Water Research Foundation
advancing the science of water

Los Angeles Department of Water & Power

State of the Science: Plastic Pipe

Project #4680

State of the Science:
Plastic Pipe

About the Water Research Foundation

The Water Research Foundation (WRF) is a member-supported, international, 501(c)3 nonprofit organization that sponsors research that enables water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

WRF's mission is to advance the science of water to improve the quality of life. To achieve this mission, WRF sponsors studies on all aspects of drinking water, including resources, treatment, and distribution. Nearly 1,000 water utilities, consulting firms, and manufacturers in North America and abroad contribute subscription payments to support WRF's work. Additional funding comes from collaborative partnerships with other national and international organizations and the U.S. federal government, allowing for resources to be leveraged, expertise to be shared, and broad-based knowledge to be developed and disseminated.

From its headquarters in Denver, Colorado, WRF's staff directs and supports the efforts of more than 800 volunteers who serve on the board of trustees and various committees. These volunteers represent many facets of the water industry, and contribute their expertise to select and monitor research studies that benefit the entire drinking water community.

Research results are disseminated through a number of channels, including reports, the Website, Webcasts, workshops, and periodicals.

WRF serves as a cooperative program providing subscribers the opportunity to pool their resources and build upon each other's expertise. By applying WRF research findings, subscribers can save substantial costs and stay on the leading edge of drinking water science and technology. Since its inception, WRF has supplied the water community with more than $460 million in applied research value.

More information about WRF and how to become a subscriber is available at www.WaterRF.org.

State of the Science: Plastic Pipe

Prepared by:
Katherine D. Martel and Ken Klewicki
The Cadmus Group, Inc., 100 5th Avenue, Suite 100, Waltham, MA 02451

Jointly sponsored by:
Water Research Foundation
6666 West Quincy Avenue, Denver, CO 80235-3098

and

Los Angeles Department of Water & Power
111 N. Hope Street, Rm. 1425, Los Angeles, CA 90012

Published by:

DISCLAIMER

This study was jointly funded by the Water Research Foundation (WRF) and the Los Angeles Department of Water & Power (LADWP). WRF and LADWP assume no responsibility for the content of the research study reported in this publication or for the opinions or statements of fact expressed in the report. The mention of trade names for commercial products does not represent or imply the approval or endorsement of WRF or LADWP. This report is presented solely for informational purposes.

ISBN 978-1-60573-267-1

Printed in the U.S.A.

TABLE OF CONTENTS

The following Appendix is posted on the #4680 project page on the WRF website, under Project Papers:

LIST OF TABLES

LIST OF FIGURES

FOREWORD

The Water Research Foundation (Foundation) is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The Foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the United States (U.S.) Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the Foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The Foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the Foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The Foundation's trustees are pleased to offer this publication as a contribution toward that end.

Charles M. Murray
Chair, Board of Directors
Water Research Foundation

Robert C. Renner
Chief Executive Officer
Water Research Foundation

ACKNOWLEDGMENTS

The authors acknowledge the assistance and expert input from the WRF Research Manager, Jian Zhang, and the following Project Advisory Committee (PAC) members: Alvin Bautista (LADWP), David Hughes (American Water), Xavier Irias (EBMUD), and Josh Vincent (WaterOne).

This report would not be possible without the time and expert input from the following participating utilities that provided case study information, contributed to workshop discussions, and reviewed the draft report:

- American Water
- Anchorage Water and Wastewater Utility
- City of Calgary, Canada
- East Bay Municipal Utility District
- EPCOR Water Services Inc., Edmonton, Alberta, CAN
- Golden State Water Company
- Honolulu Board of Water Supply
- Los Angeles Department of Water and Power
- Louisville Water Company, KY
- New York City Department of Environmental Protection
- Seattle Public Utilities
- WaterOne, Johnson County, KS

The following staff from The Cadmus Group provided technical support. Sandie Koenig, P.E. completed a quality assurance review of the draft report. Ana Rosner developed infographics and helped with editing and formatting. Natalie Auer assisted with the literature review.

EXECUTIVE SUMMARY

The objective of this project was to develop a white paper on field applications of plastic pipe by drinking water utilities. The white paper was developed based on a literature review and a project workshop with participating utilities.

Plastic pipe has been widely used in the drinking water industry for water transmission and distribution. The primary materials of construction include polyvinyl chloride (PVC) and high density polyethylene (HDPE). PVC pipe has been commercially available since the 1950s and in widespread use since the 1970s. HDPE pipe has been commonly installed since the 1990s. Current applications include replacing aging infrastructure, connecting to new supplies, and expanding the distribution network.

PVC and HDPE are viable pipe material options for many utilities. The use of PVC and HDPE water mains varies widely by geographic location, the prevalence of corrosive or contaminated soils, system pressure and the potential for pressure surges, utility preferences and system operating characteristics, and seismic concerns. For example, in New York City, less than 1% of installed pipe is PVC or HDPE; ductile iron pipe (DIP) is the preferred material of construction. In contrast, in the City of Calgary, 56% of the installed pipe is PVC and a small percent is HDPE. In Japan, 32% of the installed pipe is PVC (JWWA 2015) and installation of earthquake resistant DIP is increasing. Some utilities use plastic pipe for small pipelines only. The use of HDPE pipe is increasing worldwide. Recent utility surveys have limited HDPE data, possibly due to limited use in North American distribution systems.

Pipe performance is site-specific and a function of soils, system pressure, temperature, and installation methods. It is possible to minimize failures through project specifications and inspections during construction. Based on project workshop findings, it appears that installation practices are continuing to improve as utilities gain more experience with plastic pipe. Utility experiences with plastic pipe failure have been compiled in several surveys; however, when surveys do not compile ancillary data (e.g., pipe age, system pressure) along with failure data, it is difficult to use survey results to draw conclusions about the aggregate performance of pipe materials.

No pipe material is earthquake proof but flexible pipe does perform better than more rigid pipe, and pipe with seismic joints (i.e., a joint disengagement mechanism) performs better than bell and spigot joints. Earthquake resistant ductile iron pipe (ERDIP) had no reported failures in the 1995 and 2011 earthquakes in Japan (Kubota Corporation 2016). During recent earthquakes in New Zealand, PE pipes had less damage compared to other pipe materials (O'Callaghan 2014).

Life cycle cost analysis comparing plastic and metallic pipe materials requires some degree of speculation due to the limited, documented lifespan of installed, commercially serviceable plastic pipes. Project workshop findings suggest that pipe material cost is incidental to the overall life cycle cost. In addition, industry experts believe that it is well worth installing pipe, plastic or otherwise, with proven structural integrity compared to the costs of repair in congested city streets such as traffic control, service interruptions, labor, and environmental damage.

RESEARCH PARTNER

- Los Angeles Department of Water & Power (LADWP)

CHAPTER 1
INTRODUCTION AND BACKGROUND

Plastic pipe has been widely used in the drinking water industry for transmission and distribution mains as well as service lines. The primary types of plastic pipe used in these applications include polyvinyl chloride (PVC) and high density polyethylene (HDPE). The Water Research Foundation (WRF), and other research institutions, pipe manufacturers, and agencies have conducted numerous studies on plastic pipe applications in the water industry. Because manufacturing processes continue to evolve, and water utilities continue to gain experience with plastic pipe performance and cost, there is a need to review and summarize recent literature and utility case studies.

The objective of this project was to develop a white paper to assess the current state of the science regarding field use of plastic pipe (PVC and HDPE) by drinking water utilities.

The white paper development was initially based on a literature review and documentation of utility case studies. Sources of information included peer-reviewed literature from industry journals, WRF publications, and information available from water utilities. The literature review focused on publications from 2012 to 2016; some background information was obtained from older publications. Conference presentations were also reviewed to identify and summarize utility experiences with plastic pipe and seismic issues. No surveys or phone interviews were conducted as part of this research effort.

The white paper was refined after receiving additional information and review comments from the project advisory committee and utility experts. An expert workshop was held in May 2016 with water utility professionals to discuss the draft white paper and utility experiences with plastic pipe design, construction, and technical performance.

BACKGROUND

The water distribution system is the network of pipes, pump stations, finished water storage facilities, valves, and other components that are used to convey finished drinking water from the system's water treatment facilities or well supplies to the customer. Distribution system pipes include transmission mains, which carry water from the water sources or treatment plants to the distribution system, and distribution mains, which carry water from the transmission mains to the service lines. In general, transmission mains are larger than 14 inches (in.) in diameter, and distribution mains range from 6 in. to 12 in. in diameter.

The age and type of materials used for transmission and distribution mains can vary widely. Older pipes tend to be unlined cast iron pipe (CIP), while newer pipes include PVC, HDPE, reinforced concrete pipe (RCP), and DIP or steel lined with cement mortar (Table 1.1). Acrylonitrile-butadiene-styrene (ABS) pipe was one of the first plastic pipes used for water distribution mains in the 1950s and early 1960s (Bottles 1970); it was replaced with PVC pipe in the mid-1960s. Many different types of polyethylene (PE) were used for water service lines in the 1950s and 1960s (Bottles 1970). Polybutylene was also used for service lines during this time period (AWWA 1979). PVC pipe has been commercially available since the 1950s and in widespread use since the 1970s. The characteristics of PVC pipe material have improved since the first few decades of manufacture. HDPE pipe has been commonly installed since the 1990s.

Table 1.1
Timeline of pipe technology in the United States

Material	Joint	Corrosion Protection		1900	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s
		Interior	Exterior										
Steel	Welded	None	None										
Steel	Welded	Cement	None										
CIP (pit cast)	Lead	None	None										
CIP	Lead	None	None										
CIP	Lead	Cement	None										
CIP	Leadite	None	None										
CIP	Leadite	Cement	None										
CIP	Rubber	Cement	None										
DIP	Rubber	Cement	None										
DIP	Rubber	Cement	PE Encasement										
AC	Rubber	Material	Material										
RCP	Rubber	Material	Material										
PCP	Rubber	Material	Material										
PVC	Rubber	Material	Material										
HDPE	Fused	Material	Material										
PVC-O	Rubber	Material	Material										
Legend:	Commercially Available				Predominantly in Use								

Source: EPA (2002)

A number of water utilities have been surveyed in recent years to gain insight into their water system infrastructure, including pipe materials used. Four studies examined and compiled this information for water utilities in the United States, Canada, and Europe.

- Grafenauer et al. (2014) collected information from nine European water utilities on the amount of small diameter (2-in. up to and including 16-in.) HDPE pipe in their systems compared to each system's total length of pipe. Surveys were received from six water providers in the UK, two in Germany, and a single large water utility in Belgium. The European survey responses represented a total population served of 42 million and a total length of pipe for all systems combined of 144,648 miles (232,789 km). It was reported that, on average, 24 percent of the water mains (34,883 miles) consisted of HDPE pipe.

- Folkman (2012) surveyed 188 water utilities in the United States and Canada in 2011 on behalf of Uni-bell, the PVC trade association, and collected pipe usage and failure data that represented more than 117,000 miles of pipe or about 10 percent of the installed water mains in the United States. Folkman (2012) found variations in PVC pipe usage by geographic region. For example, in the northeast and north central United States, about 5 percent of the installed pipe length was comprised of PVC, compared to 29 percent in the region encompassing California, Nevada, and Hawaii. No survey data were collected on HDPE pipe usage.
- AWWA (2012) compiled statistics on pipe materials used in water utilities across the United States based on the AWWA Water/Stats database, the EPA Community Water Supply Survey, and the 2002 Public Works Infrastructure Survey. The study found that PVC pipe accounted for 40 to 45 percent of small diameter water mains (up to and including 10-in. diameter) in year 2010. The study did not include statistics on HDPE pipe or PVC pipe larger than 10-in. diameter.
- Ong et al. (2008) collected survey data from 151 water utilities located in all 50 states, the District of Columbia, and 3 Canadian provinces between September 2004 and March 2005. The survey data represented 83,360 miles of water mains and more than 5.4 million service connections. Seventy percent of survey respondents reported having some plastic pipe. The types of pipe materials represented in the survey included PVC (18 percent); DIP (16 percent); asbestos cement (AC), CIP, steel, and concrete (66 percent); and PE (0.18 percent). Five and 6 percent of the service lines were comprised of PVC and PE, respectively.

HDPE Pipe Characteristics

Advantages of HDPE pipe include hydraulic efficiency, ductility, abrasion and corrosion resistance, chemical resistance, toughness, and long service life (Najafi et al. 2015). In addition, HDPE can withstand relatively high strain (8 percent) (Irias 2016). PE pipe is described as a "visco-elastic" construction material that has two unique characteristics, creep and stress relaxation (Plastics Pipe Institute n.d.). The term "creep" refers to the deformation of the pipe over time in response to a constant static load. The term "stress relaxation" refers to a slow decrease in the stress when a pipe is subject to a constant strain or deformation (Plastics Pipe Institute n.d.).

Although it is resistant to many chemicals, PE pipe cannot be used in areas prone to contamination from gasoline or chlorinated solvents; these materials can permeate PE pipe causing structural damage and contaminating the drinking water (Ong et al. 2008). However, reports of permeation incidents in water distribution systems are rare based on utility survey results.

PE pipes may be subject to oxidative damage by water disinfectants, particularly chlorine dioxide (Colin et al. 2011; Castagnetti et al. 2011). Castagnetti et al. (2011) tested HDPE pipe samples using 5 mg/L chlorine dioxide or 2.5 mg/L sodium hypochlorite and found that chlorine dioxide was the more aggressive disinfectant; however, no pipe failures occurred after 2,000 hours of exposure to the disinfectants. Additional information on Castagnetti's study is provided in Chapter 2.

In terms of hydraulic efficiency, HDPE pipe does not corrode or form tubercles, and maintains its original flow capacity over time. HDPE pipe is immune to electrolytic attack and therefore, it is not adversely affected by aqueous solutions of salts, acids, or bases (Plastics Pipe Institute n.d.).

HDPE is thermoplastic; it can be reshaped under heat and pressure (Plastics Pipe Institute 2005). Its coefficient of thermal expansion is approximately 10 times larger than the coefficient for metallic pipe (Plastics Pipe Institute n.d.) For drinking water applications, HDPE pipe typically operates within the temperature range of 32 to 140 degrees Fahrenheit (F) (Plastics Pipe Institute n.d.).

Two HDPE pipe resins are recognized by ASTM and approved by NSF International: PE3408 and PE4710 (Iles and Eddy 2014). At water temperatures of 100 degrees F, the pressure ratings for PE3408 and PE4710 are reduced by 22 and 16 percent, respectively. This means that thicker pipe is needed to compensate for reductions in the pressure rating.

HDPE pipe constructed from the PE4710 resin can be curved to a radius 25 times its diameter according to the AWWA M55 manual (Ambler 2015). For this reason, fewer fittings are required on transmission lines when the pipe alignment requires directional changes (Ambler 2015). If service connections are required along the pipe, a higher bend radius of 100 times the outside diameter (OD) is needed (Irias 2016). Minimizing bends is recommended particularly in areas where fittings are being fused, since a bent pipe may not permit a good bond. The pipe's flexibility makes it well-suited for earthquake prone areas and sites that are subject to seasonal variations in soil conditions and uneven settlement of pipe bedding (PPI 2005). Narrower trench widths can be used when installing HDPE pipe, saving both time and money (Mickelsen and Langston 2015).

HDPE pipe segments are typically connected using heat generated by butt fusion or electrofusion processes. Although HDPE pipe can be joined mechanically, there is a concern that over time mechanical joints can develop leaks due to HDPE's strain relief properties. Heat fusion eliminates joints, which are a significant source of leaks in the distribution system. Heat fusion also allows long segments of pipe to be prepared above ground and installed underground with trenchless technologies (e.g., pipe bursting). Heat fusion can be a cost-effective joining method for some HDPE applications (e.g., long runs for open cut construction and horizontal directional drilling (HDD)) (Mazurek 2006). Electrofusion sends an electrical charge into the pipe couplings, melting the couplings onto the pipeline (Mazurek 2006).

PVC Pipe Characteristics

PVC pipe is smooth, durable, non-corrosive, and resistant to bacteria and chemicals (Baird 2011). PVC is impervious to gasoline but can be readily compromised by high concentrations of benzene, toluene, and trichloroethylene according to a WRF study (Ong et al. 2008). Because only low concentrations of these materials are found with petroleum spills, the risk of high concentrations occurring appears to be small. Best practice suggests avoiding use of PVC pipe in areas of significant hydrocarbon contamination due to potential for permeation and resulting water quality problems (Irias 2016). Additional information on technical performance is provided in Chapter 2.

PVC is also thermoplastic; however, most PVC used for drinking water distribution systems in the United States is unplasticized (i.e., it contains no plasticizing additives (such as phthalates) to add flexibility) (Richardson and Edwards 2009). It is referred to as PVC-U or just PVC. PVC manufacturing requires the addition of stabilizers to limit degradation under high temperatures or exposure to UV radiation (Richardson and Edwards 2009). Modified PVC (PVC-M) contains plasticizers; it is produced and used mainly in Europe and Australia. Molecularly oriented PVC (PVC-O) does not contain plasticizers but is manufactured so that the PVC molecules are aligned in two directions by extrusion which increases pipe strength and flexibility. PVC-O is manufactured in the United States, Canada, and Europe. Fusible PVC (FPVC) is also available for potable water applications and is manufactured in accordance with AWWA standards and NSF requirements. FPVC is an example of an evolving technology that is currently being evaluated in the water industry with pilot-scale testing and some full-scale applications. A variation of PVC pipe is currently being manufactured in Korea and is also extruded. It is being analyzed in a separate WRF project by American Water (Hughes et al. 2016).

For trenchless installation, the pipe must have either fused joints or restrained bell and spigot joints. Other PVC pipe segments are joined using solvent cement. In the 1970s, Seattle Public Utilities installed Schedule 80 PVC with glued joints as an alternative to copper service lines and 2-in. galvanized iron (GI) water mains. The practice was discontinued because of the glue curing time (Muto 2016).

Current Trends of Plastic Pipe in the Water Industry

Water utilities are installing plastic pipe for raw and finished water transmission mains, distribution mains, and to replace aging infrastructure. For example:

- The 27.5-mile Victory Pipeline in Utah will deliver 4 MGD of finished water by gravity to seven different companies and cities in Duchesne County that are experiencing increased demand (Mickelsen and Langston 2015). It is constructed of 22-in. to 30-in. diameter HDPE pipe. Results of the project's hydraulic analysis showed that the pipeline would be subject to a wide range of pressure conditions.
- The San Antonio Water System's Carrizo project included installation of HDPE pipelines to collect water from the Carrizo aquifer and deliver it to a water treatment plant. The project was needed to meet increasing demand and supplement the primary source of supply from the Edwards aquifer (Iles and Eddy 2014; Smith et al. 2014). The well field collection piping included 81,000 feet (ft) of 18-in. to 36-in. HDPE pipe with DR 9 or 11. The transmission line from the well field to the treatment plant was constructed of more than 40,000 ft of 36-in. diameter HDPE pipe with DR 11, 13.5 or 17. The pipeline design conditions included an operating pressure of 160 psi and a water temperature of 105 degrees F (Smith et al. 2014).
- PVC pipe represents 50 percent of the water distribution system in Edmonton (Seargeant 2016). Of the 1,235 miles of PVC pipe, 100 miles are transmission pipe conforming to AWWA C905 in diameters between 14 in. and 36 in. PVC distribution pipe (4 to 12 in. diameter conforms to AWWA C900. DR 25 is used for transmission pipe and DR 18 is used for distribution pipe. In general, operating pressure in the water distribution system where PVC pipe is used varies from 40 psi to 70 psi. A small amount of AWWA C900 PVC DR 18 pipe has been installed in an area with an operating pressure of 120 psi to 130 psi.

