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Durability and Reliability of Large Diameter HDPE Pipe for Water Main Applications

Web Report #4485

Subject Area: Infrastructure




Durability and Reliability of Large Diameter HDPE Pipe for Water Main Applications

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Durability and Reliability of Large Diameter HDPE Pipe for Water Main Applications

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Water Research Foundation
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Water Environment Research Foundation
635 Slaters Lane, Suite G-110, Alexandria, VA 22314

and

U.S. Environmental Protection Agency
Washington, D.C.

Published by:

Water Research Foundation℠

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Printed in the U.S.A.

CONTENTS

TABLES

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 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.

Denise Kruger
Chair, Board of Trustees
Water Research Foundation

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Executive Director
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ACKNOWLEDGMENTS

This research was performed under the EPA's Innovation and Research for Water Infrastructure for the 21st Century program by the Center for Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington (UTA), as Prime Contractor, and Black and Veatch Corporation (B&V) and Benton and Associates, Inc. (B&A), as Subcontractors. Dr. Mohammad Najafi (CUIRE at UTA) was the principal investigator and Dr. Ahmad Habibian (B&V) and Dr. Firat Sever (formerly with B&A, and currently with American Structurepoint, Inc.) were the co-principal investigators.

We are grateful to the Water Research Foundation (WRF) for generously taking the lead in providing funding for this project. This work would not have been possible without the grant from EPA through WRF. We would like to thank Dr. Jian Zhang, P.E., WRF Project Manager, for his leadership and support of this important research program. The authors are truly indebted to Mr. Michael D. Royer, Physical Scientist, Urban Watershed Management Branch, U.S. EPA, who thoroughly reviewed this project report, and provided many constructive and valuable comments. We would like to thank the Project Advisory Committee (PAC) member, Mr. Brian Schade, for his helpful comments and feedback. Mr. Frank Blaha of WRF was instrumental in providing this great research opportunity. Mr. Drew Ivers, Project Coordinator; Ms. Megan Karklins, Editorial Assistant; Ms. Peg Falor, Manager, Contracts and Project Administration; Ms. Kim Van Eyzeren, Accounting & Grants Compliance Manager, Ms. Corina Santos, Contracts Administrative Assistant, and their colleagues at the Water Research Foundation were instrumental in the success of this project and their help and support are greatly appreciated.

Several water utilities, whose names follow, provided matching funds, leadership and advice for this project.

- Dennis Abraham, Ph.D., P.E., formerly with City of Rowlett, Texas (currently with Dallas County Public Works), Texas.
- Luis Aguiar, Chief Water Transmission & Distribution Division, Miami Dade Water & Sewer Department, Florida.
- Frank Crumb, Water Director, City of Fort Worth, Texas.
- John Fishburne, former Senior Engineer, Field Operations Division, City of Charlotte, North Carolina.
- Julia Hunt, P.E., Former Director of Water Utilities, City of Arlington, Texas (currently Assistant Regional Manager Operations, Trinity River Authority of Texas).
- John Jurgens, Sr., Civil Engineer Specialist, Seattle Public Utilities, Drainage and Wastewater Division, Seattle, Washington.
- Britt Klein, Administrator, Tucson Water, Maintenance Division, Arizona.
- Matthew T. Klein, Director of Resource Planning, City of Indianapolis, Indiana.
- Ed W. Lambing, P.E., Director of Engineering, Capital Improvement Design and Construction, City of Palo Alto, California.
- Holly L. Link, Engineering Support Coordinator, Water/Wastewater Standards Colorado Springs Utilities, Colorado.
- David Marshall, P.E., Engineering Services Director, Tarrant Regional Water District (TRWD), Fort Worth, Texas.

- Chad E. Owens, P.E., Assistant Manager, Natural Gas & Water Engineering, City of Springfield, Missouri.
- Jo M. Puckett, P.E., Director, City of Dallas Water Utilities; Cesar Baptista, P.E., Assistant Director of Capital Improvements; Chad Kopecki, P.E., Program Manager; Sandra Valentine, Manager of Administrative Systems; and Abidur Khan, P.E., Section Manager- Water Design, City of Dallas Water Utilities, Texas.
- Serge Trentieff, P.E., Distribution Systems Engineering, East Bay Municipal Utility District (EBMUD), California.
- Matthew A. Wirtz, P.E., Deputy Director of City Utilities, City of Fort Wayne, Indiana.
- Dean Yanagi, P.E., Civil Engineer, Arlington Water Utilities, Texas.

This research would not have been possible without support and help of many people. Special thanks go to Harvey Svetlik, Staff Engineer - Water & Energy, Georg Fischer Central Plastics LLC, and Heath Casteel, Performance Pipe, for donating the HDPE pipe samples for testing. The authors would like to thank Mr. Camille Rubeiz, P.E., Director of Engineering and member of the Municipal Advisory Board of the Plastics Pipe Institute (PPI), for his advice and feedback throughout this project. Mr. Larry Petroff, P.E., was extremely helpful for reviewing this project report and providing many constructive suggestions.

The authors also wish to express their appreciation to water utilities that responded to the survey questionnaire and provided feedback. We understand that their time was valuable, and we could not have accomplished this work without their input.

The authors are indebted to the following individuals at the University of Texas at Arlington for their help in the testing part of this project:

- Dr. Max Spindler, P.E., Retired Professor
- Mr. Jeff Johnson, Director of Maintenance, Operations, and Special Projects, Office of Facilities Management
- Mr. Toby Buhrkuhi, Electric Shop
- Mr. Gant Rueben, Mr. Jon Lawing, Mr. Luis Penalog, the UT Arlington Plumbing Shop.

Mr. Richard Redus, Inside Sales and Applications, Vinson Process was helpful in calibration and setup of the control panel and the data acquisition system.

Finally, the hard work and dedication of Ms. Divyashree, CUIRE Research Assistant, in the testing program and preparation of this report, is greatly appreciated. Mr. Dhanush N Reddy, Ms. Nikitha Damarla, and Mr. Ameya Paradkar, CUIRE graduate assistants, helped with review and formatting this report.

EXECUTIVE SUMMARY

Due to leaks and breaks, U.S. water utilities, in aggregate, lose more than a quarter of processed water between treatment plants and the tap every day. Potable water pipe rehabilitation costs may reach more than $1 trillion in the coming decade. Previous research shows that there is a need for a reliable and durable pipe material. High Density Polyethylene (HDPE) pipe is one such material to consider. The large diameter (16 in. and larger) water pipe market in the United States mainly includes steel pipe (SP), prestressed concrete cylinder pipe (PCCP), ductile iron pipe (DIP), and PVC (Polyvinyl Chloride) pipe. Currently, HDPE pipe comprises only a small portion (estimated to be 2 to 5%) of the large diameter potable water pipe market.

The main objectives of this project were:

- To explore North American water utilities' experiences with durability and reliability of large-diameter HDPE pipes in water applications.
- To identify features and characteristics of HDPE pipes in municipal water applications, such as design, installation, maintenance, etc., as well as any limitations or issues.
- To develop a protocol for fatigue (cyclic surge pressure) testing of large diameter HDPE pipe as recommended by water pipeline professionals during the initial phase of this study.

The project approach was divided into six main tasks as summarized below:

1. Search existing publications regarding durability and reliability of HDPE pipe
2. Survey of water utilities to document their experiences regarding HDPE pipe use
3. Conduct a workshop with water professionals to identify issues and corrective measures
4. Perform experiments on a 16-in. diameter HDPE pipe sample
5. Collect case studies of past HDPE pipe projects
6. Prepare a Final Report

The literature search presents an overview of past research on HDPE pipe. While this research validates HDPE as a suitable material for use in municipal piping systems, more research may help users maximize their understanding of its durability and reliability. Overall, corrosion resistance, hydraulic efficiency, flexibility, abrasion resistance, toughness, fused joints, and long service life are among the advantages listed for HDPE pipes. Permeability, repair and maintenance, long term viscoelastic growth, slow crack growth (SCG), and susceptibility to attack by strong oxidizers are issues mentioned in the literature. Proper design, specifications, installation, and operation typically mitigate any reduction in durability and reliability due to these issues.

The survey of water utilities indicated that the majority of respondents were satisfied with the durability and reliability of large diameter HDPE pipe, while 5% were unsatisfied. Survey respondents expressed concerns about tapping, repairs, and joints. They considered permeation and oxidation to be minor concerns. There were no failures reported due to oxidation or permeation in large diameter HDPE piping systems. They mentioned that some measures, such as improvements in tapping, repairs, are joints are required to improve construction techniques, as are described in this report.

The three project workshops provided valuable input to the project team and helped improve upon the project scope and experimental approach. The innovative and structured approach utilized for the workshops allowed the critical topics to be identified and discussed in an efficient manner. The workshops enabled the project team to explore different perspectives and identify several studies and experiences brought up by the project participants.

This project developed a methodology and designed the testing setup for cyclic pressure testing and fatigue evaluation of large diameter pipes. The pipe sample selected for this project was a 16-in., DR 17, PE4710 pipe containing a butt-fused joint in mid length. The pipe sample was pressurized to its pressure class (125 psi) and then cycled to 1.5 times its pressure class (188 psi) for two million times without failure. Two million pressure cycles is the equivalent number of surges applied to a pipe over 100 years of service at the rate of 50 surges per day. After completion of the two million cycle test, the same pipe sample was cycled from its pressure class (125 psi) to 2 times pressure class (250 psi) for an additional 50,000 cycles without failure. The testing protocol developed in this project can be used to evaluate other types of large diameter pipes.

The case studies collected by the project team and presented in this report provide details on successful installations of large diameter HDPE pipe. Information regarding the challenges and solutions developed during the construction operations are included in these case studies.

Overall, this project shows that large diameter HDPE pipe is a suitable pipe material for large diameter water transmission applications. This report provides strategies to address perception issues preventing wide use of large diameter HDPE pipe, and provides recommendations regarding HDPE pipe joining, fittings, specifications, design, installation, and maintenance.

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

"The Report Card on America's Drinking Water Infrastructure" states that U.S. infrastructure is in poor condition (ASCE 2013). Approximately 33% of drinking water is lost each year (Radoszewski 2009). Due to leaks and breaks, water utilities in the United States lose more than 30 billion dollars' worth of drinking water between treatment plants and taps, and approximately six billion dollars per year are needed to stop this loss (Jeyapalan 2007). In the coming decades, the cost of renewing water infrastructure could reach more than $1 trillion (ASCE 2013).

A recent study by Utah State University's Buried Structures Laboratory surveyed the failure rates of different pipe materials over a 12 month period. The failure rate for cast iron pipe was 24.4 failures/ 100 miles/year, steel pipe was 13.5 failures/100 miles/year, asbestos cement pipe was 7.1 failures/100 miles/year, ductile iron pipes was 4.9 failures/100 miles/year and PVC was 2.6 failures/100 miles/year (Folkman 2012). Due to unavailability of data on large diameter HDPE installations, Folkman did not include HDPE in his investigation.

Not considering such factors as causes of pipe failures, pipe age and diameter (large diameter pipes are designed and installed more conservatively than small diameter pipes), the above statistics show that some pipe materials have higher failure rates than others and that there is a real need for reliable and durable water pipe materials.

In another study conducted by the Center for Underground Infrastructure Research and Education (CUIRE 2013), 21 U.S. water utilities, serving a population of approximately 14 million, reported a small inventory of large diameter HDPE pipe, compared with other pipe materials. Pipe sizes for all materials ranged from 24 in. to 54 in. The large diameter HDPE pipe had an age of less than 25 years old. Table 1.1 presents performance of different pipe materials with no failures reported for HDPE pipe.

Table 1.1
Performance of different pipe materials

Pipe Material	Number of Failures	Total Length (in miles)	Failure (per 100 miles per year)
Other materials[1]	4	50	8
PVC	2	22	9
Bar-wrapped	35	258	14
DI	38	270	14
PCCP	92	613	15
Steel	110	574	19

(Continued)

[1] Other Materials include Reinforced Concrete and Asbestos Cement.

Table 1.1 (Continued)

Pipe Material	Number of Failures	Total Length (in miles)	Failure (per 100 miles per year)
CI	57	200	29
HDPE	**0**	**5**	**N A**

Source: CUIRE 2013.

Table 1.2 presents the average failure rate from the United Kingdom Water Industry Research (UKWIR) national failure database. These results are based on 17 water utilities.

Table 1.2
Average failure rates (per 62 mile) from UKWIR national failure database

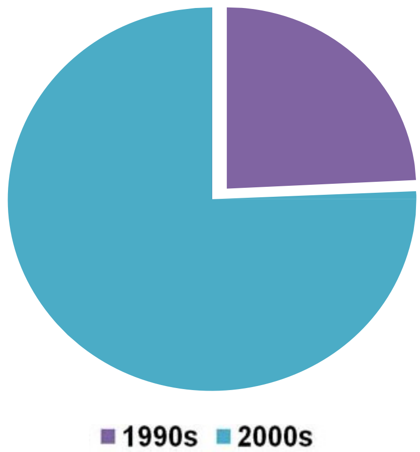
Average failure rate per 62 miles (100 km) per year	Year					
Material group	1998	1999	2000	2001	2002	Average
Asbestos cement	16.4	17.1	15.1	15.8	15.6	16
Ductile Iron	5	5.3	4.8	4.8	6.5	5.28
Iron	23.7	23.7	19.1	21.7	12.3	20.1
PE	**3.5**	**2.9**	**3.3**	**3.1**	**3.0**	**3.16**
PVC	9.6	9.1	7.2	7.4	3.3	7.32
Steel	5	6.1	5.8	5.7	33.1	11.14
Unknown	0.1	0	0	0.1	15.9	3.22

Source: Ong et al. 2008.

In a recent study, Jana Laboratories (2011) conducted a survey for performance of Polyethylene (PE) potable distribution systems. Some of the pipes reported in this study were manufactured nearly 50 years ago. According to this study, while the chemical formula for PE remained the same, PE manufacturers improved the polymer structure over the years to significantly increase slow crack growth resistance, tensile strength, ductility, allowable hydrostatic stress and other pipe material properties. Major changes were considered for new generation of PE pipe material. An example reported was the change from the "PE3408" generation of the 1990s to the current PE4710 generation developed in 2010. Out of 300 utilities, 38 utilities installed PE pipes, and 208 utilities installed PE service lines. Figure 1.1 illustrates the distribution of utilities by date of reported first installation of PE pipes in the last 20 years. The Jana Laboratories report (2011) found that most of the utilities started installing PE pipe in 1990s. Figure 1.2 presents the comparison of utility satisfaction with PE pipe by generation and shows that utilities are more satisfied with the new generation HDPE pipe. These results are based on PE installed in the last 30 years.

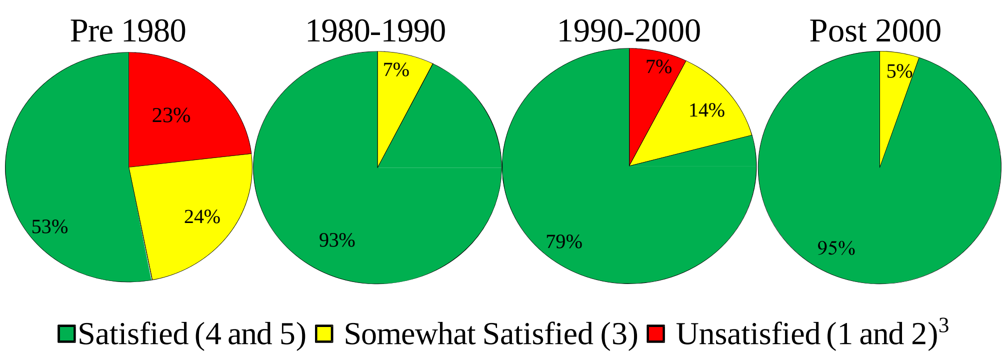
1.1.1 Market Share of HDPE Pipes in United States

In a study by the Plastics Pipe Institute[2] (2009), it was reported that while HDPE pipes have been used for municipal water applications for almost fifty years, they are still minimally used for potable water transmissions/distributions and wastewater services when compared to other types of pipe. Steel pipes, Polyvinyl Chloride (PVC) pipes, Ductile Iron (DI) pipes, Fusible PVC pipes, and Prestressed Concrete Cylinder pipes (PCCP) are other pipes that are used for municipal applications.



Source: Adapted from Jana Laboratories 2011.

Figure 1.1 Distribution of utilities by date of reported first installation of PE mains



Source: Adapted from Jana Laboratories 2011.

Figure 1.2 Comparison of utility satisfaction with PE pipe by generation

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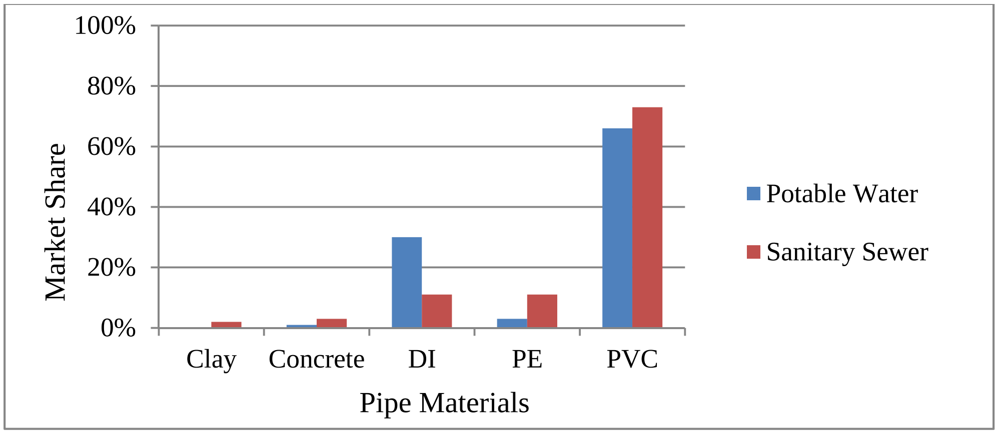
[2] "PPI is a non-profit trade association dedicated to the advocacy and advancement of use of plastics in pipe infrastructure systems because they are smart, economical and sustainable solutions. The mission of The Plastics Pipe Institute is to promote plastics as the material of choice for piping applications. ..." Available at http://plasticpipe.org/about-ppi.html.

[3] The rating was based on scale of 1 to 5, where 4 and 5 is satisfied, 3 is somewhat satisfied and 1 and 2 are unsatisfied.

A survey by Water Research Foundation (WRF) stated that only 0.18% of reported water mains were HDPE as compared to 18% and 16% for PVC and ductile iron (DI) pipes respectively (Ong et al. 2008).

Rahman (2004) reported data for pipe materials used for the North American municipal applications. The use of HDPE pipe for potable water applications was 3% of the reported 310 million ft, while the use of HDPE for sanitary sewer applications was 11% of the reported 290 million ft. In 2007, Rahman increased the HDPE water market share for 15- to 36-in. diameters to 5% (Rahman 2007).

Figure 1.3 illustrates that in 2003, the overall HDPE use in municipal applications was 6.9% of reported 600 million ft of pipeline while the use of DI and PVC pipes were 30% and 67.4% respectively. Between 2003 and 2014, the HDPE pipe shipments for diameters between 4 in. to 63 in. for potable water market have increased from 78 million pounds to 292 million pounds, approximately have tripled, based on PPI Statistical Reports 2004 – 2014 (latest data for 2015 to be published).



Source: Adapted from Rahman 2004.

Figure 1.3 North American municipal applications piping material market

In other parts of the world, HDPE is the major pipe material and its use is increasing. According to Business Wire (2014), "The global demand for HDPE increased from 15.5 million tons in 2000 to 23.1 million tons in 2009. This demand grew at a Compounded Annual Growth Rate (CAGR)[4] of 4.5% during this period. In the forecasted period from 2009-2020, the demand is expected to grow at a CAGR of 7.3%. Asia Pacific is expected to emerge as the leading region with a demand of more than 60% of the global demand for HDPE."

1.2 PROJECT OBJECTIVES

The main objectives of this project were:

1. To explore North American water utilities on their experiences with durability[5] and reliability[6] of large diameter HDPE pipes in water applications.

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[4] The compounded annual growth rate, or CAGR, measures the return on an investment over a certain period of time.

[5] According to Ballantyne (1994), durability is the ability of pipe and fittings to remain in service during its design life without significant deterioration.

2. To identify features and characteristics of HDPE pipes in municipal water applications, such as design, installation, maintenance, etc., as well as any limitations and issues.
3. To develop a protocol for fatigue (cyclic surge pressure) testing of large diameter HDPE pipe as recommended by water pipeline professionals during the initial phase of this study.

1.3 METHODOLOGY

The overall project approach was divided into six main tasks as shown in Figure 1.4 and summarized in the following sections.

Task 1 – Literature Search

A literature search was conducted to collect available information on the durability and reliability of large diameter HDPE pipe in water applications.

Task 2 – Survey of Water Utilities

A survey of North American water utilities was conducted to learn experiences with large diameter HDPE pipe use. It should be noted that the research team was challenged by low number of utility responses which is an indication of low usage rate of large diameter HDPE pipe in water applications. The low usage rate of large diameter HDPE pipe may have impacted the responses submitted by water utilities.

Task 3 – Project Workshops

During the workshops held in conjunction with this project, main objectives, scope and proposed methodology of this research project, as well as preliminary results of literature search and case studies were presented to water professionals to seek input and feedback. The recommendations presented during the workshops were instrumental in developing a testing protocol to successfully complete this project.

Task 4 –Experimental Work

The experimental task was conducted to develop procedures and perform fatigue (cyclic) testing of a new 16 in. PE4710 currently available in the market. The testing protocol can be used to evaluate other large diameter pipes for fatigue resistance.

Task 5 –Case Studies

In this task, information was collected regarding experiences with HDPE pipe as an additional measure to complement literature search, the water utility survey, and the fatigue testing.

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[6] According to Ballantyne (1994), reliability is the consistency of performing the required function without degradation or failure.

Task 6 – Final Report

The final report includes information and guidance on use of large diameter (16 in. and larger) HDPE pipelines for water applications**.**

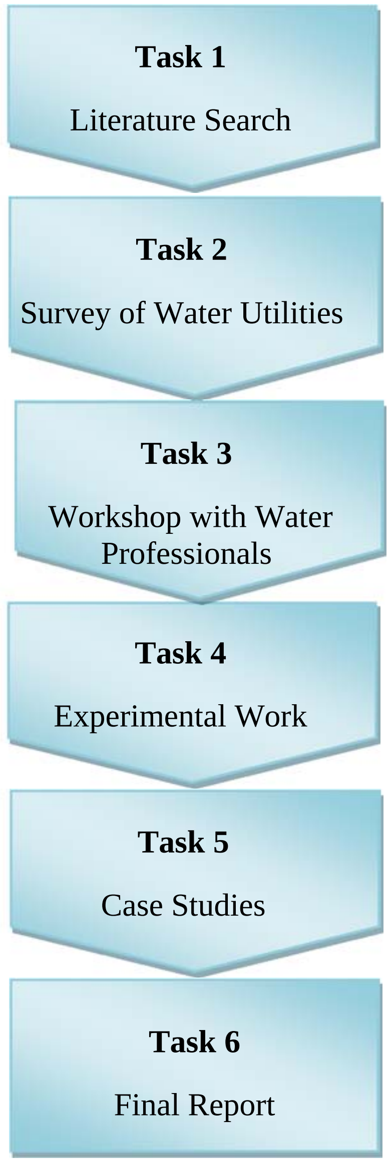


Figure 1.4 Project approach

1.4 PROJECT OUTCOME

This project provides water utilities with information on use of large diameter (16 in. and larger) HDPE pipes. Many water utilities across the country do not utilize HDPE pipe for their water applications due to lack of experience with this pipe material, and concerns they may have over its performance. This research will assist water utilities in evaluating and assessing HDPE as an option for large diameter water transmission applications. Specifically, the outcome of this project can be summarized as:

1. A literature search on large diameter HDPE pipe.
2. A survey of North American water utilities.
3. Results of three workshops held with water utilities and industry stakeholders.
4. A methodology to conduct large diameter fatigue (cyclic) testing, and perform testing of a large diameter (16 in.) of DR 17 PE4710 with fused joint pipe sample.

1.5 RESEARCH NEEDS

Drinking water infrastructure in the North America is in urgent need of renewal and replacement. Large diameter transmission mains are the most critical element of a water supply system, since a failure can cause catastrophic consequences in property damage and traffic disruptions, in addition to extended service interruptions for many customers as well as water quality concerns. Where rehabilitation or renewal by relining of an old and deteriorated large diameter water main is not feasible due to capacity concerns and structural integrity, replacement is inevitable. Recent advancements in polymer science in large diameter (16 in. and larger) HDPE pipe manufacturing can provide an option for water utilities.

1.6 CHAPTER SUMMARY

The large diameter (16 in. and larger) water pipe market in the U.S. mainly includes steel pipe (SP), prestressed concrete cylinder pipe (PCCP), ductile iron pipe (DIP) and PVC pipe. It is estimated that large diameter HDPE pipe comprises 2 to 5% of the large diameter water pipe market. As will be discussed in future chapters, this low market share is likely due to perception issues or unfamiliarity of water utilities with large diameter HDPE pipe performance. Therefore, the main objective of this research project was to explore durability and reliability of the large diameter HDPE pipe for water market. This chapter presented introduction, objectives, methodology, research needs, and expected outcome of this research.

CHAPTER 2
OVERVIEW OF LITERATURE ON LARGE DIAMETER HDPE PIPE

2.1 INTRODUCTION

PE3608/3408 (PE80 in Europe) and PE4710 (PE100 in Europe) under AWWA C901 (½ in. to 3 in.) and AWWA C906 (4 in. to 63 in.) are PE resins used for the manufacturing of HDPE pipes in the U.S. for potable water, reclaimed water and wastewater services.

Due to revisions made to ASTM standards in 2005, PE3408 is no longer available in the North American market. In 2005, PE3608 and PE4710 materials were incorporated in ASTM standards with the requirements for higher stress crack resistance, and additional hydrostatic testing requirements (ASTM D3350). This process paved the way for the classification of the North American version of PE100 material, or PE4710. The designation "PE3608/3408" used above was a transition designation, but for the remainder of this report the designation will conform to current industry practice as PE3608.

According to Plastics Pipe Institute (PPI 2007a), the PE4710 is used in water piping applications because of higher Hydrostatic Design Stress (HDS) with the following designation codes:

- Base resin density – 1st digit in the code, "4."
- Slow crack growth (SCG) – 2nd digit in the code, "7."
- Hydrostatic design stress (HDS) – 3rd and 4th digits in the code, "10."

