Management." Global Water Research Coalition, London, U.K.

Bianchetti, R. 1993. "Corrosion and Corrosion Control of Prestressed Concrete Cylinder Pipes." Corrosion Control Conference. New Orleans.

Buckland, P. and N. Hastings. 2001. "The Replacement Decision for 'Linear Assets'", International Conference of Maintenance Societies – ICOMS 2001.

Burn, S., P. Davis, T. Schiller, B. Tiganis, G. Tjandraatmjadja, M. Cardy, S. Gould, P. Sadler, and A. Whittle. 2006. *Long-Term Performance Prediction for PVC Pipes*, prepared for CSIRO, Victoria, Australia, IWA Publishing.

Burn, S., P. Davis, T. Schiller, B. Tiganis, G. Tjandraatmadja, M. Cardy, S. Gould, P. Sadler, and A.J. Whittle. 2005. *Long-Term Performance Prediction for Polyvinyl Chloride Pipe.* AWWA Research Foundation, Denver, CO.

Davis, P., S. Burn, S. Gould, M. Cardy, G. Tjandraatmadja, and P. Sadler. 2007. *Long-Term Performance Prediction of PE Pipe*. AWWA Research Foundation, Denver, CO.

Deb, A.K., Grablutz, F.M., Hasit, Y.J., Snyder, J.K., Loganathan, G.V. and N. Agbenowsi. 2002. *Prioritizing Water Main Replacement and Rehabilitation.* AWWA Research Foundation, Denver, CO.

Deb, A.K. 1994. *Water Distribution System Performance Indicators*, Water Supply IWSA (Zurich) 12(3/4), pp. 11-20.

DERM. 2001. *Guidelines for Implementing Total Management Planning - Asset Management: Asset Evaluation and Renewal Implementation Guide.* (Australia), 27 pp.

Eisenbeis, P., Y. Le Gat, K. Laffrechine, P. Le Gauffre, A. Konig, J. Rostum, L. Tuhovak and P. Valkovic. 2002. "Report No. 2.1: Report on Models Description," WP2 – Description and Validation of Technical Tools, Aug.

Farshad, M. 2006. *Plastic Pipe Systems: Failure Investigation and Diagnosis*, Elsevier Science.

Gaewski, P. and F. Blaha. 2007. *Analysis of Total Cost of Large Diameter Pipe Failures*. AWWA Research Foundation, Denver, CO.

Grigg, N.S. 2007. *Main Break Prediction, Prevention and Control.* AWWA Research Foundation, Denver, CO.

Grigg, N.S. 2004. *Assessment and Renewal of Water Distribution Systems.* AWWA Research Foundation, Denver, CO.

Grablutz, F. and S. Hanneken. 2000. "Economic Modeling for Prioritizing Pipe Replacement Programs," presented at the AWWA Infrastructure Conference and Exhibition, Baltimore, MD, 14 March.

Hadzilacos, T., D. Kalles, N. Preston, P. Melbourne, L. Camarinopoulos, M. Eimermacher, V. Kallidromitis, S. Frondistou-Yannas and S. Saegrov. 2000. "UTILNETS: A Water Mains Rehabilitation Decision Support System," *Comp., Envir. and Urb. Syst.*, 24(3), 215-232.

Hartwell, J. 1994. *Findings of Petrographic Investigations of Embedded Cylinder Prestressed Concrete Pipe*, prepared for U.S. Bureau of Reclamation (USBR), Denver, CO, September.

Horn, G. 2010. Personal Communication between James Thomson and Gregg Horn of DIPRA.

Hu, Y., Wang, D., and R. Chowdhury. 2010. "Condition Assessment Methods for AC Pipe and Current Practices." Centre for Sustainable Infrastructure Research, National Research Council Canada, Regina, SK. September.

Institute of Public Works Engineering Australia (IPWEA). 2006. *The International Infrastructure Management Manual.* NAMS Group, New Zealand.

Kleiner, Y., and B. Rajani. 2004. "Quantifying Effectiveness of Cathodic Protection in Watermains: Theory." *ASCE Journal of Infrastructure Systems*, 10(2), 43-51.

Kleiner, Y., R. Sadiq, and B.B. Rajani. 2006. "Modeling the Deterioration of Buried Infrastructure as a Fuzzy Markov Process." *Journal of Water Supply Research and Technology*, 55(2), 67-80.

Kleiner, Y. and B.B. Rajani. 2001 . "Comprehensive Review of Structural Deterioration of Water Mains: Statistical Models." *Urban Water*, 3, (3), pp. 157-176.