- Ogden City, Utah is replacing a 1910 vintage 24-in. diameter steel pipeline with a combination of FPVC and harnessed bell and spigot PVC pipe. Phase 1 was completed in 2013 (Moffett et al. 2014). FPVC was installed for the higher pressure section of the pipeline in the lower canyon, and harnessed bell and spigot PVC pipe (DR 18) was used at higher elevations.
- Marin Municipal Water District in California installs about 7 miles of steel or PVC pipelines each year, replacing old CI and GI water mains. The District's standard is to use PVC for new pipelines less than 12 in. in diameter. Welded steel pipe with a mortar lining and tape coating is installed to improve the seismic reliability of the water distribution system. According to their website, the District replaced more than 76 miles of pipe between 1997 and 2014.
- The city of Calgary has installed large diameter PVC transmission mains (Line 2016). Currently, about 9-km (5.6-miles) of PVC mains have a diameter of 500-mm (20-in.) to 900-mm (36-in.).
- In 2015, the city of Florence in Colorado installed more than 2 miles of new PVC piping to upgrade an area of the regional water system serving the town of Williamsburg. The new 4-in. through 8-in. diameter PVC pipe replaced water mains that were originally installed in the 1980s and 1990s by local developers and considered to be substandard, undersized, and prone to frequent failures according to the engineer's report (GMS 2013) (Figure 1.1). The original piping material included various pressure classes of PVC installed at minimum depths due to bedrock. Bedding materials included rubble and debris.

Figure 1.1 Installation of new PVC distribution piping in Williamsburg, Colorado

International Trends

The first use of PVC pipe in drinking water systems was reportedly in Germany in 1936 (Kurrus 2015). Marangoni (2012) estimated that 30 percent of water mains in Germany are PVC or PE; other materials include iron/CI (53 percent) and concrete (10 percent).

Smeets et al. (2009) estimated that 40 percent of water mains in the Netherlands are PVC; other materials include AC (36 percent), CIP (14 percent), PE (2.5 percent) and others (7.5 percent). Dutch water systems and several other northern European countries (e.g., Germany, Austria) use pipe materials that are non-reactive and biologically stable to control microbial activity in the distribution system with no or minimal disinfectant residual (Smeets et al. 2009).

In Italy, water distribution networks consist of the following materials of construction: plastic (20 percent), iron/CI (21 percent), steel (35 percent), AC and concrete (16 percent), and other materials (6 percent) (Marangoni 2012).

In Japan, 61 percent of installed pipe is seismic type DIP and 32 percent is "hard-type" PVC (JWWA 2015). Other types of installed pipe include CIP, steel, PE, and AC. From 2000 to 2013, the length of PVC water mains in Japan has increased by 20 percent and the length of CIP and AC water mains has decreased as a result (JWWA 2015). The ongoing long term plan is to replace older water mains with more earthquake-resistant pipe. For example, the Kubota Corporation based in Osaka, Japan, produces earthquake resistant DIP (ERDIP) which has a unique segmented design. The pipe has bell and spigot joints that expand or contract up to 1 percent of the standard pipe length with a deflection angle of up to 8 degrees to fully absorb lateral movement. Currently, about 90 percent of orders for new DIP in Japan is ERDIP. Japan has also made leakage management a priority by conducting leak detection surveys, and replacing or repairing deteriorated pipe. In 2006, more than 92 percent of distributed water was reaching the taps (i.e., the leakage rate is less than 8 percent (JWWA 2015).

China started to manufacture plastic pipe in the 1970s and the first applications in engineered construction were in the 1980's (Qiao et al. 2014). The amount of plastic pipe in urban water systems increased from 7 to 22 percent from 2003 to 2012 (Qiao et al. 2014). The authors do not provide further details on the types of plastic pipe. At the end of 2012, the total length of plastic pipe in urban water systems was 103,940 km (64,585 miles) compared to a total length of pipe of 481,485 km (299,181 miles). A comparison of pipe materials used in 2003 and 2012 is listed in Table 1.2. About 42 percent of the current pipe network, primarily large diameter concrete mains, may need to be replaced in the future in order to meet drinking water health standards promulgated in 2013 (Qiao et al. 2014). Also, the current leakage rates in water networks ranges from 10 to 30 percent due to failures of old pipe materials Qiao et al. 2014).

Table 1.2
Materials of construction for urban water systems in China

Pipe Material	**2003**	**2012**
	% of total pipe length	
Plastic	6.7	21.6
CIP	31.1	14.5
DIP	9.3	25.1
Steel	15.1	7.8
PCP or RCP	7.0	4.2
AC	4.5	1.5
Others	11.8	13.7

Source: Data from Qiao et al. 2014

CHAPTER 2
TECHNICAL PERFORMANCE OF PLASTIC PIPE

Typical failure mechanisms of water mains and service lines include deterioration of pipe materials, joints, and operational issues. Failure mechanisms and rates of failure differ by pipe material. Structural failure is caused by pipe wall defects or problems with the soil envelope used to support the pipe (e.g., loss of bedding or soil cover, ground movement due to earthquakes or seasonal temperature changes). For example, the shrinkage of expansive clay soils during hot summers or drought conditions exerts more bending stresses on the pipe and transmits a higher traffic load to the pipe (Mordak and Wheeler 1988 as cited in Spencer et al. (2015). Where drought conditions are prevalent, main breaks can occur if the soil shrinks and the pipe shifts. Pipes fail when the pipe structure weakens and can no longer handle stresses such as high water pressure. More breaks tend to occur in cold winters (or summer droughts) because of the increased stress. Also, the pipe's year of installation can provide some indication of the expected service life because manufacturing techniques and materials have changed over time.

The most common problems that lead to failures in plastic pipe relate to material handling and installation and environmental factors including excessive deflection, joint misalignment and/or leakage, poor service connection installations, longitudinal breaks from stress, exposure to sunlight, high system pressure, pressure surges, exposure to solvents, and damage caused from tapping (National Research Council 2006). Factors such as poor product workmanship, poor installation methods, and lack of proper maintenance can lead to increased rates of failure including failures that occur long after the pipe is installed. Poor quality backfill can create a stress point that leads to cracking. All plastic service line materials and gaskets are subject to failure due to improper installation or operation. PE service lines are particularly sensitive to kinking and improper backfilling.

TECHNICAL PERFORMANCE OF PVC PIPE

Physical degradation of PVC pipe including physical aging is described in the literature. Struik (1977) defined the physical aging process as a "slow and gradual approach to equilibrium" which can change the pipe material's properties (e.g., creep, ductility, tensile strength) generally as the result of stress. Other definitions of physical aging include "a process of structural relaxation" (Demčenko et al. 2012) and "change as a function of the history of the product" (Breen 2006). Over time, localized deformations in the plastic material will result in decreased toughness which can lead to increased susceptibility to fractures and third party damage (Demčenko et al. 2012).

Chemical degradation of PVC pipe is defined as "a breakage of covalent bonds caused by temperature, oxygen or other factors" (Breen 2006). The rate of chemical degradation in buried PVC pipe is very low (Breen 2006); however, pipe that has been exposed to solar UV radiation may have a lower impact strength (Hughes 2016a).

Mechanical degradation of PVC pipe such as crack initiation and crack growth can occur during pipe installation and continue during pipe operations due to internal and external loads (Breen 2006). For example, pipe can crack due to poor compaction of the pipe bedding material which increases the tensile stresses on the pipe. Cracking can be caused by improper tapping.

Additional mechanical stresses occur due to soil settlement and traffic loads and system pressure which creates hoop stresses on the pipe (Breen 2006). The effects of internal and external loads can vary significantly for each PVC pipe depending on factors such as wall thickness, production quality, and installation methods (Breen et al. 2005).

Although PVC pipe's structural characteristics are relatively unaffected by gasoline and low levels of benzene, toluene, and trichloroethylene encountered in field conditions (Ong et al. 2008), it was noted in the project workshop that most utilities avoid using PVC in contaminated soils due to concerns about permeation that could affect water quality and vulnerability of gaskets. Gaskets are often the weak link in such applications. Special gaskets are used when required, regardless of the pipe material in contaminated soils.

Utility field experiences with PVC pipe failure and technical performance were discussed and documented at the project workshop. Brief case studies are summarized below:

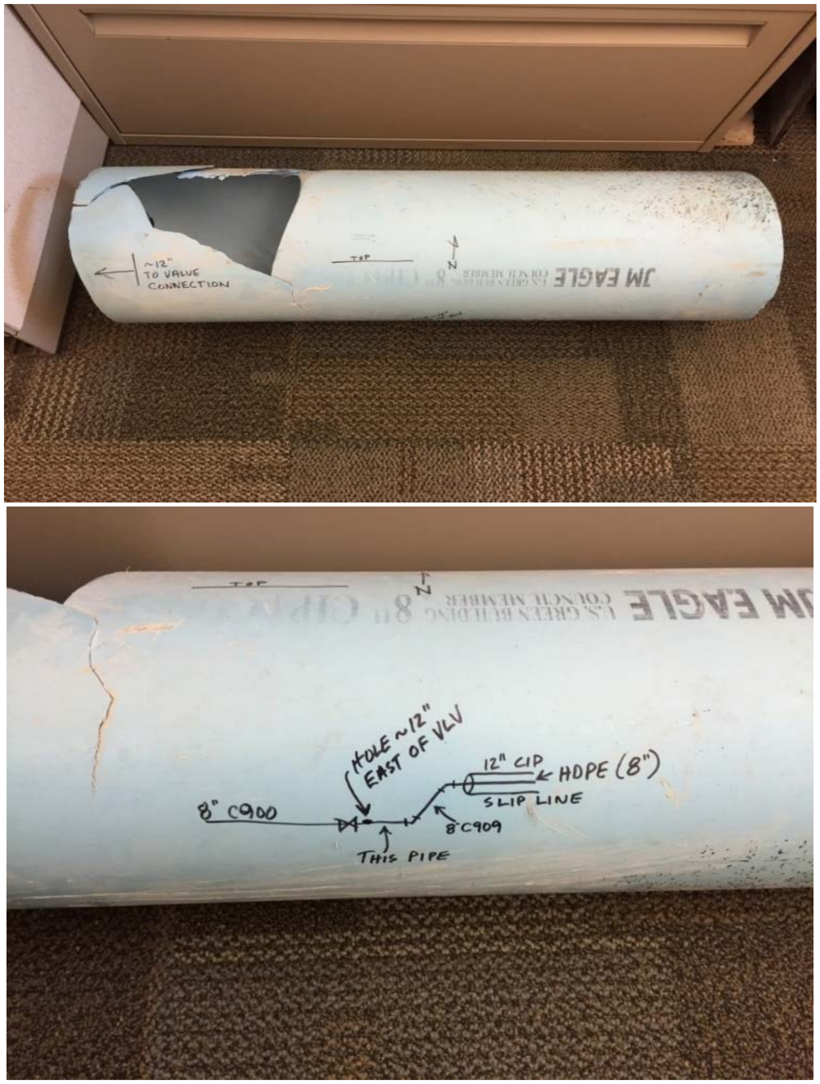
- Golden State Water Company has experienced failures of PVC pipe (Carver 2016). Causative factors included point loadings from installing PVC pipe without proper bedding in rocky conditions; improper manufacturing practices and lack of adhering to AWWA and Underwriters Laboratories (UL) manufacturing standards; and/or hydrocarbons in surrounding soils.
- Anchorage Water and Wastewater Utility (AWWU) has experienced limited failures with PVC pipe. PVC pipe installations in Girdwood from the 1970s have performed well even though the pipe is thinner than existing standards (Standard Dimension Ratio[1] (SDR) 25 vs. SDR 18) (Nuss 2016). This PVC pipe has had 4 documented failures, all on 6-in. diameter mains installed in 1973 or 1974. Failures occurred between 1993 and 2008 and were stress-related. Other PVC installation issues (e.g., rolled gaskets, improper re-beveling of pipe, and tapping deficiencies) were identified during the acceptance testing (i.e., pressure testing) and fixed prior to placing the pipe into service.
- LADWP experienced the failure of an AWWA C900 PVC pipeline due to large pressure fluctuations (Figure 2.1) (Bautista 2016). In 1992, an 875-foot (ft) section of 12-in. diameter C900 PVC pipe was installed as part of the LA Greenbelt Reclaimed Water Pipeline. The pipeline is located along the south side of the Los Angeles River from Barham Boulevard to the end of the line at the Universal Studios customer's meter. The pipeline is located in the Recycled Water 740 pressure zone which has an operating pressure of 90 psi and surge pressures that can exceed twice the operating pressure. The PVC portion of the pipeline had three breaks from 2008 to 2010 and three more breaks in 2011. All segments of this PVC pipeline have since been replaced with DIP and no further breaks have been reported by LADWP.

[1] Standard dimension ratio is the ratio of the pipe OD to the pipe wall thickness.

Source: Bautista 2016

Figure 2.1 AWWA C900 PVC pipe failure in 2009 due to large pressure fluctuations

- WaterOne in Johnson County, Kansas experienced the failure of an 8-in. diameter PVC (C909) pipe at a tie-in just outside of a 12-in. diameter sliplined CIP (Figure 2.2) (Pietig 2016). The failure was due to movement (i.e., expansion, contraction) of the 8-in. diameter HDPE pipe inside the 12-in. diameter CIP and improper use of a PVC locking wedge-type restraint product on C909 pipe for which the product was not rated. The movement of the HDPE pipe increased the stress at this connection point, and the pipe failed right at the mechanical joint fitting. The pipe was installed in 2014 and the failure occurred in 2015. The repair costs exceeded $26,000. WaterOne uses both C900 and C909 PVC pipe, but the locking-wedge-type restraint should have only been used on the C900 pipe.



Source: Pietig 2016

Figure 2.2 PVC (C909) pipe failure at WaterOne

- American Water reported on a PVC pipe failure during a tapping event (Figure 2.3). The causative factors included pipe class selection (i.e., the pipe wall thickness); the selected tapping saddle; the tapping speed; and the tapping location (i.e., tapping on the top of the pipe places the highest stress on the pipe) (Hughes 2016a). The tapped hole on one failed pipe showed some burned PVC material on the cut surface that served to weaken the PVC pipe. Tapping heat can be generated by a dull cutter, lack of lubrication, or cutting at an excessive speed (Hughes 2016a).

Source: Hughes 2016a

Figure 2.3 PVC pipe failure due to tapping at California American

- The Honolulu Board of Water Supply (HBWS) has experienced PVC pipe failures caused by joint over-stabbing, rock impingement, or high pressures (Fuke 2016). Demanding construction issues such as tough excavation conditions (e.g., basalt, coral), and delays may have led to construction compromises such as pipe bending and the pipe being stored in sunlight for an extended period of time. The HBWS has also experienced service saddle failures on PVC pipes that has compromised the service life of the pipe. During an on-going investigation of PVC pipe failures, evidence was found that improper bedding/pipe zone material caused some breaks and over-stabbed joints (i.e., excessive insertion of socket end into bell end of pipe) caused others. Although there has been no evidence that pressures in BWS systems are excessive, analysis of the break statistics indicated that pressure was a contributing factor.
- EBMUD has had tapping failures that resulted in long, rapid cracks in PVC and FPVC pipe (Figure 2.4) (Irias 2016).

Source: Irias 2016

Figure 2.4 PVC pipe failure due to tapping at EBMUD

- Since 1996, EPCOR in Edmonton, Canada has experienced 14 issues related to PVC (C905) pipe that required excavations (Seargeant 2016). Of the 1,100 miles of PVC pipe currently in service, more than 100 miles are C905 pipe in diameters from 14 in. to 36 in. Many of the 14 issues were a result of failures on non-PVC appurtenances. Improper jointing of the pipe (deflection to accommodate a change of direction) at a connection to a metallic fitting resulted in leakage of water where the necessary insertion depth into the fitting bell was not achieved. This flow of water eroded the pipe material, ultimately resulting in a hole and split in the PVC pipe (Figure 2.5). Another PVC pipe failure occurred when a copper service was hit by an excavator (Figure 2.6). The number of annual water main breaks on the overall water distribution system has decreased from more than 1,600 in 1985 to less than 300 in 2015 (Seargeant 2016). Approximately 50 percent of the original CIP network has been replaced with PVC pipe over the last 30 years.

Source: Seargeant 2016

Figure 2.5 Erosion of pipe material from a poorly sealed joint

Source: Seargeant 2016

Figure 2.6 PVC Pipe split when water service hit during construction

- The City of Calgary, Canada, has experienced a low failure rate in PVC water mains (Brander 2004). PVC main breaks account for 1 to 3 percent of total annual breaks in the distribution system even though 50 percent of the installed mains are PVC (Dueck 2010). Based on the city's historical record of failures in pipe up to 30 years old, 157 of 10,495 failures (1.5 percent) occurred in PVC pipe (Dueck 2010). This low failure rate was attributed to a conservative approach for design, construction, and inspection as discussed in Chapter 4.

All of the 20 PVC pipe failures recorded from 1991 to 2004 in Calgary were due to installation errors (e.g., cracks that propagated from a tapping point or a saddle clamp, leakage at a gasket, pipe deflection) and occurred in pipe that was between 2 and 17 years old (Brander 2004). Dueck (2010) identified the probable causes of three PVC pipe failures that occurred in 2008-2009. For example (Figure 2.7), the failure of a 7-year-old, 250 mm (10-in.) PVC pipe (SDR 18) in December 2008 included several probable causes: over-insertion of spigot into bell, soil movement (bedding conditions), and longitudinal bending combined with joint deflection. The lack of vertical separation from an existing utility was identified as the cause of other failures studied.

Source: Dueck 2010

Figure 2.7 City of Calgary PVC pipe failure in December 2008

- In EPCOR's water network in Edmonton, 156 of 28,980 (0.54%) water main repairs have occurred on PVC pipes since the first pipe was installed in 1977. The problems were attributed to installation errors, which have decreased over time through education of the contracting and engineering industry in the area.

Utility field experiences with PVC pipe failure and technical performance were compiled in utility surveys:

- Folkman (2012) conducted a utility survey in the United States and Canada to collect information on failure rates for different pipe materials. The survey represented 117,603 miles of pipe installed at 188 utilities. Overall, the pipe failure data varied widely from one utility to the next. PVC pipe had the lowest failure rate compared to CIP, DIP, steel, concrete, and AC. Over a 12-month period, PVC had an average failure rate of 2.6 failures per 100 miles per year, compared to DIP (4.9), concrete pressure pipe (5.4), AC (7.1), steel (13.5) and CIP (24.4). Of the PVC pipe failures reported by survey respondents, 2 percent of the failed pipe was estimated to be 41-60 years old; 46 percent was 21-40 years old; and 52 percent was 0-20 years old. Longitudinal cracking was the predominant failure mode for PVC pipe and corrosion was the major factor for iron pipe.
- Takahashi et al. (2010) conducted two water utility surveys to evaluate how leakage rates increased with pipe age for different pipe materials. The surveys conducted in fiscal years 2004-2005 and 2006-2007 collected data from 296 and 255 water utilities in Japan, respectively. The survey data represented 16 to 19 percent of the 1,600 water utilities in Japan and more than 22,000 leakage events. Results shown in Table 2.1 are specific to the surveyed utilities and cannot be used to make general conclusions about pipe performance in Japan or elsewhere. The local soil conditions, total length of pipe material, pipe jointing methods, corrosion control measures, and other factors all affect pipe condition and leakage rates. The results show that the number of leakage events increased with pipe age for CIP and AC pipe, but decreased with age for DIP. PVC and steel pipe had an increasing number of leakage events until the pipe was 30-35 years old, and then the number of events decreased.
- Takahashi et al. (2010) estimated tentative leakage rates by pipe age (number/km/year) for 6,453 of the 22,000 leakage events collected from utility surveys (Table 2.2).