According to American Society for Testing and Materials (ASTM) standard specification D-3350, the pipe material designation codes for other HDPE materials are (PPI 2007a):

1. PE3608 has a density cell class of 3 and a Slow Crack Growth (SCG) cell class of 6 (in accordance with ASTM D3350). PE3608 has 800 psi maximum recommended Hydrostatic Design Stress (HDS) for water at 73ºF.
2. PE4710 has a density cell class of 4 and a Slow Crack Growth (SCG) cell class of 7 (in accordance with ASTM D3350). It has 1,000 psi maximum recommended Hydrostatic Design Stress (HDS) for water at 73ºF.

AWWA C906 (2007) defines working pressure as "the maximum anticipated, sustained operating pressure applied to the pipe, exclusive of transient pressures." The maximum working pressure for a pipe must be less than or equal to the pipe's pressure class. According to AWWA C906, the pressure class (PC) is "the design capacity able to resist working pressure up to 80ºF service temperature with specified allowances for recurring positive surge pressures above working pressures." American Water Works Association (AWWA) is expected to publish the newly revised AWWA C906 with inclusion of PE4710 in July 2015.

Table 2.1 presents a summary of differences for PE3608 and PE4710. Table 2.2 presents pressure ratings for PE3608 and PE4710 for specific Dimension Ratios (DRs[7]).

[7] Pipe outside diameter divided by the minimum wall thickness

Table 2.1
Differences between PE3608 and PE4710

Parameters	PE3608	PE4710
Resin density	Class 3	Class 4
Base resin density	0.941-0.947 g/cc	0.947-0.955 g/cc
Slow crack growth	For Class 6 is at least 100 hours*	For class 7 is at least 500 hours*
Hydrostatic design	800 psi	1,000 psi
Pressure class	Lower for specified DR	Higher for specified DR when compared for PE3608
Flow capacity	For the same pressure class as PE4710 the flow capacity is less.	For the same pressure class as PE3608 the flow capacity increases.

Source: Adapted from PPI 2007a.
* Slow crack growth is measured per ASTM F1473 (PENT test), where a notched molded plaque is subjected to tensile stress at 80^{o}F

Table 2.2
Sample HDPE pipe pressure ratings for water at 80^{o}F

DR	Pipe Pressure Ratings	
	PE3608	PE4710
	HDS - 800 psi	HDS – 1,000 psi
7.3	255	317
9	200	250
11	160	200
13.5	130	160
17	100	125
21	80	100

Source: PPI 2007a.
[1]HDS – Hydrostatic Design Stress

2.2 HDPE PIPE STANDARD DEVELOPMENT

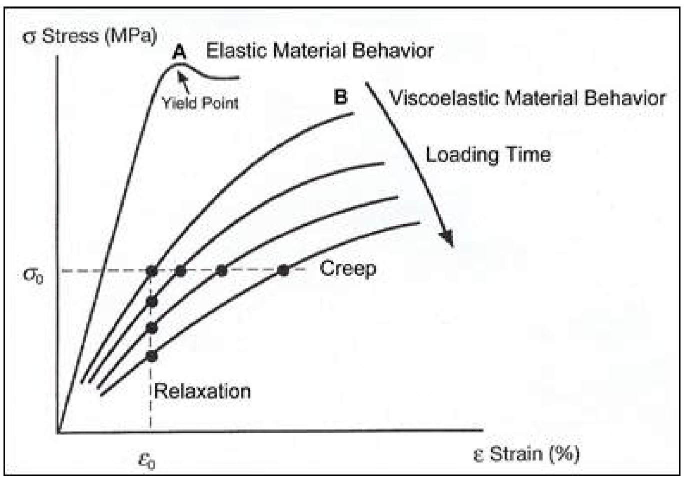
According to Rubeiz (2004), polyethylene piping systems have been available since 1948. ASTM established a Plastics Pipe Committee (PPC) in 1955. American Water Works Association (AWWA) Standard C901, HDPE for water tubes (up to 3 in. in diameter), was first approved in 1978. AWWA Standard C906, the first edition of the AWWA standard for HDPE water distribution pipes (for diameters between 4 in. and 63 in.), was first developed in 1990. AWWA, in 2006, published M55, a manual to assist in the design and installation of PE pipes.

2.3 HDPE PIPE CHARACTERISTICS

2.3.1 Structural Properties

2.3.1.1 Viscoelasticity

HDPE material is viscoelastic. Due to the molecular nature, HDPE is a complex combination of elastic-like and fluid-like elements. Figure 2.1 illustrates the viscoelastic nature of HDPE with small instantaneous elastic strain that is then followed by a time-dependent strain. This phenomenon is related to fatigue resistance of surges in the pipe (PPI 2008). When subjected to a constant stress below the yield stress, HDPE material will continuously deform, although at a very slow rate. The pipe can undergo small viscous deformations which may relieve localized overstressing (up to a certain limit). Under constant strain, the stress level will decrease with time, such that the bending stress in the pipe material installed in a curved position decreases with time. This allows a relatively sharp bending radius for HDPE pipe. For example, the 16 in. diameter, DR 17 pipe sample tested in this project, can be installed in a curved path with a bending radius equal to 27 times its outside diameter (OD) which is 36 ft.



Source: Najafi 2010.

Figure 2.1 Stress-strain relationship in elastic and viscoelastic materials

The viscous deformation under constant loading (creep compliance) will cause the pipe material modulus to decrease over time. This modulus is referred to as an “apparent modulus,” and is expressed as a function of time. For calculating deformation, the time period of loading must be known to select the appropriate modulus value. For example, PE4710 has a short-term apparent modulus of 130,000 psi at 73°F and a 50-year modulus of 29,000 psi at 73°F (PPI 2008). For HDPE material stressed below yield point, unloading will result in rebounding and recovery of its initial apparent modulus value.

2.3.1.2 Pressure Rating and Durability

The pressure rating of HDPE pipe is determined by laboratory testing per ASTM D2837 (2013f), “Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products.” ASTM standard D2837 establishes the “hydrostatic design basis,” HDB, of HDPE pipe material. The HDB categorizes pipe material’s long-term hydrostatic strength, or LTHS. The HDB for PE4710 as well as PE3608 is 1,600 psi. The permitted hydrostatic design stress is obtained by applying a design factor (DF) to the HDB. The pressure rating can be calculated from the hydrostatic design stress. The Plastics Pipe Institute’s Hydrostatic Stress Board assigns DF values to various thermoplastic piping materials, including HDPE. The assigned DF values are intended to allow the pipe to function at design pressures and temperatures indefinitely under typical service conditions (PPI 2008). Therefore, the design factor accounts for normal and secondary stresses due to pipe installation, bending, etc.

2.3.1.3 Slow Crack Growth (SCG) Resistance

Severe stress concentrations, impingements, defects, and other localized stress intensifications may lead to the development of cracks in plastics at stresses less than their tensile strengths. This can affect pressurized pipe operating at or below its hydrostatic design stress. The gradual extension of such a crack over time is referred to as slow crack growth or SCG. The key in preventing SCG is to make the material tough enough that cracks never develop, or, if they do, they cannot propagate. ASTM F1473 (2013e), “Notch Tensile Test to Measure the Resistance to Slow Crack Growth of HDPE Pipe and Resins,” measures the SCG resistance of PE materials. Early generation HDPE materials had PENT values of less than a few hours. When the ASTM designations were changed in 2005, the minimum PENT value requirements were raised to greater than 100 hours, with greater than 500 hours for PE3608 and PE4710. In addition, PE4710 has additional testing requirements that improve SCG resistance. These requirements include tighter tolerances on the stress rupture curve as well as linearity of the stress rupture curve for at least 50 years. Slow crack growth is infrequent in large diameter pipes made with the newer generation materials (Boros 2011).

2.3.1.4 Effects of Disinfectants in Potable Water Applications

The Plastics Pipe Institute’s TR-19 (2007b), “Thermo-plastic piping for the Transport of Chemicals” reports that plastics are susceptible to chemical attack by strong oxidizers. Oxidizers can break the chemical bonds within the polymers and alter the plastic’s properties. Strong oxidizers attack most plastics including HDPE. They also attack concrete and metallic pipe materials. The occurrence of strong oxidizers in drinking water for the purpose of disinfection is at a very low concentration making the rate of chemical attack slow over a broad range of service temperatures. HDPE pipes contain additives which protect the pipe from the oxidizing effects of disinfectants. These pipes also have to meet the NSF/ANSI 61 toxicological requirements. In September 2009, Jana Laboratories issued a report, “Long-Term Performance of Polyethylene Piping Materials in Potable Water Applications,” stating that HDPE pipe can last in excess of 100 years under most water quality conditions, service environments, and disinfection techniques (Jana Laboratories 2009). A 2010 study, Impact of Potable Water Disinfectants on PE Pipe, by

Jana Laboratories examined the projected lifespan of polyethylene pipe under typical operating conditions at water utilities in Indiana, Florida, North Carolina, and California. Based on testing per ASTM F2263 (2014), "Standard Test Method Evaluating the Oxidative Resistance of Polyethylene (PE) Water Pipe to Chlorinated Water," Jana again projected HDPE lifespan to be more than 100 years (Jana Laboratories 2010).

2.3.2 Surge Pressures

The flow rate in a municipal water pipeline varies throughout the day. Some of these variations occur due to pump starts and stops and valve opening and closings. These sudden changes to flow create water hammer (surge pressure) in the pipeline. Design standards for HDPE pipe anticipate and account for water hammer. AWWA C901 and C906 permit frequent recurring surges in the pipeline due to water hammer to be as great as 1.5 times the pipe's pressure class. AWWA standards also permit occasional surges up to two times the pressure class. These standards provide a safety factor between the pipe's ductile rupture (dynamic burst strength) and the peak surge pressure, as well as protecting against fatigue due to recurring application of the surge pressure.

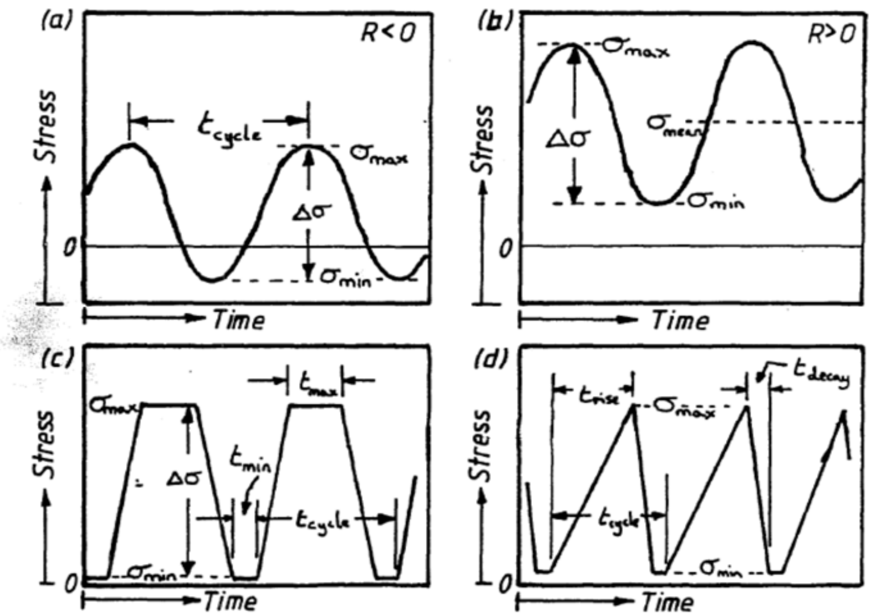
2.3.3 Fatigue Resistance

One of the key finding of Crabtree and Oliphant's (2011) research was a complete lack of reported HDPE pipe fatigue failure in service. In 1990, Bowman attested fatigue response of polyvinyl chloride and polyethylene pipe systems. Bowman stated that butt-fusion joints have the best projected fatigue lifetimes, and are capable of withstanding significant surge stresses at 68˚-73˚F. Figure 2.2 presents different surge pressure loading profiles.

In 1998, Marshall et al. reported on testing of the fatigue life of PE4710 using a three-point bending test. A design graph for cyclic fatigue, giving cycles to failure versus stress, was published in UKWIR (1999). This graph can be used to predict fatigue failure for PE4710 pipe. AWWA C906 permits recurring surges to 1.5 times PC which is equal to 1,500 psi. At 1,500 psi, the fatigue intercept on Marshall's graph is 7,200,000 cycles. This equates to roughly 200 surge cycles per day for 100 years.

In 2012, on behalf of the Plastics Pipe Institute, Oliphant et al. conducted an engineering assessment of the resistance of HDPE pipe to fatigue loading. The assessment included a literature comparison of PE and PVC fatigue resistance. It also included a literature review and utility survey to confirm design fatigue loads and surge velocities (Oliphant et al. 2012). The primary finding of the study was that the fatigue resistance of PE4710 materials, based on the available data, was excellent.

Crabtree and Oliphant (2011) performed cyclic pressure testing on small diameter PE4710 pipes. Pipe samples of 4 in., DR 17, 125 psi pressure class were cycled from zero (0) psi to 1.5 times PC (187.5 psi), and later from zero (0) psi to 2.0 times PC. Table 2.3 presents the results.



Source: Bowman 1990 (Reprinted, with permission, from STP1093 Buried Plastic Pipe Technology, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428).

Figure 2.2 Schematic presentations of different surge loading profiles, (a) & (b) Sinusoidal, (c) Trapezoidal, and (d) Saw tooth

Table 2.3
Small diameter PE4710 recurring surge tests (Cycles 0 to 1.5 times PC)

Test Specimens	Cycles at 1.5 times PC (Recurring Surge)	Status
Straight pipe	11,213,023 10,038,073 6,754,833	No failures
Pipe with butt-fused joint	10,952,363 11,017,153	No failures

Source: Crabtree and Oliphant 2011.

The fatigue testing data available at the onset of this project was limited to *small diameter* pipe samples or lab specimens. The data in Chapter 5 of this report is for a *large diameter* pipe, 16 in. The test method developed as part of this project can be used to confirm the applicability of the previous small diameter testing to large diameter pipes.

Petroff (2013) presented the effects of flow velocity on surge pressure. As the velocity increases, pipes with lower dimension ratios (DR) (thicker walls) may be required to handle the surge pressures. AwwaRF's (currently WRF) 2000 report, *Guidance Manual for Maintaining Distribution System Water Quality*, recommends "a velocity of 5 fps or greater to remove biofilm, promote scouring and removal of loose deposits, and to reduce disinfection." This velocity is equal to what many utilities consider a safe upper limit, although some utilities may increase the velocity to 8 fps. Table 2.4 presents examples of surge pressures for different velocities.

Table 2.4
DR 21 pressure design examples for different velocities for PE4710 pipe at 73˚F

Working Pressure (psi)	DR	Pressure Class (PC)	Design Flow Velocity (fps)	Surge Pressure (psi)	Working Pressure + Surge (psi)	WP + Occasional Surge Allowance (PC+1.0 PC)	WP + Recurring Surge Allowance (PC+0.5 PC)
	21	100	4	40	140	200	150
100	21	100	5	50	150	200	150
	21	100	6	60	160	200	150

Source: Petroff 2013 (with permission from ASCE).

According to Petroff (2013), the HDPE safety factors vary from 3.6 to 80, as shown in Table 2.5. Table 2.5 further presents number of cycles required to fail PE4710 based on 55 surges per day and having a working pressure at 1.1 to 1.5 times pressure class. Equations 2.1 and 2.2 are used to calculate number of cycles to failure based on the peak pressures.

$$\text{Number of Cycles} = 10^{\frac{1.708 - Log(\frac{Peak\ Stress}{145})}{0.101}} \qquad \text{(Eq. 2.1)}$$

$$\text{Peak Stress} = (P_{\text{PUMPING}} + P_{\text{SURGE}}) * \frac{(DR-1)}{2} \qquad \text{(Eq. 2.2)}$$

Table 2.5
Cycles to failure for PE4710 and PE100

Working plus Surge Pressure (WP + PS)	Peak Stress (psi)	Cycles to Failure	Fatigue Life (years) @ 55 surges/day	Safety Factor Against Fatigue Failure for 100 years @ 55 surges/day
1.1*PC	1,100	160,000,000	7,970	80
1.2*PC	1,200	66,000,000	3,288	33
1.3*PC	1,300	30,000,000	1,494	15
1.4*PC	1,400	14,000,000	697	7
1.5*PC	1,500	7,200,000	359	3.6

Source: Petroff 2013 (with permission from ASCE).

2.3.4 Compensation for Elevated Temperatures

The role of operating temperature is important in the performance of HDPE water pipes. The working pressure rating of a HDPE pipe is lowered when the temperature is above 80°F. For municipal water pipes, the service temperature for HDPE pipe is limited to a maximum of 100°F. A temperature compensation multiplier is applied to the HDPE pipe pressure class (PC) as shown in Table 2.6.

Table 2.6
Temperature compensation multiplier applied to HDPE pressure class

Maximum operating temperature	Temperature compensation multiplier
Below 80°F	1.0
From 81°F to 90°F	0.9
From 91°F to 100°F	0.8
Above 100°F	---

Source: Adapted from AWWA (M55) 2006.

2.3.5 Thermal and Pressure Expansion

Similar to any other material, HDPE pipe expands and contracts with changes in temperature. Pipe expansion and contraction coefficients should be considered in the pipe design and selection, even though buried pipelines are theoretically confined due to soil embedment.

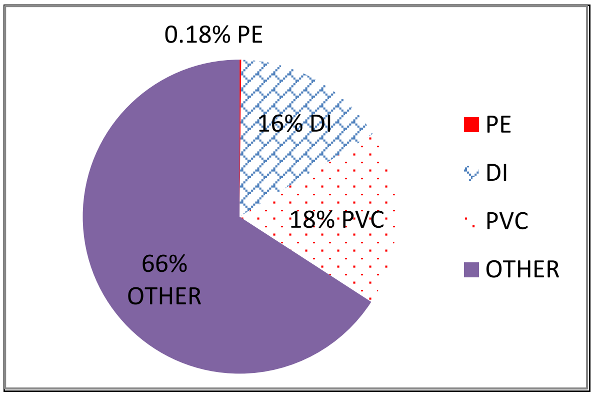
The unrestrained coefficient of thermal expansion for HDPE pipe is approximately 9×10^{-5} in./in./˚F (PPI 2008). Temperature changes can cause HDPE pipes to undergo length changes, which may result in longitudinal stresses. Anchored or restrained pipe conditions may apply higher stresses to the pipe. Therefore, care must be taken during installation to avoid high stresses caused by expansions and contractions above a certain limit. If the resulting stress or thrust loads are significant, the restrained pipe must be designed to resist the anticipated loads. Particular care must be taken in designing connections, fittings, and transitions between HDPE pipe and other types of pipe materials, particularly transitions with gasketed joints. As was observed during the experimental part of this project (see Chapter 5), HDPE pipes tend to expand circumferentially and contract longitudinally when pressurized. As such, connected bell and spigot joined pipes can pull apart, unless they are properly restrained.

2.3.6 Permeability

Potable water pipelines installed underground can be contaminated by various chemical and organic substance sources. In the event of hydrocarbons around a water pipe system, contaminants diffuse or permeate through the pipe wall and joints into the water carried by the pipe. Hydrocarbon compounds abbreviated as BTEX include benzene, toluene, ethyl benzene and xylenes. These organic compounds are the main sources of ground contamination. A research by Ong et al. (2008) entitled “Impact of Hydrocarbon on PE/PVC Pipes and Pipe Gaskets,” reported on permeation of organic compounds. A survey conducted through this research indicated that 151 utilities reported an inventory of 83,360 miles of water mains, with

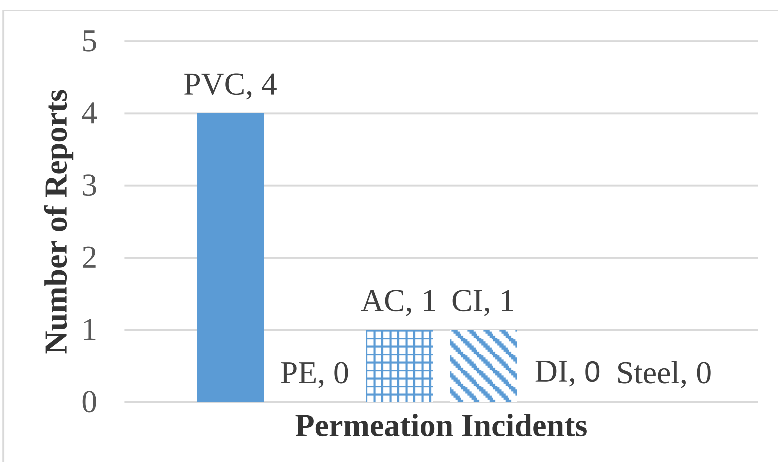
70% of the utilities having at least some plastic materials. Figure 2.3 illustrates that PVC and ductile iron (DI) pipes accounted for 18% and 16% of miles of mains respectively, and HDPE accounted for 0.18% of miles of mains (Figure 2.3). Respondents stated that 0.54% of water mains had a risk of permeation. Approximately, one permeation incident per 14,000 miles of mains was reported. Of the 6 reported permeation incidents, three involved gasoline, one involved chlorinated solvent, and two involved unknown materials. Figure 2.4 presents pipes involved in permeation incidents to be PVC (4), asbestos cement (AC) (1), and cast iron (CI) (1).

Koo (2013) provided a BTEX permeation calculation methodology for the water industry use. In a response to a WRF report (Ong et al. 2008), Koo discussed the health effects, regulations, transport mechanisms and properties of BTEX associated with permeation process. Koo (2012) showed that the research conducted in 73˚F temperature without taking into account the effects of lower temperatures on rate of permeation (lower temperatures in ground conditions will result in lower permeability) is not applicable to HDPE pipe.



Source: Adapted from Ong et al 2008.

Figure 2.3 Permeation percentages for 151 utilities reporting 83,360 total miles (134,155 km) of water mains



Source: Adapted from Ong et al 2008.

Figure 2.4 Reported permeation incidents

Due to the importance of wall thickness in reducing permeation, Koo (2013) attested that the conclusion drawn from the WRF report (Ong et al. 2008) regarding the one (1) in. HDPE thickness requirement is highly conservative. He stated that the presence of BTEX contamination in soil along HDPE water pipelines does not necessarily mean that contamination in the drinking water exceeds regulatory conditions.

In 2009, Plastics Pipe Institute (PPI) commented that while overall impact of hydrocarbons is small, measures need to be taken to limit the impact of hydrocarbon permeation with the following three options suggested:

1) To surround the pipe with good clean soil of Class I or Class II[8] soil embedment (backfill) materials,
2) To sleeve the pipe in areas where hydrocarbon contamination exists, and
3) To reroute the pipe around the contaminated area.

Ong et al. (2008) suggested replacement of HDPE pipe with another pipe material if permeation is observed. However, Plastics Pipe Institute states that permeation is not an issue in large diameter water mains as there is no stagnation of water inside large diameter pipes. An increase in density of pipe material, such as, PE4710 compared with PE3608, will result in a lower permeability as well (PPI 2008).

2.3.7 Seismic Resistance

In 1995, there was a severe earthquake in Awaji (Kobe), Japan. The HDPE pipe for potable water piping used in this region performed "very well with few failures," when compared to other pipe materials (Rubeiz 2009). Table 2.7 presents the failure rates of different pipe materials. While this report did not specify pipe diameters, due to their better design and installations, large diameter pipes are usually more resistant to seismic loads than smaller diameter pipes.

Table 2.7
Kobe earthquake water pipe failure rates

Type of pipe	Water pipe damage/mile (damage/km)
PE	0.00 (0.00)
Steel	0.26 (0.437)
DIP	0.303 (0.488)
PVC	0.88 (1.43)
CIP	0.937 (1.508)
AC	1.107 (1.782)

Source: Adapted from Rubeiz 2009.

For common distribution pipes and service laterals from under one (1) in. to 8 in. diameters, HDPE pipe (either butt-fused or electro-welded with clamped joints) had excellent earthquake performance, as evidenced in three earthquakes reported by Eidinger and Davis (2012) in a WRF report. Eidinger and Davis (2012) also reported that the toughness, ductility

[8] Refer to ASTM D 2321 for soil descriptions.

and flexibility of HDPE pipes combined with their fully restrained butt-fused joints, make it well suited for installation in dynamic soil environments and in areas prone to earthquakes. Table 2.8 illustrates the vulnerability of different pipe materials to ground deformation and shows that HDPE pipe with fused joint has low vulnerability to ground deformation compared to other commonly used water pipeline materials. Krishnaswamy (2005) presented an example of strength of HDPE pipes that was found in the investigations in the aftermath of the Kobe (Japan) earthquake during which many fires and explosions from damaged gas pipelines caused considerable loss to life and property. However, there were no indications of HDPE pipe failures even under these severe service conditions.

Table 2.8
Commonly used water pipeline materials, standards and vulnerability to ground deformation

Material Type and Diameter	AWWA Standard	Joint Type
Low Vulnerability to Ground Deformation[1]		
Ductile iron	C100s series	Bell-and-spigot, rubber gasket, restrained
Polyethylene	C906	Fused
Steel	C200s series	Arc welded
Steel	No designation	Riveted
Steel	C200s series	Bell-and-spigot, rubber gasket, restrained
Low to Moderate Vulnerability to Ground Deformation[1]		
Concrete cylinder	C300, C303	Bell-and-spigot, restrained
Ductile iron	C100s series	Bell-and-spigot, rubber gasket, unrestrained
Polyvinyl chloride	C900, C905	Bell-and-spigot, restrained
Moderate Vulnerability to Ground Deformation[1]		
Cast Iron >8 in. diameter	No designation	Bell-and-spigot, rubber gasket
Polyvinyl chloride	C900, C905	Bell-and-spigot, unrestrained
Steel	C200s series	Bell-and-spigot, rubber gasket, unrestrained
Moderate to High Vulnerability to Ground Deformation[1]		
Concrete cylinder	C300, C303	Bell-and-spigot, unrestrained
Steel	No designation	Gas welded
High Vulnerability to Ground Deformation[1]		
Cast iron	No designation	Bell-and-spigot, leaded or mortared

Source: Adapted from Ballantyne 1994.
[1] Resistance of a pipe to ground movements due to seismic and dynamic loads

2.3.8 Leakage

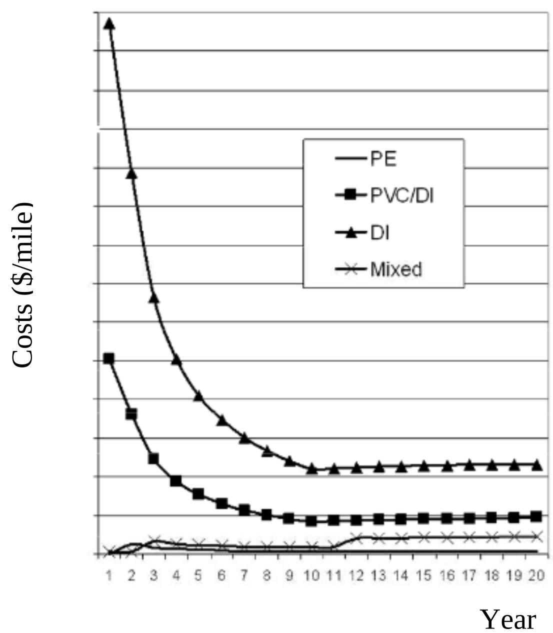
Loss of water through leaks is a significant cost for many water utilities and often overlooked. Ambrose et al. (2010) estimated leakage cost based on two leakage models as follow:

- Background leakage, which occurs mainly through pipe joints and perforations.
- Leakage from burst failures such as longitudinal splits and circumferential breaks.