Kleiner, Y., and B. Rajani. 2009. "I-WARP: Individual Water Main Renewal Planner." Computing and Control in the Water Industry 2009: Integrating Water Systems, Sheffield, U.K.

Le Gat, Y. and P. Eisenbeis. 2000. "Using Maintenance Records to Forecast Failures in Water Networks," *Urban Water*, 2(3), 173-181.

Los Angeles Department of Water and Power (LADWP). 2010. *Summer 2009 Water Main Leaks Preliminary Investigation Report*. 14 pp. LADWP, Los Angeles, CA. 14 pp.

Malandain, J., P. Le Gauffre and M. Miramond. 1999. “Organizing a Decision Support System for Infrastructure Maintenance: Application to Water Supply Systems,” J. of Dec. Syt., 8(2), 203-222.

Marlow, D., S. Heart, S. Burn, A. Urquhart, S. Gould, M. Anderson, S. Cook, M. Ambrose, B. Madin, A. and Fitzgerald. 2007. "Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets." Water Environment Research Foundation, Alexandria, VA.

Marlow, D., P. Davis, D. Trans, D. Beale, S. Burn, and A. Urquhart. 2009. *Remaining Asset Life: A State of the Art Review*, prepared for WERF, WERF Project No. SAM1R06d, Alexandria, VA.

Matichich, M., R. Booth, J. Rogers, E. Rothstein, E. Speranza, C. Stanger, E. Wagner, and P. Gruenwald. 2006. *Asset Management Planning and Reporting Options for Water Utilities.* AWWA Research Foundation, Denver, CO.

Moglia, M., S. Burn, and S. Meddings. 2006. “Decision Support System for Water Pipeline Renewal Prioritization,” *Journal of Information Technology in Construction* 2: 237-256.

Moser, A.P. and K.G. Kellogg. 1994. *Evaluation of Polyvinyl Chloride (PVC) Pipe Performance*. AWWA Research Foundation, Denver, CO.

National Research Council of the National Academies (NRC). 1995. *Measuring and Improving Performance*. National Academies Press, Washington, D.C.

Nelson, R. 2005. “Evaluating Pipeline Reinvestment Needs & GASB 34,” Presented at the North American Society for Trenchless Technology (NASTT) NO-DIG 2005 Conference, Orlando, FL, 24-27 April.

O’Day, D.K., R. Weiss, S. Chiavari, and D. Blair. 1986. *Water Main Evaluation for Rehabilitation/Replacement*. AWWA Research Foundation, Denver, CO.

OFWAT. 2000. “Serviceability of the Water Main and Sewer Networks in England and Wales up to March 1999.” OFWAT Information Note No 35A, London, England.

Ojdrovic, R.P., C. Moody, M.T. Schroeder, M.S. Zarghamee, and M. Scali. 2007. “Condition Assessment of an Asbestos Cement Pipeline,” *Pipelines 2007 Conference Proceedings: Advances and Experiences with Trenchless Pipeline Projects*.

Opus Consultants. 2001. "New Zealand Asbestos Cement Water Mains Manual" Wellington, New Zealand.

Pelletier, G., Mailhot, A., and J.P. Villeneuve. 2003. “Modeling Water Main Breaks." Journal of Water Resource and Management, 129(2), 115-123.

Price, R., R. Lewis, and B. Erlin. 1990. "Effects of Environment on the Durability of Prestressed Concrete Cylinder Pipe.” ASCE Conference Pipelines in the Constructed Environment.

Rajani, B.B. 2000. *Investigation of Grey Cast Iron Water Mains to Develop a Methodology for Estimating Service Life*. AWWA Research Foundation, Denver, CO.

Rajani, B. and Y. Kleiner. 2001. "Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models," *Urban Water*, 3(3), 151-164.

Rajani, B. and Y. Kleiner. 2002. "Towards Pro-active Rehabilitation Planning of Water Supply Systems," *Proceedings of the International Conference on Computer Rehabilitation of Water Networks CARE-W*, Dresden, Germany, November, pp. 29-38.

Romer, A.E., G.E.C. Bell, D. Ellison, and B. Clark. 2008. *Failure of Pre-Stressed Concrete Cylinder Pipe*. AWWA Research Foundation, Denver, CO.

Rose, D. 2008. Power Point Presentation. EPA Technical Forum. Washington, D.C.