Table 2.1
Number of leakage events for different pipe materials in Japanese survey

	Number of Leakage Events (% of Total Events for Pipe Age)					
Age (years)	**CIP**	**Steel**	**AC**	**PVC**	**DIP**	**Total**
46-50	178 (70.3%)	20 (7.9%)	29 (11.5%)	23 (9.1%)	3 (1.2%)	253
41-45	233 (42.4%)	39 (7.1%)	85 (15.5%)	159 (29.0%)	33 (6.0%)	549
36-40	201 (17%)	78 (7%)	58 (5%)	678 (59%)	142 (12%)	1,157
31-35	48 (3%)	145 (8%)	69 (4%)	1,270 (72%)	231 (13%)	1,763
26-30		164 (18.1%)	24 (2.65%)	551 (60.75%)	168 (18.5%)	907
21-25		77 (17.4%)		256 (57.8%)	110 (24.8%)	443
16-20		30 (11.3)		151 (57.0%)	84 (31.7)	265
11-15		12 (8.5)		71 (50%)	59 (41.5%)	142
6-10		8		35	62	105
0-5		5		15	39	59

Source: Data from Takahashi et al. 2010

Table 2.2
Estimated leakage rates for different pipe materials (number/100 km/year)

Age (years)	CIP	Steel	AC	PVC	DIP
46-50	6.7	2.9	18.4	95.8	0.6
41-45	3.1	1.9	22.5	17.4	0.6
36-40	1.4	2.1	18.7	15.9	0.7
31-35	0.7	3.8	9.1	12.6	0.6
26-30		3.3	1.0	3.9	0.4
21-25		1.5		1.5	0.2
16-20		1.0		0.9	0.1
11-15		0.5		0.4	0.1
6-10		0.3		0.2	0.1
0-5		0.3		2.8	0.1

Source: Data from Takahashi et al. 2010

- Burn et al. (2005) evaluated the long-term performance of PVC pipe based on a water utility survey, literature review, and field testing. Seventeen water utilities provided survey responses including 4 in the United States, 4 in Canada, and 9 in Australia. Survey results showed that the number of recorded failures of PVC pipe was low compared to other pipe materials. Estimated PVC pipe failure rates in the United States and Canada varied from a low of 0.2 failures per 100 miles per year (Calgary, Canada) to 2.7 failures per 100 miles per year (United Water Toms River, New Jersey); the authors cautioned against comparing utility failure rates because of differences in data reporting methods. Also, variations in the reported failure modes by survey respondents suggested that pipe installation is an important factor.

  Pipe testing and other engineering studies provide technical performance information:

- American Water and several other utility representatives at the project workshop noted that pipe testing following a failure can be conducted to verify that the pipe meets its factory specifications (Hughes 2016a; Irias 2016; Fuke 2016). For example, the Honolulu Board of Water Supply recently conducted pipe testing on three failed pipe sections (Fuke 2016).

Testing included fracture analysis, acetone immersion, heat reversion, and tensile and impact tests. All three pipe samples were found to essentially meet factory specifications. The pipe failures were attributed to rock impingement.

- EPCOR has removed PVC pipe from service and undertaken testing on a number of occasions since 1994 (Seargeant 2016). Results have been presented at conferences held by AWWA and other organizations since that time. The results have consistently shown little to no degradation in pipe performance properties when compared to new pipe, even after 25 years of service.
- Kurrus (2015) researched the high failure rates of PVC water pipe in several municipalities near Phoenix, Arizona in the 1990s. Causative factors were initially determined to be fatigue and thermal stability; however, Kurrus conducted pressure monitoring and fatigue analyses, and concluded that the pipe did not fail prematurely due to fatigue. He also monitored water temperatures for 12 months in one community and determined that the maximum expected pipe temperature would be 91 degrees F which is lower than the acceptable design temperature of 100 degrees F. One community experienced multiple leaks on 6-in. and 8-in. Class 160 SDR 26 PVC pipe installed in 1982; the pipeline leaks were identified from 2007 to 2012. When the leaks were repaired, the pipe bedding and backfill material was found to be a causative factor; it was composed of native material including large rocks. Based on ASTM test results for samples of the failed pipe, the author concluded that fatigue and temperature were not causative factors.
- Failure rates for various pipe materials used at Colorado Springs Utilities were determined based on an engineering evaluation of pipe failure records (Garcia and Funchion 2014). Findings included:
    - Non-metal pipe had a lower failure rate (0.36 failures per mile of pipe) compared to CIP (4.87 failures per mile), DIP (1.28 failures per mile), and steel (0.92 failures per mile).
    - Of 4,076 pipe failures that occurred in Colorado Springs between 1993 and 2012, more than 85 percent were CIP or DIP installed after 1950 when pipe manufacturing processes were changed to produce thinner walled pipe. The authors did not provide separate statistics for CIP and DIP failures.
    - Over time, plastic pipe failure rates did not increase or decrease but iron pipe failure rates increased. This may be simply a byproduct of the relatively young age of the plastic pipes compared to the iron pipes.
- Lively (2012) documented utility experiences with rapid crack propagation in PVC pipes. While the actual number of incidents has been very low, the consequences can be serious since a crack may run for considerable distance and hence involve considerable property damage and disruption. PVC pipe failure due to rapid crack propagation may be a result of mishandling pipe in the trench, contractor error, rock impingement, or other damage.
- Burn et al. (2005) analyzed failure rates for PVC in the United Kingdom, which tracks main breaks throughout the country. While PVC manufactured in Europe (and Australia) is not directly comparable to U.S. and Canadian PVC (i.e., the PVC pipe manufacturing processes use different stabilizers), the analysis may hold some interest. Burn et al. noted that the failure rate for all types of failures was flat until pipe reached about 34 years of age. Failure rates for fractures increased from less than 2 per 100 km per year to 10 per 100 km per year beginning at year 42. Similar failure rates for joints and fittings began at age 45. These increases are thought to reflect changes in manufacture and installation that were

instituted in 1971 and 1973. (It should be noted that a steep increase in failure rates at a critical age is typical of all materials as part of the so-called "bathtub" curve that is often observed across a wide range of products and materials [Irias 2016]).

- Based on the results of slow crack growth tests and C-ring fracture toughness tests on U.S. PVC pipe, Burn et al. (2005) modeled fracture rates and pipe age for pipe 4 to 12 in. in diameter in the 150 psi class. Pipe ages up to 110 years were included. Failure rates increased with pipe diameter; for example, for 4-in. pipe, the failure rate increased from 0.2 to 2.2 per 100 km per year over time at pressures of 123 psi, but for 6-in. pipe at the same pressure increased to 4 per 100 km per year. For 12-in. pipe, the failure rate increased to 7 per 100 km per year almost immediately before leveling off at 9 per 100 km per year. (This lab data does not necessarily match real-world experience, in which the superior beam strength of larger-diameter pipes may lead to larger pipes generally performing somewhat better than smaller pipes in the face of external soil loads [Irias 2016]).

TECHNICAL PERFORMANCE OF HDPE PIPE

Utility field experiences with HDPE pipe failure and technical performance were discussed and documented at the project workshop. Brief case studies are summarized below:

- In 2007, LADWP experienced a leak on an HDPE coupling (Figure 2.8) connecting HDPE and steel pipelines. Thermal expansion and contraction of the pipe materials, which created stress on the end connections, were believed to be the cause of the leaks (Bautista 2016).

Source: Bautista 2016

Figure 2.8 HDPE coupling leak at LADWP

- In 2005, EPCOR Water installed a 152-mm (6-in.) diameter HDPE water service to Louise McKinney Park in Edmonton, a known landslide area. This park is constructed in a river valley on an unstable slope which is continuously moving. A specialty double ball flextend expansion joint was used at the upper fault line and at the toe of the slope for this project. The expansion joint was designed to accommodate 40 to 45 years of horizontal and vertical movement (at the current rate of movement). The installation has been in service for more than 10 years with no problems (Seargeant 2016).

- In 1997, LADWP installed a 34-in. diameter HDPE pipe by sliplining inside a 23,500-ft riveted steel pipeline (i.e., the Roscoe Trunk Line); sections of the steel pipeline were 42-in. and 45-in. diameter (Bautista 2016). From 2004 to 2015, 14 leaks occurred on this pipeline at a total repair cost to date of $3.3 million. LADWP has learned that leaks are difficult to locate inside host pipe or casing, and the fused connections are the typical failure point for HDPE pipe (Bautista 2016).
- EPCOR's greatest failures in the water distribution system have been related to HDPE water mains, in particular, the failure of improperly fused joints between specialty items such as tees and straight pipe (Seargeant 2016). Three types of failures include:
    - HDPE butt fusion joint failure and pipe separation due to improper butt fusion method (Figure 2.9);
    - Hairline crack on neck of pipe at a stub end; and
    - Restrained mechanical coupling leak (Figure 2.10)

A butt fusion joint failure occurred in February 2011 when the joint at the stub end totally separated by at least 457 mm (18 in.). The HDPE pipe, installed in 1995, had an OD of 686 mm (27 in.) and an inside diameter of 580 mm (23 in.). The pipe was sliplined inside a 762-mm (30-in.) steel water transmission main. The failure was attributed to cold fused areas (Seargeant 2016). The pipe was installed at a warmer temperature during summer months and the fused joint failed at colder temperature when the water in the pipe was at its coldest. The annual change in water temperature ranged from 1 degree C to 23 degrees C.

Source: Seargeant 2016

Figure 2.9 HDPE butt fusion joint failure in Edmonton, Canada

Source: Seargeant 2016

Figure 2.10 Restrained mechanical coupling leak at transition from HDPE to PVC

- EBMUD conducted an experiment to evaluate the performance of a 6-in. SDR 11 HDPE pipe when it was bent to a radius of 25 times its diameter (Irias 2016). Services were fused to the pipe on the inside and ODs at 95, 60 and 25 times the diameter. The services were cut out and destructively tested. The result of this one test showed that electrofusion tapping on the 60 and 25 times locations failed the destructive test. To gain confidence in the results, the test needs to be repeated.
- AWWU in Anchorage has experienced limited failures with HDPE pipe. Three documented HDPE failures were related to leaking electrical fusion couplings and occurred within 5 years of installation.

Utility field experiences with pipe failure and technical performance were compiled in utility surveys:

- The technical performance of large diameter (16 in. and larger) HDPE pipe was evaluated by Najafi et al. (2015) by surveying North American utilities and documenting case studies from these water utilities. The survey data represent 39 utilities including 31 that fully answered the survey and 8 that provided partial responses. In total, the utility survey represents 338 miles of installed large HDPE mains, most of which was less than 10 years old in 2013. Survey findings on the durability and reliability of large diameter HDPE mains are summarized below:
    - The majority of survey respondents were very satisfied with the durability and reliability of HDPE water mains.
    - Nine of 31 survey respondents reported at least one leak in an HDPE water main. Causes of leaks included: improper welding of joints, third party damage, faulty

service saddles, pipe puncture during construction, and damage to a river crossing during a flood.
    - The most important factors affecting life cycle costs were identified as: ease of maintenance, maintenance costs, life expectancy, and leak free joints.
    - There is an industry need for written procedures on tapping and repair of HDPE mains, and also for connecting HDPE pipe to other pipe materials.
    - Permeation and oxidation are minor concerns; no failures were reported as a result of permeation or oxidation. As observed earlier, most utilities avoid installing plastic pipe of any kind where this might be a problem.
- Grafenauer et al. (2014) reported survey results from 9 European utilities on HDPE mains, most of which were installed more than 10 years prior to the survey. The most commonly reported problem was fusion failure due to either third party damage to original butt fused joints or failure of electrofusion joints. The authors noted that joint failures are often due to incorrect installation; pipe alignment, scraping, and cleaning need to be executed correctly in order for the joint to be fail safe.
- Venkatesh (2012) conducted a utility survey on performance of HDPE water mains. He collected survey responses from 13 water utilities across the United States representing a total of 13,107 miles of small diameter (2-in. to 16-in.) HDPE mains. The average failure rate of small diameter HDPE water mains was determined to be 0.5 failures per year per 100 miles. The most common causes of failures reported were fusion failure (pipe diameter 6-in. to 16-in. only), third party damage due to improper construction practices, inadequate wall thickness, and poor installation.

Pipe testing and other engineering studies provide technical performance information on HDPE pipe:

- Bredács et al. (2014) performed thermo-oxidative testing on 40-year old PE service line samples from Austria after conditioning the pipe samples for up to 1.5 years by oven aging at different temperatures. Test results showed that all pipe samples would reach or exceed the design service life of 50 years.
- In China, failure of PE pipe is often due to leaking joints between the PE pipe and the original CIP. Zhihao and Xiaoming (2012) conducted field testing to evaluate variations in longitudinal dimensions of PE pipe caused by environmental temperature changes. Based on the testing results, the authors recommended design solutions and changes to installation practices to minimize temperature changes in the pipe.
- Castagnetti et al. (2011) constructed a pipe testing apparatus to evaluate the mechanical and chemical effects of disinfectants on HDPE pipe (PE100, nominal diameter DN 32). The disinfectants tested included chlorine dioxide (5 mg/L) and chlorine (2.5 mg/L). Testing included monotonic tensile tests, oxidation induction time tests, and pressure tests. Results from the tensile and oxidation induction tests showed that chlorine dioxide was a more aggressive disinfectant; however, pressure tests at a constant temperature showed no pipe failures occurred after 2,000 hours of exposure to disinfectants.
- Davis et al. (2007) compiled failure data and anecdotal information on PE pipe failures from utilities in the United States, Canada, UK, and Australia to assess field performance. UK failure records showed an average failure rate of 3.2 per 100 km per year. Failure records from Australia were deemed less accurate than UK records and estimated failure

rates of 5.9 to 21.2 per 100 km per year. Of 33 U.S. and Canadian water utilities that provided information, none reported failures in larger diameter PE pipe, but these pipelines were all less than 12 years old and relatively short lengths (i.e., less than 10 miles). U.S. and Canadian utilities provided anecdotal information describing fractures in small PE service lines; however, the authors noted that the older PE materials were more susceptible to cracking than newer materials.

- Hassinen et al. (2004) studied corrosion in HDPE pipe exposed to chlorinated water (3 mg/L) at elevated temperatures (105 degrees C, or 221 degrees F) and found evidence of polymer degradation on the unprotected inner walls of the pipe.

SEISMIC PERFORMANCE OF VARIOUS PIPE MATERIALS

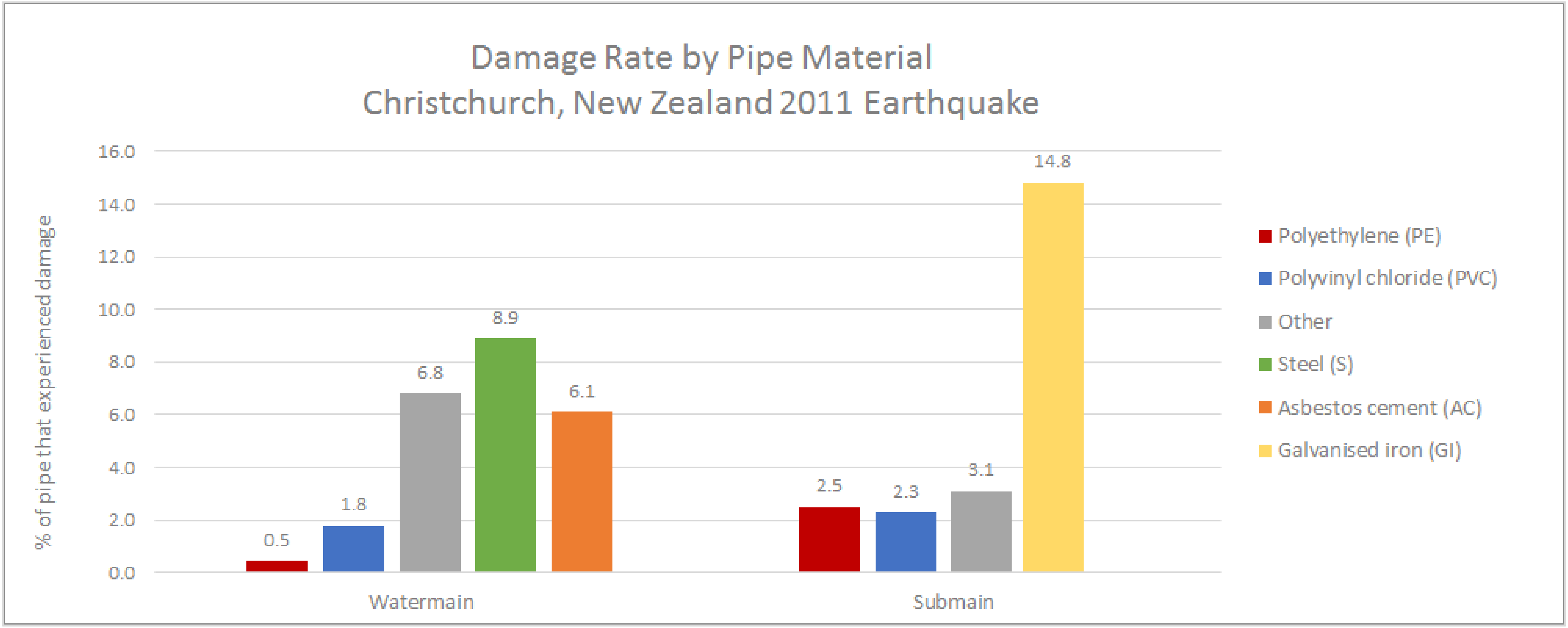
Earthquake hazards affecting pipelines include shaking and permanent ground deformation. Pipe performance during seismic conditions is related to five characteristics (Ballantyne 2010):

- Ruggedness (i.e., the pipe's ability to resist shear and compression failures);
- Resistance to failure when bent (i.e., the pipe's ability to resist failure from bending the pipe barrel);
- Joint flexibility (i.e., ability to elongate, compress, and rotate); and
- Joint restraint (i.e., a system that keeps the pipe joints from separating).
- Pipe condition (e.g., a pipe that is in poor condition is more susceptible to failure due to earthquake hazards than a similar pipe in good condition).

Several papers summarized pipe performance during recent earthquakes. No pipe material is earthquake proof but flexible pipe does perform better than more rigid pipe. Because earthquake damage to pipes often occurs when the pipe sections are pulled apart at the joints, the method of pipe jointing is important.

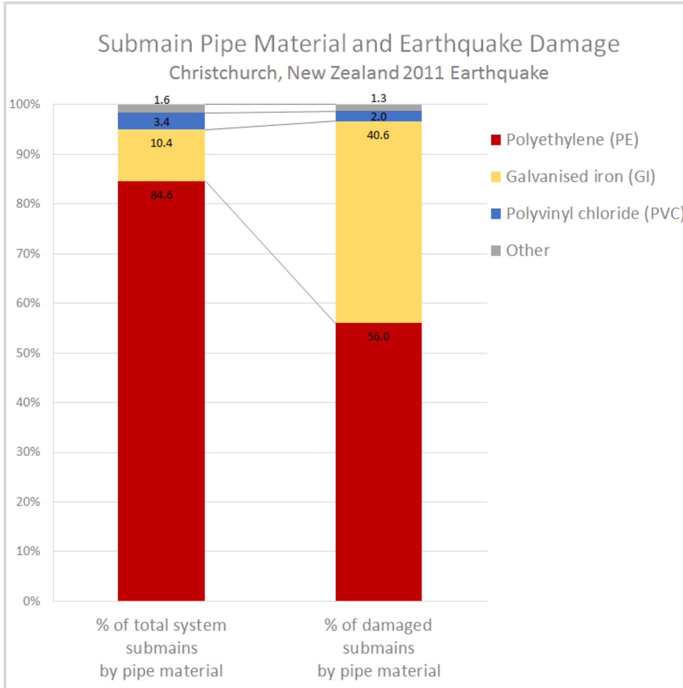
- During the 1995 Kobe Earthquake (i.e., Hyougo-ken Nambu Earthquake) and the 2011 Tohoku Earthquake in Japan, DIP that had seismic joints (i.e., a joint disengagement mechanism) suffered no damage (Miyajima 2014). Seismic joint types S and S-II were developed in 1982 to prevent joint separation. They bend and expand to accommodate differential settlement of soft ground and ground deformation induced by soil liquefaction (Miyajima 2014). Based on the 1995 earthquake, two new types of seismic joints were developed for DIP: NS joints were developed in the late 1990s, and GX joints were under development in 2014 (Miyajima 2014).
- ERDIP has withstood a number of major earthquakes; no damage was reported due to the 1995 and 2011 earthquakes in Japan (Kubota Corporation 2016).
- O'Callaghan (2014) studied performance of various pipe materials and joint systems during 10 earthquakes in New Zealand from 1987 to 2014 based on direct observations and experience. Both deep and shallow earthquakes caused pipe damage but the shallow earthquakes and associated liquefaction effects caused more severe pipe damage. Overall findings show that both PVC and PE pipes suffered significantly less damage compared to AC, steel, GI, and other pipe materials. Minimal or no damage was observed in PE or PVC pipe in non-liquefaction areas.