Ambrose et al. (2010) also performed leakage cost simulation of HDPE, PVC/DI, DI and mixed pipe material for a medium water network of 100,000 costumers and concluded that HDPE pipe has the lowest leakage cost.

Based on the American Water Works Association (AWWA)'s Manual M36, the largest leaks occur in the large diameter water mains, and can be as much as 1,000 GPM (3,785 LPM) (AWWA 1999). AWWA also states leak detection cost which can add up to $800 per mile of water mains (in 1999 dollars). This cost will be in addition to the cost of water, which includes water treatment costs, and pipe repair costs (Rubeiz 2004). Figure 2.5 illustrates a leakage cost relationship for small water networks.

Fused joints potentially eliminate leaks at the pipe joints. PPI (2008) reports that allowable water leakage for PE pipe is zero, as compared to allowable water leakage rates of 10% or greater, typically accepted in the industry.



Source: Ambrose et al. 2010.

Figure 2.5 Leakage cost relationship

2.3.9 Advantages and Limitations of HDPE Pipe

HDPE is recognized as the standard piping material for Horizontal Directional Drilling (HDD) and pipe bursting by extensive use of HDPE pipe in these trenchless applications (Najafi 2010). Ortega et al. (2004) presented a case study regarding use of HDPE pipe in difficult installation conditions using trenchless technology.

Table 2.9
Advantages and limitations of HDPE pipes

Advantages	Limitations
Resistance to both internal and external corrosion. Low internal friction. Smooth interior.	Older PE materials are subjected to environmental stress cracking due to improper embedment or excessive stress intensification due to rock impingement local bending. Newer materials (such as PE3608/PE4710) have enhanced resistance.
Butt-fused connections effectively create a continuous *jointless* leak free pipeline.	Trained labor and special equipment required for butt-fusion per ASTM F2160, AWWA M55 and others.
Abrasion resistant. Used to convey sand and fly ash slurry.	Slightly smaller inside diameter than other pipes of the same outside diameter size. However, proper design will minimize this issue. Design with PE4710 DIPS will increase inside diameter and flow area.
High ductility and flexibility. Lightweight in smaller diameters. Typical minimum bend radius of 25-30 times pipe diameter.	Cannot be located unless buried with metallic wire or tape. Follow AWWA M55 requirements for inclusion of a metallic wire or tape.
Excellent resistance to fatigue and recurring surge pressures and earthquakes.	Sensitive to temperature differentials, resulting in measurable expansion and contraction unless constrained by soil friction. Can pull apart unrestrained bell and spigot joints in adjoining pipelines.
May be repaired using mechanical couplings and saddles and fusion and Electro-fusion.	Color pipe products cannot be subjected to prolonged (> 3 years) unprotected storage, and installations must be buried.
High resistance to failure by impact, even at very low temperatures.	
Resists shatter-type or rapid crack-propagation failure.	
Does not easily crack under expansive forces of freezing water.	

(Continued)

Table 2.9 (Continued)

Advantages	Limitations
PE with carbon black has a long UV resistance and allows for above-ground and buried installations.	

Source: Adapted from Najafi 2010

Compatibility with trenchless technology has been one of the major benefits of HDPE pipe. In 1992, AwwaRF (currently WRF) carried out surveys and tests on failed HDPE pipes (Thompson et al. 1992). The test results showed that most of the failures were related to installation procedures rather than the properties of HDPE pipes. This report indicated the requirement of skilled manpower for installation of HDPE pipe, such as recommended by AWWA (C906, M55), and ASTM (F2620, F1055, F1962, F2164, D2774) standards and manuals[9]. Table 2.9 summarizes the advantages and limitations of HDPE pipes. It should be noted that HDPE pipe properties have improved with the availability of newer PE4710 pipe materials.

2.4 Chapter Summary

This chapter presented main parameters impacting performance of HDPE pipe as well as an overview of its benefits and limitations. The advantages include fused joints providing a leak free piping system with fully restrained joints, excellent hydraulic efficiency and abrasion resistance. The corrosion resistance of HDPE pipe provides a long service life. The effects of strong oxidizers, slow crack growth, permeation and other issues presented in this chapter must be considered during HDPE pipe design and installation. All types of pipe materials have certain benefits and limitations. The HDPE can be a pipe of choice dependent on the project and site conditions.

[9] The requirement for skilled manpower for installation of HDPE pipe was also recommended during the water utility survey and the project workshops. See Chapters 3 and 4 of this report.

CHAPTER 3
WATER UTILITY SURVEY

3.1 INTRODUCTION

To supplement the literature search, a survey of North American water utilities was conducted to gather information regarding their experiences and concerns with HDPE pipe, 16 in. and larger diameter sizes, used in water transmissions. The survey respondents were asked questions about their large diameter HDPE pipe experiences. The questionnaire used in this survey is provided in Appendix A. The project team was challenged conducting this survey due to relatively limited recent installation of large diameter HDPE pipes. This chapter presents results of this survey.

3.2 SURVEY OBJECTIVES

The main objective of this survey was to obtain as much information as possible from the participating water utilities regarding performance of large diameter HDPE pipe and its advantages and limitations.

3.3 METHODOLOGY

This survey was conducted by the Center for Underground Infrastructure Research and Education (CUIRE) as a separate part of this research project. A commercial Website (Survey Monkey) was used to send questionnaires to more than 300 North American water utilities. Figure 3.1 illustrates number and categories of survey responses. Out of the 300 solicited surveys, 96 responses were received, with only 39 respondents stating they have large diameter HDPE in their systems. Out of these 39 who said they have large diameter HDPE, 31 utilities fully completed the survey, and 8 utilities partially completed the survey, as indicated with different number of responses in the following sections.

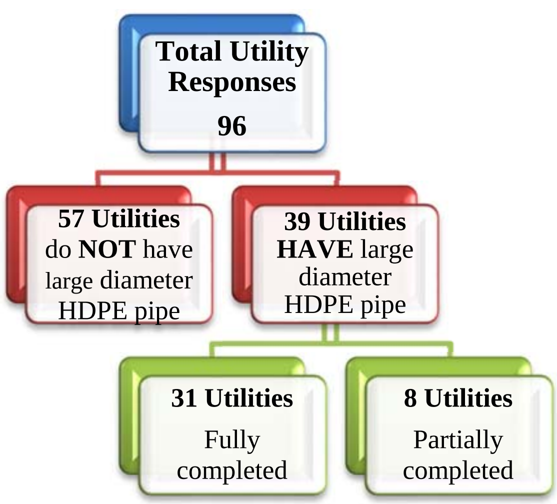


Figure 3.1 Category of survey responses

3.4 SURVEY RESULTS

3.4.1 Contact Information

Q1: Contact Information

This question collected contact information of responding water utilities, such as names, positions, organizations, addresses, emails, and phone numbers.

3.4.2 HDPE Footage

Q2: Do you have large diameter (16 in. and larger) HDPE water pipe in use?

Figure 3.2 presents the available large diameter HDPE pipes in water applications. Only 41% of the water utilities had large diameter HDPE, and the remaining 59% either used smaller HDPE diameters, or had no experience with HDPE pipes. Therefore, survey analysis was limited to 39 respondents with some respondents only partially completed the survey, as indicated with different number of responses in the following sections.

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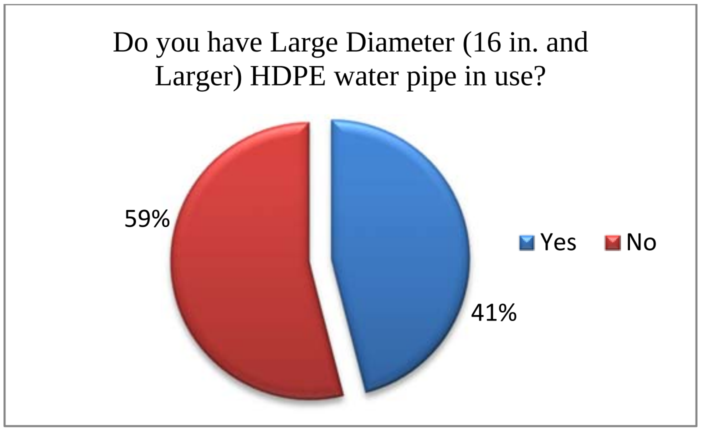


Figure 3.2 Availability of large diameter HDPE in use (based on 96 respondents)

3.4.3 Population Distribution

Q3: What is the population of the area served by your organization?

Figure 3.3 presents overall distribution of population served among survey respondents in each state. The highest number of population served by water utilities in Texas with large diameter HDPE pipes was 4.6 million people. The second highest was Colorado followed by California and Maryland. The lowest population served was in Oregon with Arkansas and Louisiana participants with slightly higher populations.

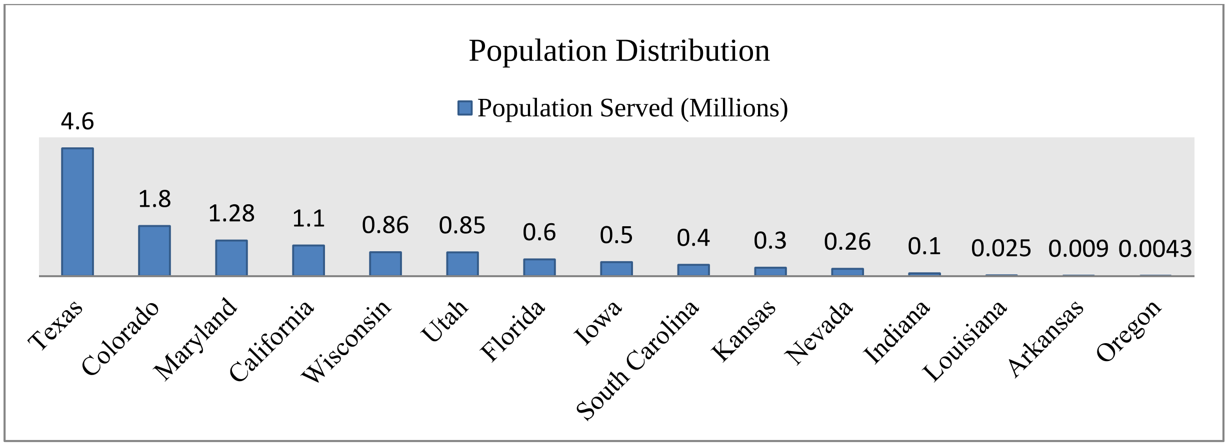


Figure 3.3 Population distribution in each state (based on 29 respondents)

3.4.4 HDPE Pipe Age Distribution

Q4: In your installed large diameter (16 in. and larger) HDPE water pipe in use, what length (miles) is:

Table 3.1
HDPE pipes age distribution*

Classification		miles	No. of Responses
PE4710	Less than 5 years old	91	19
PE4710	Between 5 to 10 years old	115	11
PE3608/PE3408	Less than 5 years old	44	12
PE3608/PE3408	Between 5 to 10 years old	68	12
PE3608/PE3408	More than 10 years old	16	12

*Age calculated as of 2013

Table 3.1 presents age distribution of HDPE pipes in miles. The majority of reported large diameter HDPE pipe in operation is PE4710, and is less than 10 years old (within 5-10 years ago). Figure 3.4 illustrates the age distribution of HDPE pipes. It should be noted that some survey respondents were not confident about type of HDPE (PE4710 or PE3608/3408) in their system, however, it can be concluded that most recent large diameter HDPE pipe installations are PE4710. The confusion in PE4710 or PE3608/3408 may have impacted other survey responses as well.

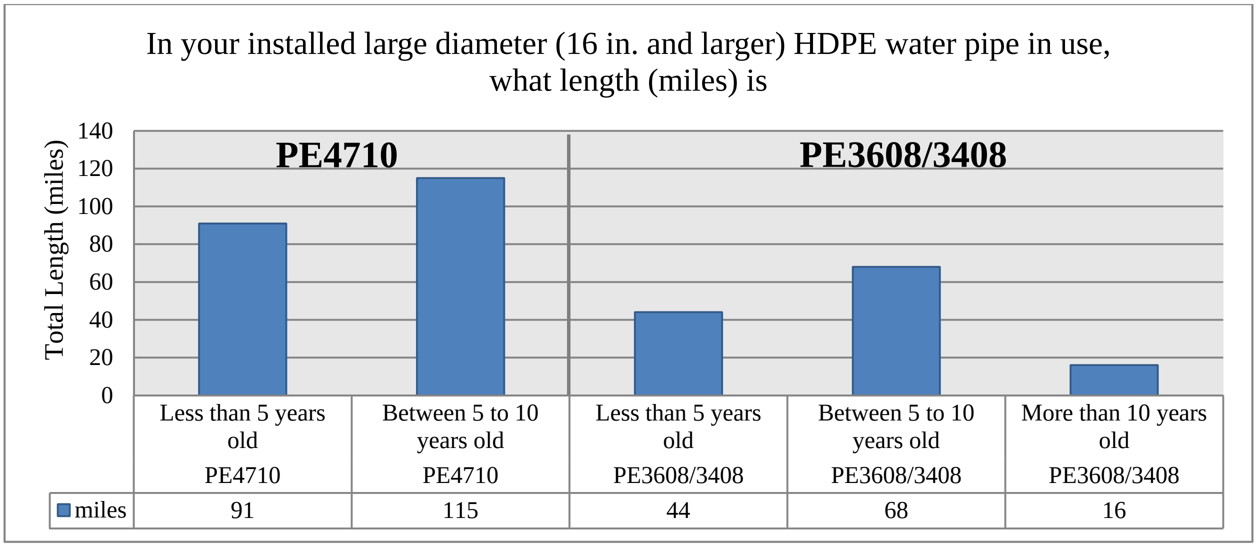


Figure 3.4 Number of respondents reported age distribution of HDPE pipes (based on 31 respondents)

3.4.5 HDPE Pipes Diameter Distribution

Q5: In your installed large diameter (16 in. and larger) HDPE water pipe, what length (miles) is:

Table 3.2
HDPE pipes diameter distribution

Classifications		miles	No. of Responses
PE4710	16 in. - 24 in.	161	17
PE4710	Larger than 24 in.	44	12
PE3608/PE3408	16 in. - 24 in.	75	17
PE3608/PE3408	Larger than 24 in.	58	16
Total		338 miles	

Table 3.2 presents HDPE pipes diameter distribution in miles. Most of the respondent water utilities have used PE4710 and PE3608/3408, in 16 in. to 24 in. diameters compared to diameter larger than 24 in. Figure 3.5 illustrates HDPE pipe diameter distribution.

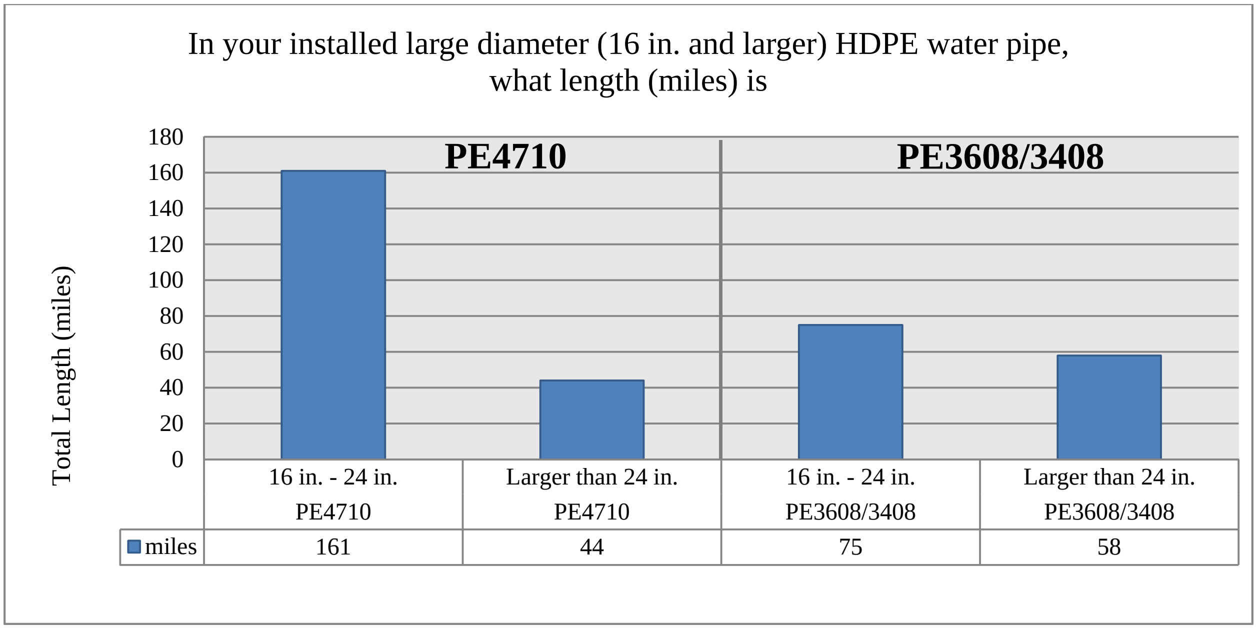


Figure 3.5 Number of respondents reported diameter distribution of HDPE pipes (based on 30 respondents)

3.4.6 Type of Permitted HDPE Pipe

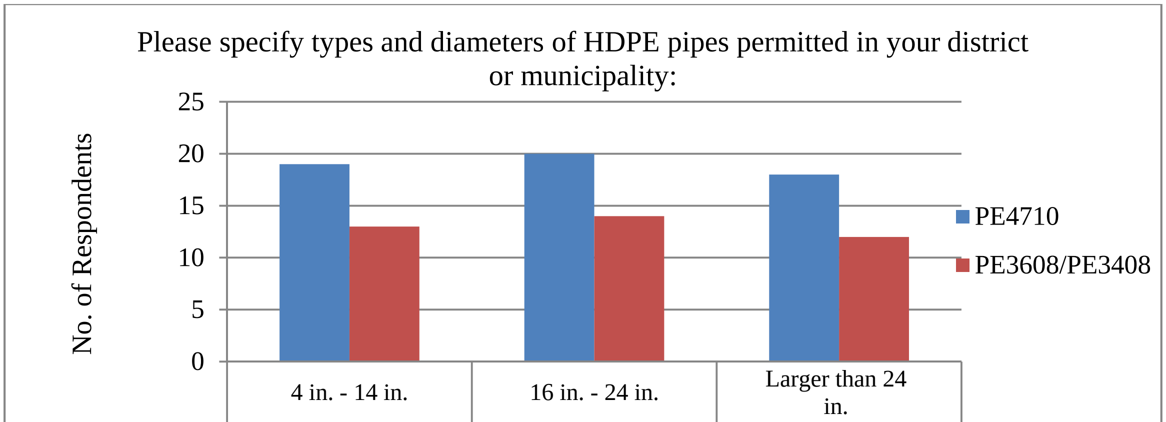
Q6: Please specify types and diameters of HDPE pipes permitted in your district or municipality:

Table 3.3 and Figure 3.6 present types of HDPE pipe diameters permitted in the responding water utility districts. It should be noted that the same water utility responded for different diameters, so there are multiple responses for each water utility.

Table 3.3
Types of permitted HDPE pipes

Pipe Type	4 in. – 14 in.	16 in. – 24 in.	Larger than 24 in.	Total No. of Responses
PE4710	19	20	18	24*
PE3608/PE3408	13	14	12	17*

* Multiple responses were reported



	4 in. - 14 in.	16 in. - 24 in.	Larger than 24 in.
PE4710	19	20	18
PE3608/PE3408	13	14	12

Figure 3.6 Number of respondents reported types and diameters of permitted HDPE pipes (based on 32 respondents)

3.4.7 Restriction in Use of HDPE Pipes

Q7: If you have any restrictions in use of HDPE pipes, please provide reasons.

Due to some confusion with understanding this question, responses are provided in Appendix A, Section A.3.

3.4.8 Pipe Installation Methods

Q8: Please specify restricted HDPE pipe installation methods in your district or municipality:

Survey responses indicated that there are more HDPE pipe installations using trenchless technology, such as, horizontal directional drilling (HDD), sliplining, and pipe bursting, than open-cut methods. While it is generally perceived that trenchless technology costs more than open-cut method, trenchless technology with HDPE pipes in urban environment is reported to be less expensive than open-cut (Najafi 2013). This factor might have been one of the main reasons that most water utilities reported use of HDPE pipe with trenchless technology.

3.4.9 Leakage

Q9: Have you had any leaks from your HDPE water pipe system (16 in. and larger)?

Approximately one third (9 out of 31 water utilities) reported having seen a leak at least in one of their HDPE water main systems. Some respondents indicated that two main causes of leaks are improper construction methods and third party damage. Other water leak causes, as stated by water utilities, were:

- HDPE fittings, mechanical joints and flanged adapters to DIP joints.
- Damage from other contractor's equipment.
- Flooding and washing out a river crossing.
- Faulty service saddles.
- Failure at access vaults and service connections.
- Improper welding of joints.
- Pipe punctures during construction.
- Third-party damage.

3.4.10 Causes/Modes of Rupture/Leakage for PE4710

Q10: On a scale of 1 to 5, with 1 being "lowest frequency of occurrence" and 5 being "highest frequency of occurrence," how would you rate the following causes/modes of rupture for PE4710 HDPE pipe material according to its frequency of occurrence?

Based on 26 respondents, Tables 3.4 and 3.5 present potential causes of rupture or leakage in PE4710 for diameters 16 in. to 24 in., and larger than 24 in.

Among several causes, the survey results indicated that third party damage, installation defects, joint rupture, and fittings, are the major parameters that need to be considered for 16 in. to 24 in. for PE4710 pipe. On the other hand, for pipe sizes larger than 24 in., installation defect was a major issue and the main concern.

Majority of water utilities reported no leaks in their system with following comments included in their responses:

- No problem with all these factors.
- No leakage in HDPE 16 in. and larger pipe.
- Our large diameter HDPE pipe has been installed less than 5 years ago, and we have had no failures.
- No pipe failures.
- Pipe has been installed less than a year and no rupture/damage was observed.

3.4.11 Causes/Modes of Rupture/Leakage for PE3608/3408

Q11: On a scale of 1 to 5, with 1 being "lowest frequency of occurrence" and 5 being "highest frequency of occurrence," how would you rate the following causes/modes of rupture for PE3608/3408 HDPE pipe material according to its frequency of occurrence?

Based on 26 respondents, Tables 3.6 and 3.7 present causes of rupture or leakage in PE3608/3408 for diameters 16 in. to 24 in., and larger than 24 in. The survey analysis indicated that major issues were third party damage, installation defects, manufacturing defects, and fittings for 16 in. to 24 in. pipes. For 24 in. and larger, installation defects, fusion, electro-fusion, fittings, and third party damage were the major issues.

Some respondents included the following comments:

- Common failure mechanism is when one end of the pipe is firmly held in-place (attached with an existing pipe). During compaction of the adjacent soil, part of the pipe is driven downward with severe force. The connection point to the firmly held HDPE can be severely bent and "sheared" off. This happens with PEX services as well.
- Flange adapter HDPE to DIP application requires a specialized contractor to install, and requires engineered bolt torque values.
- No breaks or failures.

Table 3.4
Number of responses for causes of rupture or leakage for PE4710 (16 in. to 24 in.)

PE4710							
16 in. to 24 in.	Not Available	5 (High Freq)	4	3	2	1 (Low Freq)	No. of Responses[10]
Installation defects	22	1	0	2	0	2	27
Fittings	23	1	1	2	0	0	27
Electro-fusion	24	1	0	0	2	0	27
Expansion/Contraction	27	0	0	0	0	0	27
Permeation	27	0	0	0	0	0	27
Freeze/Thaw	27	0	0	0	0	0	27
Fusion	25	1	0	0	0	1	27
Seismic/Ground movement	27	0	0	0	0	0	27
Third party damage	23	1	1	1	0	1	27
Excessive internal pressure	27	0	0	0	0	0	27
Joint rupture	22	1	0	1	2	1	27
Ultraviolet radiation	27	0	0	0	0	0	27
Water temperature	27	0	0	0	0	0	27
Soil conditions	27	0	0	0	0	0	27
Circumferential rupture	27	0	0	0	0	0	27
Manufacturing defects	24	0	0	0	0	3	27
Buckling/Collapse	26	0	0	0	0	1	27
Fatigue	26	0	0	0	0	1	27
Longitudinal rupture	27	0	0	0	0	0	27
Oxidation/Disinfection	27	0	0	0	0	0	27

[10] Multiple causes were reported for some leaks

Table 3.5
Number of responses for causes of rupture or leakage for PE4710 (larger than 24 in.)

PE4710							
Larger than 24 in.	Not Available	5 (High Freq)	4	3	2	1 (Low Freq)	No. of Responses[11]
Installation defects	23	1	1	0	1	1	27
Fittings	25	1	0	0	1	0	27
Electro-fusion	25	0	1	0	1	0	27
Expansion/Contraction	27	0	0	0	0	0	27
Permeation	27	0	0	0	0	0	27
Freeze/Thaw	27	0	0	0	0	0	27
Fusion	25	0	0	1	0	1	27
Seismic/Ground movement	27	0	0	0	0	0	27
Third party damage	26	1	0	0	0	0	27
Excessive internal pressure	26	0	0	1	0	0	27
Joint rupture	26	0	0	0	1	0	27
Ultraviolet radiation	27	0	0	0	0	0	27
Water temperature	27	0	0	0	0	0	27
Soil conditions	27	0	0	0	0	0	27
Circumferential rupture	26	0	0	0	1	0	27
Manufacturing defects	26	0	0	1	0	0	27
Buckling/Collapse	27	0	0	0	0	0	27
Fatigue	27	0	0	0	0	0	27
Longitudinal rupture	27	0	0	0	0	0	27
Oxidation/Disinfection	27	0	0	0	0	0	27

[11] Multiple causes were reported for some leaks

Table 3.6
Number of responses for causes of rupture or leakage for PE3608/3408 (16 in. to 24 in.)