Rostum, J., S. Saegrov, J. Vatn and G.K. Hanson. 2000. "Aquarel – A Computer Program for Water Network Reliability Analysis Combining Hydraulic, Reliability and Failure Time Models," *Water Network Modeling for Optimal Design and Management*, Woodbury Park, UK, Sept. 11-12.

Sekuler, L. and C. Banciulescu. 2009. "Developing a CIP Using Deterioration Modeling and Field Sampling Approach," presented at the AWWA Third Leading-Edge Conference on Strategic Asset Management, Miami, FL, November 11-13.

Stone, S., E. Dzuray, D. Meisegeier, A. Dahlborg, and M. Erickson. 2002. *Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems*, prepared for U.S. EPA National Risk Management Research Laboratory, EPA/600/R-02/029, Edison, NJ.

Thomson, J. 2010. *Inspection Guidelines for Wastewater Force Mains*, prepared for WERF, WERF Project No. 04-CTS-6URa, May.

Travers, F. 1994. *Acoustic Monitoring of Prestressed Concrete Pipe at the Agua Fria River Siphon*, prepared for U.S. Bureau of Reclamation (USBR), Denver, CO, December.

Trew, J. and D. Mills. 2011. "Case Study No.1 Polythene Pipe Failures on Water Mains." UKWIR National Sewers and Water Mains Failure Database. January.

Ugarelli, R. and S. Bruaset. 2010. *Review of Deterioration Modelling Approaches for Ageing Infrastructure*. SINTEF Building and Infrastructure. Norway. August.

U.K. Water Industry Research (UKWIR). 2001. *Understanding Burst Rate Patterns of Water Pipe*., Report 01/WM/02/14, U.K. Water Industry Research, Queen Anne's Gate, London, U.K.

U.K. Water Industry Research (UKWIR). 2004. *Nationally Agreed Failure Data and Analysis Methodology for Water Mains*. Vol. 1 (03/RG/05/7) and Vol. 2 (03/RG/05/8). U.K. Water Industry Research, Queen Anne's Gate, London, U.K.

United States Environmental Protection Agency (U.S. EPA). 2002. Deteriorating Buried Infrastructure Management Challenges and Strategies. Prepared by American Water Works Service Company for U.S. EPA, Office of Water. Washington, DC.

United States Environmental Protection Agency (U.S. EPA). 2011a. *Evaluation of Condition Assessment Technologies for Water Transmission and Distribution Systems*. Office of Research and Development. Cincinnati, OH.

United States Environmental Protection Agency (U.S. EPA). 2011b. "National Primary Drinking Water Regulations."

Uyeda, H.K., M.T. Peabody, and D.T. Johnson. 1994. *Concrete Pipe Failure Jordan Aqueduct*, Reach 3, prepared for U.S. Bureau of Reclamation (USBR), Denver, CO, July.

Von Fay, K.F. and M.T. Peabody. 1994. *Historical Performance of Buried Water Pipe Lines*, prepared for U.S. Bureau of Reclamation (USBR), Denver, CO, September.

Water Research Center (WRc). 2003. *Manual of Sewer Condition Classification*, fourth edition, December.

Water Environmental Research Foundation (WERF). 2007. *Condition Assessment Strategies and Protocols for Water and Wastewater Utility Assets*. Water Environment Research Foundation, Alexandria, VA.

Water Research Foundation (WaterRF). In progress a. *Long-Term Performance of Ductile-Iron Pipe*, research being conducted by the National Research Council of Canada, WaterRF Project No. 3036.

Water Research Foundation (WaterRF). In progress b. *Fracture Failure of Large Diameter Cast Iron Water Mains*, research being conducted by the National Research Council of Canada, WaterRF Project No. 4035.

Water Research Foundation (WaterRF). In progress c. *Long-Term Performance Prediction of Steel Pipe*, partnership with Commonwealth Scientific & Industrial Research Organization, Australia, WaterRF Project No. 4318.

Water Research Foundation (WaterRF). In progress d. *Long Term Performance of Asbestos Cement Pipe*, research being conducted by the National Research Council of Canada, WaterRF Project No. 4093.

Water Research Foundation (WaterRF). In progress e. Access to UKWIR Failure Data for Analysis Methodology for Water Mains. WaterRF Project No. 4195.

Weimer, D. 2001. "Water Loss Management and Techniques." DVGW Technical Report, Germany.

Woodhouse, J. 1999."Innovative Approaches to Decision Making for the Management of Aging Physical Assets." The SALVO Project.