- Cubrinovski et al. (2011) compared failure rates of different pipe materials (percent of total pipe length) during the February 22, 2011 earthquake in Christchurch, New Zealand. Pipe performance results are unique to the Christchurch system and cannot be generalized to other systems' conditions. Based on pipeline repairs conducted from February to June 2011, 5.1 percent of the total pipe length in Christchurch was damaged by this earthquake. Damage rates for different pipe materials are summarized in Figure 2.11 and Figure 2.12. The term "submain" in Figure 2.11 and Figure 2.12, refers to a parallel lateral main in the sidewalk adjacent to the road; service connections are taken off the submain. Water mains have diameters of 100-mm to 600-mm (4-in. to 24-in.) and submains have diameters of 50-mm and 63-mm (2-in. and 2.5-in.). Because data for all pipe ages is combined, the data shown in these figures may appear to be skewed. Although Cubrinovski et al. (2011) do not describe the jointing method for installed PE pipe (e.g., fused), they do state that the preferred pipe material for new installations is fused PE pipe.



Source: Cubrinovski et al. 2011

Figure 2.11 Damage rate (% pipe length) of water mains and submains (small mains) by pipe material, Christchurch, New Zealand 2011 earthquake



Source: Cubrinovski et al. 2011

Figure 2.12 Percent of total submain (small main) system vs. percent damage of submain by pipe material

- Ballantyne (2010) studied performance of different pipe materials and utility pipe repair records following earthquakes in Kobe, Japan (1995); Northridge, California (1994); and Loma Prieta, California (1989). Findings included:
    - PE pipe with fused joints had a relative low vulnerability to failure compared with other pipe materials and joint types.
    - PVC pipe had a low to moderate vulnerability to failure depending on the site-specific conditions (e.g., type of pipe joint, soil conditions, and the intensity and duration of ground shaking and deformation). PVC pipe with restrained bell and spigot joints were less vulnerable than pipe with unrestrained bell and spigot joints.
    - DIP and steel pipe had a low to moderate vulnerability of failure except for steel pipe with gas welded joints which had a moderate to high vulnerability.
    - PE and copper service lines performed better than solvent-welded joint PVC and screwed-joint steel pipe.

OPERATIONAL ISSUES RELATED TO PIPELINE PERFORMANCE

Routine and emergency operating practices can result in variations in critical hydraulic parameters such as pressure, flow, and water age that can affect pipe performance. For example, when maintenance work is performed, system operators may temporarily valve off an area to isolate the work area, causing changes in flow direction, pressure and velocity.

The operating pressure in a water distribution system fluctuates over time and location, depending on several factors such as pipe elevation, operating set points for booster pumps and system valves, storage tank water levels and water demand variations.

Pressure transients (also called pressure surges or water hammer) can occur when an abrupt change in water velocity occurs, due to a sudden valve closure, pump shutdown, hydrant operations, or loss of power. The resulting pressure wave, with alternating low and high pressures, travels back and forth through the distribution system until the pressure is stabilized. When transient pressures are high, pipe breaks can occur, particularly if a pipeline is weak from structural deterioration. Pressure transients can also cause main breaks in structurally sound pipe at joints, tees, valves and other fittings, especially where the pipe is not properly restrained.

Folkman et al. (2013) studied the effects of pressure fluctuation on failure rates of PVC pipe and determined that fatigue damage is insignificant when pressure fluctuations are limited to 20 psi. However, a recent survey indicates that 17 percent of utilities experience pressure fluctuations greater than 20 psi (Folkman et al. 2013). EBMUD and American Water do not install PVC pipelines as suction or discharge pipelines immediately adjacent to pumping plant facilities.

Najafi et al. (2015) conducted fatigue tests on 16-in. diameter HDPE pipe samples (DR 17, PE4710 pipe containing a butt-fused joint) to evaluate the durability of HDPE pipe during recurring pressure surges. Phase one testing was conducted between 125 psi and 188 psi for two million cycles which is the equivalent number of surges applied to a pipe over 100 years of service at a rate of 50 surges per day. A second phase tested the same pipe sample at pressures of 125 psi to 250 psi for 50,000 cycles. No pipe samples failed during these tests. After 6 months of phase one testing, the diameter of the pipe sample had increased by 0.52 in. at the butt-fused joint. After phase two testing, the pipe diameter had increased an additional 0.02 in. at this same location. The testing protocol developed by Najafi et al. (2015) can be used to evaluate other pipe samples.

An engineering evaluation of pipe failures in Colorado Springs determined the relationship between system pressures and failure rates (Garcia and Funchion 2014). System pressure ranged from 50 psi to greater than 200 psi. Pipe failure rates increased linearly with system pressure and failure rates were markedly higher in pipes with operating pressures greater than 80 psi. Water mains operating in the pressure range of 80 to 120 psi had a leakage rate of 2.2 leaks per mile compared to a leakage rate of 0.9 leaks per mile in water mains operating at less than 60 psi.

CHAPTER 3
PLANNING

This section describes utility experiences with planning strategies as they relate to plastic pipe projects. Industry practices for master planning, capital improvement planning, and preliminary engineering are covered in other reference materials. Some planning tasks that should be considered for all pipeline projects include selecting a pipe material, identifying the best route or alignment, developing cost opinions, obtaining easements, planning for service interruptions and temporary water service, and coordinating with government agencies. When pipelines are installed in roadways, planning is needed for traffic control and contractor access. The pipe's proposed location is marked on the pavement or ground surface and other utilities are located using the state's "One Call" dig safe program.

Some planning tasks are unique to trenchless technology construction methods or installation of HDPE by open-cut construction. Prior to installing the pipeline, an alignment study is conducted and horizontal and vertical alignments of all adjacent utilities are identified. If necessary, the proposed alignment is revised to avoid interferences with existing utilities.

The following utility examples highlight planning considerations for plastic pipe projects:

- The City of Calgary leveraged public awareness of the high rate of main breaks in the 1970s and early 1980s to garner support for increased main repair and replacement costs. In 1978, PVC was first allowed for new construction, replacing yellow jacketed DI (YDI) (i.e., a 40 mil (1.6mm) thick PE coating extruded directly onto the pipe in the factory) as the preferred material (Line 2016). In 1981, Calgary started allowing PVC for water main replacement projects. PVC pipe is primarily used for applications requiring pipe diameters < 16 in. and in areas with corrosive soil (defined as soil resistivity <2,000 ohm-cm). Construction costs increased with the YDI pipe, and then were just accepted as "the cost of doing business" when PVC replaced YDI as the material of choice (Line 2016). Successful implementation of the stricter specifications was only possible because City staff and contractors embraced the new approach.
- Seattle Public Utilities is currently building a business case to justify use of PVC pipe as an alternative to DIP on future water main projects in corrosive soils (Muto 2016). The utility needs to overcome negative institutional attitude about plastic pipe that is based on the high failure rate of polybutylene service pipe installed from 1978 to 1990.
- Utilities considering how to use HDPE pipe should stay abreast of the challenges and solutions experienced by other utilities (Irias 2016). One forum for exchanging utility information is the Municipal Advisory Board which is a group sponsored by the Plastics Pipe Institute. Further information is available online at http://plasticpipe.org/municipal_pipe/advisory/index.html.
- When designing projects utilizing FPVC pipe, EPCOR includes provisions to accommodate the expansion and contraction of the pipe due to temperature fluctuations experienced in the water conveyed (Seargeant 2016). Water temperatures vary between 32 and 65 degrees F between winter and summer in Edmonton.
- Construction of an HDPE transmission main in San Antonio required organization and coordination amongst the pipe supplier, pipe producer, fusion crews, and contractor

personnel (Smith et al. 2014). The unique MegaMc Poly Horse pipe handling equipment used on this project minimized the time spent moving and handling the pipe, and helped to improve the project's overall productivity. The installation rate was close to 1200 linear ft per day.

- The City of Palo Alto's HDD specifications require that the pipe be supported on rollers or other devices during installation to avoid damaging the pipe and to minimize friction (Scoby 2012).
- AWWU in Anchorage plans the locations of pipe joints to minimize the number of electrofusion couplings. This is especially true at 90-degree bends. Prior to construction, electrofusion coupling locations have to be approved by the Engineering Division Director.

The sections below discuss utility experiences with selecting pipe materials and determining life cycle costs.

SELECTING PIPE MATERIAL

Project-specific conditions require water utilities to be open-minded with the type(s) of pipe material specified; one type of pipe material will probably not be suitable for all projects (Mazurek 2006). Different materials may be selected for a project's small and large diameter pipe (Iles and Eddy 2014). Selection of pipe material may be based on cost, system pressure, prevalence of pressure transients, soil conditions, utility and industry standards, and/or utility preference. Iles and Eddy (2014) identified other selection criteria including pipe strength, corrosion resistance, high water temperatures, constructability, durability, and maintenance requirements. Some utilities including LADWP and EBMUD do not install PVC pipe near pump stations due to its susceptibility to failure during pressure surges (Bautista 2016; Irias 2016).

Utility experiences with pipe selection were discussed at the project workshop. Brief case studies are described below:

- Louisville Water Company (LWC) utilizes C900 SDR 18 PVC in applications where pressures are less than 100 psi and SDR 14 when system pressure is less than 120 psi (Raney 2016). Typically, 12 in. is the largest diameter PVC main that is utilized. PVC has proven to be a very reliable product. In the past 5 years, only 4 percent of main breaks (101 of the 2,494 breaks) have been on PVC water mains. LWC uses PVC pipe because it is less expensive than other materials (e.g., DIP); it is chemically inert, allowing for use in areas with highly corrosive soils; it can be used in directional drilling projects which are less disruptive and avoid problems of conventional open trench installation; and installation is easier compared to DIP. LWC does not use PVC pipe on primary roads because it may have some issues under pavement (i.e., issue with live load). LWC identified several disadvantages of using PVC pipe: it does not have an established record like DIP and its porosity could allow chemical or hydrocarbon infiltration.
- American Water notes that research supports the premise that thicker pipe walls are more resilient to pressure stress and pipe failures (Hughes 2016a). American Water's minimum criteria for PVC pipe is DR18 material and in some locations including American Water's largest PVC user, St Louis County, DR 14 is specified. The goal is commonly to have the normal operating pressure at 60% or less of the old AWWA pressure class ratings (pre-2007). The additional cost to use a thicker minimum is minimal in a life cycle cost analysis.

American Water does not allow DR25. The previous example of the tap failure on this class of pipe was an example of how someone slipped past the specification in error.

- Golden State Water Company uses the following pipe selection criteria (Carver 2016):
    - For 6-, 8- and 12-in. diameter pipe, PVC is less expensive to construct in Southern California than DIP because of ease of installation. For 16- to 30-in. diameter pipe, the water company prefers DIP rather than similar sized C905 PVC pipe because the thicker wall of the PVC pipe reduces the interior diameter and the amount of flow that can be carried. For diameters 30-in. and larger, plastic pipe is not generally used; CML&C steel pipe is used because it is less expensive than similar sized DIP.
    - PVC pipe is used in areas with aggressive soils and DIP is used in areas with rocks and cobbles. For sites that have rocks, cobbles, and aggressive soils, PVC pipe is wrapped in a geo-fabric to prevent migration of the cobbles.
    - HDPE pipe is used for crossing busy intersections or railroad tracks. It is installed inside a larger diameter steel, DIP, or PVC casing pipe.
- EBMUD uses PVC pipe with push-on joints for 6- and 8-in. diameters only (Irias 2016). PVC water mains are installed on low traffic streets with less than a 15 percent grade, dead-end mains, and other low flow areas. PVC is selected only when system pressure is less than 140 psi. Steel pipe is used for other applications. PVC is not used in seismic hazard zones such as fault, liquefaction, or landslide zones. PVC is not used for offset returns around existing utilities.
- EBMUD uses HDPE pipe on a case-by-case basis when exceptional ductility is needed or for trenchless applications; HDPE is not yet an approved EBMUD standard (Irias 2016). Before HDPE can become an EBMUD standard, quality assurance procedures and repair methods need further development (Irias 2016).
- WaterOne switched from DIP to PVC in 2008 for open cut installations due to external corrosion issues with metallic pipe; soils are highly corrosive (Pietig 2016). Also, PVC has lower material cost compared to DIP (Table 3.1) and lower installation costs. A length of 6-in. diameter PVC pipe can be carried by two people whereas a similar size DIP would need to be moved by a boom truck. DIP is used for short relocation work for more rigid applications if the existing pipe is metallic. WaterOne uses HDPE for pipe bursting and sliplining applications, and HDPE or Certa-Lok PVC for horizontal directional drilling applications. Plastic pipe has a thicker pipe wall for long transmission mains or sliplining projects compared to other pipe materials.

Table 3.1
Comparison of pipe material cost at WaterOne (Nov. 2014 prices)

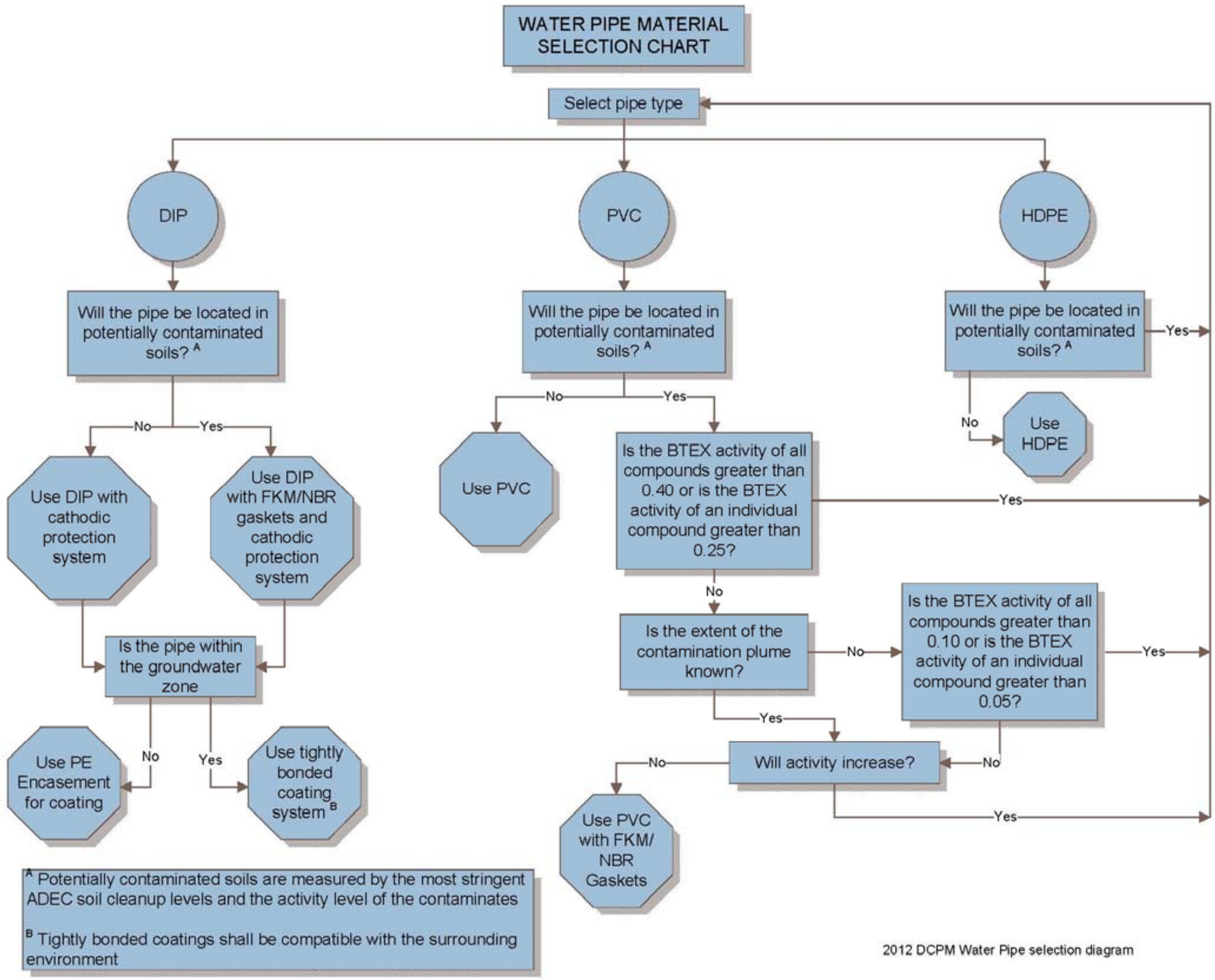
	Pipe Diameter		
Pipe Material	**6-in.**	**8-in.**	**12-in.**
DIP	$10.41/ft	$17.15/ft	$27.31/ft
DIP restrained joint	$12.11/ft	$19.43/ft	$31.08/ft
PVC C909	$3.76/ft	$6.65/ft	$13.69/ft
PVC C900 restrained joint	$6.18/ft	$10.42/ft	$22.36/ft
HDPE with fusion welded joints	$7.65/ft	$13.08/ft	$21.24/ft

Source: Data from Pietig 2016

- EPCOR in Edmonton, Canada has preferentially installed PVC water mains since 1977 (Seargeant 2016). The largest PVC main currently installed is 36 in. (900 mm). For new projects, EPCOR is considering installing PVC mains up to 48 in. (1200 mm) in diameter due to the operational reliability of smaller diameter PVC pipe and the cost effectiveness of the material because the pipe is now manufactured locally. EPCOR has also used HDPE up to 36 in. (900 mm) in diameter, mostly in sliplining applications, but has experienced failures of butt-fused welded joints in many HDPE installations. For this reason, EPCOR is now using FPVC as an alternative to HDPE in this application.
- LADWP plans to use plastic pipe where the soils are corrosive (defined as soil resistivity <500 ohm-cm) and where system pressure is less than 150 psi (Bautista 2016). LADWP has identified more than 340 miles of existing pipelines in highly corrosive soils with moderate pressure (up to 150 psi) where plastic pipe may provide optimum service characteristics. Plastic pipe will also be used in areas with a high water table, particularly areas with saline water intrusion. Plastic pipe will also be used for recycled water applications in which the source water is corrosive. LADWP selects the pipe material for a project's specific needs and criteria; favorable characteristics of pipe material alternatives have been identified. For example, HDPE, steel, and ERDIP are suitable for seismic conditions in Los Angeles. Based on 100 years of available performance data, steel pipe is also selected for large diameter pipe projects and projects serving high pressure areas. DIP is the most widely used pipe material by water utilities. With more than 100 years of available performance data, it is known to be a very strong pipe material.
- HBWS uses a conservative approach when using PVC pipe (Fuke 2016). The utility uses C900 and C905 (16-in. only) pipe. HBWS specifies only SDR 14 PVC pipe and it can only be used for areas where static pressures do not exceed 100 psi. Fused PVC pipe is only considered for directional drilling applications on a case-to-case basis.
- AWWU in Anchorage started using HDPE and PVC pipe because of corrosion related failures of DIP and difficulties in obtaining preferred corrosion protection options (e.g. tightly bonded coatings) (Nuss 2016). AWWU originally selected HDPE because of their experience with crack failures on Schedule 40 PVC pipe that was installed in the 1970s and the known brittleness of PVC, especially when subjected to extremely cold weather. AWWU has found several issues with the use of HDPE:
    - Connections to existing infrastructure are difficult due to the HDPE pipe wall thickness.
    - For rehabilitation and replacement projects, the presence of other utilities at shallow depths makes it difficult to install HDPE without the use of electrofusion couplings. AWWU has experienced several electrofusion coupling related failures.
    - The AWWU service area has many hydrocarbon-contaminated soil sites, making HDPE and PVC a poor selection.