PE3608/3408							
16 in. to 24 in.	Not Available	5 (High Freq)	4	3	2	1 (Low Freq)	No. of Responses[12]
Installation defects	23	1	1	1	0	1	27
Fittings	23	2	0	0	1	1	27
Electro-fusion	24	1	0	0	0	2	27
Expansion/Contraction	25	0	1	0	0	0	27
Permeation	27	0	0	0	0	0	27
Freeze/Thaw	27	0	0	0	0	0	27
Fusion	24	0	1	0	1	1	27
Seismic/Ground movement	27	0	0	0	0	0	27
Third party damage	23	1	1	0	1	1	27
External internal Pressure	27	0	0	0	0	0	27
Joint rupture	25	0	0	1	0	1	27
Ultraviolet radiation	26	0	1	0	0	0	27
Water temperature	26	0	1	0	0	0	27
Soil conditions	27	0	0	0	0	0	27
Circumferential rupture	27	0	0	0	0	0	27
Manufacturing defects	24	0	0	0	1	2	27
Buckling/Collapse	27	0	0	0	0	0	27
Fatigue	27	0	0	0	0	0	27
Longitudinal rupture	27	0	0	0	0	0	27
Oxidation/Disinfection	27	0	0	0	0	0	27

[12] Multiple causes were reported for some leaks.

Table 3.7
Number of responses for causes of rupture or leakage for PE3608/3408 (larger than 24 in.)

PE3608/3408							
Larger than 24 in.	Not Available	5 (High Freq)	4	3	2	1 (Low Freq)	No. of Responses[13]
Installation defects	22	1	0	2	0	2	27
Fittings	23	1	0	3	0	1	27
Electro-fusion	23	0	1	0	1	2	27
Expansion/Contraction	26	1	0	0	0	0	27
Permeation	27	0	0	0	0	0	27
Freeze/Thaw	27	0	0	0	0	0	27
Fusion	23	1	0	1	1	1	27
Seismic/Ground movement	26	0	0	1	0	0	27
Third party damage	23	1	0	0	2	1	27
Excessive internal pressure	26	0	0	1	0	0	27
Joint rupture	25	1	0	0	0	1	27
Ultraviolet radiation	26	0	1	0	0	0	27
Water temperature	26	0	0	1	0	0	27
Soil conditions	26	0	0	0	0	1	27
Circumferential rupture	25	0	0	1	1	0	27
Manufacturing defects	25	0	0	1	0	2	27
Buckling/Collapse	27	0	0	0	0	0	27
Fatigue	27	0	0	0	0	0	27
Longitudinal rupture	27	0	0	0	0	0	27
Oxidation/Disinfection	27	0	0	0	0	0	27

[13] Multiple causes were reported for some leaks

3.4.12 Concerns and Issues of Using HDPE Pipes

Q12: On a scale of 1 to 5, with 1 being "lowest impact" and 5 being "highest impact," rank concerns or issues you have faced using (16 in. and larger) HDPE pipes:

Figure 3.7 illustrates that highest critical concerns for PE4710 were repairs, tapping, and lack of ease of use. Figure 3.8 illustrates that critical concerns for PE3608/PE3408 were tapping, repairs, joints, and lack of ease of use.

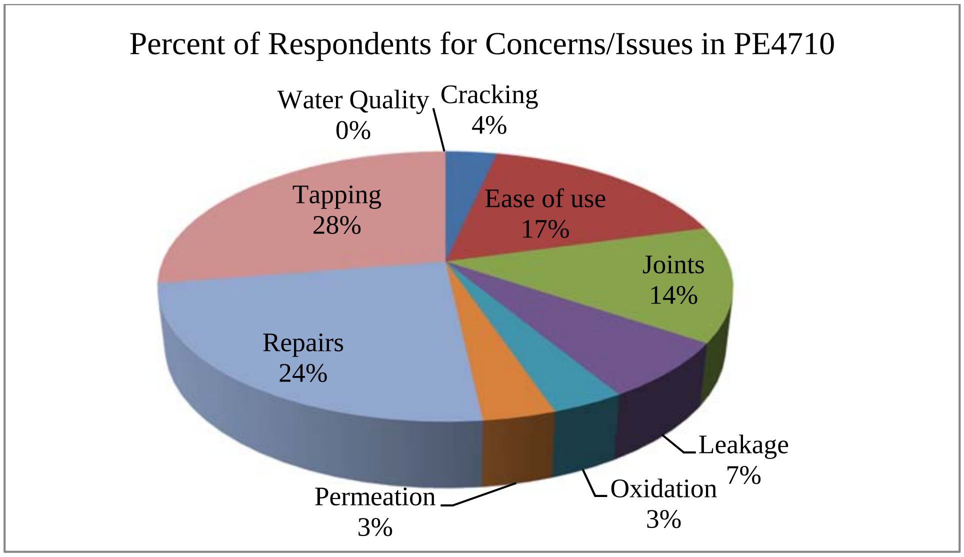


Figure 3.7 Concern/issues for PE4710 (based on 22 respondents)

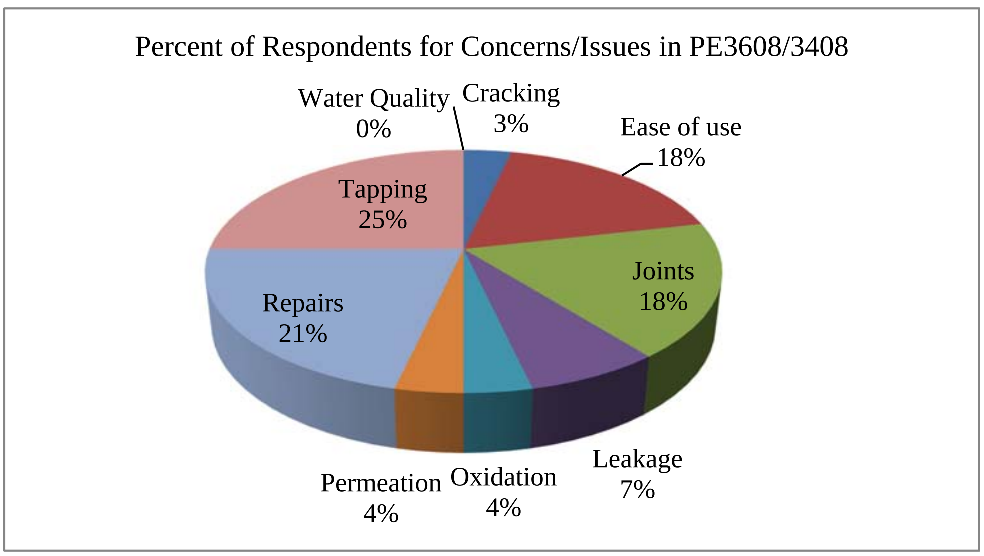


Figure 3.8 Concerns/issues for PE3608/3408 (based on 22 respondents)

3.4.13 Life Cycle Cost

Q13: On a scale of 1 to 5, with 1 being "lowest impact" and 5 being "highest impact," how would you rate the following factors impacting the life cycle cost of (16 in. and larger) HDPE water pipelines:

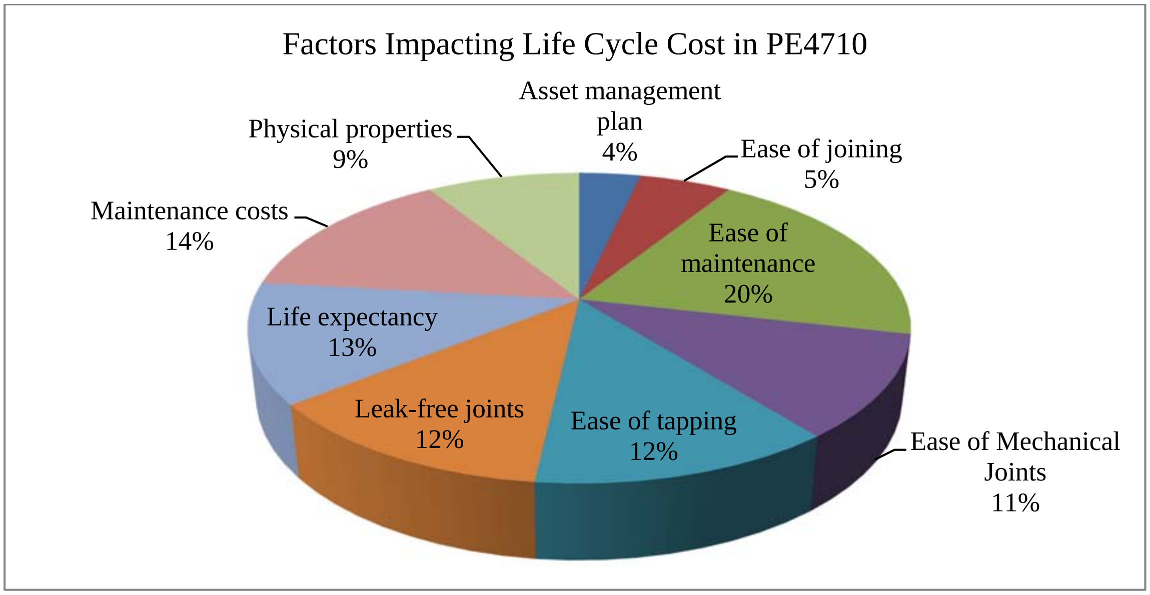


Figure 3.9 Factors impacting life cycle costs for PE4710 (based on 26 respondents)

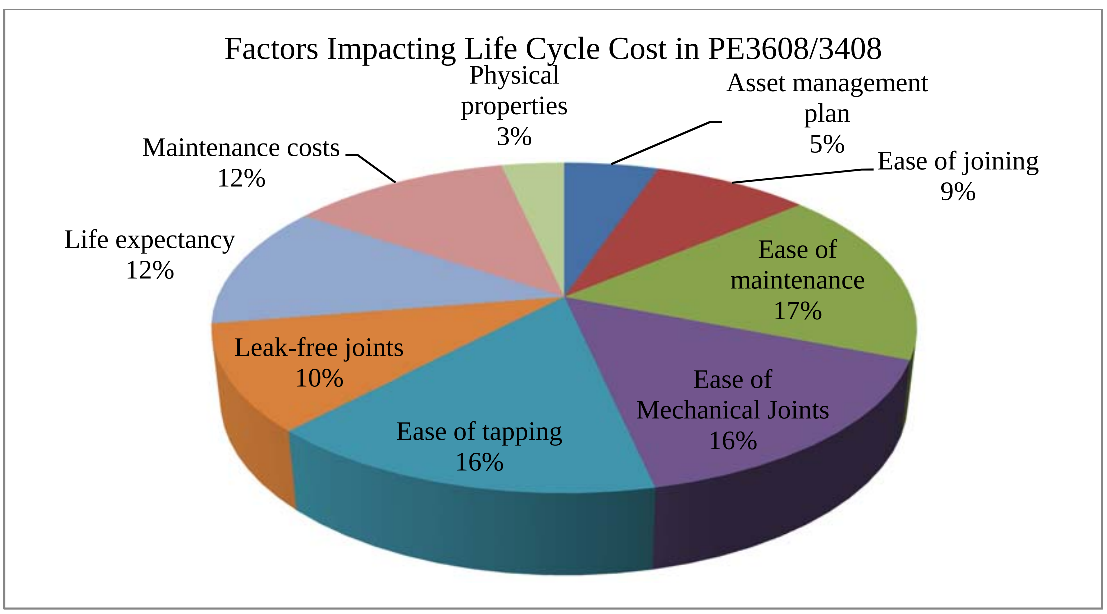


Figure 3.10 Factors impacting life cycle costs for PE3608/3408 (based on 26 respondents)

Figure 3.9 illustrates that the most important factors impacting life cycle cost of HDPE pipes were "ease of maintenance," and "maintenance costs," followed by "life expectancy," "leak free joints," and "ease of tapping." Similarly, Figure 3.10 illustrates that "ease of maintenance," "ease of mechanical joints," and "ease of tapping," were most important factors for PE3608/PE3408.

3.4.14 Rating the Durability and Reliability of HDPE Pipes

Q14: On a scale of 1 to 5, with 1 being "unsatisfied" and 5 being "very satisfied," how would you rate your experience with durability and reliability of (16 in. and larger) HDPE pipes for water main applications?

Table 3.8 presents that responding water utilities were satisfied with the durability and reliability of 16 in. and larger HDPE pipes for water main applications**.** According to responding utilities, and as shown in Figures 3.11 and 3.12, PE4710 is more durable and reliable than PE3608/3408.

Table 3.8
Durability and reliability of HDPE pipes[14]

	PE4710						PE3608/PE3408					
	Responses	5	4	3	2	1	Responses	5	4	3	2	1
Durability	21	11	2	8	0	0	17	7	5	3	2	0
Reliability	21	12	3	5	1	0	17	8	4	3	2	0

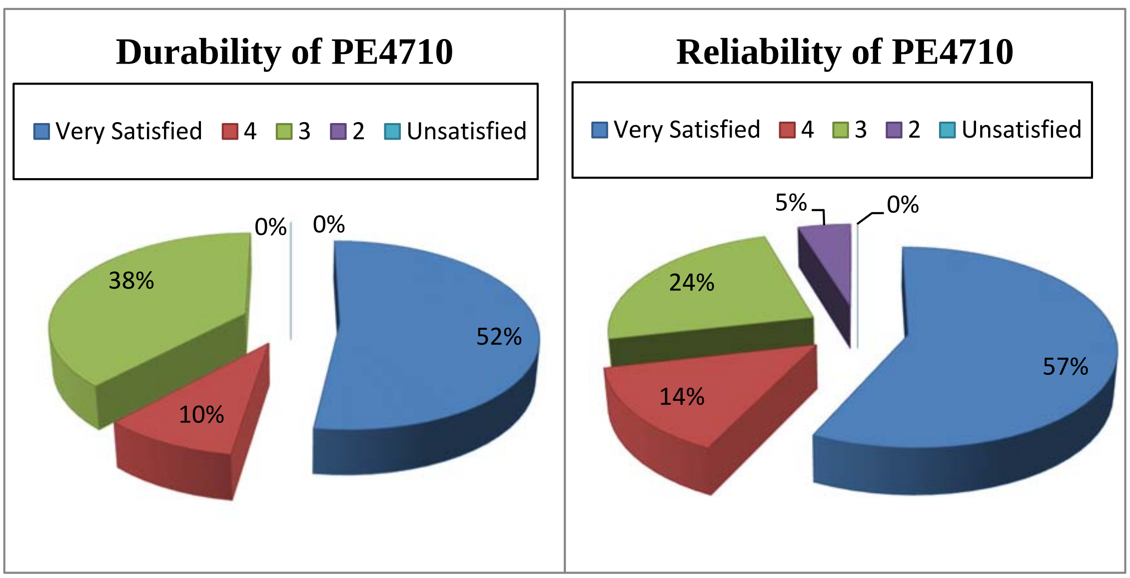


Figure 3.11 Percentage of respondents rating for *durability & reliability of* PE4710 (based on 21 respondents)

[14] The total No. of respondents was 27 with different pipe distributions.

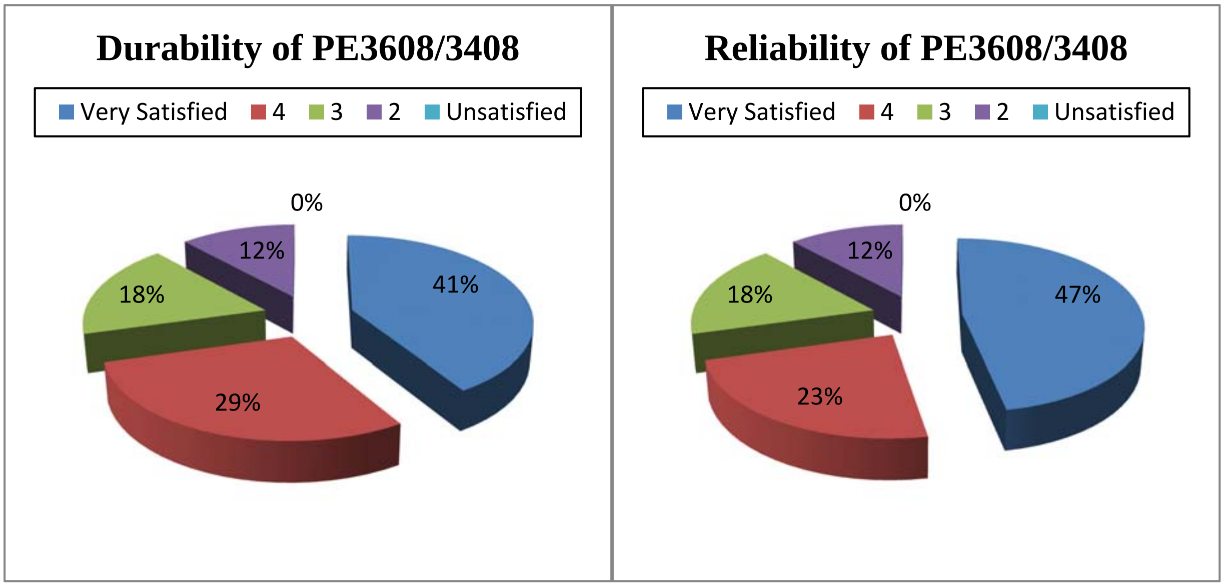


Figure 3.12 Percentage of respondents rating for durability & reliability of PE3608/3408 (based on 17 respondents)

3.4.15 Comments and Suggestions

Q15. Please provide any comments/suggestions, such as, research topics or testing needs. Please send us any case study or pipeline rupture report.

Table 3.9 summarizes general comments received from responding water utilities.

Table 3.9
General comments from responding water utilities

Comments	Description
Leakage Issues	1. Failure at access vault and service connections. 2. Leakages are found mainly at fittings, flanged adapter to DIP joints. 3. Improper welding of joints. 4. Damage due to contractor's equipment.
General Concerns	1. Molded fittings for pipes larger than 12-in. are not available, therefore fabricated fittings is the largest concern. 2. Additional permeation testing recommended especially at joints. 3. Problems in end caps, service connections, access vault connections and oxidation. 4. Accelerated testing is required to define the expected life of large diameters.
Positive Comments	1. Water hammer/high pressures are major problems for C900 PVC, so HDPE was installed. 2. Suitable for area of landslides with high pressures.

3.5 CHAPTER SUMMARY

The majority of responding water utilities, which had large diameter PE4710 pipe, were satisfied with its performance. They rated cracking, permeation and oxidation to be minor issues. Survey respondents expressed concerns about tapping, repairs, joints and indicated measures are required to improve construction techniques, as were described in this chapter. The results of this survey complement results and recommendations obtained in Chapter 4, project workshops.

CHAPTER 4
PROJECT WORKSHOPS

4.1 INTRODUCTION

An element of this research project called for holding project workshops with industry professionals to seek input on the critical issues to be addressed during the course of this project. To fulfill this requirement, three workshops were organized as listed in Table 4.1.

Table 4.1
Summary of project workshops

Workshop No.	Location	Date
1	Springfield, Missouri	April 12, 2013
2	Denver, Colorado	June 10, 2013
3	Fort Worth, Texas	June 23, 2013

This chapter provides the highlights and findings of the three workshops listed in Table 4.1. Additional details are provided in Appendix B.

4.2 WORKSHOPS OBJECTIVES

The objectives of the Project Workshops were to obtain as much input as possible from the participating industry professionals, water utilities, HDPE manufacturers/vendors and Plastics Pipe Institute (PPI) representatives by conducting small and large group discussions.

4.3 METHODOLOGY

The workshops were held in conjunction with industry events to maximize participation and minimize travel costs. Potential participants were invited through e-mail invitation. Delphi technique, brainstorming technique, and breakout sessions were among the strategies utilized to maximize participation from the attendees.

4.3.1 Workshops Agenda

The workshops began with an introduction of participants, followed by a presentation by the Principal Investigator (PI) to set the stage for brainstorming and interactive discussion by workshop participants. The workshops concluded by providing a summary of discussions.

In the first workshop, a structured process was utilized to identify and prioritize the issues which merited discussion. Breakout groups were organized to discuss the high priority issues. Another element of the workshop agenda was a discussion of the experimental work and testing to be performed for the project. Additionally, the survey form was shared with workshop participants and their input was sought to enhance the objectivity of survey questions.

In the second and third workshops, the list of issues from prior workshop was shared with workshop participants and was amended through participants input. An informal poll of the workshop participants was taken to identify high priority issues for discussion. Additionally, substantial discussion of testing protocol took place during workshops #2 and #3 and valuable input was received. The preliminary results of the survey were also shared with the participants of workshop #3.

4.3.2 Attendees

Each workshop was attended by more than 20 professionals from HDPE manufacturers/vendors, water utility representatives from larger utilities, design consultants, contractors, university faculty, representatives from PPI, and key project team members. Table 4.2 shows the affiliation of the three workshops participants. While the number of participants from each affiliation category varied from one workshop to another, the overall distribution of participants' affiliation was relatively balanced as shown in Figure 4.1. Overall, 30% of participants were from utilities, 20% were from pipe/equipment suppliers, and the consultants, research/educational organizations, professional/industry associations, and project team members made up the remaining 50% of the participants. If the project team members were excluded from the percentage calculations, the utility participation would increase to 38% and pipe/manufacturer participation would increase to 24%, with the consultants, research/educational organizations, and professional/industry professional making up the remaining 38%. Figure 4.2 shows the distribution of participants' affiliation, excluding the project team members.

Table 4.2
Workshops participants' affiliation

Participant Category	Workshop #1	Workshop #2	Workshop #3	Total	% of Total Including Project Team	%of Total Excluding Project Team
Utility Representative	9	7	3	19	29%	38.0%
Consultant	3	1	4	8	12%	16.0%
Pipe/Equipment Supplier	3	7	2	12	18%	24.0%
Research/Educational Organization	1	1	5	7	11%	14.0%
Professional/Industry Association	2	1	1	4	6%	8.0%
Project Team	6	4	5	15	23%	N/A
Total	24	21	20	65	100%	100%

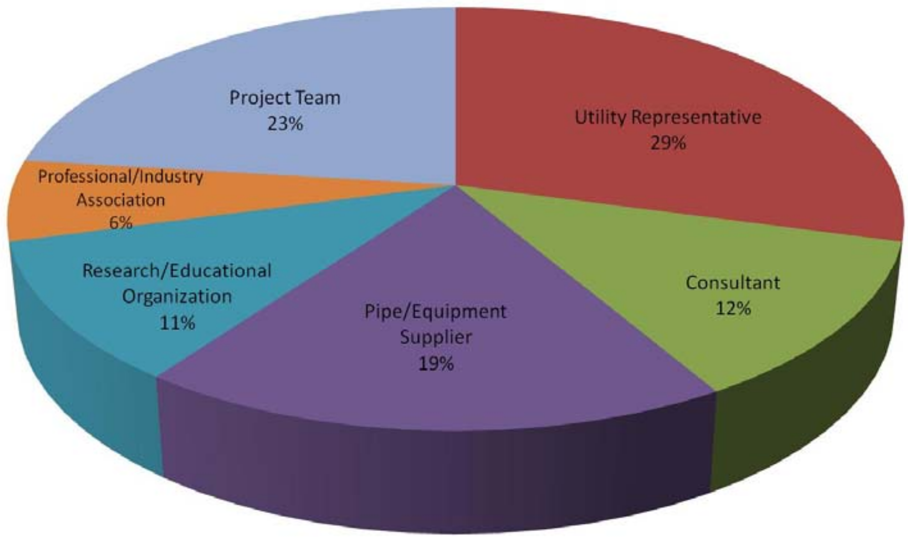


Figure 4.1 Participants' affiliation (three workshops combined)

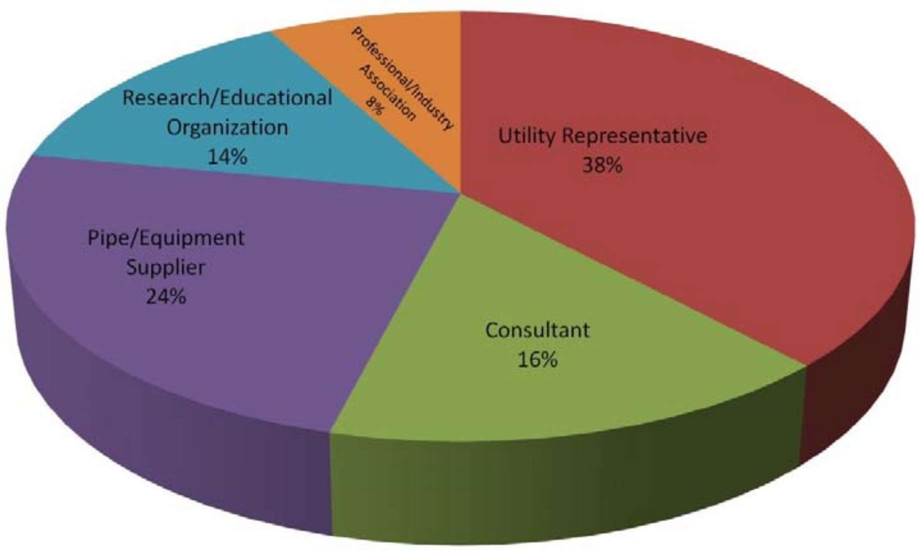


Figure 4.2 Participants' affiliation (three workshops combined, but excluding project team members)

4.4 FINDINGS AND RESULTS

This section of the report covers the various topics discussed during the workshops. The following topics were covered:

- Discussion of What Constitutes Large Diameter HDPE Pipe
- Identification of Critical Issues
- Discussion on Survey Form & Results
- Discussion on Testing
- Discussion on Case Studies
- Discussion of High Priority Topics

4.4.1 Discussion of What Constitutes Large Diameter HDPE Pipe

The original project scope had identified 24 in. as the boundary for categorizing HDPE pipe as "large diameter." A discussion of this issue during workshop #1 revealed that almost all of the participants and specifically the utility representatives participating in workshop #1 felt that the threshold for large size HDPE pipe is 16 in. The participants indicated that the lowering of the size threshold will expand the experience base with use of HDPE, as history of use with larger pipe sizes may not be extensive. As a result, the project team, with concurrence from WRF Project Manager, decided to lower the threshold from 24 in. to 16 in.

4.4.2 Identification of Critical Issues

During the brainstorming session of workshop #1, the participants offered various issues that could be of critical significance to understanding the durability and reliability of HDPE pipe. Overall, 22 issues were identified during workshop #1. Additional issues were offered by participants of workshop #3. Table 4.3 summarizes the issues raised by the participants of the three workshops.