  HDPE is still an allowed product, but it has limited applications. AWWU researched other cold climate applications of C900 PVC and decided that PVC is now a preferred material (Nuss 2016). AWWU still uses DIP for certain applications (diameter larger than 16 in.; seismic applications; and for soils contaminated with hydrocarbons). One of the largest DIP manufacturers is now selling pipe with factory-applied zinc coating with option to field apply tightly bonded coatings (non-asphalt coating). Used in conjunction with PE encasement, DIP provides an acceptable corrosion protection option.

- Based on project experience dealing with contaminated soil, AWWU created a flow chart to help their designers select the most appropriate pipe material for the local conditions (AWWU 2012) (Figure 3.1). For certain types of contaminated soil, AWWU uses DIP instead of PVC or HDPE pipe. This flow chart is an example of the decision methodology used by one particular utility. It includes issues such as use of fluoroelastomer (FKM) gaskets and nitrile butadiene rubber (NBR) gaskets, and evaluating gasoline contaminated soils (i.e., contamination with benzene, toluene, ethylbenzene, and xylenes (BTEX)).



Source: AWWU 2012

Figure 3.1: Utility example of flow chart for selecting pipe materials

Criteria used to select HDPE over other pipe materials were documented by Najafi et al. (2015) in utility case studies (Table 3.2). HDPE pipe should not be installed in areas where the soil is contaminated with organic solvents or where future soil contamination is a concern (PPI 2005). The solvents could permeate the pipe and soften the pipe material; they also can affect the performance of gaskets.

Table 3.2
Utility experiences with selecting HDPE compared to other pipe materials

Utility, State	Application	Diameter; Length	Material Selection Factors
LADWP, California	Sliplining to replace existing 40-in. CI trunk line	36-in.; 1,690 ft	Smooth interior of HDPE pipe. Ability to use trenchless installation allowed fast construction and minimal traffic disruption.
Eastern Navajo Reservation, New Mexico	Finished water transmission, up to 290 psi.	24-in.; 69,000 ft	DIP was originally specified but changed to HDPE because of corrosive soil. HDPE perceived to be stronger than PVC. Large seasonal waterways crossings with shifting soils and erosion.
San Antonio Water System, Texas	Raw water transmission from Carrizzo aquifer, 150 psi	36-in.; 40,000 ft	Primary reason was utility experience with low maintenance needs on their other HDPE mains. Other factors include its resistance to corrosive soils, flexibility, and constructability.
Colorado Springs Utilities, Colorado	Raw water transmission, replacement of two leaking steel mains, 100 psi	36-in.; 3,000 ft	Constructability, flexibility, and resistance to corrosion. Expedited construction schedule was required due to weather conditions at this high altitude location (up to 14,000 ft).
Seminole County Regional Water Authority, Florida	Raw water transmission, low pressure, 45 MGD capacity	42-in.; 41,100 ft	Limited accessibility throughout pipeline corridor; material's flexibility, corrosion resistance and expected design life; low friction; and fused joints.

Source: Data from Najafi et al. 2015

For the San Antonio Water System's Carrizo project, the selection of pipe materials was carefully evaluated due to corrosive soils and potentially corrosive water (Iles and Eddy 2014). The water's average dissolved solids concentration (500-3,000 mg/L) was a design consideration due to its potentially corrosive effects on the interior pipe walls (Smith et al. 2014). Also, water temperature was expected to reach 105 degrees F at a system pressure of 160 psi (Smith et al. 2014). HDPE pipe was selected for the project, and specifically, the PE4710 resin was selected instead of the PE3408 resin because it can be installed with thinner walls and standard size fittings (Iles and Eddy 2014). The PE3408 resin was first considered because San Antonio had used it for other applications and it met the requirements of the AWWA standards. However, the pressure rating of the PE3408 resin is decreased by a factor of 0.78 for the project's design temperature which would require thicker pipe walls and therefore increase the project cost.

The Mojave Water Agency in California selected PVC for Phase 4A of the Mojave River Pipeline which extends approximately 76 miles from the California Aqueduct in the Phelan area to groundwater recharge sites along the Mojave River. The pipeline was completed in 2006 to deliver water to the Mojave Basin area to supplement native water supplies. The Phase 4A pipeline installation was completed in 2004 and included 40,450 ft of 24-in. diameter SDR 32.5 PVC pressure pipe rated at 125 psi (Fisher 2005). The installation rate was 1,500 ft per day. The use of PVC in this project phase saved $800,000 compared to the steel pipe alternative. No operational issues were identified after one year in service (Fisher 2005).

An ongoing WRF Project #4650 is conducting laboratory and field testing of structurally enhanced iPVC pipe and developing guidelines on pipe selection criteria and installation requirements (Hughes et al. 2016). The iPVC pipe is currently manufactured in Korea and being installed in China, Japan, and Korea. The iPVC pipe is NSF certified and exceeds the AWWA C900 standard requirements. Preliminary findings from field testing have demonstrated that the iPVC pipe has high impact resistance, ductility, and strength (Hughes et al. 2016).

LIFE CYCLE COSTS

Life cycle costs include not only the costs of design and construction, but also the costs of operating and maintaining an asset such as a pipeline. One of the key messages from the project workshop was that installed pipe material cost is incidental to the life cycle cost, and repair costs represent the majority of the cost. This section includes utility experiences regarding life cycle costs as presented in the literature, workshop presentations, and other utility information. Life cycle cost information was not well represented in the literature reviewed. Many utilities do not have the necessary data, time, or resources to compile life cycle costs for pipe replacement programs (Ambrose et al. 2008).

The cost of a water distribution system rehabilitation or replacement project is governed by many factors besides the cost of the construction materials and method. Other cost factors include the geographic location (e.g., urban, suburban, rural); weather conditions; extent of traffic control; permit requirements; number of service connections; need for temporary water service; site conditions (e.g., surface interferences, subsurface obstructions, soil type); paving; number of sites; and extent of cleaning required. LADWP has found that pipe material cost (both plastic and metallic pipe) is generally less than 5 percent of the total construction cost (Bautista 2016).

Costs of failure include direct costs, indirect costs, and social costs (Knight et al. 2015).

- Direct costs include costs to repair the water main, and restore environmental damage.
- Indirect costs include costs to businesses that were affected by service outage or the environmental damage; and degradation of adjacent utilities or structures.
- Social costs include water quality issues, traffic delays, loss of customer confidence in water service; and environmental impacts.

An important component of a life cycle cost analysis is estimating the expected service life of water mains and the estimated direct and indirect costs of repair, replacement, and pipe failure (Ambrose et al. 2008). Service life is a major unknown for all pipe materials and is not consistently defined (Irias 2016).

Pavement practices can have a strong bearing on life cycle costs (Irias 2016). In particular, the practice of Full Depth Reclamation (FDR) (i.e., a process by which pavement and some underlying materials are recycled/rehabilitated to depths of greater than 24 in.) needs to be addressed in a pipe's life cycle cost estimate. Because the useful life of pavement is usually far less than a pipe's service life, the replacement cost for the pavement needs to be included in the pipe's life cycle cost. Several utility participants at the project workshop also mentioned that the characteristic failure modes, and the associated economic and social costs of the various failure modes, are critically important to decisions related to selecting pipe material.

Gaewski and Blaha (2007) compiled the total cost for 30 large diameter pipe failures across the United States including 4 failures in California. The failures included water mains with diameters ranging from 20 in. to 96 in. The materials of construction for the 30 failures included PVC (1 case), CIP (14), prestressed concrete cylinder pipe (11), and steel (4). The average cost of the 30 pipe failures was $1.7 million including direct costs and societal costs, with costs ranging from $6,000 to 8.5 million. Direct costs included water utility labor for repairs and customer relations, repair materials, outside contractors and engineers, cost of lost water, and forensic studies. Societal costs included traffic impacts, customer water outages, public health impacts, property damage, and damage to adjacent utilities and public transportation systems.

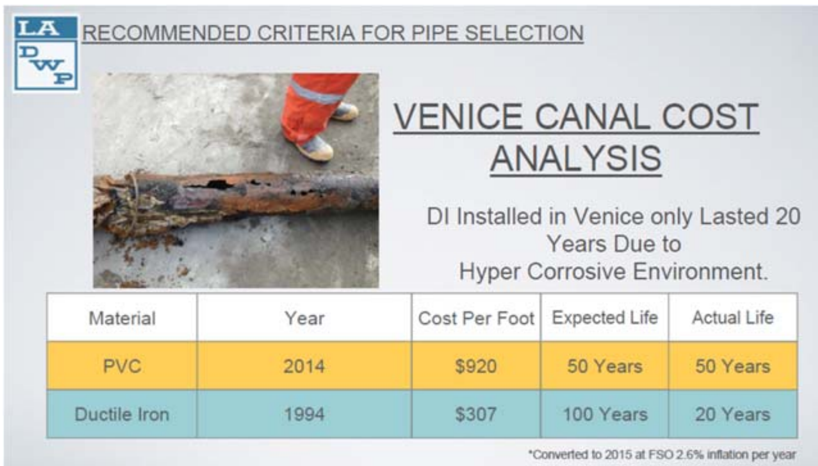
As noted previously, PVC pipe failures tend to run longitudinally which lead to pipe blowouts and more damage and loss of water than a typical circumferential break. Brander (2004) noted that PVC pipe failures can be costlier and damaging compared to metallic water main failures. In Calgary, some PVC pipe failures were due to crack propagation along the full length of a pipe, resulting in large water loss and property damage.

A Life Cycle Cost Analysis of Networks (LICAN) was developed by CSIRO in Australia to help utilities compare alternative materials for water main projects (Ambrose et al. 2008). User input includes pipe inventory (material, size, and age for every pipe segment), and installation, repair, and replacement costs for different pipe materials and pipe sizes. The model includes the cost of water loss but does not include the cost of pipe failure due to third party damage.

Utility experiences with life cycle cost analyses are provided below.

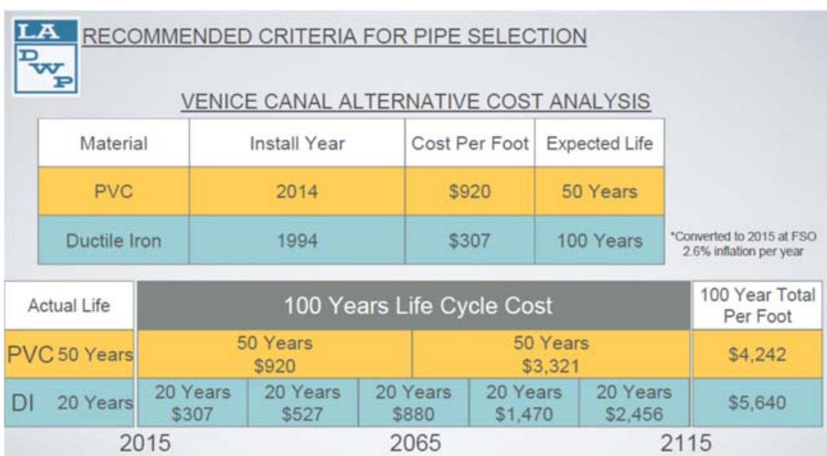
- Ambrose et al. (2008) used a case study example to illustrate how a utility would use the LICAN model to compare the life cycle costs of different pipe materials. For the selected case, a medium sized network serving 100,000 customers, the model showed that a pipe network comprised of PE water mains would have the lowest life cycle costs for a 100-year planning horizon and a network with DIP water mains would have the highest costs. Pipe networks comprised of a mix of plastic and DIP water mains would have life cycle costs between the low and high costs. The comparatively lower costs for the PE network were related to the lower failure rate of PE water mains and resulting lower repair costs; and also the reduced costs for water losses because of the smaller leakage rate from the PE pipe's fused joints. Ambrose et al. (2008) estimated that repair costs represent 70 to 80 percent of the total life cycle costs for a pipe network.
- Seattle Public Utilities (SPU) in Washington uses a triple bottom line approach and full life cycle costs in evaluating pipeline and other asset management projects (Kirmeyer et al. 2008). The triple bottom line approach considers financial, social, and environmental evaluation criteria. SPU has developed standard templates for completing an economic analysis of project alternatives.

- For AWWU in Anchorage, initial installation cost savings cannot be easily ascertained. Depth of burial is extreme and the resulting project specifications have made interpretation of data difficult to assess relative to typical installations in North America.
- LADWP completed a life cycle cost analysis for a project in 2014. This example illustrates the selection of the proper pipe material based on site-specific conditions (e.g., highly corrosive environment) for the Venice Canal area of West Los Angeles. Figure 3.2 compares PVC and DIP costs based on the expected, documented life of pipe material installed in a corrosive soil environment. Figure 3.3 shows the life cycle costs based on the expected life cycle for non-corrosive soil conditions. Figure 3.3 demonstrates that plastic pipe was the right choice from a life cycle and cost basis.



Source: Bautista 2016

Figure 3.2 LADWP Venice Canal project life cycle costs for corrosive environment



Source: Bautista 2016

Figure 3.3: LADWP Venice Canal Project Life Cycle Costs for Non-Corrosive Environment

CHAPTER 4
DESIGN AND CONSTRUCTION

INDUSTRY STANDARDS, GUIDANCE AND REGULATIONS

An important design consideration is selecting the type of pipe material that will perform well for a project's specific pressure conditions. Pipe is given a pressure rating by applying a safety factor to the determined long-term pressure capacity of the pipe material. Pressure ratings should consider not only the static pressures but also the momentary low and high pressures that can occur during transient pressure surges. For example, the AWWA C900 Standard for PVC water distribution pipe uses a surge allowance and a safety factor of 2.5 to determine the allowable pressures for each pressure class of pipe (Table 4.1). The Uni-Bell PVC Pipe Association (n.d.) uses a safety factor of 2.0 to determine allowable pressures for PVC pipe (Table 4.1). The AWWA C906-15 Standard for PE pressure pipe and fittings includes pressure classes and allowable surge pressures for HDPE (PE4710) pipe (Table 4.2). Note that AWWA's definitions of pressure class for different pipe materials are not identical (PPI 2016). Refer to the AWWA standards (AWWA 2007, 2015) and Manuals of Practice (AWWA 2002, 2006) for more information.

Table 4.1
Selected pressure classes and ratings for PVC pipe

Standard Dimension Ratio (SDR)	AWWA C900 Pressure Class (Pre-2007) (psi)	AWWA C900 Pressure Class (Post-2007) (psi)	Uni-Bell Pressure Rating (psi)
25	100	165	165
18	150	235	235
14	200	305	305

Source: Data from AWWA 2007 and Uni-Bell PVC Pipe Association n.d.

Table 4.2
Selected pressure classes and allowable surge pressures for PE4710 pipe

Standard Dimension Ratio (SDR)	Pressure Class for Water at 73 degrees F (psi)	Recurring Surge Pressure (psi)	Occasional Surge Pressure (psi)
17	125	188	250
13.5	160	240	320
11	200	300	400

Source: Data from Plastics Pipe Institute 2016

Based on experience, some utilities are specifying thicker pipe material than the minimum requirements. For example:

- American Water's largest PVC user, St. Louis County, specifies SDR 14 PVC pipe because it is expected that the extra thickness in pipe wall will result in a longer service life (Hughes

2016a). SDR 18 PVC pipe is used for locations with system pressures of 100 psi or less. SDR 25 PVC pipe is not allowed in American Water systems.

- EBMUD specifies SDR 14 PVC pipe because it is less fragile and thus less prone to shattering compared to SDR 18 PVC pipe prior to installation or during tapping (Irias 2016). Before 2007, EBMUD used SDR 14 PVC for pressures up to 140 psi. When AWWA rewrote the C900 standard in 2007, effectively changing a 150 psi rated pipe to a 235 psi (SDR 18) rating, EBMUD used SDR 18 PVC but the pipe shattered when accidentally dropped from the truck. Because of that event, EBMUD has switched back to specifying SDR 14 PVC.
- WaterOne in Johnson County, Kansas uses PVC Class 235 (SDR 18) and HDPE Class 160 (SDR13.5) with average system pressure of 90 psi (range = 40 psi to 150 psi) (Pietig 2016).
- AWWU requires SDR 18 PVC pipe that meets AWWA standards for diameters of 4 in. through 16 in. (Nuss 2016). Use of PVC pipe larger than 16 in. in diameter requires approval from the AWWU Engineering Director.

AWWA Standards outline the recommended design, construction, and testing requirements for pipe and other waterworks products. These standards undergo a review and approval process by the American National Standards Institute (ANSI) and are therefore referred to as ANSI/AWWA standards. They are often cited in project specifications. The current ANSI/AWWA standards for PVC and HDPE pipe include:

- ANSI/AWWA Standard C605-13. Underground Installation of Polyvinyl Chloride (PVC) and Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe and Fittings.
- ANSI/AWWA Standard C651-14. Disinfecting Water Mains.
- ANSI/AWWA Standard C900-07. Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 In. Through 12 In. for Water Transmission and Distribution.
- ANSI/AWWA Standard C901-08. Polyethylene (PE) Pressure Pipe and Tubing, ½ In. Through 3 In. for Water Service.
- ANSI/AWWA Standard C903-05. Polyethylene–Aluminum–Polyethylene & Cross-Linked Polyethylene–Aluminum–Cross-Linked Polyethylene Composite Pressure Pipes, ½ In. Through 2 In. for Water Service.
- ANSI/AWWA Standard C904-16. Polyethylene (PE) Pressure Pipe and Tubing, ½ In. Through 3 In. for Water Service.
- ANSI/AWWA Standard C905-10. Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14 In. Through 48 In.
- ANSI/AWWA Standard C906-15. Polyethylene (PE) Pressure Pipe and Fittings, 4 In. Through 65 In. for Waterworks.
- ANSI/AWWA Standard C907-12. Injection-Molded Polyvinyl Chloride (PVC) Pressure Fittings, 4 In. Through 12 In. for Water Distribution.
- ANSI/AWWA Standard C909-16. Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4 In. Through 24 In. for Water, Wastewater, and Reclaimed Water Service.

Several technical manuals provide comprehensive resources for pipeline design, specification, installation, and maintenance issues. Pipe suppliers also publish technical bulletins.

- M23 PVC Pipe – Design and Installation (AWWA 2002)

- M55 PE Pipe – Design and Installation (AWWA 2006)
- Handbook of PVC Pipe – Design and Construction (Uni-Bell)
- Handbook of Polyethylene Pipe (Plastics Pipe Institute).

ASTM International has several standards that outline requirements for design and installation PE pipe:

- D2239-12a Standard Specification for Polyethylene (PE) Plastic Pipe Based on Controlled Inside Diameter
- D3035 -15 Standard Specification for Polyethylene (PE) Plastic Pipe (DR-PR) Based on Controlled Outside Diameter

NSF International has several standards that are referenced in waterworks products and projects:

- NSF/ANSI Standard 14: Plastic Pipe and Fitting Testing is the testing and certification of plastic pipe products against appropriate standards.
- NSF/ANSI Standard 60: Drinking Water Treatment Chemicals – Health Effects sets health effects criteria for water treatment chemicals (e.g., corrosion and scale inhibitors, disinfection chemicals).
- NSF/ANSI Standard 61: Drinking Water System Components – Health Effects sets health effects criteria for pipes and related products (e.g., fittings), pipe coatings, joining and sealing materials (e.g., gaskets, adhesives, and lubricants), mechanical devices (e.g., water meters, valves) and non-metallic potable water materials.

Ten States Standards is another industry standard that is referenced in project specifications (Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers 2012). This standard requires that pipe materials conform to the latest versions of AWWA and ANSI/NSF standards and be acceptable to the reviewing authority. It also requires that materials used for rehabilitation of water mains shall meet ANSI/NSF standards.

The PVC Pipe Association has prepared sample specifications for projects using PVC pipe. The specifications refer to the ANSI/AWWA and NSF/ANSI standards described above and other recommended industry practices. The samples specifications and other technical resources can be downloaded from the Association's website (http://www.uni-bell.org/).

Some water utilities have developed their own design and/or construction requirements that are used as a guide for project specifications. Some examples include:

- The City of Calgary requires the use of sand or clean gravel for pipe bedding and the first lift of backfill that surrounds the installed pipe (Brander 2004). All "potentially injurious" materials must be removed from the sand or gravel. Because of this requirement, it is not possible to use native soils as pipe bedding or backfill. Most contractors use sand or pea gravel. Otherwise, the city's specifications follow the PVC Pipe Association's Handbook of PVC Pipe Design and Construction guidelines.
- Calgary's specification also requires (Line 2016):
    - A vertical separation of 300 mm (12 in.) between water, sanitary, and storm drain crossings.