Table 4.3
Issues raised by workshop participants

Issue #	Workshop #	Issue
1	1	Perception Issue
2	1	Third Party Damage (Outside Damage)
3	1	Comparison to Other Pipe Products
4	1	Installation Aspects/Contractor
5	1	Proven Track Record – EUROPE
6	1	Modes of Failure
7	1	Amount of Maintenance – Life Cycle Cost Analysis
8	1	Service Life
9	1	Life Reliability Curves
10	1	Specifications, Design, Installation/Contractor, Inspection, & Maintenance
11	1	Asset Management Plan
12	1	Connection/Fittings
13	1	PE Material History/Variations
14	1	Permeations of Hydrocarbons
15	1	Disinfection Byproducts Impact
16	1	Seismic Activities
17	1	Regional Issues
18	1	Freeze/Thaw
19	1	Expansion/Contraction – Effects on Fittings
20	1	Trenchless Installation – Scoring
21	1	Jointing Methods/Fusion, Mechanical
22	1	Fusion at Colder Temperatures
23	3	Change of Surface Conditions
24	3	QA/QC of Manufacturers

(Continued)

Table 4.3 (Continued)

Issue #	Workshop #	Issue
25	3	Life Cycle Cost
26	3	Internal Abrasion
27	3	Life Time Prediction Curve
28	3	Training/Qualifications
29	3	Supply Chain Management
30	3	Tracking (Asset Management)
31	3	Learning from other Applications (Example: Book on use of HDPE for Ocean Outfalls)
32	3	Time to Repair & How to Repair
33	3	Lead Time for Fittings

Following the brainstorming session, the participants were asked to rank from 1 to 1,000 the issues raised in Table 4.3 for further discussion. Figure 4.3 shows the scoring provided by participants for each of the 22 issues during workshop #1.

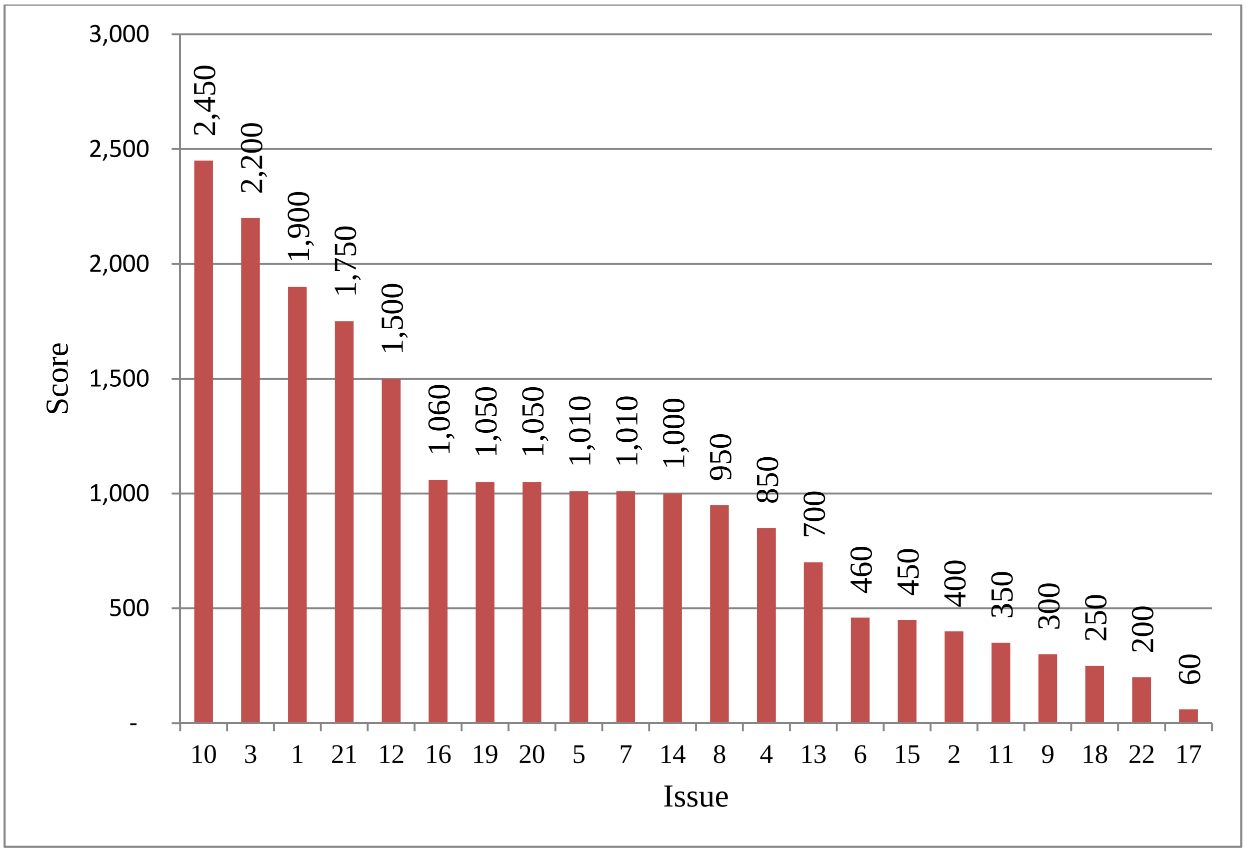


Figure 4.3 Ranking of issues by workshop #1 participants

The scoring chart showed a clear delineation between issues 10, 3, 1, 21 and 12 on the one hand and the remaining issues on the other. Table 4.4 shows the list of these top five issues picked by the participants of workshop #1 for further discussion. Three breakout groups were formed to discuss these five issues.

Table 4.4
Top five issues from workshop #1

Issue #	Top Five Issues	Group
10	Specifications, Design, Installation/Contractor, Inspection, Maintenance	1
1 & 3	Perception Issue & Comparison to Other Pipe Products	2
21 & 12	Jointing Methods/Fusion, Mechanical, Connection/Fittings	3

Workshop #2 participants selected eight issues as listed in Table 4.5 as high priority. When asked to limit the prioritized issues to five topics only, the participants essentially selected the same issues as the participants of workshop #1, further validating the critical nature of these issues. The five issues highlighted in **bold** in Table 4.5 were discussed in further detail during workshop #3.

Table 4.5
Short-listed issues from workshop #2

Topic #	Topics
1*	**Design**
2	**Installation**
3	**Repair and Operations & Maintenance (O&M)**
4	Change of Surface Conditions
5	QA/QC of Manufacturers
6	Life Cycle Cost
7	**Perception**
8	**Connections/Fittings**

*The highlighted items were discussed in more details at Workshop #2

During workshop #3, the participants added 12 issues to the list of issues as shown in Table 4.3. An open discussion was held and the participants offered their perspectives and concerns. Lively discussion of issues of interest to participants took place during workshop #3.

The subsequent sections of this chapter provide a synopsis of discussions at the three project workshops.

4.4.3 Discussion on Survey Form & Results

During workshop #1, the survey form was shared with workshop participants and their input was sought to enhance the objectivity of survey questions. Valuable input was offered by workshop participants. The survey form was revised based on the comments received from workshop participants.

During workshop #2, the Principal Investigator indicated that the survey form had been sent to more than 100 U.S. utilities. Workshop participants pointed out that the project team should ensure that the survey form would be sent to the following utilities as they have installed 16 in. and larger HDPE pipe:

1. Tucson, AZ
2. San Antonio, TX
3. St. Petersburg, FL
4. Indianapolis, IN
5. Jacksonville, FL
6. West Palm Beach County, FL

It was also suggested that the project team send the survey form to pipe manufacturers so that they can forward it to their clients. This will help project team to get as many case studies as possible.

During workshop #3, the preliminary results of the survey from 49 utilities were shared with the participants. The Principal Investigator indicated that the recipients of the survey form had expanded from the initial 100 to more than 300 U.S. utilities including the utilities suggested by the participants of workshop #2. A comment was made by a workshop participant that the results of the survey should be validated. The project team indicated that the results of the survey will be analyzed to ensure its objectivity to the extent possible.

4.4.4 Discussion on Testing

In workshop #1, a discussion took place on the need for and type of testing. The following testing possibilities were brought up by the participants and a discussion on the merits and drawback of each took place. While the inclination of the participants was that fatigue testing would be useful, no formal voting took place and no definitive conclusion was arrived at regarding testing.

1. High pressure cyclic loading fatigue test – 10 million cyclic loads with 1.5 times the pressure rating will be applied to the HDPE pipe. This will show the behavior of the pipe under surge pressure.
2. Joints: Testing HDPE pipe with fused joints, mechanical joints and fittings (e.g. tees and bends). This will show performance of the joints along with pipe.
3. Comparison: Perform same test on HDPE and PVC pipe and compare the results.

In workshop #2, a tentative high pressure cyclic loading fatigue test setup which had been devised by the project team was presented. The participants provided the following comments:

1. Proper literature review should be conducted to confirm this test is not a repetition of testing done in the past. It was pointed out that this type of test has been conducted on the small diameter (4 – 12 in.) HDPE pipes, but no testing has been done on 16 in. or larger diameter HDPE pipe.
2. The test pipe should be instrumented with strain gauges.
3. The test pipe should be given enough time to retract after each cyclic loading.
4. Once the test reaches 10 million cycles, the test piece should be tested for creep and other properties. It should also be visually inspected.
5. The test pipe should be brought to failure (burst test) after the test ends.
6. The test pipe should be subjected to bending and cyclic loading to see its behavior after it has gone through the 10 million fatigue cycle.

Similar to workshop #2, the high pressure cyclic loading fatigue test setup was also presented at workshop #3. The participants provided the following comments:

1. Fatigue test has not been conducted for large diameter (16 in. and larger) HDPE pipes in the past. Full-scale testing would be beneficial.
2. The test pipe should be instrumented with strain gages.
3. Using regular water with no additives is sufficient.
4. More than one sample should be tested to compare the results.
5. End caps should be designed with proper air and water release valves.
6. Air and water release valves should be installed on end caps to avoid their effect on pipe.
7. Test should be conducted in a controlled temperature environment.
8. The shape of the cycling load wave should be designed such that the pipe has adequate time to respond before the next cycle arrives.
9. Explore fatigue testing done by other researchers to determine the appropriate frequency of loading.
10. If the results are to be compared with previously available data, the test configuration should be compatible with previous testing. For example, restraining of end caps would be needed for this purpose. However, if the tests are to stand on their own, restraining of caps would not be necessary.

Based on the input provided by participants of the three workshops, the project team concluded to move forward with the fatigue test. Suggestions provided by workshop participants provided valuable input to the project team to enhance the testing setup, instrumentation, and testing procedure.

4.4.5 Discussion on Case Studies

During workshop #1, the participants suggested a number of utilities that may provide case studies based on their experience with large diameter HDPE. The suggested utilities are:

1. City of Palo Alto, CA
2. City of Charlotte, NC
3. Miami – Dade , FL
4. City of Colorado Springs, CO
5. City of Springfield, MO
6. Water One, KS

It was pointed out that it is advantageous to prepare a template that utilities can use for reporting case histories. Such a template would include utility name, project name, pipe size, pipe length, construction cost; background, design parameters, construction challenges, project highlights, and conclusions.

During workshop #2, the case study template developed by the project team was shared with the participants. Additional utilities to be targeted for obtaining case studies were suggested:

1. City of Colorado Springs, CO

2. City of Springfield, MO
3. City of Phoenix, AZ
4. Tarrant Regional Water District (TRWD), TX

The representative from TRWD indicated that they had installed 6,000 ft of 42-in. HDPE pipe (100 psi) in 2002 and have had no problems with this line since its installation.

During workshop #3, the highlights of eight case studies were presented. Participants suggested a case by case cost comparison of case studies with pipe materials other than HDPE. The project team will investigate if this cost comparison is feasible.

4.4.6 Discussion of High Priority Topics

During the course of each workshop, detailed discussions of high priority issues were conducted. During workshop #1, the participants were divided into three small groups to discuss high priority issues. However, for workshop #2 and #3, a project team member engaged all the participants in a discussion of high priority issues. A summary of the discussions is presented in the subsequent sections of this chapter.

4.4.6.1 Perception Issue

The participants of workshop #1 identified perception as a high priority issue. The participants of workshop #2 and #3 also concurred with this characterization. The participants felt that the utility engineers and engineering consultants generally perceive HDPE pipe as being suitable for small diameter and/or low pressure applications, and as a result automatically rule it out as an option for large diameter pressure pipe applications.

Table 4.6 summarizes the reasons behind the perception issue based on comments provided by workshop participants.

Table 4.6
Reasons for perception issue

Broad reason	Specific reasons
Lack of knowledge about the product	1. In order for utility to approve the use of HDPE for large diameter pressure application, there is a need to have acceptance from all the stakeholders in the utility including decision makers, specification writers, field staff and users. This would require a high level of education and engagement. 2. Two big issues are training and familiarity. Utility workers want to be comfortable with using a product and familiar with the repair methods and materials. 3. Perception that HDPE is not for water application.

Perceived risk associated with the use of a material a utility has not used in the past	4. HDPE is a new product for this type of application 5. HDPE is not in our comfort zone; we do not have experience with it. 6. Some associate HDPE with Polybutylene pipe which has had a negative history. 7. Utilities are resistant to change. They need a driver to change. The perception is that since the utility has not used HDPE for large diameter pressure application in the past, there may be unknown risks associated with its use.
Perceived risk associated with the use of a material a utility has not used in the past	The utility cannot quantify this risk and as a result avoids using the product not to incur any potential additional risk. The only way to convince the utility is to help them quantify this perceived risk and provide a case for the potential benefits which may be realized if this risk is taken.
Other	8. Requires new tools and equipment. 9. Requires additional inventory items for repair. 10. Cost is a consideration

The workshop participants also offered a number of strategies to overcome the perception issue as listed in Table 4.7.

Table 4.7
Strategies to overcome perception issues

Strategy #	Description
1	Success stories and lessons learned – take advantage of the experiences of utilities that are using HDPE and share their stories. Failures can also be a great learning tool.
2	Need to hear testimonials from utilities. These will resonate with other utilities.
3	Establish a Center of Excellence for HDPE Pipe to promote "Best Practices" for HDPE pipe.
4	Highlight the advantages of HDPE pipe such as its leak free nature due to butt-fused joints.
5	Utilities that provide both water and gas service can be more inclined to use HDPE for water applications as they already may have an experience base with use of HDPE for gas applications.
6	Education is the key. Must educate staff so that they are familiar with the material, installation and repair methods, etc. As an example, many utilities are willing to use HDPE for complex, environmentally sensitive projects that typically involve trenchless installation by horizontal directional drilling (HDD) or pipe bursting. However, the same utilities do not consider HDPE suitable for less complicated projects. Education can help utilities overcome this dichotomy.
7	Life cycle cost – too much emphasis is often placed on the pipe cost and not the bigger picture. Must factor into decision the life of the pipe, maintenance costs etc. to get the full picture. As an example, in Colorado Springs, material price for HDPE is higher than ductile iron but there are other considerations including HDPE response to dynamic pressure, soil conditions and seismic activity. HDPE can become more cost competitive for large diameter applications when life cycle costs are considered.
8	Highlight the specific applications for HDPE. Identify usage in right applications. Help utilities understand where it makes sense to use. As an example, Colorado Springs indicated they have had failures and growing pains. Their drive to use HDPE started with corrosion issues.
9	Contractors have a lot to offer and can be helpful, need to listen to their experiences.

4.4.6.2 Design, Installation/Contractor, Inspection & Maintenance Issues

The workshops participants overwhelmingly expressed an opinion that comprehensive specifications, along with accurate design, proper installation, and timely maintenance would offer a long lasting solution for a pipeline project, regardless of the pipe material used. The participants identified a number of needs related to these issues as listed in Table 4.8.

Table 4.8
Design, installation/contractor, inspection and maintenance issues

Issue	Details
Design	There is a need for experienced and trained design engineers.
Pipe Manufacture	HDPE is offered in many sizes, wall thicknesses and cell classifications. While this versatility provides flexibility, it also can cause confusion.
Tapping & Repair	Procedures for tapping and repair of HDPE as well as how to properly connect to other pipe materials are not readily available. The latter issue is specially impacted for low DR pipes where the thick HDPE pipe may require a reducer to match the outer diameter of the cast iron, ductile iron or PVC pipe it is being connected to.

The workshops participants offered a number of strategies to address the issues related to specification, design, installation, and maintenance as listed in Table 4.9.

Table 4.9
Strategies to address design, installation & maintenance issues

Strategy #	Description
1	Industry should consider providing regular training for design engineers.
2	Industry should consider developing design tools for engineers to use.
3	Utilities should use Quality-based Selection (QBS) process to select qualified design consultants. Selection based on price can lead to inferior design
4	Utilities should consider specifying an acceptable level of qualifications for contractors
5	Contractors should strive to hire trained personnel or offer full training and supervision for their personnel who may not be fully experienced
6	Industry should consider certification at various levels to improve quality
7	Industry should consider developing design, installation, and maintenance guidelines similar to guidelines developed by American Gas Association (AGA)
8	Industry should consider collecting and compiling specifications developed by various utilities and making them available to all users
9	Inspection during production, delivery and installation is critical for long-term success. Inspector training and certification should be considered by the industry.
10	Gas pipeline contractors should be encouraged to consider serving the water market
11	Pipe manufacturers should consider having regular field observations to promote best practices
12	Specification should address all critical issues including requirements for equipment, proof testing, groundwater control, backfill requirements, and acceptance testing requirements
13	Industry should consider developing standard guidelines for maintenance aspects such as repair of HDPE pipe and tapping of HDPE pipe
14	Industry should consider providing training and certification for HDPE pipe repair professionals
15	Industry should consider developing guidelines for non-destructive evaluation of HDPE and provide a recommended schedule for inspection based on a set timetable or based on the bathtub curve

(Continued)

Table 4.9 (Continued)

Strategy #	Description
16	Utilities should consider engaging qualified professionals to perform forensic evaluation of failure incidents to learn from the failure and ensure the root cause of failure is established and eliminated from future design. During forensic evaluation, it is critical that the field personnel be interviewed as they are often most knowledgeable about what might have led to the failure.
17	A simplification of HDPE pipe product line items may be beneficial to reduce confusion
19	The consequence of failure should be considered as a factor in pipe material selection. The consequence of failure should be quantified in dollar terms and should consider financial loss due to failure (for example, if the water supply to a hotel is interrupted)[15].

It was the strong view of workshops participants that there is a need for the development of uniform specifications and guidelines for design, installation and maintenance of HDPE pipe, and the benefits such documents would offer to the utilities that decide to specify HDPE for large diameter pressure applications. While the Plastics Pipe Institute (PPI) and the American Water Works Association (AWWA) have published standards and guidelines for use of HDPE, uniform specifications, which utilities can readily use, are not available. The participants of workshop #1 developed the following list for the items that should be addressed in specifications for HDPE pipe.

1. Fittings
2. Fusion process requirements
3. Mechanical connections
4. Quality Assurance/Quality Control
5. Testing
6. Certifications
7. Design specifications
    a. Connection to other materials
    b. Joint Restraints
    c. Thermal movement
    d. Poisson effects
    e. Disinfection (Chlorine)
8. Training
9. Inspections (pre and post)
10. Construction specification
    a. Bedding/haunching and backfill
    b. Handling
    c. Trenchless specifications
    d. Fitting specifications

[15] See WRF #4332 - a spreadsheet to help utilities consider consequences of failure during asset management decision making.

11. Repair methodology
12. Equipment qualification
13. Installer qualification
14. Geotechnical specifications
15. Design life

4.4.6.3 Jointing Methods/ Fittings (Fusion & mechanical) Issues

The workshops participants frequently brought up the issue of fittings. While butt fusion was considered as an established process for joining pipe sections, there seemed to be a need for a better understanding of options for fittings and connecting of HDPE to other pipe materials. Table 4.10 summarizes the issues brought up by workshops participants.

Table 4.10
Joining methods/fitting issues

Issue	Details
Availability of Fittings for large Diameter HDPE Pipe	1. Not all HDPE pipe suppliers offer HDPE fittings and the utility has to search for other vendors for such fittings. Fittings are only available for smaller pipe sizes.
Information on Joining Methods/Fittings	2. There is a need for procedures to make the fittings, such as MJ and saddle requirements 3. There is a need for a sourcebook on information on fittings and jointing 4. There is a need to know what works and what does not work as far as fittings are concerned 5. There is a need for standard specifications for HDPE and PVC connections
Lack of Training	6. Installation of large diameter applications needs specialized training 7. Contractors without proper and specialty training leads to substandard installations
Other	8. There are a number of issues with connecting HDPE to other pipe materials, which are often referred to as "end-of-the-pipe" problems 9. Mechanical Joint (MJ) adapters do not work for connecting butterfly valves to 12-in. and larger HDPE pipe 10. DIP/IPS sizing causes some confusion

The workshops participants offered a number of strategies to overcome the joining method/fittings issues. These strategies are listed in Table 4. 11.

Table 4.11
Strategies to address joining methods/fittings issues

Strategy #	Description
1	Pipe manufacturers should consider offering fittings as well so that the utility is dealing with a single source for its needs
2	Pipe manufacturers should consider providing fittings (either molded or fabricated) for larger pipe sizes Solutions should be developed for connecting HDPE to valves and other pipe materials Special orders should be minimized to the extent possible
3	Pipe manufacturer should consider streamlining their product lines and reduce the variety of products offered (DIP/IPS size, various classifications) to reduce potential for confusion
4	The experience gained in the gas experience should be shared with water industry
5	Manufacturers and industry associations should consider offering training for design, installation, inspection, and maintenance of HDPE pipe
6	Industry associations should consider providing certifications for utility and contractor personnel regarding handling, installation, joining and maintenance of HDPE pipe Industry associations should also consider equipment certification
7	There should be requirements developed by the industry for contractor qualifications and certification
8	Development of training materials for trade school programs can improve the quality of installed pipelines
9	Establishing a Center of Excellence can promote "Best Practices" for HDPE pipe
10	When connecting HDPE to another pipe, the end of HDPE pipe should be restrained by a thrust collar or otherwise restrained. If not, there is potential for the joint to pull open due to temperature effects.

In view of the strong views expressed by workshops participants on the need for information on fittings, a three member team was formed to develop a brief overview of best practices for HDPE fittings and connections. This write-up is included in Appendix B (Page 106) of this report.

4.5 CHAPTER SUMMARY

The project workshops provided valuable input to the project and assisted the project team to improve upon the project scope and experimental approach. The structured approach utilized for the workshops allowed the critical topics to be identified in an efficient manner. The limited and valuable time of participants was mostly devoted to discussion of the most critical topics. The workshops enabled the project team to explore different perspectives and identify several studies and experiences brought up by the project participants. Specifically, the following areas were explored in detail during the course of the three workshops organized by the project team:

- Perceptions issues related to use of HDPE for large diameter pipes and strategies to address those issues.
- Outstanding issues related to specifications, design, installation and maintenance of large diameter HDPE pipe and strategies to address those issues.
- Issues related to pipe joining and fittings and strategies to address those issues.

The following specific strategies were offered for the HDPE pipe industry:

- Establishing a Center of Excellence for HDPE Pipe to promote “Best Practices” for HDPE pipe.
- Documenting successful installations of HDPE pipe.
- Encouraging utilities that provide both water and gas service to use HDPE for water applications as they already may have an experience base with use of HDPE for gas applications.
- Encouraging contractors with gas pipe installation experience to serve the water market.
- Highlighting the advantages of HDPE pipe such as its leak free nature due to butt-fused joints.
- Sharing the experience of gas market with water market.
- Developing guidelines for design professionals, installers, inspectors, and operators of HDPE pipe.
- Developing “Best Practices” for all aspects of HDPE pipe.
- Developing guidelines for evaluation and condition assessment of HDPE pipe.
- Developing and offering training to all professionals involved in the design, installation, inspection, and maintenance of HDPE pipe.
- Partnering with trade schools to train the required workforce.
- Developing and offering certification for various professionals involved in the design, installation, inspection, and maintenance of HDPE pipe.

The following specific recommendations were offered for utilities:

- Considering life cycle cost when selecting a pipe material.
- Utilizing Quality-based Selection (QBS) process to select qualified design consultants.
- Specifying an acceptable level of qualifications for contractors.
- Engaging qualified professionals to perform forensic evaluation of failure incidents to learn from the failure and ensure the root cause of failure is established and eliminated from future design.

The following specific recommendation was offered for pipe installers:

- Hiring trained personnel or offering full training and supervision for their personnel who may not be fully experienced.

The following specific recommendations were offered for pipe manufacturers:

- Streamlining of HDPE pipe product lines to reduce variety of products available and minimize confusion.
- Offering fittings as well so that the utility is dealing with a single source for its needs.
- Developing solutions for connecting HDPE to valves and other pipe materials
- Offering regular field observations to promote best practices.

CHAPTER 5
EXPERIMENTAL WORK

5.1 INTRODUCTION

Long-term pressure design and performance of plastic piping material is evaluated using ASTM D1598 (2009) and ASTM D2837 (2013f). Design factors for long-term durability are established by the PPI's Hydrostatic Stress Board[16] (Boros 2011). The elevated temperatures and sustained pressure requirements for PE4710 material are addressed by ASTM F714 (2013) and AWWA C906 (2006) as well as Pennsylvania Edge-Notch Tensile Test (PENT) testing per ASTM F1473 (2013). While these studies indicate a high resistance to fatigue for HDPE, the data were gathered on small diameter pipes. However, testing is required for large diameter pipes to confirm the fatigue test results for all pipe sizes. The literature search presented in Chapter 2 of this report did not reveal any cyclical pressure testing of large diameter pipes. In addition, the fatigue testing of a large diameter HDPE pipe was ranked with high priority during the project workshops (see Chapter 4) with water utilities and other pipe professionals.

Reliable and durable water mains must have adequate resistance against recurring pressure surges to avoid fatigue failures. However, one area of durability that has not been thoroughly investigated is the fatigue resistance to recurring pressure surges for large diameter HDPE pipes. This chapter will cover the experimental work to help in evaluating the reliability and durability of large diameter HDPE pipe.

Transient pressure variations commonly occur in water mains and transmissions lines during daily operations. Pump starts and stops and valve openings and closings can cause sudden and significant changes in flow. The amplitude and frequency of the resulting pressure variations (pressure surges) may affect the durability of the piping material. AWWA C906 permits frequent pressure surges to 1.5 times the pipe's pressure class (PC) and occasional pressure surges up to two times the pipe's pressure class. These factors are based on PE4710's short-term rupture strength with an understanding that a very large number of surges can occur in HDPE pipe during its design life.

This research project developed a testing protocol and successfully executed a fatigue test on a 16-in. diameter, 15-ft, DR 17 with a butt-fused joint in the middle, The phase one testing was conducted between 125 psi and 188 psi or 1.5 times its pressure class for two million cycles. A second phase was later added using the same pipe sample to evaluate occasional surges between 125 psi to 250 psi (two times pressure class) for 50,000 cycles. Currently, there are no known ASTM standards to evaluate large diameter HDPE performance under recurring surge pressures. This test complements other studies on the durability and reliability of large diameter PE4710 in water transmission systems. This test complements studies on the durability and reliability of large diameter PE4710 in water transmission systems.

[16] The primary functions of the Hydrostatic Stress Board (HSB) of PPI are to issue recommendations to industry regarding the strength of thermoplastic piping materials intended for pressure applications, and to develop appropriate policies and procedures for the conduct of this activity. The HSB's recommendations are often referenced by North American plastics piping standards for the qualifying of thermoplastic piping materials for pressure piping service, and for the establishment of pipe pressure ratings.