  - "Bell and spigot joints shall be made such that the factory insertion line is visible after installation. Joints without a visible insertion line shall be re-made at the Engineer's request." (Line 2016)
- WaterOne includes the following requirements in their specifications (Pietig 2016):
  - The specified bedding conditions for PVC and HDPE pipe are ½ in. clean gravel (gradation not allowing larger than ½ in. rock).
  - For PVC pipe, no deflection is allowed at joints. PVC pipe should be assembled above ground, in a straight line, then curved and laid in the trench. All curvature results from the bending of the pipe lengths.
  - WaterOne currently uses DI fittings with a fusion-bonded coating. No anodes are used on distribution system fittings.
  - WaterOne recommends de-beading interior of HDPE transmission mains (the fusion bead was about an inch high for every 40 ft of 24-in. diameter HDPE).
- HBWS has revised pipe specifications based on past issues with PVC pipe failures (Fuke 2016). PVC fittings are no longer accepted. Only DI C110 fittings are acceptable for use with PVC pipes. Service saddles are not used on new pipe installations. Tapped tees are required for service connections on new mains. Deflection couplings are not allowed and pipe bending is not allowed.
- AWWU uses the following design requirements (Nuss 2016):
  - PVC water main and service piping must be installed with an over insertion prevention device equal to EBAA Iron Mega Stop or the Cert-Lok bi-directionally restraint system.
  - HDPE and fittings are to be manufactured in accordance with AWWA C906 with the additional stipulation that the HDPE is to be manufactured from PE4710 using PE compounds that meet or exceed ASTM D3350 Cell Classification 445574. HDPE pipe and fitting material compound is to contain color and ultraviolet (UV) stabilizer meeting or exceeding the requirements of Code C per ASTM D3350.
  - Electrofusion fittings are not allowed unless specifically approved by AWWU. Any electrofusion couplings must be surveyed and their location documented on the record drawings. All fittings are to have pressure class ratings not less than the pressure class rating of the pipe to which they are joined.
  - Due to potential for contaminated soils, AWWU also requires designers to follow additional requirements for validating the use of PVC or HDPE pipe in a given area. All designers submitting plans for water projects must, at a minimum, review the Alaska Department of Environmental Conservation (ADEC) Division of Spill Prevention and Response maintained database of contaminated sites and perform soil data collection.
- City of Houston (2015). Water line design requirements are described in Chapter 7 of the city's infrastructure design manual. For example, the city requires use of restrained joint pipe for lines 20-in. in diameter or less with less than 4 ft or more than 8 ft of cover. Allowed direct bury alternates include PVC pipe with integral restrained joint system, or DI restrained joint fittings, epoxy lined and coated.
- City of San Diego (2004). The specifications section Division 02 Site Work covers plastic pipe requirements in specifications numbered 02642-02646. Division-15 Mechanical includes specifications for piping components, supports, identification systems, valves, and insulation.

State and county regulations may also include requirements for pipeline design or construction. For example, California design standards for water distribution systems are described in the California Waterworks Standards (California Department of Public Health 2008).

The greatest design issue facing EPCOR in Edmonton, Canada with respect to plastic pipes is accounting for the overall change in length of FPVC or HDPE pipe due to thermal changes (Seargeant 2016). Potable water temperatures in Edmonton vary over the course of the year from 32.5 degrees F to 65 degrees F. Temperature variations of this magnitude are known to cause changes in the lengths of plastic pipes. EPCOR's typical use of bell and spigot-jointed PVC pipe means that the expansion and contraction of the PVC pipe is provided for at each joint, making the impact of the temperature changes a non-issue with non-fused pipe. The design considerations extend beyond the initial installation to ensuring that future work affecting a fused pipe does not compromise that initial installation. There is no guarantee that work will not be undertaken on the pipe at a temperature significantly different from the temperature at which the pipe was installed. For instance, installation of a new tee in a section of FPVC pipe will require cutting of the fused pipe, enabling contractive forces within the pipe to potentially cause problems. The design of the installation of the new tee must provide for continuity of that contractive force within the fused pipe when a section of that pipe is removed.

SEISMIC REQUIREMENTS AND GUIDELINES

Seismic guidelines for water pipelines, *Design Guideline for Seismic Resistant Water Pipeline Installations or Seismic Guidelines for Water Pipelines – March 2005*, were prepared by a team of water utility engineers and academics for the American Lifelines Alliance, a partnership between the Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (Eidinger 2005). The guidelines provide three performance-based design methods and use generally recognized engineering principles and practices; they are not mandatory and do not constitute a standard or code. The design guidelines can be modified for individual projects depending on system-specific needs.

Seismic requirements in the United States are under development by an ASCE committee (Irias 2016). Ballantyne (2010) suggested that restrained joint PE, DIP, or welded steel pipe should be used to resist large ground movement and in areas susceptible to liquefaction.

Seismic guidelines in Japan were prepared by the Japan Water Works Association, *Guidelines for Earthquake-Resistant Design Methods for Waterworks Facilities*. The 1997 version of the guidelines incorporated lessons learned in the 1995 earthquake (Miyajima 2014) including required levels of performance (Table 4.3).

Table 4.3
Level of required earthquake resistant performance

Degree of Importance	Earthquake Level 1	Earthquake Level 2
Facility Rank A	Operational capacity is not affected.	Seismic damage is minor and does not severely affect operational capacity. Restoration requires minimal effort.
Facility Rank B	Seismic damage is minor and does not severely affect operational capacity. Restoration requires minimal effort.	Seismic damage is minor and does not severely affect operational capacity. Restoration is necessary.

Source: Data from Miyajima 2014

Utilities may develop their own project-specific criteria for seismic design of pipelines. For example:

- San Francisco Public Utility Commission (SFPUC) identified requirements for seismic upgrades to the Hetch Hetchy water system that crosses three major faults (Richardson et al. 2013). The primary goal was to maintain (or restore within 24 hours) potable water supply to 24 municipalities. For certain facilities, the average or peak capacity was defined. The criteria included general concepts; for example, failure of an individual component was acceptable as long as the overall system was functional.
- LADWP is developing a seismic resilient pipe network which is intended to be designed and constructed to accommodate earthquake damage with the ability to continue providing, or limit, water service outage times tolerable to community recovery efforts (Bautista 2016). Pipes within the overall water pipe network are to be selected with sufficient robustness to the earthquake hazards they are exposed to prevent damage based on their level of criticality to supporting community recovery. Implementation of this concept is undertaken with due recognition that not all pipes can be damage-proof, but the network can be developed to limit or prevent service loses. The plan is to essentially create an arterial subnetwork within the existing transmission and distribution systems. Development is planned in coordination with LADWP's on-going pipe replacement program.

DESIGN ISSUES

Utility field experiences with design issues were discussed at the project workshop. The following examples describe specific design issues with plastic pipe and how they were resolved.

- For a current project (4,500 ft of C900 PVC) in Seattle, one design issue was cathodic protection of services (Muto 2016). Appurtenances included epoxy-coated saddles and stainless steel bolts. Five-pound zinc anodes were installed on each saddle.
- Golden State Water Company's specification for pipe bedding is intended to avoid point loadings from rocks (Carver 2016). Proper pipe bedding includes a minimum of 6 in. of

compacted sand bed to the flow line; 6 in. of sand compacted on both sides of the pipe to the top of pipe; and 12 in. of sand compacted over the top of the pipe. In areas where cobbles and rocks are present, an additional requirement is to wrap the bedding and the pipe in a geotextile fabric for the length of the trench to help prevent rocks from migrating through the sand and onto the pipe.

- Casing spacers are required to hold HDPE pipe straight and prevent movement during installation and with pressure changes (Carver 2016).
- When designing HDPE pipe distribution systems, well planned valve spacing is important for future maintenance (Irias 2016).
- Service connections on HDPE pipe with a bend radius less than 100 times the OD should be listed as a known design standard. If a future service connection is required on an existing HDPE pipe with less than 100 x OD, then this is a major issue because the service connection cannot be tapped with full certainty of an acceptable electrofusion weld (Irias 2016).

Utility experiences with design issues related to plastic pipe applications were discussed in the literature. Kurrus (2015) identified design guidelines for using PVC C900 water distribution pipe in desert climates: for pipes buried 3 ft or deeper, assume the temperature will not exceed 100 degrees F, which is an acceptable design temperature; monitor system pressures and conduct a fatigue analysis; and install the pipe according to recommended guidelines for bedding and backfill.

For San Antonio Water System's Carrizo pipeline project, several design decisions and requirements were implemented due to the relative newness of HDPE pipe including: specifying stainless steel pipe connections to HDPE pipe; requiring joint testing; and allowing multiple pipe manufacturers to produce the pipe with a single pipe supplier (Iles and Eddy 2014).

CONSTRUCTION METHODS

Besides conventional open cut construction, water utilities are using trenchless technologies (e.g., HDD, pipe bursting) and other construction methods (e.g., float-sink) to install plastic pipe. In this section these alternative construction methods are briefly described and illustrated using several project examples.

Pipe Bursting

Utilities are installing PVC and HDPE pipe using pipe bursting technology to replace old CIP, PVC, and AC pipe. The technique involves pulling a "bursting" head through the existing pipe, which splits it. The new pipe is pulled behind and through the void.

Pipe bursting can be used to replace existing pipes from 2-in. to 36-in. diameter; the new pipe diameter can be the same size or up to 3x the original pipe diameter depending on project-specific factors such as soils, pipe depth, (Mallakis 2015). Nationally, savings of 20 to 50 percent can be achieved with pipe bursting compared to traditional open cut construction (Mallakis 2015). Less material is removed and replaced, and there is less dewatering; less equipment and labor; utilize existing utility corridor and right-of-way; less traffic control, smaller work zone (Mallakis 2015). More information on pipe bursting is provided in Chapter 16 of the Plastics Pipe Institute's PE Handbook, and Chapter 10 of AWWA's M28 manual, Rehabilitation of Water Mains.

The City of Casselberry, Florida installed 35 miles of HDPE (PE4710 resin) water mains using pipe bursting to replace old and failing AC water mains (Ambler 2015). The city selected HDPE pipe because of its flexibility, strength, and trenchless track record in the water industry. The city originally selected FPVC but it cracked and failed in pilot testing. They found that pipe bursting was a safe method for replacing AC pipe; results from the project's negative exposure assessment tests indicated that the level of asbestos fibers released was less than Occupational Safety and Health Administration (OSHA) limits. The production rate of water main installation averaged 300 to 400 linear ft per day. Pipe bursting was more cost effective and proceeded quicker than open cut construction. Design costs were also lower. (The reader should note that pipe bursting of AC pipe is not an accepted practice in many locations in the United States).

The City of Lee's Summit in Missouri replaced old CIP water mains in residential areas using pipe bursting (York 2013). Projects completed from 2007 to 2010 installed 15,000 ft of 6-in. diameter FPVC pipe and 10-in. and 12-in. HDPE pipe. Pipe bursting was cost-competitive with open-trench construction and reduced restoration costs. In 2012 and 2013, 27,400 ft of plastic pipe (HDPE, bell and spigot PVC, and FPVC) was installed using trenchless methods including pipe bursting. Several pipe bursting projects had an average construction cost of $91 per ft.

Horizontal Directional Drilling

In 2015, the City of Corpus Christi, Texas installed 6,250 ft of 18-in. diameter PVC by HDD for two major water crossings on a water transmission main project (McMullan et al. 2015). The HDD technology helped to minimize impacts to natural resources in the area and reduced the time needed for permitting. The design team consulted with several HDD contractors to select the best pipeline alignment with consideration to constructability issues and permit requirements.

The City of Houston, Texas replaced failing 8-in. and 12-in. AC water mains using HDD with standard AWWA C900 PVC Pipe and the Mega-stop® bell protection system (Shumard and Moravits 2013). The project included installation of 2,500 ft of 8-in. and 580 ft of 12-in. PVC pipe. Use of the Mega-stop® product allowed the installer to "push standard bell and spigot PVC pipe through bored or cased holes without the danger associated with over-belling the joints" (Shumard and Moravits 2013). It also saved 40 percent in materials costs.

In 2003, LADWP installed 2,700 ft of 26-in. and 24-in. diameter HDPE inside a 30-in. steel casing crossing the Los Angeles Harbor (Figure 4.1) (Bautista 2016). In 2004, a second HDD project installed 3,000 ft of 30-in. diameter HDPE in the same area on East Basin Channel near Berth 216 to supply potable water to Terminal Island. Steel casing was required to mitigate the potential impact of petroleum products on the HDPE material in the channel's water. The flexibility of HDPE was very beneficial to the project installation.

Source: Bautista 2016

Figure 4.1 LADWP HDPE pipe installation by HDD in Los Angeles Harbor

Sliplining

Sliplining is a structural lining process that involves installing a new watertight pipeline inside of a host pipeline that is leaking or otherwise in need of replacement. The annular space between the two pipelines is sealed with grout. Both FPVC and HDPE are used for sliplining applications. Because the new pipeline is a smaller diameter than the host pipeline, sliplining can only be used in applications where a smaller diameter pipe can meet the system's flow and pressure requirements. Sliplining a pipeline with FPVC is a feasible and cost-effective construction method when boring or open cut methods are not practical (Force 2013).

Las Vegas Valley Water District needed to rehabilitate a leaking 36-in. diameter steel pipeline located 25 ft below an interstate highway (Force 2013). The work was further constrained by steep embankments and the pipeline's proximity to a busy tourist area. The District decided to slipline the existing pipe with a 30-in. diameter DR 25 FPVC pipe based on cost, technical performance, and risk. Standard DI fittings were used for connections to the steel pipe and installation of appurtenances.

New Jersey American Water identified lessons learned based on sliplining applications (Wolan 2016):

- Sliplining may not be the best installation method for pipelines with services.
- A large layout area is required.
- It is difficult to navigate bends.
- The carrier pipe has limited flexibility.

- The hydraulic capacity of the new pipeline must be verified. Sliplining significantly reduces the pipe diameter.

Swagelining

Swagelining is a structural lining process that involves installation of a PE liner with a larger OD than the ID of the host pipe. The liner pipe is pulled through a reduction die which temporarily reduces the liner pipe's diameter, and then it is pulled through the host pipe (Wolan et al. 2014). Because of the tight fit, grouting is not required between the liner and the host pipe. Swagelining can be used for water transmission mains (i.e., the host pipe) with diameters of 16-in. through 60-in. (PPI 2013).

The city of Amarillo, Texas used swagelining to install a HDPE (PE4710) liner inside 5,300 ft of a 30-in. diameter CIP (PPI 2013). The OD of the HDPE liner was 32-in. and the SDR was 32.5. The project was completed in two phases in 2011 and 2012. The average pull distance was 1,800 ft.

Float-Sink Construction Method

Colorado Springs Utilities used the float-sink construction method to install 2,450 ft of 36-in. HDPE pipeline across a reservoir (Bass et al. 2015). A DR 11 pipe was selected due to constructability considerations. The new pipeline was floated into position with the ends capped, using concrete ballasts to achieve 50 percent buoyancy. After it was floated to the correct location, the pipeline was filled with water, causing it to sink to the reservoir bottom. The new raw water transmission main replaced two parallel steel pipelines (14-in. and 16-in.) that had deteriorated beyond their useful service life. Construction was completed in 2013 and the pipeline was put into service in spring of 2014. No operational issues occurred during the first year of operation.

CONSTRUCTION ISSUES

Utility field experiences with construction issues were discussed at the project workshop. The following examples describe specific issues with plastic pipe and how they were resolved.

- The City of Calgary's low failure rate for PVC pipe is attributed to a conservative approach for installation, rigid enforcement of construction standards by inspectors, and mandatory correction of all construction errors (Brander 2004). Calgary has a "zero-tolerance" policy on excessive bending of pipe or deflections at joints, poor bedding, and poor quality of tapping. No pipe greater than 200 mm (8 in.) may have any joint deflection at all. No pipe of any diameter is allowed to be bent along the pipe-length, as this causes some stress. Calgary inspectors have learned that permitting deviations of even a few degrees on a water main greater than 200 mm (8 in.) in diameter presents a slight but measurable risk of leakage at the gasket, which affects performance of the gasket, the bedding, and the pipe itself (Brander 2004). Calgary requires all contractors to keep coupons from tapping and to mark the coupons with the physical location of the tap. The inspector can identify problems by examining the coupons. The City inspector's judgement is considered final (Line 2016).

- EPCOR Water in Edmonton saw initial installation problems with PVC in the late 1970's (Seargeant 2016). The problems were overcome with support to contractors from the manufacturer and diligent inspection of construction.
- In 2013, WaterOne experienced the immediate failure (i.e., split) of a 6-in. diameter PVC (C900) pipe at a connection to a DI fitting with a wedge-restraint device (Figure 4.2) (Pietig 2016). The connection was performed in sub-freezing January weather. Other possible causative factors were an improper bolt tightening procedure and a rough, jagged saw cut at the end of the pipe.

Source: Pietig 2016

Figure 4.2 WaterOne PVC (C900) pipe failure

- For a current project (4,500 ft of C900 PVC) in Seattle, one construction issue was tapping for service transfers (Muto 2016). Seattle Public Utilities crews have limited experience with PVC and low quality tapping equipment was purchased. Another problem was limited vendor training.
- WaterOne has encountered the separation of PVC pipe joints equipped with Bulldog™ restrained joints (Pietig 2016). The restraint mechanism was activated by pushing the spigot into the bell end of the pipe containing the Bulldog™ gripper ring and ring casing. The failure was caused by gaskets installed backwards at the factory. New color-coding of the front and back of gasket and a better quality control process have prevented additional failures.
- In 2016, WaterOne dealt with the immediate failure (i.e., shear failure) of an 8-in. diameter PVC (C900) pipe during installation of a 24-in. diameter reinforced concrete storm pipe (Pietig 2016). The failure was caused by improper pipe support as the larger storm pipe was installed underneath the 8-in. PVC pipe by a third-party contractor. WaterOne typically uses DIP for longer, vertical offset relocations.
- A lubricant is necessary to enable proper connection of the bell and spigot joints. When more lubricant than necessary is used, some of the excess lubricant ends up on the inside of the pipe (Seargeant 2016). When mixed with potable water, this lubricant can result in

taste and odor problems with water. Standard amounts of flushing of the water main are not always successful in eliminating this excess lubricant, particularly in lower temperature water. The solubility of the lubricant material is generally reduced as water temperature decreases, particularly below 50 degrees F. Extended flushing is sometimes required to eliminate the excess lubricant (Seargeant 2016).

- Based on experiences with PVC pipe failures, American Water emphasizes the importance of bedding materials and preparation, and inspector training. PVC pipe material in storage should be rotated and covered (i.e., protected from the sun) (Hughes 2016a).
- AWWU had many issues when first installing HDPE (Nuss 2016). First, they allowed electrofusion couplings because butt fusion was challenging with very deep and wet trenches. Many of these electrofusion couplings failed, so AWWU disallowed their use. This made HDPE installations more challenging. With butt fusion it was necessary to rehabilitate mains in built out right-of-ways that had existing utilities. There was not adequate space to fuse above ground, and fusing in deep wet trenches was not always feasible. Also, stocking HDPE valves (flanged) and HDPE pipe and repair clamps (e.g., special sleeves, special ODs) was not desirable for in-house inventory or pipe suppliers.
- HDPE electrofusion service saddles require trained installers and a clean, dry environment (Irias 2016). Directionally-drilled HDPE installations are particularly challenging for electrofusion due to the presence of drilling fluids and mud. WaterOne has experienced failures and leaks on electrofusion service saddles and has discontinued use of electrofusion branch saddles for hydrants or valve taps (Pietig 2016). For example:
    - In 2015, a 12-in. diameter electrofusion coupling failed after 2 years in service at a repair cost that exceeded $13,000.
    - In 2013, a 12x6 in. electrofusion branch saddle failed after 6 months in service; the repair cost was $5,664.
    - Electrofusion couplings failed if installed under tension due to pipe misalignment.
- WaterOne noted the difficulty in pouring concrete thrust blocks when other utilities are co-located in the same trench (Pietig 2016). Adequate space is needed.
- Golden State Water Company in California has several recommendations for handling and installing plastic pipe (Carver 2016).
    - PVC and HDPE pipe should only be handled using nylon straps; chains or steel cable should not be used.
    - Pipe should be lowered into position in the trench; it should never be pushed, kicked or dropped.
    - For PVC pipe, a depression should be dug under the bell so that the entire length of pipe rests on the bottom of the trench, not just the bell end. Pipe failure at the bells will occur if the pipe barrel is not supported for its full length.