5.2 OBJECTIVES

The objective of this experiment was to conduct high pressure cyclic loading (fatigue)tests on a new HDPE pipe with a butt-fused joint. The result of this test determines whether or not a 16-in. diameter HDPE (DR 17) can withstand cyclic loads that are 1.5 times its pressure class for two million cycles, and 2 times its pressure class for 50,000 cycles. Two million cycles is equivalent to 100 years of service life based on an average of 50 daily surges. The 50,000 cycles corresponds for 10 occasional surges per week for 100 years.

5.3 APPROACH

The testing plan included testing one 15-ft long; 16-in. outside diameter HDPE pipe with a fusion joint in mid length. A ratio of 10 times diameter (10 x 16 in. /12 = 13.3 ft) was used to select the 15-ft length (including end cap thickness) to reduce impact of end seals. The selection and design of pipe sample were results of many meetings with Mr. Harvey Svetlik, Georg Fischer Central Plastics LLC; and Mr. Heath Casteel, Performance Pipe. The research team would like to thank and acknowledge support and help of these companies and their representatives to this project and to the whole pipeline industry. The CUIRE Laboratory at UT Arlington was used to perform this experiment. The testing operation was monitored using pressure transducers, a control panel and a computerized data acquisition system.

5.4 PIPE SAMPLES

The HDPE pipe samples were manufactured and delivered to CUIRE Laboratory on July 11, 2013, and were equipped with a 6-in. thickness fused end caps, two 1-in. tubes for inlet and outlet on one end cap, and one ¼-in. air release valve on the other end cap. The pipe sample was laid horizontally with one percent slope, to facilitate air release. Table 5.1 presents pipe sample measurements. Figure 5.1 shows the pipe sample and the control sample.

Table 5.1
HDPE pipe sample measurements

Type	Outside Diameter (in.)	Dimension Ratio (DR)	Pipe wall Thickness (in.)	Pipe Length (ft)	Inlet/Outlet Tubes		
					Air pressure Release Valve (in.)	Inner Diameter (in.)	Outer Diameter (in.)
Pipe Sample	16	17	0.94	14.97	¼	0.995	1.328
Control Sample	16	17	0.94	14.98	¼	0.996	1.325

Note: Dynamic Instantaneous Effective Modulus of HDPE Pipe, E_d = 150,000 psi

5.5 EXPERIMENTAL SETUP

This section describes the experimental setup and role of each device. The setup comprised of a 450-gallon water reservoir, a multi-stage centrifugal pump (10 HP), a data acquisition system, a control board, several pressure transducers, a DC power supply, one pipe sample (16 in. diameter), one control pipe sample, and control valves including one back-flow pressure valve, two solenoid/pressure ball valves, and two butterfly valves. A galvanized steel piping system with pipe diameters of one in. and 2 in. connected the equipment. Physical properties of PE4710 HDPE such as modulus of elasticity and its viscoelastic nature to consider expansion, contraction and long-term loading impact to calculate discharge, increase in temperature, and head-loss were considered while designing the test setup. Figure 5.1 shows the pipe sample and the control sample. Figure 5.2 illustrates a schematic diagram of experimental setup. Refer to Appendix C for description of testing equipment.

Figure 5.1 HDPE samples[17]

5.6 TESTING OPERATION

Regular tap water was allowed to flow from reservoir to the pump, located 10 ft below bottom of the reservoir, to create a head pressure of 480 ft. The pump delivered a pressure of 208 psi. Since the pressure cycles were between 125 psi and 188 psi, a “backflow control valve” was used to back pressure the extra water from the pump to reservoir, which is about 20 psi. The 188 psi from the pump was used to pressurize the pipe sample using “inlet and outlet solenoid valves.” These valves were electrically operated using the “control board.” One of the pressure transducers which was connected at the end of pipe sample was connected directly to the control board (CB). Once the water wave pressure activated the transducer, a signal was sent to the

[17] Although four pipe samples were delivered to the laboratory, due to time and budget constraints, the testing was performed on one 16-in. diameter PE4710 (AWWA C906) pipe sample, which is currently available in the market.

control board to operate solenoid valves. Another pressure transducer was connected to the oscilloscope used with data acquisition system to determine the waveform pattern.

Once the inlet valve opened, the pressure increased to 188 psi, and then the inlet valve closed. The pressure impacted the pipe sample for approximately one second, and at this time, the outlet valve opened. Once pressure decreased to 125 psi, the outlet valve was closed and water from outlet valve went back to the reservoir. This process repeated for 2 million cycles. The control board was connected to a data logger to obtain results from the data acquisition software. An oscilloscope was connected to the control board to determine the pressure wave from the transducer. To maintain the water pressure at 70°-73°F, two window air conditioning units were added with their grids inserted in the water reservoir.

Some factors influencing the testing conditions were:

1. Variation between maximum/minimum pressures.
2. Water temperature and room temperature.
3. Frequency and duration of surges.
4. Chemical substance present in the water.

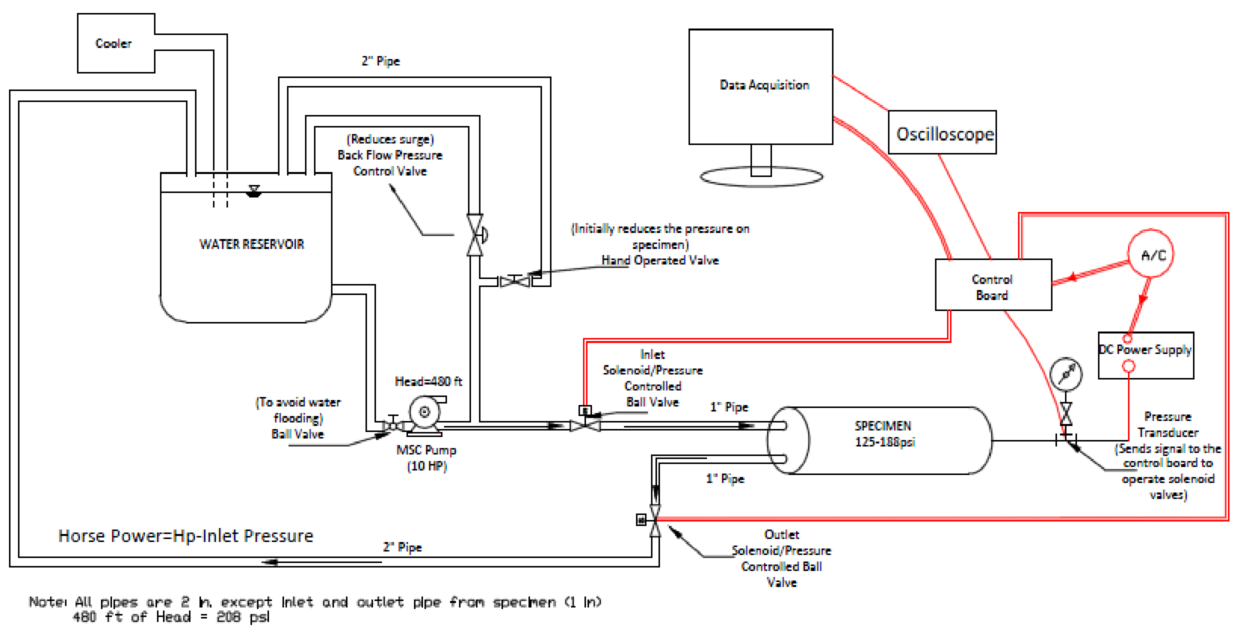


Figure 5.2 Schematic diagram of experiment setup

5.7 TEST RESULTS – PHASE 1

In Phase 1, the testing was performed for 2 million cycles. The pipe sample was periodically observed and measured for any dimensional changes. Figure 5.3 illustrates the cycle time of each surge (i.e., 8 to 12 seconds). The pressure cycle shows the cycle time of one complete surge.

Polyethylene is a viscoelastic material. Diameter of the pipe sample was observed to continuously increase over time due to impact of pressure surges. The diameter increase was mainly observed near the middle joint, with no diameter changes at the end caps, because of their restraining effects. The 2-M cycles were completed in six months. At the higher temperature of 73°F, the cycle time increased to 12 seconds.

5.7.1 Project Issues

The testing operation did not start without problems. The first problem faced immediately after start of the test, was elevated water temperatures to 95°F due to water circulation friction. After two days of operation, the testing was stopped and several ideas considered, and eventually two window air conditioning units were purchased to install cooling grids inside the reservoir.

The second issue was that the control board was wrongly calibrated by the manufacturer for a pressure range of 63 psi to 156 psi (instead of 125 psi to 188 psi). After start of the test, the pressure transducer was dynamically tested using oscilloscope; and the control board calibration was corrected.

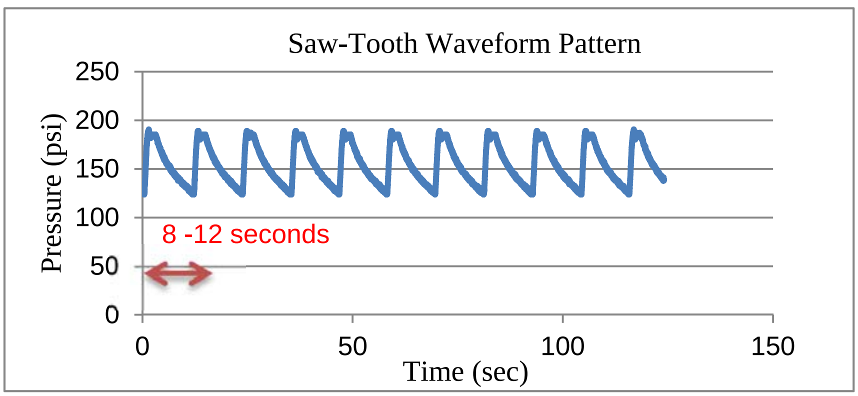


Figure 5.3 Saw-tooth waveform cycles

5.7.2 Test Results

As stated in Chapter 2, polyethylene is a viscoelastic material. Diameter of the pipe sampled was observed to increase over time due to the continuous impact of pressure surges. These dimensional changes were taking place near the middle joint, but with no changes at the end caps. The 2 M cycles were completed in six months with pressure ranges between 125 psi to 188 psi. The temperature ranges were between 70°– 73°F. At the higher temperature of 73°F, the cycle time increased to 12 seconds.

Table 5.2 presents changes in the pipe diameter. Figure 5.4 illustrates the bulged pipe sample near the butt-fused joint. The pipe diameter was evenly increased by 0.27 in. when compared to the control sample. Figures 5.5 and 5.6 illustrate the control sample and pipe sample measurements, At the conclusion of the testing (six months), there was one in. diameter increase in the circumference of the pipe sample.

Table 5.2
Diameter variations after 3 months (from 125 to 188 psi)

Date	Diameter	Duration of cycle	No of cycles completed in millions
May 31, 2014	16 in.	0 (start of test)	0
Sep 2, 2014	16.27 in.	8 sec	1.06

Figure 5.4 illustrates the bulged pipe sample near the butt-fused joint. Figures 5.5 and 5.6 illustrate pipe sample circumference measurements. After three months (September 2, 2014, onwards), while the pipe expansion stablized, it did not expand uniformly along the length. Compared to the control sample, the pipe diameter was increased by 0.27 in. At the conclusion of the testing (six months), there was a 0.52-in. diameter increase. Table 5.3 presents changes in the pipe diameter after 3 months.

Figure 5.4 Pipe bulge near the middle joint

Figure 5.5 Circumference measurement

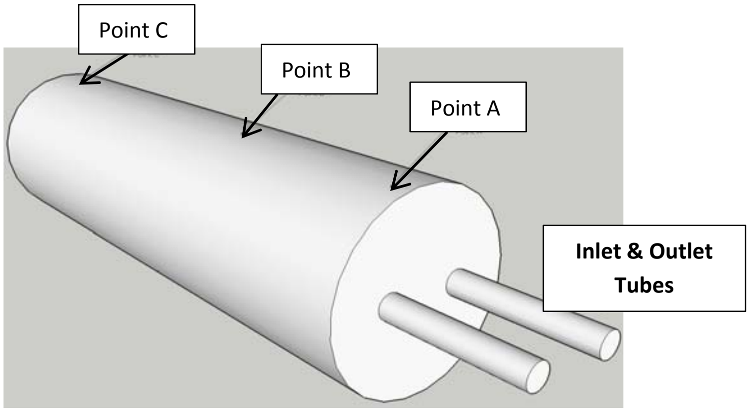


Figure 5.6 Circumference measurement locations

Figure 5.7 presents length measurement locations. For the first two weeks, no pipe sample expansion or contraction was observed. After three months, it was observed that while pipe sample diameter increased, its length decreased. The length decrease continued until 1.52 million cycles, and after that the pipe length appeared to remain the same. Table 5.4 presents length variations.

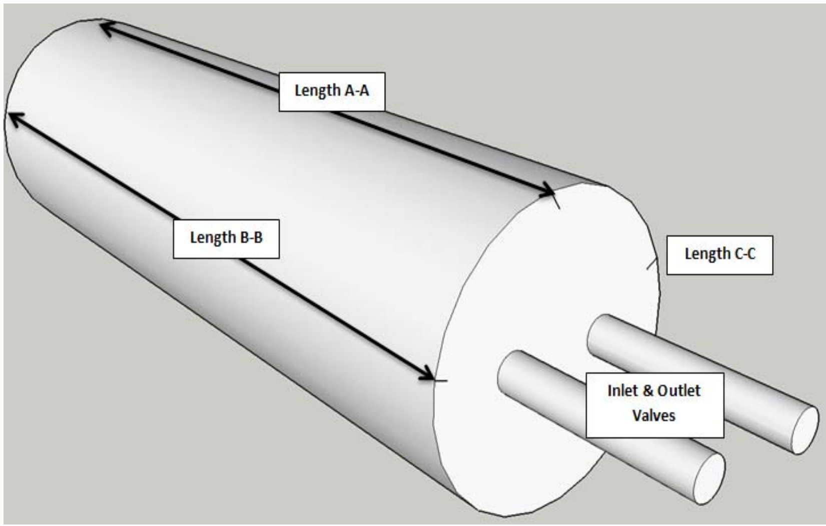


Figure 5.7 Length measurement locations

Table 5.3
Diameter variations[18]

Date (2014)	Pipe Sample Diameter						No of surges completed in millions
	Location A Near the Pump		Location B Center of the Pipe		Location C Near the Air Release Valve		
	in.	mm	in.	mm	in.	mm	
Sept 2nd	16.27	413	16.27	413	16.27	413	1.06
Sept 19th	16.35	415	16.32	414	16.27	413	1.39
Oct 4th	16.43	417	16.4	417	16.4	416	1.51
Oct 20th	16.54	420	16.49	419	16.44	418	1.62
Nov 5th	16.52	420	16.49	419	16.46	418	1.76
Nov 20th	16.52	419.8	16.49	419	16.49	419	1.89
Nov 30th	16.52	419.8	16.49	419	16.49	419	2.00

Table 5.4
Length variations

Date (2014)	Pipe Sample Length Measurements[19]						No of surges completed in millions
	Location A-A Near the Pump		Location B-B Center of the Pipe		Location C-C Near the Air Release Valve		
	ft	m	ft	m	ft	m	
Oct 6th	15.05	4.58	15.05	4.58	15.08	4.59	1.52
Oct 20th	14.99	4.57	14.99	4.57	15.00	4.57	1.62
Nov 10th	14.98	4.56	14.96	4.55	14.90	4.54	1.76
Nov 25th	14.99	4.57	14.98	4.56	14.98	4.56	1.95
Nov 30th	14.99	4.57	14.98	4.56	14.98	4.56	2.00

5.7.3 PE4710 Expected Life

Equation 5.1 can be used to show how results of this testing can be used for estimating PE4710 design life. Table 5.5 presents total number of surges for a 50- and 100-year design life.

Total No. of Surges = 50 surges/day x 365 days/year x Number of years. Eq. 5.1

[18] Note: Original pipe sample diameter was 16 in.

[19] Note: Original pipe sample length with end caps was 14.97 ft.

Based on Equations 2.1 and 2.2 (Petroff 2013) and Tables 5.3 and 5.4, Table 5.6 presents the peak stress for the pipe sample.

Table 5.5
Number of surges for 50 and 100 years

Years	No. of surges
50	912,500
100	1,825,000

Table 5.6
Cycles to failure for 16-in. diameter PE4710

Working pressure plus surge pressure ($W_P + S_p$)	Peak stress (psi)	Cycles to failure	Fatigue life (years) @ 50 surges/day	Safety factor against failure for 100 years @ 50 surges/day
1.2 x PC	1,246	45,907,200	2,515	25
1.5 x PC	1,504	7,123,000	390	4

5.7.4 Pipe Sample Dimensional Changes

The total difference between the initial and final diameter measurements was 0.52 in. After 1.76 million cycles, the diameter measurement did not change until 2 million cycles were reached. Table 5.7 presents expansion of pipe sample for one million and two million surge cycles.

Table 5.7
Diameter expansion of pipe sample for number of surges completed

Surges	Expansion	
	in.	mm
1,000,000	0.27	6.858
2,000,000	0.52	13.21

5.8 TEST RESULTS – PHASE 2

The Phase 2 testing was conducted to evaluate resistance of HDPE pipe to occasional surge pressures up to two times its pressure class. To perform this test, the research team had to replace the pump to a 15-HP pump, and the solenoid valves to 300 psi. For this test, the same pipe sample (with 2 M cycles completed in Phase 1) was used to pressurize from 125 psi to 250 psi for 50,000 cycles at 73° F. The test started on February 10, 2015, and ended on March 10, 2015. This test was conducted during daytime only, and not continuously, as it was done for Phase 1. Figure 5.8 illustrates the saw tooth waveform cycles for Phase 2, with each cycle spanning 8 to 10 seconds.

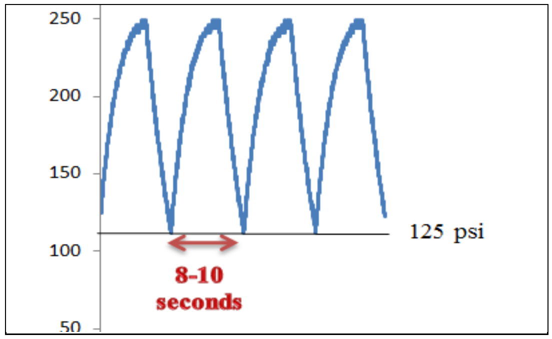
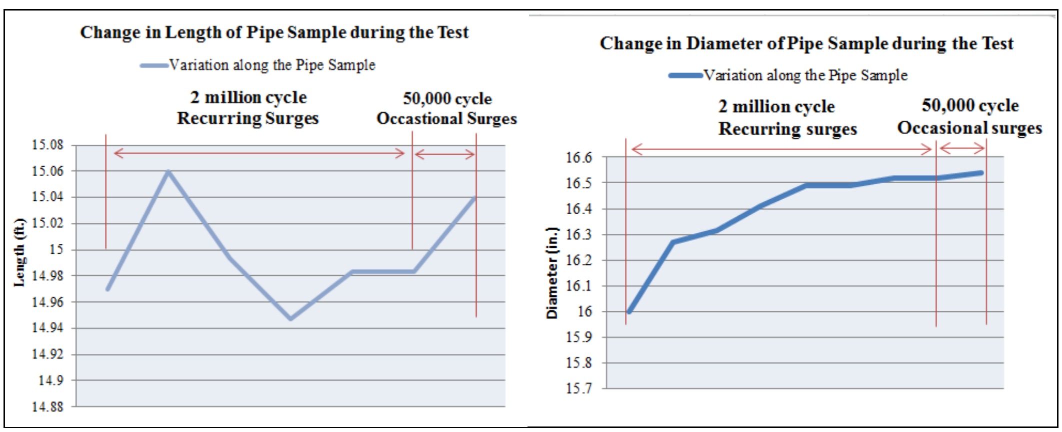


Figure 5.8 Saw-tooth waveform cycle for occasional surges

Figure 5.9 illustrates the variation in lengths and diameters for both Phase One and Phase 2 of the project. The length measurements do not show good correlations with diameter measurements. This might be due to rounding issues during the measurements.



(a) **(b)**

Figure 5.9. Variations in (a) length, and (b) diameter

Table 5.8 presents final diameter and length measurements after 50,000 occasional surges were completed.

Table 5.8
Changes in pipe sample for 50,000 occasional surges

Start date	End date	Diameter (in.)		Length (ft)	
		Before	After	Before	After
February 10, 2015	March 10, 2015	16.52	16.54	14.99	15.04

5.9 CHAPTER SUMMARY

One area of durability that has not been thoroughly investigated is fatigue resistance to recurring and occasional pressure surges for large diameter HDPE pipes. This chapter covered the experimental portion of WRF project #4485 to help in evaluating the reliability and durability of large diameter HDPE pipes. A testing methodology was developed and a 16-in., 15-ft, PE4710 pipe sample was tested for 2,000,000 cycles at 1.5 times pressure class. No failure was observed in the pipe sample, including the butt-fused joint, end caps, inlet and outlet tubes, and the air release valve. The same pipe sample was tested for an additional 50,000 cycles for twice the pressure class and no failure was observed. The pipe sample dimensional variations were not uniform along the pipe due to stiffness of end seals and surge movement along the pipe length. The fatigue testing protocol developed in this project can be used to test other large diameter pipe materials.

CHAPTER 6
CASE STUDIES

6.1 BACKGROUND AND OBJECTIVE

"Real world" experience is important in applied research, and this fact is perhaps more pronounced for the pipeline industry. As such, the Project Team started to gather information about actual large diameter HDPE transmission main projects from the beginning of this study. These experiences from public and private water utilities as well as other private enterprises were presented as case studies, the format of which is discussed further below.

The objective of the task of Case Studies is to utilize past experience with high density polyethylene (HDPE) for large diameter (transmission main) applications. The information and knowledge gathered via collecting case studies have been instrumental to date in fine tuning the scope of the project as well as enhancing the content of the project report with the "real world" experience in pursuit of understanding the durability and reliability of HDPE for water transmission mains.

6.2 METHODOLOGY

The project team contacted a number of water utilities (public and private) and engineers/managers that were involved in HDPE transmission main projects. In addition to raw and drinking water transmission mains, HDPE transmission pipelines are used for irrigation. A case of brine solution conveyance is included as the pipelines used in these types of projects operate under very similar conditions with drinking water transmission mains. In addition, the project team made attempts to utilize other media (i.e., project workshops, conferences, and social media on the internet) to solicit case studies from the utilities that have experience with HDPE transmission mains. Collecting case studies from water utilities imposed a challenge for the project team for the following reasons:

1. The number of utilities that use HDPE for transmission mains is limited (hence this project).
2. The majority of the few water utilities that use HDPE for transmission mains as their primary choice of pipe material, had attended the project workshops; thereby less motivated to provide specific case studies to share their experience in a different platform.

The case studies gathered from water utilities, manufacturers, and consulting engineers were edited by the project team to deliver the appropriate content commensurate with the objectives of this research project.

A standard Case Study template was prepared by the Project Team to help the participants compile the information sought, and receive their contribution in an organized manner. The Case Study template sections included:

- General Information (utility/owner name, project location, pipe size, pipe length, operation pressures and flow rate, construction cost, etc.)
- Background – overall information about the project and basis of design.

- Design Parameters – main drivers of the design (external/internal loads, soil conditions, topography, etc.)
- Construction Challenges – any problems during construction that resulted in change orders or delays and cost overruns.
- Project Highlights – significance of the project (i.e., supplied water for many customers).
- Conclusions and Recommendations – owner/engineer's opinion on the overall experience with HDPE transmission main. What lessons were learned? Will they consider using it again?

Eleven case studies were compiled as a part of this project. These key studies are summarized below. Details of the case studies presented above, in the case study template, are attached to this report as Appendix D.

1. Seminole County Regional Water Treatment Facility, Yankee Lake, Seminole County, Florida, USA (42 in., 41,100 ft).

   The Yankee Lake raw water transmission main was built to convey surface water from St. Johns River for drinking water supply and irrigation. It is a low pressure transmission main with 45 mgd firm capacity.

   HDPE pipe was selected for the project based on the limited accessibility throughout the raw water pipeline corridor, its flexibility, resistance to corrosion, a 50- to 100 years expected design life, low friction coefficient, fused joints, and the close proximity to a high voltage overhead power lines.

   The joints were connected by butt fusion, and 10 out of 775 joints were rejected during the fusion process due to misalignment. Nevertheless, the butt fusion rejection was slightly over 1%, and this was deemed successful.

   The Yankee Lake project in Seminole County, FL, is one of the first to use the St. Johns River as an alternative water supply to meet the future drinking water needs of its customers. The project is a crucial part of the St. Johns River Water Management District's long-term water supply plan to reduce groundwater use and increase drinking water alternatives. The new pipelines installed in Phase I of this project will provide up to 5.5 mgd for reclaim water augmentation. The treated water is conveyed to the adjacent reuse facility, where it is blended with the reuse stream prior to distribution for irrigation (public access reuse). Figure 6.1 illustrates a view of a sharp bend that was negotiated with the butt-fused, 42 in., HDPE pipe.

Figure 6.1 A view of a sharp bend that was negotiated with the butt-fused, 42 in., HDPE pipe. Yankee Lake, Seminole County, Florida

2. Silver Lake Sliplining, Los Angeles County, California, USA (36 in., 1,690 ft).

Figure 6.2 Jacking the 36 in. HDPE pipe into the 40 in. host pipe

Figure 6.2 illustrates Los Angeles Department of Water and Power (LADWP) used 36-in. HDPE to slipline a 40-in. cast iron pipe. The smooth interior of HDPE pipe with high Hazen Williams's friction factor and ability for trenchless installation were among the reasons for selecting HDPE.

LADWP hired a third party expert to inspect the butt fusion operation and required the inspector to approve every joint fused by the contractor. The project was completed with success and the HDPE sliplined transmission main has been in service without any problems. Accordingly, LADWP thinks sliplining with large diameter HDPE is a viable option, where the conditions (hydraulic, pressure requirements, etc.) are met, and states the following as chief advantages of using HDPE for large diameter pipes:

- Enables trenchless installation (or minimal excavation regarding the access pits) utilizing the existing pipe as a conduit. Accordingly, there is essentially no risk of damage to adjacent utilities or structures and it is quick to install.
- HDPE pipes are not affected by metallic corrosion.
- It costs significantly less than replacement cost of welded steel pipe.

LADWP further points out the following as the cons of large diameter HDPE pipe for sliplining transmission mains:

- Difficulty in tapping future connections.
- Difficulty in locating leak origin should the liner fail, because the leak travels along the annular space to a point where the host pipe has holes or other types of openings. This is not a HDPE problem exclusively but one associated with any liner pipe.
- Must account for expansion and contraction of HDPE.
- Reduction in flow capacity due to annular space requirement for sliplining with respect to the thick HDPE pipe walls.

3. Katrine Water Project, Glasgow, Scotland, (43 in., 15,000 ft).

Scottish Water, a utility firm that supplies water for Glasgow, Scotland, was required to build a water supply system to use Loch (Lake) Katrine as the primary source of water for the Mugdock Water Treatment Plant. The new water supply system included two parallel transmission mains that had to span the lake.