Fusion and electrofusion require skilled operators (Grafenauer et al. 2014). When AWWU allows HDPE installations, they require the contractor staff to be trained and provide proof of recent training (Nuss 2016). AWWU also requires data loggers on the fusion machines and quality assurance samples of fused joints to be cut out and sent for testing. The data loggers record information such as identification numbers for the fusion machine and the operator, pressure, and time.

Several construction issues were identified in San Antonio while installing the Carrizo pipeline (Iles and Eddy 2014): special considerations for local livestock, incurring possible joint damage when dragging long runs of fused pipe; and only allowing personnel (pipe supplier's employees) with required training to fuse the joints.

Utility case studies documented construction issues during water main installation (Table 4.4).

Table 4.4
Utility experiences with construction of HDPE water mains operations and maintenance

Utility, State	Application	Diameter; Length	Construction Issues
LADWP, California	Sliplining to replace existing 40-in. CIP	36-in.; 1,690 ft	No issues but hired a third party inspector to approve all fused joints. Fusing took more effort than anticipated due to limited space and access. The new pipe required a "delicate installation" through the host steel pipe to avoid surface abrasion and bending.
Eastern Navajo Reservation, New Mexico	Finished water transmission	24-in.; 69,000 ft	One batch of pipe was defective. It showed embrittlement during joint fusion process and caused joints to fail. Pipe replaced at no cost to the owner.
City of Houston, Texas	Water transmission, rated at 100 psi, surge pressures up to 150 psi.	36-in.; 25,000 ft	A 45-degree bend and a flanged connection to concrete pressure pipe were visually evaluated with open pits. No leakage found, and no ballooning or elongation of main was observed.
Seminole County Regional Water Authority, Florida	Raw water transmission, low pressure, 45 MGD capacity	42-in.; 41,100 ft	10 of 775 joints were rejected during the butt fusion process due to misalignment. This failure rate was acceptable.

Source: Data from Najafi et al. 2015

OPERATIONAL STRATEGIES

Recommended operational strategies to optimize service life of water mains include:

- Evaluating and mitigating occurrence of pressure surges in the distribution system.
- Developing and implementing a system-wide pressure management strategy.
- Identifying and repairing leaks.
- Developing and implementing a valve inspection and maintenance program.

Specific steps for a pressure management strategy include: reviewing the system's overall hydraulic model; performing transient pressure analyses; identifying areas of the system subject to failure due to high pressures; and identifying mains subject to pressure surges and high operating pressures that require condition assessment (Garcia and Funchion 2014).

MAINTENANCE PRACTICES

In order to maintain pipes, service lines, and appurtenances, water systems need to know their physical location and condition (Hughes et al. 2014).

Locating Plastic Pipe

Locating plastic pipes is challenging because they do not conduct electricity or a magnetic field (Hughes et al. 2014). Existing buried plastic pipe may not be equipped with a tracer wire or locating tape. Early applications of tracer wire were simply a wire buried on top of the pipe; the wire material was often not robust and failures were common. For example, Louisville Water Company noted some problems with locating PVC pipe due to breaking or improper installation of tracer wire (Raney 2016). WaterOne experienced damage to tracer wire during service taps and relocations (Pietig 2016).

The following are recommended strategies for locating plastic pipe (Hughes et al. 2014):

- Use operator knowledge of piping layout together with any existing maps and known location of above ground appurtenances (e.g., valve boxes, curb boxes, and hydrants).
- For new PVC and HDPE pipes, install robust tracer wire (e.g., copper clad steel cable) that is designed specifically for the pipe installation method used. Bring the wire to the surface through valve boxes to provide a conductive tracer. AWWU uses this practice and performs acceptance testing of the locate wire when construction is complete and prior to paving (Nuss 2016).
- Install electronic markers underground at key locations along the pipe (e.g., service connections and pipe bends). The markers can then be activated and read by a device above ground.
- Collect GPS locations when pipe is excavated for repairs or new connections.
- Use pulse generating units but know that they have a limited range (up to 250-300 ft). These devices induce a signal into the water and it can be acoustically measured.
- Understand limitations of sonde insertion locators. These devices can be inserted into the pipe and then traced from the ground. They are limited to main lines and may not be able to travel the full length of pipeline. Any equipment inserted into pipelines should meet NSF standards and disinfection requirements.

There are other techniques for locating plastic pipe (e.g., ground penetrating radar) that are more expensive and have limited range and success (Hughes et al. 2014).

Golden State Water Company requires the installation of an insulated #10 solid copper wire taped to the top of the pipe every 5 ft (Carver 2016). The tracer wire is brought to the surface alongside fire hydrants and air/vacuum valve installations rather than into valve cans. The valve can installation tends to cause the tracer wire to get wound up in the valve key and broken off when the key is removed. A commercially available tracer wire junction box is installed in the concrete pad adjacent to the fire hydrant or air/vacuum valve can for easier locating in the future. The contractor is required to test the tracer wire for electrical continuity prior to final acceptance of the project.

WaterOne in Johnson County, Kansas uses 3M electronic marker rope and balls for locating plastic pipe. Also, the utility is improving their GPS process for importing data into a geographic information system (GIS) (Pietig 2016).

Inspections and Condition Assessment

Condition assessment can help determine the probability of failure for a pipeline and its remaining service life. Condition assessment technologies are limited for water mains because it is difficult to access pressure pipelines and there are contamination concerns with such equipment being in contact with the finished water. Also, when pipe failures are due to localized issues (e.g., pressure, external loads, corrosive soil), leak and break history can be the best predictor of future failures rather than condition assessment data or pipe age (Irias 2016). Condition assessment efforts may fail to identify the factors that will ultimately lead to failure for a given pipe; for example, it is not uncommon for samples of failed pipe to still meet the strength specification for new pipe.

The state of technology for structural condition assessment of water transmission and distribution piping was reviewed by Liu et al. (2012). A new AWWA Manual of Water Supply Practices M77, *Condition Assessment of Water Mains and Transmission Pipelines*, is under development with publication expected in 2016.

Condition assessment technologies for plastic water mains include visual inspection, electro-scanning, acoustic monitoring, ultrasonic testing, and condition assessment based on soil properties. Le Gouellec and Cornwell (2007) recommended the use of tracer gas and ground-penetrating radar to detect leaks in plastic service lines.

Visual inspections are normally conducted on external surfaces of plastic pipe when the pipe is exposed for repairs. The repair crew can document soil bedding and fill conditions, as well as the pipe condition beyond the immediate repair. Photos and written documents should be filed in the utility's maintenance management system or other database where it can be accessed in the future.

Electro scanning technology uses low voltage conductivity to measure the amount of electric current that flows through pipe defects (Hansen 2016). It can be used to estimate the magnitude and location of potential leaks along non-metallic pipelines. The technology is well-established for assessing the condition of gravity sewers and has recently been adapted for use in water mains (Hansen 2016). Its use of direct measurements provides a quantitative analysis of leak potential without relying on visual observation.

Acoustic monitoring technologies can be used to evaluate the structural condition of piping and for leak detection. Acoustic systems can also be used to detect cracks, and determine the state of piping connections and pipe bedding (Liu et al. 2012). Some acoustic monitoring systems can detect leaks in plastic pipe but their range is significantly less than with metal pipe. The rapid loss of sound in plastic pipe makes it difficult to detect leaks at a long range (Hughes et al. 2011). Improvements in the technology have increased the sensitivity to subsonic noise (Hughes et al. 2014). Acoustic leak detection is challenging on plastic pipes that have repair clamps or transitions between two different pipe materials (Hughes et al. 2011). Field testing was completed to evaluate commercially available acoustic leak detection equipment including listening devices and leak noise correlators (NRCC (2011) as cited by Baird 2011). Research findings showed that commercial leak noise correlators could locate all gasketed joint leaks in plastic water distribution pipes.

When inspections or condition assessments are conducted on plastic pipe, the findings should be classified and recorded in a standard manner so that the criticality of all pipes can be ranked and prioritized. The on-going WRF Project No. 4498 is developing a defect coding system for water mains to help create a uniform classification of defects (Knight et al. 2015). The coding system is intended to be independent of the inspection technology used.

Repairs to In-service Pipe

Grafenauer et al. (2014) collected detailed survey responses on utility experiences repairing HDPE mains for diameters ranging from 2 in. to 16 in. Of the 20 responses received in 2012, 11 were from water providers in the United States, 6 were from the UK, 2 from Germany and 1 was from a water utility in Belgium. Survey collection in Europe included on-site visits to utility locations. Wet and dirty conditions encountered during repairs provide challenges for use of fusion or electrofusion repair methods. Highly skilled operators are needed for such repairs. Full circle clamps and mechanical couplings are sometimes used when conditions make it difficult to use fusion or electrofusion but questions remain on whether these repair methods can be considered reliable and permanent.

Louisville Water Company noted strengths and weaknesses with maintaining PVC pipe (Raney 2016). It is much easier to handle compared to DIP and it has few maintenance issues. Most observed problems are with fittings and joints and not the pipe itself. It is resistant to circumferential fractures. If PVC pipe has been bent, then it has a tendency to break when tapped. It is less resilient during tapping operations (i.e. dull bits and aggressive drilling lead to splitting). It is vulnerable to splitting fractures. In the case of failure, it can only be replaced.

WaterOne noted that electrofusion cannot be used to repair HDPE pipe when the trench contains water (Pietig 2016). Many mechanical coupling products are also not rated for thermal expansion forces which makes HDPE repairs extremely challenging if trench conditions remain wet.

CHAPTER 5
UTILITY CASE STUDIES

This chapter includes four utility case studies on plastic pipe applications: EBMUD and the City of Palo Alto in California; EPCOR in Edmonton, Canada; and AWWU in Anchorage, Alaska. The case studies describe field experiences with pipe design, installation, costs, and lessons learned.

EAST BAY MUNICIPAL UTILITY DISTRICT, CALIFORNIA

The East Bay Municipal Utility District (EBMUD) serves approximately 1.3 million residents in the Eastern portion of the San Francisco Bay area. Of the 4,200 miles of total water mains, approximately 400 miles are PVC and 10 miles are HDPE.

EBMUD has more than 30 years of experience installing PVC pipelines using a conservative approach. PVC applications are limited to diameters of 8 in. or less using Carnegie joints. Steel or HDPE pipe is preferred in some applications such as road and fault crossings, landslide prone areas, steep slopes, high pressures, and excessive cover. HDPE pipe is also used in areas with corrosive soil and for dead end mains in ground movement areas because the steel pipe mortar causes pH spikes.

EBMUD has experienced rapid cracking of PVC pipe due to poor installation and tapping practices. The types of PVC pipe failures have included: joint leaks (38% of total failures), longitudinal fractures (33%), blown sections (19%), and circumferential (10%) (Burn et al. 2005). Following the 1989 Loma Prieta earthquake, PVC water mains required about 0.002 repairs per 1,000 ft, while steel pipe required 0.012 repairs per 1,000 ft (Prashar et al. 2014).

> **EBMUD Highlights**
>
> Population: 1,300,000
>
> Miles of Pipe: 4,200
>
> Types of Plastic Pipe: PVC, HDPE
>
> Issues faced: Installation problems causing premature failure and difficulties in tapping. Seismic issues.
>
> Successes: Cost savings through the use of PVC and HDPE with HDD.

Challenges with HDPE have included failed joints due to poor electrofusion practices and difficulties in tapping operations (Irias and Huntamer 2016). EBMUD is currently working to resolve internal maintenance concerns about the installation of HDPE service saddles and their ability to repair HDPE pipelines during emergency situations.

Lessons Learned

As EBMUD gains more experience and confidence with HDPE pipeline, it is likely to increase the use of HDPE and reduce the number of new PVC installations. Cost savings can be achieved by selecting the appropriate pipe material for each application. It is important to allocate adequate resources for staff training and development of written practices and specifications to minimize errors in pipe installation and repair.

CITY OF PALO ALTO, CALIFORNIA

The city of Palo Alto, California owns and operates all of its utility systems including drinking water, wastewater, and natural gas. The drinking water system has a variety of pipe materials including DIP, CIP, concrete cylinder pipe, AC, PVC, and HDPE.

The city began a concerted effort to increase pipe replacement rates in 1992. They started with natural gas lines and used PE2046 pipes. A leak detection survey of new gas mains showing no leaks, coupled with modeling results that estimated >100-year service life convinced the city to start replacing water mains with HDPE (PE4710) (Scoby 2012).

The city replaces about 15,000 ft of water mains each year. CI and other aging pipelines are replaced with HDPE mains. The first few projects used open trench installation. In 2009, a trial project was conducted using HDD and soon the city adapted HDD as their standard replacement technique. HDD reduced replacement costs from $87.91/ft to $66.83/ft, allowing increased replacement rates up to 30,000 ft per year (Scoby 2012). As of 2012, the system had replaced 20 percent of its drinking water system (Scoby 2012). According to the city's website, a project completed in June 2016 included installation of nearly 12,000 ft of HDPE mains (8-in. to 16-in. diameter).

> ### Palo Alto Highlights
>
> **Population Served:** 60,000
>
> **Miles of Pipe:** 219
>
> **Plastic Pipe Used:** HDPE
>
> **Issues faced:** Ensuring proper joint connections, preventing installation damage.
>
> **Successes:** Cost savings achieved using HDD and HDPE have allowed the city to accelerate its pipe replacement program.

To help ensure proper installation of pipes and avoid premature leaks, the city trained its staff on fusing HDPE pipes. The properly fused pipes had joint strength equal to the pipe strength (Pischik 2010). The city specified maximum pull forces allowed during installation and required that the pipe be supported on rollers during installation and not dragged. Any pipes with scratches greater than 10 percent of the pipe thickness were removed (Scoby 2012). The system used a chlorine solution of 12 percent for disinfection to avoid damaging pipe (Pischik 2010).

Another challenge the city faced was connecting the new HDPE pipe to existing pipe. Where existing pipe had flanged connections, PE flanges were used. Mechanical couplings were installed to connect to existing CIP or AC pipes. Mechanical joint connections were used for existing DI or PVC pipes. Anchors were used on connections to prevent joint pullout (Pischik 2010).

Lessons Learned

HDD is a cost-effective method for installing HDPE pipe. Staff training and detailed specifications can help to reduce errors and premature leaks.

EPCOR, EDMONTON, CANADA

EPCOR is the utility serving the City of Edmonton, Alberta, Canada with a population of 878,000. In addition, EPCOR provides water through regional wholesalers to an additional 450,000 persons. Prior to 1977, EPCOR had used pit CIP, spun CIP, and AC pipe (Fisher 2008). In 1977, health concerns led to a trial installation of AWWA C900 PVC pipe. PVC pipe quickly became the material of choice. Pipe breaks continued to climb, reaching a peak of 1,670 breaks in 1985, mostly due to external corrosion of old CIP. This prompted the utility to adopt a 13.5 percent surcharge to fund the acceleration of the iron pipe replacement program. In 2013, the number of breaks had dropped to 278. In 2015, PVC pipe represented 50 percent of the total pipe length.

In order to determine whether lower pipe break rates were because of superior performance of PVC or pipe age, EPCOR compiled break statistics for a similar time frame for the different pipe materials. Table 5.1 shows the results.

Table 5.1
EPCOR Pipe Break Rates

Pipe Material	Miles	Number of Breaks in First 36 Years of Service
Spun CIP	760	17,131
AC	762	882
PVC	1,041	141

Source: Data from Seargeant (2014)

In 1994, to better predict future performance of PVC pipe, EPCOR excavated and tested two sections of pipe installed in 1977. The pipe samples were subject to the same strength tests required of new AWWA C900 pipe. Tests found the old pipe met all strength requirements and still had a burst pressure greater than 1,000 psi. Additional tests in 2005 on PVC pipe after 25 years of service had similar results (Seargeant 2014).

EPCOR Highlights

Population Served: 1.45 million

Miles of Pipe: >2,000

Types of Plastic Pipe:

C900 PVC (6- to 12-in. diameter); C905 PVC (14- to 36-in. diameter)

Issues faced with Initial PVC Pipe Installations:

128 miles installed over first 10 years with 10 breaks in that time.

Causative factors of PVC pipe failures: rocks in fill material causing pipe split; corrosion of bolts in connections to existing non-metal pipe; and shifting of joints during installation causing gasket leaks.

Taste and odor problems when lubricant was over-applied.

Successes:

The water main break rate decreased significantly after many of the problematic metallic pipes were replaced with PVC.

Lessons Learned

The technical performance of different pipe materials can be evaluated by reviewing historical water main break records and conducting tests on installed pipe. Comparing records for pipes of similar ages is more informative than reviewing only summary statistics. Utilities should stay abreast of improvements in pipe materials and revise practices and specifications as warranted.

ANCHORAGE WATER AND WASTEWATER UTILITY, ANCHORAGE, ALASKA

The water distribution network serving Anchorage is composed of 14 different pipe materials installed over a span of 69 years. The majority of installed pipe is DIP (516 miles), followed by CIP (151 miles), AC (97 miles), concrete cylinder pipe (35 miles), PVC (12 miles), welded steel (9.5 miles), and HDPE (6.8 miles). The average pipe age is 32 years. The capital improvement program includes projects to replace old CIP and increase the diameter of certain transmission mains. The plan assumes AWWU will replace 1.5 miles of aging distribution mains per year.

AWWU started using plastic pipe due to corrosive soil conditions and the inability of pipe manufacturers to provide appropriate corrosion protection for DIP. Based on other local utilities negative experiences with schedule 40 PVC pipe, AWWU preferentially installed HDPE 4710. Difficulties with fusing joints on HDPE pipe led to a reevaluation of PVC pipe and selection of C900/C905 PVC pipe as the utility's standard pipe material. DR 18 PVC is used for up to 12-in. diameter and SDR 14 PVC is used for 12-in. to 16-in. diameters. AWWU uses zinc-coated DIP with PE wrapping and special seismic joints in areas with contaminated soil.

Based on bid prices AWWU has found that pipe project costs can vary widely and plastic pipe is not always the least expensive option. Based on eight recent bids costs for PVC pipe projects ranged from $770/ft to $2,100/ft with an average of $1,680/ft. DIP project costs ranged from $1,646/ft to $1,929/ft with an average of $1,740/ft.

AWWU has experienced limited failures with PVC and HDPE pipe. Four HDPE pipe failures have been documented and they were all related to leaking electrical fusion couplings and each occurred within 5 years of installation. Analysis from previous failures indicates the couplings did not achieve full fusion to the pipe. This is suspected to be a result of improper/inconsistent electricity applied to the coupler at the time of installation.

AWWU has documented only 4 failures on PVC water mains. The failures all happened on 6-in. diameter PVC mains installed in 1973 or 1974. All PVC pipe failures were stress-related and occurred between 1993 and 2008. AWWU has learned that the pipe needs to be handled with care. AWWU has had issues with field cutting of the PVC pipe and re-establishing the stab depth lines and re-beveling the joints. As a result, AWWU requires the use of Mega-Stop® and thrust blocks in addition to passive restraint systems (Mega-Lug®). The biggest challenge has been addressing the allowable type of tapping bits. AWWU required tapping saddles (no direct taps allowed), but the types of tapping bits created some problems, like using a hole saw and having the tap leak.

Lessons Learned

It is difficult to compare the costs of pipe projects because each project has special considerations and significant variability in how the contractors prepared their bid.

REFERENCES

Ambler, E.A., 2015. The Path Forward for Pipe Bursting Asbestos Cement Pipe. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.