Good chemical resistance, high operational reliability, corrosion resistance, fused joints that enable leak tightness of the system, were the main reasons for selecting HDPE (PE100) for the transmission mains used in the Lake Katrine project. The pipeline was designed for 58 psi internal pressure, and the expected service life is 100 years. Figure 6.3 illustrates a part of the Katrine lake pipeline spanned a reservoir.

Figure 6.3 A part of the Katrine Lake pipeline spanned a reservoir. Fused pipe segments were sunk down the reservoir using anchoring weights

The Katrine Water Project was Scottish Water's largest water treatment investment project in Scotland. The estimated cost of the work accounted from 120 to

140 million Euros (154 to 179 million USD). At peak times, approximately 300 people were employed at the various sites. The HDPE transmission mains used for the project have been in service for more than six years with no problems reported to date.

4. Eastern Navajo Reservation, New Mexico, USA (24 in., 69,000 ft).

The Eastern Navajo Water Pipeline project consists of installation of 24 in. transmission main to provide drinking water for eight rural communities of the Navajo Reservation in the desert South-west, where drinking water supply has historically been very scarce. Figure 6.4 presents the sample fused fittings used for Eastern Navajo HDPE transmission main.

Figure 6.4 Sample fused fittings used for the Eastern Navajo HDPE transmission main

Initially ductile iron pipe was specified for the project. Then the Bureau of Reclamation raised concerns about the corrosiveness of the soil; and therefore, the pipe material was changed to HDPE. The reason for choosing HDPE over PVC was that the project team felt it had more strength than PVC. Working pressures in the pipeline are as high as 290 psi. Moreover, the project area has many large seasonal waterway crossings with shifting soils and aggressive erosion.

HDPE pipe was supplied by four different pipe manufacturers, each of which provided pipe in multiple pressure classes (DRs), as specified. One batch of pipe was later discovered to show embrittlement during the joint fusion process, which caused the fusion joints to fail the high-speed tensile impact test due to brittle, rather than ductile, failure. The joints had a significantly less ductile failure mode that was characteristic of one particular resin. These joint failures were later found to be due to the pipe, not the fusion process, and were traced back to a single rail car of raw HDPE feedstock that was shipped to the pipe extruder. The apparently defective pipe was removed and replaced at no additional cost to the owner, and without adversely impacting the project schedule.

Despite the initial difficulty, this problem was resolved to the full satisfaction of the owner and the engineer. No further problems with pipe material or joint fusion process were detected for the rest of this project, nor in the follow-on Phase 3 project (17 miles of 20 in. HDPE pipeline). The pipe has been in service for four years.

5. MTD Pipeline, Ludington-Manistee, Michigan, USA (20 in., 158,000 ft).

Dow Chemical had investigated performance and possible cost benefits of HDPE for pipe applications for years, and they decided to use a bimodal HDPE resin for the pipe (DR 11) for a 20 in. pipeline that conveys brine from Martin Marietta plant to that of Dow Chemical. Dow Chemical manufactures bimodal resin. Bimodal resin is a PE4710 resin with typically high PENT values.

Figure 6.5 Open trench installation of the 20-in. HDPE pipeline that conveys brine solution at 150 psi design pressure

The design pressure was 150 psi and the pipe material had to be durable regarding high salt content in the brine solution that was to be conveyed between the two plants.

The construction challenges included installation in cold winter months (at temperatures as low as 15 °F), and directional drilling for river and highway crossings in environmentally sensitive areas.

The estimated total weight of the HDPE materials used is 6.3 million pounds, which represented the highest volume of PE100 material for any single design-build project using this material in North America at the time.

6. Houston, Texas, USA (36 in., 25,000 ft).

The City of Houston (City), as the regional provider of drinking water, has had an interest in evaluating new products and materials for the water distribution and transmission system. As such, a 30 in. inside diameter (ID) high-density polyethylene (HDPE) water main was constructed as a “demo” project under the City’s Surface Water Transmission Program. The HDPE water main was installed in the fall of 1997. The material specifications required the HDPE to be rated at 100 psi (DR 17) with surge pressures up to 150 psi, undergo a field hydrostatic test of 150 psi, and the use of heat-fused butt joints.

Two locations were identified as critical areas to be representative of the total length of HDPE installed; i.e., a 45-degree bend (see Figure 6.6) and a flanged connection to concrete pressure pipe at two road intersections. The HDPE water main was exposed at each of these locations for visual evaluation of the pipe's performance.

Figure 6.6 45-deg bend used in the Houston pilot study

No leaks were observed in the butt-fused joints or at the flanged connection. Also, the OD of the HDPE water main was measured at each of the exposed locations to determine if ballooning or elongation of the HDPE line had occurred as a result of thrust. The OD of the pipe matched the original OD prior to installation. However, if these phenomena occur simultaneously, they may have offsetting effects that are difficult to quantify individually. Based on the results of the limited assessment, the HDPE water main at each of the referenced locations was performing adequately.

7. Fisher Island Transmission Main, Miami Dade County, Florida, USA (30 in., 1,600 ft).

Fisher Island residents rely on a pipeline from the mainland through the Port of Miami for their fresh water supply. Additionally, because it is part of a water system loop, the pipeline enables the Miami Dade Water & Sewer Department (MDWASD) to maintain system pressure when cruise ships at the Port of Miami are filling prior to their departures. Age, leaks, and the deepening of the Port of Miami's main shipping channels, and Fisherman's Channel, required this important pipeline to be replaced.

The primary driver of the design was the installation method. A trenchless method (directional drilling) was selected to minimize the environmental nuisance and also allow for deeper installation beneath the seabed. This increased depth is warranted to enable dredging of the shipping channel in the Port of Miami deeper draft vessels, which travel through the Panama Canal. Figure 6.7 presents the aerial view of the drill rig used to install the 20 in. HDPE transmission main to Fisher Island.

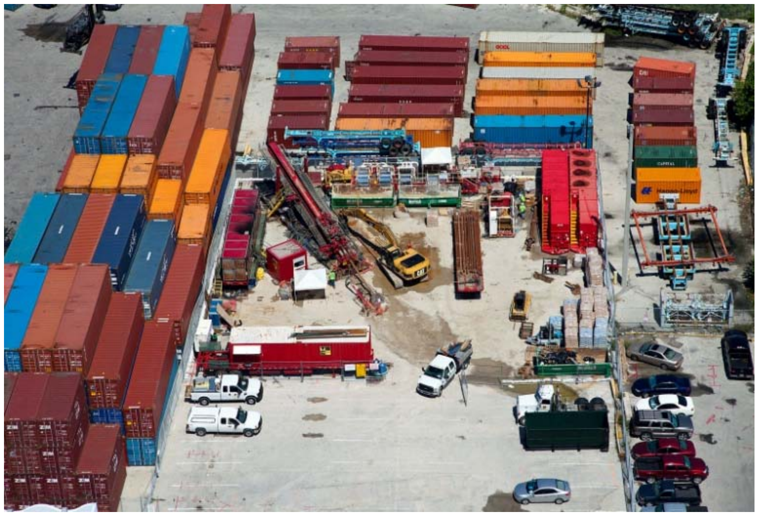


Figure 6.7 Aerial view of the drill rig used to install the 20 in. HDPE transmission main to Fisher Island

DR11 HDPE with PE4710 resin was selected in lieu of PE3608 resin due to its inherent ability to withstand higher tension loads and greater service life for an HDD installation this critical in nature. Steel was also considered for this HDD water main, but not implemented into design due to cost, high susceptibility to corrosion in salt water environment, and additional QA/QC time required for analyzing and testing of welded joints.

The project enables safe and reliable delivery of drinking water to the Fisher Island residents and allows MDWASD to maintain pressure in the system on days when cruise ships are taking on water for their voyages. It is designed around the proposed dredging at the Port of Miami. This will turn the Port of Miami into one of the only three ports on the East Coast that can harbor the Panamax ships with 13,000 container capacity.

8. Regional Carizzo Project, San Antonio, Texas, USA (36 in., 40,000 ft).

San Antonio currently obtains more than 90% of its drinking water from the Edwards Aquifer. The Regional Carrizo Water Supply Project will enable San Antonio Water System (SAWS) to have a major alternative water supply from the Carrizo Aquifer. This Project assists San Antonio Water System (SAWS) in diversifying its water sources thus reducing its reliance on the Edwards Aquifer. The Regional Carrizo project consists of a well field with nine wells, and it supplies an average of 10.4 mgd. SAWS choose HDPE for piping among the wells and conveyance of groundwater to the San Antonio distribution system. HDPE was chosen for the project, which included approximately 40,000 ft of 36-in pipe. Figure 6.8 illustrates the pipe segment stacked in field prior to installation. The primary reason for choosing HDPE was because SAWS had essentially done no maintenance on the HDPE pipes installed prior to the Regional Carizzo Project. The project includes pipe installation in remote areas, tens of miles away from the utility; hence minimum maintenance was the primary factor for pipe material selection. Other reasons for choosing HDPE includes its resistance to corrosive soils, flexibility and constructability.

Figure 6.8 HDPE pipe segments stacked in field prior to installation

9. Gatehampton Bore Hole Project, Gatehampton, UK (14 to 31 in.)

This project involves an HDPE (PE 100) transmission main built to supply raw water from wells. HDPE pipes with sizes ranging from 14 to 31 in. were installed vertically (at the boreholes) and horizontally. DR 17 HDPE was used, and the pipeline was designed for high surge pressures, as well as expected negative pressures due to surge. The fundamental reasons for selecting HDPE were flexibility and constructability, which helped reducing the number of fittings. Figure 6.9 presents the view of Gatehampton Bore Hole project during installation.

Figure 6.9 A view of the Gatehampton Bore Hole project site during installation

Gatehampton project was completed successfully as the largest groundwater withdrawal project in Europe. The project has substantially increased the raw water supply for the Cleeve Water Treatment Works.

10. Broken Land Parkway Transmission Main, Howard County, Maryland (30 in.)

Howard County chose HDPE for a critical 30 in. water transmission main. Figure 6.10 illustrates Howard County HDPE pipe installation. The soils through which the transmission main is being installed were found to be corrosive, and HDPE high resistance to corrosion was the primary reason behind the project team's decision. The County also liked flexibility of HDPE in addition to using fused joins, which minimized any metal appurtenances used in the project.

Figure 6.10 Resistance to corrosion and flexibility were the primary reasons for Howard County to select HDPE

This project is the first transmission main project of Howard County, using HDPE. The project is under construction and ahead of its schedule. The County has had positive experience with this pipe material so far, and planning to continue to use it for future projects.

11. South Catamount Reservoir Transfer Pipeline, Teller County, Colorado

Colorado Spring Utilities (CSU) decided to replace two leaking pipelines, 16 in. and 14 in. steel placed in the early 1950s, that conveyed raw water between two reservoirs located at the high altitudes of the Rocky Mountains. The South Catamount (South) storage reservoir was built earlier, and was fed through the steel pipelines. In the late 1950s the dam for the North Catamount Reservoir was built; the new reservoir was placed on top of the steel pipelines. Corrosion of the steel pipes resulted in leakage from the steel pipes to the extent that the South Reservoir started to contain less than adequate water. As such, CSU decided to replace the existing two steel pipes with a 36 in. diameter HDPE pipe. HDPE was the material of choice due to its constructability, flexibility, and resistance to corrosion. The pipeline was sunk into North reservoir using anchor weight, and had to be built in a short windows due to harsh and inconsistent weather conditions at the project site. The 36 in. pipeline was built successfully, and CSU, which is a user of HDPE in their distribution system, has decided to continue to use HDPE for similar applications. Figure 6.11 presents the fast construction of the South Catamount reservoir transfer pipeline under design-build contract.

Figure 6.11 Flexibility of HDPE enabled fast construction of the South Catamount reservoir transfer pipeline under a design-build contract

Table 6.1 provides a summary of the key findings of the case studies compiled as a part of the project.

Table 6.1
Case study key findings

Case study location	Pipe size (in.)	Pressure (psi)	Years in service	Reasons for selecting HDPE	Installation challenges	Notes
Seminole County, Florida	42	56	3	Flexibility, fused joints, low friction coefficient	Small fraction (1.3%) of joints failed during fusion.	Major water supply project in Central Florida.
Los Angeles, California	36	NA	8	Low friction coefficient, trenchless installation (slip-lining)	None – LAWP hired 3rd party welding inspector.	LADWP continues to use HDPE. Difficulty in tapping for future connections was noted as a drawback.
Glasgow, Scotland	39-43	58	12	Lower cost, 2-3 year application development support by contractor/manufacturer	Spanning a lake with HDPE required sink weights.	Part of the largest water supply project in Scotland.
Ludington-Manistee, Michigan	20	150	11	Resistance to corrosion, leak free joints	Challenging vertical alignment, extreme cold	Largest design-build HDPE project in North America

(Continued)

Table 6.1 (Continued)

Case study location	Pipe size (in.)	Pressure (psi)	Years in service	Reasons for selecting HDPE	Installation challenges	Notes
Houston, Texas	30 – 36	NA	17	HDPE passed the pilot test with 45-deg bend	None reported	30 in. HDPE installed with 45-deg bend with fused and flanged joints. No failure reported
Gate Hampton, United Kingdom	Up to 32	NA	6	Ability to negotiate tight bends and withstand surge pressures at bore holes	Pipeline runs through a small town with narrow streets and tight bends	Largest groundwater withdrawal project in Europe
Fisher Island (Miami), Florida	30	70	2	Environmentally friendly installation with HDD	Calcareous soil imposed challenge for drilling rod	Designed around dredging at the canal utilizing flexibility of HDPE
Navajo Reservation, New Mexico	24	Up to 290	4	Corrosion resistance	One batch of defective pipes failed during fusion process.	When complete, the overall project will supply water for 10,000 people
San Antonio, Texas	36	150	0	Seamless butt fused joints, easy maintenance	Acquired construction easements for staging.	Largest HDPE project by SAWS, second largest transmission main to San Antonio

(Continued)

Table 6.1 (Continued)

Case study location	Pipe size (in.)	Pressure (psi)	Years in service	Reasons for selecting HDPE	Installation challenges	Notes
Howard County, Maryland	30	NA	0	Corrosion resistance, flexibility	Difficulty with fusing 400 ft pipe segments. Large construction site.	Significant project for Howard County. Fast construction to be completed ahead of schedule.
Teller County, Colorado	36	100	1	Constructability, corrosion resistance, flexibility	Extreme and inconsistent weather patterns	Largest groundwater withdrawal project in Europe

6.3 CHAPTER SUMMARY

The case studies compiled as a part of this project are essentially successful installations of large diameter HDPE pipe. Nevertheless, some problems pertaining particularly to construction challenges in addition to others were stated by the utilities that had provided case studies. The overall project team experience with the case studies to date has resulted in the following key findings:

1. The primary reasons for selecting HDPE for large diameter transmission mains are:
    a. Flexibility
    b. Fusible joints
    c. Corrosion resistance
    d. Ability to install trenchless
    e. Cost savings (occasionally)
2. Using HDPE pipes may save significant amount of money in comparison with steel and ductile iron (no savings reported in comparison with PVC).
3. Some utilities preferred HDPE over PVC, because they think it can deal better with surge pressures.
4. Failures discovered to date were mostly due to improper butt fusion, hence failures at the joints.
5. One case study indicated a different response to the fusion test for a particular stack of pipes received from the same manufacturer. The same project (Eastern Navajo) received pipes from four other manufacturers, and no problems were encountered with the other pipes.
6. HDPE pipelines were used for major transmission main projects in Europe (PE100) and HDPE4710 in the USA with dimension ratios ranging from 9 to 17.

CHAPTER 7
CONCLUSIONS

Due to leaks and breaks, U.S. water utilities in aggregate lose more than a quarter of processed water between treatment plants and the tap every day. Potable water pipe rehabilitation costs may reach more than $1 trillion in the coming decade. Previous research shows that there is a need for a reliable and durable pipe material. High Density Polyethylene (HDPE) pipe is one such material to consider. The large diameter (16 in. and larger) water pipe market in the U.S. mainly includes steel pipe (SP), precast concrete cylinder pipe (PCCP), ductile iron pipe (DIP) and PVC (Polyvinyl Chloride) pipe. Large diameter HDPE pipe currently comprises 2 to 5% of the large diameter water pipe market. Therefore, the main objectives of this project were:

- To explore North American water utilities on their experiences with durability and reliability of large diameter HDPE pipes in water applications.
- To identify features and characteristics of HDPE pipes in municipal water applications, such as design, installation, maintenance, etc., as well as any limitations and issues.
- To develop a protocol for fatigue (cyclic surge pressure) testing of large diameter HDPE pipe as recommended by water pipeline professionals during the initial phase of this study.

The project approach was divided into six main tasks as summarized below:

1. Literature Search
    a. Search existing publications regarding durability and reliability of HDPE pipe.
2. Survey of Water Utilities
    a. Conduct survey of water utilities to gain their experiences regarding HDPE pipe use.
3. Workshop with Water Professionals
    a. Perform workshop with water professionals
    b. Identify issues and corrective measures
4. Experimental Work
    a. Perform experiments on a 16 in. diameter HDPE pipe sample
5. Case Studies
    a. Collect case studies of past HDPE pipe projects
6. Final Report

The literature search identified main parameters impacting performance of HDPE pipe as well as an overview of its benefits and limitations. The advantages may include fused joints providing a leak free piping system with fully restrained joints, excellent hydraulic efficiency and abrasion resistance. The corrosion resistance of HDPE pipe provides a long service life. The effects of strong oxidizers, slow crack growth, permeation and other issues presented in this chapter must be considered during the HDPE pipe design and installation. All types of pipe materials have certain benefits and limitations. The HDPE can be a pipe of choice dependent on the project and site conditions.

The survey of water utilities indicated that majority of respondents were satisfied with the durability and reliability of large diameter HDPE pipe, while 5% were unsatisfied. Survey respondents also expressed concerns about tapping, repairs and joints. They considered permeation and oxidation to be minor concerns. There were no failures reported due to oxidation or permeation in large diameter HDPE piping systems. The respondents stated that measures are required to improve construction techniques.

The project workshops provided valuable input to the project and assisted the project team to improve upon the project scope and experimental approach. The structured approach utilized for the workshop allowed the critical topics to be identified in an efficient manner. The limited and valuable time of participants was mostly devoted to discussion of the most critical topics. The workshop enabled the project team to explore different perspectives and identify several studies and experiences brought up by the project participants. Specifically, perception issues, connection/fittings, design, installation, and repair and operation and maintenance were identified as deserving special attention during the course of this research project.

During project workshops participants recommended fatigue testing of a large diameter HDPE pipe be conducted as part of this project. The use of large diameter HDPE pipe has been questioned for its ability to handle the recurring surge events associated with water mains and transmission lines. While this ability has been verified for small diameter pipes, it lacked validation for the larger sizes. A testing concept for fatigue resistance of large diameter HDPE pipe was developed under this research project. The testing operation and required equipment are described in Chapter 5. A 16-in., DR 17, 15-ft long, with a butt-fused joint in the middle was successfully tested with 2 million cycles of surge pressures from 125 psi to 188 psi (1.5 times pipe pressure class). The pipe did not fail or leaked after approximately 6 months of continuous testing. There were some dimensional changes along the pipe length and pipe diameter at the conclusion of testing. The same pipe sampled was tested for an additional 50,000 cycles of surge pressures from 125 psi to 250 psi (two times pipe's pressure class). The pipe did not fail or leaked after conclusion of this testing as well.

The case studies showed successful installations of large diameter HDPE pipe. Nevertheless, some problems pertaining particularly to construction challenges, in addition to others, were stated by the utilities that provided case studies. Case studies demonstrated that the primary reasons for selecting HDPE for large diameter transmission mains are flexibility, fusible joints, corrosion resistance, compatibility with trenchless technology methods, and occasional cost savings.

The conclusion of this project indicates that proper construction, particularly fusion, is important in achieving a successful project as well as understanding methods for tapping and repairing the large diameter HDPE pipe.

APPENDIX A
SURVEY

EPA/WRF PROJECT 04485 – DURABILITY AND RELIABILITY OF LARGE DIAMETER (16 in. AND LARGER) HDPE PIPE FOR WATER MAINS

A.1. SURVEY DEFINITIONS

Buckling: Unpredictable deformation observed in the pipe as a result of instability of pipe due to the increasing loads which might lead to complete loss in carrying capacity of pipe *(Plastics Pipe Institute, 2008)*

Corrosion: The destruction of materials or its properties because of reaction with its (environment) surroundings *(Plastics Pipe Institute, 2008)*

CUIRE: Center for Underground Infrastructure Research and Education

Durability: Ability of pipe and fittings to remain in service during its design life without significant deterioration *(Ballantyne, 1994)*

Excessive Internal Pressure: Force exerted circumferentially on the pipe from inside per square unit area of the pipe is internal pressure. Excessive term is used if it results in pipe failure *(Plastics Pipe Institute, 2008)*

Electro-fusion: A heat fusion joining process where the heat source is an integral part of the fitting *(Plastics Pipe Institute, 2008)*

Fatigue: The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material *(Plastics Pipe Institute, 2008)*

HDPE: A plastic resin made by the copolymerization of ethylene and a small amount of another hydrocarbon. The resulting base resin density, before additives or pigments, is greater than 0.941 g/cm *(Plastics Pipe Institute, 2008)*

Joint: The means of connecting sectional length of pipeline system into a continuous line using various type of jointing materials *(Plastics Pipe Institute, 2008)*

Life Cycle Cost: Sum of all recurring and one-time (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system. It includes purchase price, installation cost, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or its useful life *(Plastics Pipe Institute, 2008)*

Manufacturing Defects: An error or flaw in a pipe, introduced during the manufacturing rather than the design phase *(Plastics Pipe Institute, 2008)*

Oxidation: The erosion damage observed in the pipe due to its surrounding environment *(Plastics Pipe Institute, 2008)*

PE3608/3408: The term PE3608/3408 is based on the standard thermoplastics pipe material designation code defined in ASTM F412 and has been referenced extensively within the North American piping industry since the early 1980s. It identifies the piping product as a polyethylene grade P36 with a density cell class of 3 in accordance with D3350, a slow crack growth cell class of 4 also in accordance with D3350, and an 800 psi maximum hydrostatic design stress at 23°C (73°F) as recommended by the Plastics Pipe Institute *(Plastics Pipe Institute, 2008)*

PE4710: The term PE4710 identifies the piping product as a polyethylene grade P47 with a density cell class of 4 in accordance with D3350, a slow crack growth cell class of 7 also in accordance with D3350, and an 1000 psi maximum hydrostatic design stress at 23°C (73°F) as recommended by the Plastics Pipe Institute *(Plastics Pipe Institute, 2008)*

Permeation: Permeation of piping materials and non-metallic joints can be defined as the passage of contaminants external to the pipe, through porous, non-metallic materials, into the drinking water. The problem of permeation is generally limited to plastic, non-metallic materials *(Plastics Pipe Institute, 2008)*

Polyethylene (PE): Polyethylene (PE) is a thermoplastic material produced from the polymerization of ethylene. PE plastic pipe is manufactured by extrusion in sizes ranging from ½ in. to 63 in. PE is available in rolled coils of various lengths or in straight lengths up to 40 ft. Generally small diameters are coiled and large diameters (>6 in. OD) are in straight lengths. PE pipe is available in many varieties of wall thicknesses, based on three distinct dimensioning systems: • Pipe Size Based on Controlled Outside Diameter (DR) • Iron Pipe Size Inside Diameter, IPS-ID (SIDR) • Copper Tube Size Outside Diameter (CTS) PE pipe is available in many forms and colors such as the following: • Single extrusion colored or black pipe • Black pipe with coextruded color striping • Black or natural pipe with a coextruded colored layer • Third Party Damage: Damage caused by someone other than pipeline operator and owner *(Plastics Pipe Institute, 2008)*

Reliability: Consistency of performing the required function without degradation or failure *(Ballantyne, 1994)*

A.2. SURVEY QUESTIONNAIRES ON WEBSITE

EPA/WRF PROJECT 04485 – DURABILITY AND RELIABILITY OF LARGE DIAMETER (16 IN. AND LARGER) HDPE PIPE FOR WATER MAINS

This project will investigate the durability and reliability of large diameter (16 in. and larger) HDPE water mains and fittings as a solution to the water infrastructure. The below national survey is critical as a first step to achieve this objective, since it will provide valuable information regarding the durability and reliability of 16 in. and larger HDPE water pipes and fittings.

This survey contains 15 questions and is expected to take less than 30 minutes and we request you to complete at your earliest convenience. Your answers are voluntary and you are free to answer any question or to stop participating at any time. Your name and information will be strictly confidential to the maximum extent allowable by law and your responses will be used in aggregate for the purpose of this research.

Your time and efforts in completing this survey would be greatly appreciated. To show our appreciation, we will send you a copy of the research findings upon completion scheduled for summer 2015. If you have any questions or concerns, please feel free to contact CUIRE at 817-272-9177 or Divyashree, CUIRE Graduate Research Assistant, at divyashree@mavs.uta.edu or the principal investigator of this project, Dr. Mohammad Najafi at najafi@uta.edu.

1. Contact Information

*Name:

*Organization:

*Position:

*Address:

*City/Town:

*State:

*ZIP Code:

*Email

Address:

*Phone
Number:
Fax Number:

2. *Do you have large diameter (16 in. and larger) HDPE water pipe in use?

Yes No

3. What is the population of the area served by your organization?

4. In your installed large diameter (16 in. and larger) HDPE water pipe in use, what length (miles) is:

PE4710 (Less than 5 years old)

PE4710 (Between 5 to 10 years old)

PE3608/PE3408 (Less than 5 years old)

PE3608/PE3408 (Between 5 to 10 years old)

PE3608/PE3408 (More than 10 years old)

5. In your installed large diameter (16 in. and larger) HDPE water Pipe, what length (miles) is:

PE4710 (16 in.-24 in.)

PE4710 (Larger than 24 in.)

PE3608/PE3408 (16 in.-24 in.)

PE3608/PE3408 (Larger than 24 in.)

6. Please specify types and diameters of HDPE pipes permitted in your district or municipality:

	4 in.-14 in.	16 in.-24 in.	Larger than 24 in.
PE4710	☐	☐	☐
PE3608/PE3408	☐	☐	☐

Other (please specify)

7. If you have any restrictions in use of HDPE pipes, please provide reasons:

8. Please specify restricted HDPE pipe installation methods in your district or municipality:

	Direct Buried (open-cut)	Trenchless Application (HDD, Pipe Bursting, Slip lining, etc.)
PE4710	☐	☐
PE3608/PE3408	☐	☐

Please specify restricted pipe sizes

9. Have you had any leaks from your HDPE water pipe system (16 in. and larger)?

Yes ○

No ○

If yes, please specify:

10. On a scale of 1 to 5, with 1 being "lowest frequency of occurrence" and 5 being "highest frequency of occurrence," how would you rate the following causes/modes of rupture for PE4710 HDPE pipe material according to its frequency of occurrence?