Ambrose, M., S. Burn, D. DeSilva, and M. Rahilly. 2008. *Life Cycle Analysis of Networks*. Plastics Pipe Institute and CSIRO.

AWWA (American Water Works Association). 1979. The Use of Plastics in Distribution Systems. Committee Report. *Jour. AWWA*, 71(7): 373-375.

———. 2002. M23 PVC Pipe – Design and Installation. Denver, Colo.: AWWA.

———. 2004. Water:\Stats 2002 Distribution Survey [CD-ROM]. Denver, Colo.: AWWA.

———. 2006. M55 PE Pipe – Design and Installation. Denver, Colo.: AWWA.

———. 2007. ANSI/AWWA Standard C900-07. Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 In. Through 12 In. for Water Transmission and Distribution. Denver, Colo.: AWWA.

———. 2012. *Buried No Longer: Confronting America's Water Infrastructure Challenge*. Denver, Colo.: AWWA. Available online at: http://www.awwa.org/Portals/0/files/legreg/documents/BuriedNoLonger.pdf

———. 2015. ANSI/AWWA Standard C906-15. Polyethylene (PE) Pressure Pipe and Fittings, 4 In. Through 65 In. for Waterworks. Denver, Colo.: AWWA.

Anchorage Water and Wastewater Utility (AWWU). 2012. Design and Construction Practices Manual. Available online at: https://www.awwu.biz/website/media/documents/2012DesignCriteria/2012_DCPM/2012_DCPM_Publish.pdf.

Baird, G.M. 2011. The Silver Bullet for Aging Water Distribution Systems? *Jour. AWWA*, 14-23.

Ballantyne, D. 2010. Seismic vulnerability assessment and design of pipelines. *Jour. AWWA*, 102(5): 88-97.

———. 2013. Development of seismic design guidelines for distribution piping. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.

Bass, B., H. Link, A.E. Romer, and T. Weidmann. 2015. Design and Construction Case History—South Catamount Transfer Pipeline Float-Sink. In *Proc. Of the ASCE Pipelines Conference*.

Bautista, A. 2016. *LADWP Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.

Bottles, D.G. 1970. Use of Plastic Pipe. *JAWWA*, 62(1): 55-58.

Brander, R. 2004. Minimizing Failures to PVC Water Mains. In *Proc. Of the 12th Plastic Pipes Conference*. Plastic Pipes Conference Association.

Bredács, M., A. Frank, D. Nitsche, A. Riha, and G. Pinter. 2014. Prediction of residual lifetimes of small diameter polyethylene pipes. In *Proc. Of the 17th Plastic Pipes Conference*. Plastic Pipes Conference Association.

Breen, J. 2006. Expected lifetime of existing PVC water systems; summary. TNO report, MT-RAP-06-18693/mso.

Breen, J., A. Boersma, P.G.G. Slaats, and J.H.G. Vreeburg. 2005. Long term performance of existing PVC water distribution systems. Research sponsored by Kiwa Water Research, Dyka, LVM, Pipelife, Shin-Etsu, Solvin, and Wavin.

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 PVC Pipes*. Denver, Colo. AwwaRF and CSIRO.

California Department of Public Health. 2008. California Waterworks Standards. Available online at: http://www.cdph.ca.gov/services/DPOPP/regs/Pages/R-14-03-RevisionofWaterworksStandards.aspx

Carver, P.S. 2016. *Golden State Water Company Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.

Castagnetti, D., G. S. Mammano, and E. Dragoni. 2011. Effect of chlorinated water on the oxidative resistance and the mechanical strength of polyethylene pipes. *Polymer Testing*, 30(3); 277-285.

City of Houston. 2015. Infrastructure Design Manual. Department of Public Works and Engineering. Available online at: https://edocs.publicworks.houstontx.gov/documents/design_manuals/idm.pdf.

City of San Diego. 2004. *Standard and Guide Specifications. Divisions 1-9*. Available online at: https://www.sandiego.gov/water/cip/guidelines.

Colin, X., J. Verdu, and B. Rabaud. 2011. Chapter 4. Degradation of Polyethylene Pipes by Water Disinfectants. In *Water Disinfection*. Editor K.M. Buchanan. 109-142.

Cubrinovski, M., M. Hughes, B. Bradley, I. McCahon, Y. McDonald, H. Simpson, R. Cameron, M. Christison, B. Henderson, R. Orense, and T. O'Rourke. 2011. *Liquefaction Impacts on Pipe Networks*. University of Canterbury. Research Report 2011-04.

Davis, P. S. Burn, S. Gould, M. Cardy, G. Tjandraatmadja, and P. Sadler. 2007. *Long-Term Performance Prediction for PE Pipes*. Denver, Colo. AwwaRF, AWWA, and CSIRO.

Demčenko, A., R. Akkerman, P.B. Nagy, and R. Loendersloot. 2012. Non-collinear wave mixing for non-linear ultrasonic detection of physical ageing in PVC. *NDT&E International*, 49(2012), 34-39.

Dueck, R. 2010. *PVC Failures*. Presentation at Urban Development Institute Breakfast Seminar. September 8, 2010.

EBMUD (East Bay Municipal Utility District). 2006. Engineering Standard Practice 512.1 Water Main and Services Design Criteria.

Eidinger, J. 2005. *Seismic Guidelines for Water Pipelines*. Prepared for National Institute of Building Sciences. Available online at: www.americanlifelinesalliance.org

EPA (U.S. Environmental Protection Agency). 2002. Deteriorating buried infrastructure management challenges and strategies. Available online at: https://www.epa.gov/sites/production/files/2015-09/documents/2007_09_04_disinfection_tcr_whitepaper_tcr_infrastructure.pdf.

Fisher, C. 2005. *The Mojave River Pipeline Project*. Available online at: http://www.uni-bell.org/resources/The%20Mojave%20River.pdf.

———. 2008. *The Edmonton Story*. Available online at: http://www.uni-bell.org/resources/The%20Edmonton%20Story.pdf.

Folkman, S. 2012. *Water Main Break Rates in the USA and Canada: A Comprehensive Study*. Utah State University Buried Structures Laboratory. Study funded by Uni-Bell PVC Pipe Association and Water Finance Research Foundation.

Folkman, S., S. Rowley, and T. Fronk. 2013. Predicting Time to Failure of PVC Pipe Subjected to Small Pressure Fluctuations. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.

Force, J. 2013. Sliplining Rehabilitates Critical Water Supply Line. *OPFLOW*, 39(11): 18-19.
Fuke, M. 2016. *Honolulu Board of Water Supply Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.
Gaewski, P.E., and F.J. Blaha. 2007. *Analysis of Total Cost of Large Diameter Pipe Failures*. Supplemental Report. Available online at: http://www.waterrf.org/resources/pages/PublicSpecialReports-detail.aspx?ItemID=5
Garcia, D. and S. Funchion. 2014. How to Select and Prioritize the Replacement of Water Mains: An Owner's Perspective. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.
GMS (GMS, Inc. Consulting Engineers). 2013. Preliminary Engineering Report for Water System Evaluation. Available online at: http://williamsburgcolorado.com/website/uploads/docs/gms_report.pdf.
Grafenauer, T., N. Najafi, T. Sangster, and L.M. Slavin. 2014. Repair of In-Service HDPE Water Distribution Pipe. In *Proc. Of the ASCE Pipelines Conference*.
Great Lakes – Upper Mississippi River Board of State and Provincial Public Health and Environmental Managers. 2012. *Recommended Standards for Water Works*. Health Education Service, Albany, NY.
Hansen, C. 2016. Multi-sensor Condition Assessment Tool Features Low-Voltage Conductivity Technology to Find and Measure Water Losses. In *Proc. Of the AWWA Annual Conference*. Denver, Colo.: AWWA.
Hassinen, J., M. Lundbäck, M. Ifwarson, and U.W. Gedde. 2004. Deterioration of polyethylene pipes exposed to chlorinated water. *Polymer Degradation and Stability*, 84(2): 261-267.
Holland, B. 2008. *Reducing Waste and Inefficiency in Water Distribution. Canadian Taxpayers Federation*. www.undergroundsolutions.com/articles/Municipal_TheTaxpayer.pdf.
Hughes, D.M. 2016a. *American Water Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.
———. 2016b. *An Evaluation of the Value of Structurally Enhanced PVC Pipe*. Project Update January 2016. Denver, Colo.: WRF.
Hughes, D.M., Y. Kleiner, B. Rajani, and J.-E. Sink. 2011. *Continuous System Acoustic Monitoring: From Start to Repair*. Denver, Colo.: Water Research Foundation.
Hughes, D.M., J. Oxenford, and R. Titus. 2014. *Pipe Location and Leakage Management for Small Water Systems*. Denver, Colo.: Water Research Foundation.
Hughes, D.M., C. Venkatesh, A. Paradkar, and M. Najafi. 2016. The Innovative Plastic Pipe: Ductile iPVC Pipe. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.
Iles, K. and A. Eddy. 2014. How a Cost Effective Solution to Corrosion Became the Largest Domestic Order of HDPE Pipe. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.
Irias, X. 2016. *EBMUD Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.
Irias, X. and J. Huntamer. 2016. Personal communication with project team.
JWWA (Japan Water Works Association). 2015. *Water Supply in Japan 2015*. Available online at: http://www.jwwa.or.jp/jigyou/kaigai_file/2015WaterSupplyInJapan.pdf
Kirmeyer, G.J., A. Graham, H. Hansen, and D. Spiers. 2008. Drinking Water Asset Management Programs Best Management Practice: Case Studies from the North American Drinking Water Community. Denver, Colo.: Water Research Foundation.

Knight, M., R. Younis, J. Jung, Y. Kleiner, J. Matthews, and J. Zhang. 2015. Framework for Potable Water Pipeline Defect Coding and Condition Rating System. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.
Kubota Corporation. 2016. http://www.kubota-global.net/products/ironpipe/index.html. Accessed May 20, 2016.
Kurrus, J.A. 2015. PVC C900 Water Pipe Proves Longevity in Arizona's Desert Climate. *Jour. AWWA*, 107(7): 38-44.
Le Gouellec, Y.A. and D.A. Cornwell. 2007. *Installation, Condition Assessment, and Reliability of Service Lines*. Denver, Colo. AwwaRF, AWWA, and IWA Publishing.
Line, J. 2016. *City of Calgary Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop
Liu, Z., Y. Kleiner, B. Rajani, L. Wang, and W. Condit. 2012. *Condition Assessment Technologies for Water Transmission and Distribution Systems*. EPA/600/R-12/017.
Lively, K.S. 2012. Design to Prevent Long Running Cracks in Plastic Pipe for Water Applications. In *Proc. Of the ASCE Pipelines Conference*.
Mallakis, G. 2015. Pipe Bursting Water Mains. In *Proc. of the AWWA Annual Conference*. Denver, Colo.: AWWA.
Marangoni, A. 2012. An Assessment of the Competitiveness of PVC Piping System. The Total Cost of Ownership Approach. In *Proc. Of the 16th Plastic Pipes Conference*. Plastic Pipes Conference Association.
Mazurek, M. 2006. Baltimore County Says: Pipe Futures Are Plastic. *Opflow*, 20-22.
McMullan, J.D., D. Deng, J. Williams, and R. Botteicher. 2015. Padre Island Water Supply Project Minimizes Environmental Impact Using HDD Technology. In *Proc. Of the ASCE Pipelines Conference*.
Miyajima, M. 2014. Resilient Water Supply System for Earthquake and Tsunami. *Jour. of Water Supply: Research and Technology*, 63(2): 86-94.
Mickelsen, T. and D. Langston. 2015. Victory Pipeline Duchesne County Utah Water Conservancy District. In *Proc. Of the ASCE Pipelines Conference*.
Moffett, K., Q. Hamson, and R. Botteicher. 2014. Waterline Replacement Project in Ogden Canyon, UT Presents Unique Construction Challenges. In *Proc. Of the ASCE Pipelines Conference*.
Mordak, J. and J. Wheeler. 1988. *Deterioration of Asbestos Cement Water Mains*. Final Report to the Department of the Environment. Water Research Center, Wiltshire, U.K.
Muto, D. 2016. *Seattle Public Utilities Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.
Najafi, M., A. Habibian, and V.F. Sever. 2015. *Durability and Reliability of Large Diameter HDPE Pipe for Water Main Applications*. Denver, Colo.: Water Research Foundation.
National Research Council. 2006. Drinking Water Distribution Systems: Assessing and Reducing Risks.
NRCC (National Research Council Canada). 2011. Leak Detection Methods for Plastic Water Distribution Pipes. www.nrc-cnrc.gc.ca.
Nuss, S. 2016. *Anchorage Water and Wastewater Utility Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.
O'Callaghan, F.W. 2014. Pipe Performance Experiences During Seismic Events in New Zealand During the Last 27 Years. In *Proc. Of the 17th Plastic Pipes Conference*. Plastic Pipes Conference Association.

Ong, S.K., J.A. Gaunt, F. Mao, C.L. Cheng, L. Esteve-Agelet, and C.R. Hurburgh. 2008. *Impact of Hydrocarbons on PE/PVC Pipes and Pipe Gaskets*. Denver, Colo.: AwwaRF, AWWA and IWA Publishing.

Pietig, S. 2016. *WaterOne Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.

Pischik, A. 2010. Using HDPE 4710 for Water Main Replacement Projects. Presentation at the Northern California Pipe User's Group 18th Annual Sharing Technologies Seminar.

PPI (Plastics Pipe Institute). No date. *Handbook of Polyethylene Pipe*. Second Edition. Available online at: http://www.plasticpipe.org/.

———. 2005. Polyethylene Pipe. Flexible, Lightweight PE Gaining Ground. *OPFLOW*, July 2005: 24-25.

———. 2009. Polyethylene Piping Systems Field Manual for Municipal Water Applications. Available online at: http://plasticpipe.org/publications/pe-handbook.html.

———. 2013. Water Transmission & Sewer Force Main Renewal – 16 Inch Through 60 Inch. Available online at: https://plasticpipe.org/pdf/water-transmission-sewer-force-main-renewsl-16-60.pdf

———. 2016. PPI Position Paper on HDPE (PE4710) Distribution Potable Water Pipe Sizes and Pressure Classes. Available online at: http://plasticpipe.org/pdf/ppi-position-paper-hdpe-potable-water-pc-pipe-size.pdf.

Prashar, Y., R. McMullin, X. Irias, M. Flores, and K. Khatri. 2014. Pipeline Fragility Assessment against Liquefaction Induced Differential Settlement in City of Alameda, and Oakland, California. In *Proc. Of the ASCE Pipelines Conference.*

Qiao, Q. X. Zheng, and S. Shu. 2014. Application of Plastic Pipe in Municipal Water Supply, China. In *Proc. Of the 17th Plastic Pipes Conference*. Plastic Pipes Conference Association.

Raney, J. 2016. *Louisville Water Company Experience with PVC Plastic Pipe*. Information Prepared for Project Team.

Richardson, R., and M. Edwards. 2009. *Vinyl chloride and organotin stabilizers in water contacting new and aged PVC pipes*. Web Report 2991. Denver, Colo.: Water Research Foundation.

Richardson, T., M. Smith, L. Gullette, A. Mavroudis, and M. Monaghan. 2013. Seismic Upgrades in the Watershed. In *Proc. Of the ASCE Pipelines Conference*.

Rubeiz, C. 2009. Performance of Pipes during Earthquakes. In *Pipelines 2009*, edited by J.J. Galleher and M.K. Kenny, 1205-1215.

Scoby, G. 2012. US Case Studies in HDPE 4710 Potable Water Distribution Systems. In *Proc. Of the 15th Plastic Pipes Conference*. Plastic Pipes Conference Association.

Seargeant, D. 2014. EPCOR's Continuing Success with PVC Water Main Pipe. In *Proc. Of the 17th Plastic Pipes Conference*. Plastic Pipes Conference Association.

———. 2016. *EPCOR Experience with Plastic Pipe*. Summary Information Prepared for Project Workshop.

Shumard, D. and P. Moravits. 2013. New Pipeline Construction Product Allows for Simple Installation of Standard PVC Pipe in Houston HDD Project. In *Proc. Of the ASCE Pipelines Conference*.

Smeets, P.W.M.H, G.J. Medema, and J.C. van Dijk. 2009. The Dutch secret: how to provide safe drinking water without chlorine in the Netherlands. *Drinking Water Engineering and Science*, 2:1-14.

Smith, H., S. Sandstrum, and M. James. 2014. Thirsty City Turns to Plastic Pipe. In *Proc. Of the 17th Plastic Pipes Conference*. Plastic Pipes Conference Association.
Spencer, D., D. Ellison, G. Bell, S. Reiber, K. Von Aspern, and V. Snoeyink. 2015. *Development of an Effective Management Strategy for Asbestos Cement Pipe*. Denver, Colo.: Water Research Foundation.
Struik, L.C.E. 1977. Physical Aging in Plastics and Other Glassy Materials. *Polymer Engineering and Science*, 17(3): 165-173.
Takahashi, Y., H. Matsushita, Y. Suzuki, H. Taniguchi, and A. Koizumi. 2010. Establishment of Leakage Accident Rate Curves for Drinking Water Pipes. In Proc. Of the International Water Association World Water Congress & Exhibition.
Thames, R. 2010. In the field – Internal joint restraint rescues Port of Tampa. *Opflow*, 36(3): 8-9.
Uni-Bell PVC Pipe Association. No date (n.d.). Thermoplastic Pressure Pipe Design and Selection. Available online at: http://www.uni-bell.org/resources/UNI-TR-7%20-%20Thermoplastic%20Pressure_.pdf
Venkatesh, C. 2012. Performance Comparison of High Density Polyethylene Pipe (HDPE) in Municipal Water Applications. Master's Thesis Prepared for The University of Texas at Arlington.
WL Plastics. 2015. Duchesne County Realizes Many Benefits from Fully-Fused Leak-Free HDPE Pipe System. Available online at: http://www.plasticpipe.org/pdf/mid-case-study-duchesen-ut.pdf.
Wolan, M. 2016. Learning Along the Way: New Jersey American Water's Rehabilitation Experience. In *Proc. Of the AWWA Annual Conference*. Denver, Colo., AWWA.
Wolan, M., J. C. Gillespie, and D. Hughes. 2014. Cements, Polys, and Resins Oh My!!! A Water Utility's Journey Evaluating and Implementing Different Main Rehabilitation Options. In *Proc. Of the AWWA Annual Conference*. Denver, Colo.: AWWA.
York, K.L. 2013. Lee's Summit Continues to Use Trenchless Technology to Rehabilitate Its Potable Water Distribution System. In *Proc. Of the ASCE Pipelines Conference*.
Zhihao, Z. and Z. Xiaoming. 2012. Effects of Environmental Temperatures on PE Water Pipe Application. In *Proc. Of the 15th Plastic Pipes Conference*. Plastic Pipes Conference Association.

ABBREVIATIONS

ABS	Acrylonitrile-butadiene-styrene
AC	Asbestos cement
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
AWWU	Anchorage Water and Wastewater Utility
C	Celsius
CIP	Cast iron pipe
DIP	Ductile iron pipe
EBMUD	East Bay Municipal Utility District
EPA	U.S. Environmental Protection Agency
ERDIP	Earthquake resistant ductile iron pipe
F	Fahrenheit
FDR	Full depth reclamation
FPVC	Fusible PVC
Ft	Foot or feet
GI	Galvanized iron
HBWS	Honolulu Board of Water Supply
HDPE	High density polyethylene
ID	Inside diameter
In.	Inch
Km	kilometer
LADWP	Los Angeles Department of Water and Power
MGD	Million gallons per day
mg/L	Milligrams per liter
Mm	millimeter
NSF	NSF International
OD	Outside diameter
PCP	Prestressed concrete pipe
PE	Polyethylene
psi	Pounds per square inch
PVC	Polyvinyl chloride
PVC-O	Molecularly oriented PVC

PVC-U	Unplasticized PVC
RCP	Reinforced concrete pipe
SDR	Standard dimension ratio
SPU	Seattle Public Utilities
UL	Underwriters Laboratories
U.S.	United States
WRF	Water Research Foundation