	16 in.-24 in.	Larger than 24 in.
Third Party Damage		

	16 in.-24 in.	Larger than 24 in.
Installation Defects		
Manufacturing Defects		
Buckling/Collapse		
Fatigue		
Circumferential Rupture due to Bending		
Longitudinal Rupture		
Excessive Internal Pressure		
Expansion/Contraction		
Fittings		
Joint Rupture		
Permeation		
Oxidation/Disinfection		
Ultraviolet Radiation		
Freeze/Thaw		
Fusion		
Electro-fusion		
Water Temperature		
Seismic/Ground Movements		

	16 in.-24 in.	Larger than 24 in.
Soil Conditions		
Other		

11. On a scale of 1 to 5, with 1 being "lowest frequency of occurrence" and 5 being "highest frequency of occurrence," how would you rate the following causes/modes of rupture for PE3608/PE3408 HDPE pipe material according to its frequency of occurrence?

	16 in.-24 in.	Larger than 24 in.
Third Party Damage		
Installation Defects		
Manufacturing Defects		
Buckling/Collapse		
Fatigue		
Circumferential Rupture due to Bending		
Longitudinal Rupture		
Excessive Internal Pressure		
Expansion/Contraction		
Fittings		
Joint Rupture		
Permeation		
Oxidation/Disinfection		
Ultraviolet Radiation		

	16 in.-24 in.	Larger than 24 in.
Freeze/Thaw		
Fusion		
Electro-fusion		
Water Temperature		
Seismic/Ground Movements		
Soil Conditions		
Other		

12. On a scale of 1 to 5, with 1 being "lowest impact" and 5 being "highest impact," rank concerns or issues you have faced using (16 in. and larger) HDPE pipes:

	PE4710	PE3608/PE3408
Cracking		
Ease of Use		
Joints		
Leakage		
Oxidation		
Permeation		
Repairs		
Tapping		
Water Quality		

13. On a scale of 1 to 5, with 1 being "lowest impact" and 5 being "highest impact," how would you rate the following factors impacting the life cycle cost of (16 in. and larger) HDPE water pipelines:

	PE4710	PE3608/PE3408

Asset Management Plan		
Ease of Joining		
Ease of Maintenance and Repair		
Ease of Mechanical Joints		
Ease of Tapping		
Leak-Free Joints		
Life Expectancy		
Maintenance Costs		
Physical Properties		

14. On a scale of 1 to 5, with 1 being "unsatisfied" and 5 being "very satisfied," how would you rate your experience with durability and reliability of (16 in. and larger) HDPE pipes for water main applications?

	Durability	Reliability
PE4710		
PE3608/PE3408		

15. Please provide any comments/suggestions, such as, research topics or testing needs. Please send us any case study or pipeline rupture report.

A.3. Surveys Excluded from Main Report Due to Misinterpretations

Below are survey responses to questions 7, 10 and 11 that caused misinterpretations by responding water utilities. As reported in Chapter 3, three survey respondents stated that there were no leaks in their HDPE piping system; one survey said the pipe separated during insertion, and another respondent had one leak from a poor fusion. All these respondents rated each and every "cause of rupture," instead of addressing the "specific issue" they faced with their pipeline. Their responses were not based on observed performance of their HDPE piping systems, but on hypothetical or theoretical causes of rupture. With further investigations, it became apparent that survey respondents had misinterpreted questions 7, 10 and 11.

Q7: If you have any restrictions in use of HDPE pipes, please provide reasons:

The responses regarding restrictions on the use of HDPE pipe varied widely with utilities indicating different needs, usage experience, and departmental philosophies. While most utilities have few restrictions here are the ones submitted in the survey.

- Generally used only in HDD installation.
- HDPE is used in areas of landslide or highly corrosive soils with high pressure.
- PE4710 is only HDPE material specified in areas of known contamination.
- Must be pressure class 125 psi.
- No taps allowed due to the expansion and contraction of the pipe that affects the saddles and sleeves.
- Special projects only (no current service/hydrant connections or potential for future service connections). Generally used for transmission mains only.
- 40-ft sections pose a problem in areas with a lot of services and other utilities to work around developers have to get permission from public works prior to installing HDPE Pipe.
- Using HDPE only in low pressure /gravity sliplines.
- Minimum DR17.
- Use AWWA design factors.
- Limit use of PE4710 to special circumstances.
- Flange adapter HDPE to DIP application requires a specialist contractor to install and engineered bolt torque values (Arizona Utilities).

Q10: On a scale of 1 to 5, with 1 being "lowest frequency of occurrence" and 5 being "highest frequency of occurrence," how would you rate the following causes/modes of rupture for PE4710 HDPE pipe material according to its frequency of occurrence?

Table A.3.1
Rating causes of rupture or leakage for PE4710 (16 in. to 24 in.)

PE4710							
16 in. to 24 in.	N/A	5	4	3	2	1	No. of Responses[20]
Installation defects	1	1*	0	1	0	2	5
Fittings	1	0	0	2	0	2	5
Electro-fusion	2	0	0	0	0	3	5
Expansion/Contraction	1	0	0	1	0	3	5
Permeation	1	1	0	0	0	3	5
Freeze/Thaw	2	0	0	0	0	3	5
Fusion	2	0	0	0	0	3	5
Seismic/Ground movement	1	0	0	0	1	3	5
Third party damage	1	0	1	0	0	3	5
Excessive internal pressure	1	0	0	0	1	3	5
Joint rupture	1	0	0	1	0	3	5
Ultraviolet radiation	1	0	1	0	0	3	5
Water temperature	1	0	0	0	0	4	5
Soil conditions	1	0	0	0	1	3	5
Circumferential rupture	1	0	0	0	1	3	5
Manufacturing defects	1	0	0	0	1	3	5
Buckling/Collapse	1	0	0	0	1	3	5
Fatigue	1	0	0	1	0	3	5
Longitudinal rupture	1	0	0	0	1	3	5
Oxidation/Disinfection	1	0	1	0	0	3	5

[1]Survey respondent reported an actual leak caused by installation defect

[20] Multiple causes were reported for some leaks

Table A.3.2
Rating causes of rupture or leakage for PE4710 (Larger than 24 in.)

PE4710							
Larger than 24 in.	N/A	5	4	3	2	1	No. of Responses[21]
Installation defects	3	0	0	1	0	1	5
Fittings	3	0	0	1	0	1	5
Electro-fusion	3	0	0	1	0	1	5
Expansion/Contraction	3	0	0	1	0	1	5
Permeation	3	1*	0	0	0	1	5
Freeze/Thaw	3	0	0	0	1	1	5
Fusion	3	0	0	1	0	1	5
Seismic/Ground movement	3	0	0	0	1	1	5
Third party damage	3	0	1	0	0	1	5
Excessive internal pressure	3	0	0	0	1	1	5
Joint rupture	3	0	0	1	0	1	5
Ultraviolet radiation	3	0	1	0	0	1	5
Water temperature	3	0	0	0	0	2	5
Soil conditions	3	0	0	0	1	1	5
Circumferential rupture	3	0	0	0	1	1	5
Manufacturing defects	3	0	0	0	1	1	5
Buckling/Collapse	3	0	0	0	1	1	5
Fatigue	3	0	0	1	0	1	5
Longitudinal rupture	3	0	0	0	1	1	5
Oxidation/Disinfection	3	0	1	0	0	1	5

*Survey respondent reported an actual leak caused by permeation

Q11: On a scale of 1 to 5, with 1 being "lowest frequency of occurrence" and 5 being "highest frequency of occurrence," how would you rate the following causes/modes of rupture (or leakage) for PE3608/3408 HDPE pipe material according to its frequency of occurrence?

[21] Multiple causes were reported for some leaks.

Table A.3.3
Rating causes of rupture or leakage for PE3608/3408 (16 in. to 24 in.)

PE3608/3408							
16 in. to 24 in.	N/A	5	4	3	2	1	No. of Responses[22]
Installation defects	1	1*	1	1	0	1	5
Fittings	1	1	0	1	0	2	5
Electro-fusion	1	0	0	1	1	2	5
Expansion/Contraction	1	0	0	1	1	2	5
Permeation	2	1	0	0	0	2	5
Freeze/Thaw	1	0	0	0	2	2	5
Fusion	1	0	0	2	0	2	5
Seismic/Ground movement	1	0	0	1	1	2	5
Third party damage	1	0	1	1	0	2	5
Excessive internal Pressure	1	0	0	0	1	3	5
Joint rupture	1	0	1	1	0	2	5
Ultraviolet radiation	1	0	1	0	0	3	5
Water temperature	1	0	0	0	1	3	5
Soil conditions	1	0	0	1	1	2	5
Circumferential rupture	1	0	0	0	2	2	5
Manufacturing defects	1	0	0	0	2	2	5
Buckling/Collapse	1	0	1	0	1	2	5
Fatigue	1	0	0	0	1	3	5
Longitudinal rupture	1	0	0	0	1	3	5
Oxidation/Disinfection	1	0	1	0	0	3	5

*Survey respondent reported an actual leak caused by installation defects

[22] Multiple causes were reported for some leaks.

Table A.3.4
Rating causes of rupture or leakage for PE3608/3408 (Larger than 24 in.)

PE3608/3408							
Larger than 24 in.	N/A	5	4	3	2	1	No. of Responses[23]
Installation defects	3	0	1	1	0	0	5
Fittings	3	0	1	1	0	0	5
Electro-fusion	3	0	0	1	1	0	5
Expansion/Contraction	3	0	0	0	2	0	5
Permeation	4	1*	0	0	0	0	5
Freeze/Thaw	3	0	0	0	2	0	5
Fusion	3	0	0	2	0	0	5
Seismic/Ground movement	3	0	0	1	1	0	5
Third party damage	3	0	1	1	0	0	5
Excessive internal pressure	3	0	0	0	1	1	5
Joint rupture	3	0	0	2	0	0	5
Ultraviolet radiation	3	0	1	0	0	1	5
Water temperature	3	0	0	0	1	1	5
Soil conditions	3	0	0	1	1	0	5
Circumferential rupture	3	0	0	0	1	1	5
Manufacturing defects	3	0	0	0	2	0	5
Buckling/Collapse	3	0	1	0	1	0	5
Fatigue	3	0	0	0	1	1	5
Longitudinal rupture	3	0	0	0	1	1	5
Oxidation/Disinfection	3	1*	0	0	0	1	5

*Survey respondent reported an actual leak caused by permeation and oxidation.

[23] Multiple causes are rated for some leaks.

APPENDIX B
PROJECT WORKSHOPS

B.1 WORKSHOP #1

INTRODUCTION

An element of this research project calls for holding project workshops with industry professionals to seek input on the critical issues to be addressed during the course of this project. The first workshop was held on April 12, 2013, from 8:00 am to 12:00 pm in Springfield, Missouri. The second workshop was held on June 10, 2013, from 1:00 pm to 5.30 pm in Denver, Colorado, in conjunction with ACE 2013. The third workshop was held on June 23, 2013, from 9:00 a.m. to 12:00 pm in Fort Worth, Texas, in conjunction with the ASCE Pipelines 2013 Conference. This appendix covers the details and findings of these workshops.

OBJECTIVES

The objectives of the Project Workshops were to obtain as much input as possible from the participating industry professionals from water utilities, HDPE manufacturers/vendors and Plastics Pipe Institute (PPI) representatives by conducting small and large group discussions.

WORKSHOP AGENDA

8:00 – 8:10 a.m.	INTRODUCTIONS
8:10 – 8:30 a.m.	PRESENTATION BY P.I. ABOUT RESEARCH
8:30 – 9:15 a.m.	BRAINSTORMING (OPEN SESSION)
9:15 – 9:30 a.m.	DISCUSSION ON TESTING
9:30 – 9:45 a.m.	PRIORITIZING/RANKING IDEAS
9:45 – 10:00 a.m.	BREAK
10:00 – 10:15 a.m.	DISCUSSION OF CASE STUDIES
10:15 – 10:30 a.m.	PRESENTATION OF PRIORITIZED LIST
10:30 – 11:15 a.m.	SMALL GROUP DISCUSSION ON HIGHLY PRIORITIZED IDEAS
11:15 – 11:45 a.m.	PRESENTATION FROM EACH SMALL GROUP
11:45 – 12:00 p.m.	CONCLUSIONS, REMARKS & FUTURE ACTIVITIES

Attendees

Twenty-four attendees including HDPE manufacturers/vendors, water utility representatives from larger utilities, design consultants, contractors, university faculty, representatives from PPI, and key project team members participated in the workshop. Table B.1.1 is a complete list of workshop attendees.

Table B.1.1
List of attendees for project workshop # 1

Name	Organization	Category
Tara McGuwan	Colorado Springs Utilities	Utility Representative
Holly Link	Colorado Springs Utilities	Utility Representative
Pat White	Colorado Springs Utilities	Utility Representative
John Fishburne	City of Charlotte	Utility Representative
Greg Scoby	FES (city of Palo Alto, CA retired)	Utility Representative
Casey Hayes	Springfield, MO City Utilities	Utility Representative
Chad Owens	Springfield, MO City Utilities	Utility Representative
Steve Squibb	Springfield, MO City Utilities	Utility Representative
Luis Aguiar	Miami Dade Water County	Utility Representative
Brian Schade	Water One	Consultant
Joe Castronovo	Consultant (AECOM, retired)	Consultant
Fred Ostler	PEC	Consultant
Wes Long	Performance Pipe	Pipe/Equipment Supplier
Harvey Svetlik	Georg Fischer	Pipe/Equipment Supplier
Collin Orton	TT Technologies	Pipe/Equipment Supplier
Tom Iseley	IUPUI	Research/Educational Organization
Camille Rubeiz	PPI	Professional/Industry Association
Dede Hart	PPI	Professional/Industry Association
Mohammad Najafi	CUIRE	Project Team
Ahmad Habibian	Black & Veatch	Project Team
Joe Mantua	Black & Veatch	Project Team
Firat Sever	Benton & Associates	Project Team
S. John Calise	Benton & Associates	Project Team
Abhay Jain	CUIRE	Project Team

Introductions & Presentation by Principal Investigator (PI)

After a brief self-introduction of each Project Participant, the PI gave a PowerPoint presentation to introduce the project scope and objectives. The introductory session culminated in a forum for the participants to offer ideas and express their expectations regarding the research.

For instance, almost all of the workshop participants and specifically the utility representatives participating in the workshop stated that the threshold for large size HDPE pipe is

16 in. The lowering of the size threshold will expand the experience base with use of HDPE, as history of use with larger pipe sizes may not be extensive.

Brainstorming Session

Following the introductory session, the workshop participants were engaged in a brainstorming session with the objective of developing a list of all issues the workshop participants thought were critical to the success of the project. Table B.1.2 presents the topics that were brought up by the participants during the brainstorming session on the issues related to HDPE pipe.

Table B.1.2
Topics discussed during brainstorming session

Topic #	Topics
1	Perception Issue
2	Third Party Damage (Outside Damage)
3	Comparison to Other Pipe Products
4	Installation Aspects/Contractor
5	Proven Track Record – EUROPE
6	Modes of Failure
7	Amount of Maintenance – Life Cycle Cost Analysis
8	Service Life
9	Life Reliability Curves
10	Specifications, Design, Installation/Contractor, Inspection, Maintenance
11	Asset Management Plan
12	Connection/Fittings
13	PE Material History/Variations
14	Permeations of Hydrocarbons
15	Disinfection Byproducts Impact
16	Seismic Activities
17	Regional Issues
18	Freeze/Thaw
19	Expansion/Contraction – Effects on Fittings
20	Trenchless Installation – Scoring
21	Jointing Methods/Fusion, Mechanical
22	Fusion at Colder Temperatures

Following the brainstorming session, the participants were asked to rank these topics and the top three topics were further discussed in smaller group settings. Further details of these activities are provided in sections 9 and 10 of this appendix.

Discussion on Testing

The following testing possibilities were brought up by the participants and a discussion on the merits and drawback of each took place. No definitive conclusion was arrived at regarding testing.

A. High pressure cyclic loading fatigue test – 10 million cyclic loads with 1.5 times the pressure rating will be applied to the HDPE pipe. This will show the behavior of the pipe under surge pressure.
B. Joints: Testing HDPE pipe with, fused joints, mechanical joints and fittings (e.g. tees and bends). This will show performance of the joints along with pipe.
C. Comparison: Perform same test on HDPE and PVC pipe and compare the results.

Discussion on Case Studies

In the project workshop the participants suggested utilities that may provide case studies based on their experience with large diameter HDPE. These utilities are as follows:

1. City of Palo Alto, CA
2. City of Charlotte, NC
3. Miami – Dade , FL
4. City of Colorado Springs, CO
5. City of Springfield, MO
6. Water One, KS

A template will be provided to the utilities for case histories. It will include utility name, project name, pipe size, pipe length, construction cost, background, design parameters, construction challenges, project highlights, and conclusions.

Prioritizing and Ranking of Topics

In order to prioritize the suggested topics, each participant was given the opportunity to distribute a total of 1000 points among the top three to five topics of their choice, with no topic getting a score of more than 500. The scoring provided by the participants was collected and analyzed. Figure B.1.1 shows the total points each topic received from the participants. The top five topics were further consolidated into three broad topics as listed in Table B.1.3. Three small groups were formed to further discuss these three topics.

Table B.1.3
Top three topics

Topic #	Top Five Topics	Group
10	Specifications, Design, Installation/Contractor, Inspection, Maintenance	1
1& 3	Perception Issue & Comparison to Other Pipe Products	2
21& 12	Jointing Methods/Fusion, Mechanical, Connection/Fittings	3

Small Group Discussions

The participants were divided into three groups. One or more Project Team member was present in each group to ensure the project team was able to capture the essence of the discussion from all the three groups. Following the group discussions, a representative from each group gave a verbal report of the group's finding to the full team of participants and a short discussion ensued. The information generated by each group is presented below:

<u>Small Group #1 Specification, Design, Installation/Contractor, Inspection, Maintenance: Participants: Tara McGuwan (Leader); John Fishburne; Greg Scoby; Brian Schade; Camille Rubeiz; Abhay Jain; Casey Hayes; Tom Iseley</u>

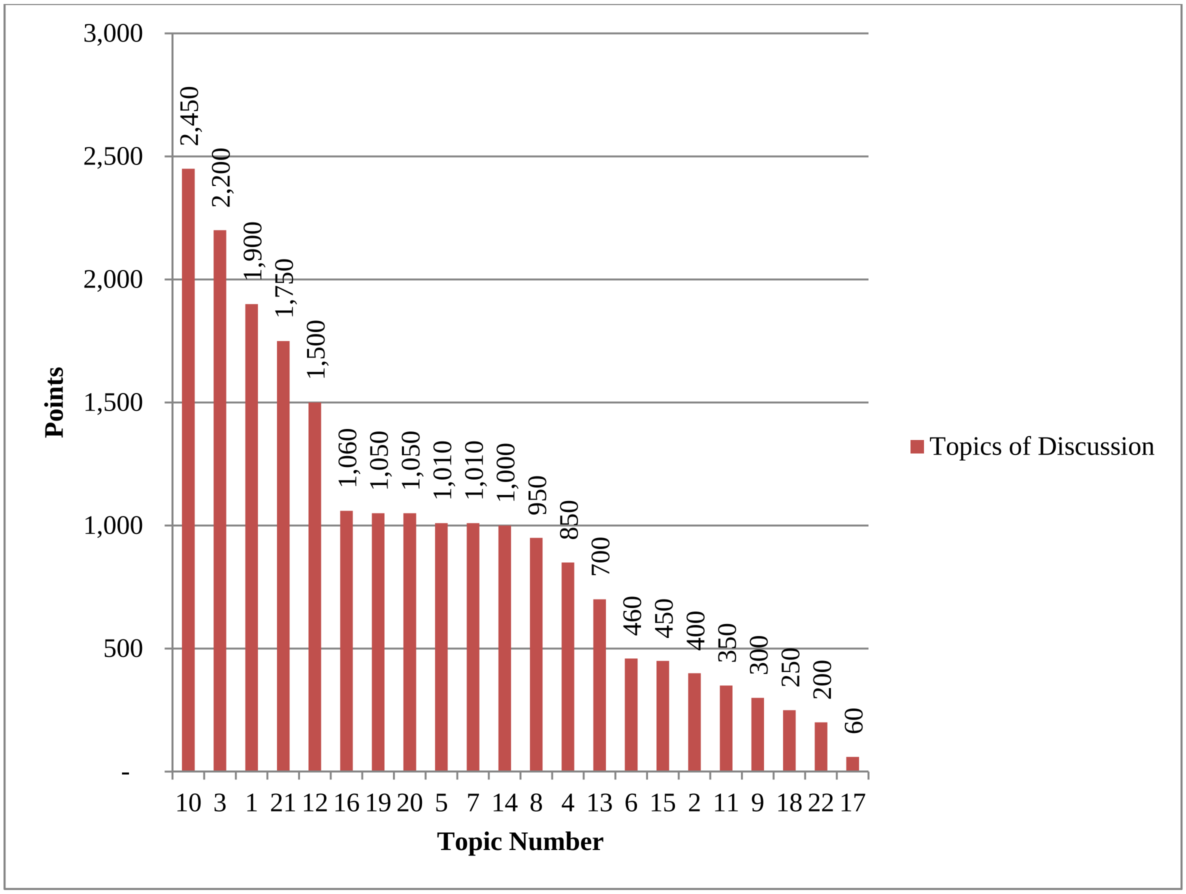


Figure B.1.1 Points received for each topic

Specifications play an important role in installation of HDPE pipe. The project should define specification for maximum durability. It should include following topics:

1. Fittings
2. Fusions
3. Mechanical Connections
4. Quality Assurance/Quality Control
5. Testing

6. Certifications
7. Design Specifications
    a. Connection to other materials
    b. Joint Restraints
    c. Thermal movement
    d. Poisson effects
    e. Disinfection (Chlorine)
8. Training
9. Inspections (pre and post)
10. Construction Specification
    a. Bedding/haunching and Backfill
    b. Handling
    c. Trenchless Specifications
    d. Fitting Specifications
11. Repair Methodology
12. Equipment Qualification
13. Installer Qualification
14. Geotechnical Specifications
15. Design Life

Small Group #2 Perception Issues/ Comparison to Other Pipe Products/:
Participants: Luis Aguiar (Leader); Joe Mantua; Holly Link; Firat Sever; Collin Orton; Wes Long; Joe Castronovo; Steve Squibb; S. John Calise

1. Lack of knowledge about the product is an issue; people associate HDPE with Polybutylene pipe. Utilities need a driver to change. Why take the chance, they consider it a risk, so there needs to be a reward identified.
2. Colorado Springs indicated they have had failures and growing pains. Their drive to use HDPE started with corrosion issues.
3. There are numerous levels that you have to educate including the decision makers, specification writers, field staff and users.
4. Two big issues are training and familiarity. Utility workers want to be comfortable with using a product and familiar with the repair methods and materials.
5. Utilities that are using HDPE in many cases are using it for the most complex, environmentally sensitive projects that typically involve trenchless installation by horizontal directional drilling (HDD) or pipe bursting. The light bulb has not gone on as they don't seem to think to use it for the less complicated projects.
6. Price is a consideration but must look at the overall picture and life cycle benefits. In Colorado Springs, material price for HDPE is higher than ductile iron but there are other considerations including HDPE response to dynamic pressure, soil conditions and seismic activity. HDPE becomes more cost competitive for large diameter applications.
7. Contractors have a lot to offer and can be helpful, need to listen to their experiences.

Overall, the areas to focus on were:

1. Success stories and lessons learned – take advantage of the experiences of utilities that are using HDPE and share their stories. Failures can be a great learning tool also.
2. Need to hear testimonials from utilities. These will resonate with other utilities
3. Education is a key. Must educate staff so that they are familiar with the material, installation and repair methods, etc.
4. Life cycle cost – too much emphasis is often placed on the pipe cost and not the bigger picture. Must factor into decision the life of the pipe, maintenance costs etc. to get the full picture.
5. What are you selling? – Highlight the advantages and specific applications for HDPE. Help utilities understand where it makes sense to use.

<u>Small Group 3 # Jointing Methods/Fittings (Fusion and Mechanical)</u>:
<u>Participants: Mohammad Najafi (Leader); Harvey Svetlik; Ahmad Habibian; Chad Owens; Pat White; Fred Ostler</u>

1. Mechanical fitting availability/hybrid fittings
2. There is a booklet on fittings – Harvey
3. Need procedures for fittings, such as MJ and saddle requirements
4. Where do you get information on fittings and jointing?
5. Gas experience should be shared with water applications
6. Training is required for large diameter applications
7. Specialty (trained) contractor is needed for proper installations
8. Need standard specifications for HDPE and PVC connections
9. Need to know what works and what does not work
10. Need information on 12 in. and larger butterfly valves – MJ adapters do not work
11. For 16 in. and larger, industry should adapt to larger sizes
12. There are “end-of-the-pipe” problems
13. Data loggers should record temperature, pressure and time
14. Similar certification as NASSCO provides is needed for staff
15. Equipment certification is also necessary
16. There should a “Polyethylene Center of Excellence.”
17. Pipe manufacturers should provide training
18. There should be contractor qualifications and certification
19. Need trade school programs
20. Need inspector training
21. The important parameters are: design, specifications, design life, contractor qualification and training, repair methodology, and operation and maintenance**.**

As provided in the following section, three members of this group volunteered to provide a short write-up on their experience regarding HDPE fittings and connections.

Polyethylene Fittings and Connections

Polyethylene pipe has been used successfully for 51 years, following its first commercial installations in 1963. Worldwide, polyethylene pipe is accepted as the primary choice of a ductile strain-tolerant material for leak-free, welded (fused) water and gas transport pipe which can endure burial loads, earthquakes, trenchless installation, and water-hammer fatigue, for an expected design service life of 100-years.

Extruding straight pipe or coiled pipe is simple. To own a pipe system or water distribution pipe net-work, a large variety of fittings and connections to other components and accessories is required. These fittings can be molded, machined, or fabricated. All pipe fittings are pressure vessel components which should be designed by pressure vessel engineers and validated by physical testing to verify their pressure performance limits. This is what USA and European and Global polyethylene pipe and fittings manufacturers have done to provide a complete system with the required longevity and system reliability. The principle of design is to reinforce the fitting geometry with extra pipe-wall mass, so as to lower local geometry stress concentrations back down to an acceptable level, parallel to the hoop-stress intensity in the system's pipe wall. The following are the typical components used in a polyethylene water distribution system. Additional information on connections can be found at:
http://plasticpipe.org/pdf/mid-pe-field-manual-municipal-water-applications.pdf

Flanges: The basic connection to valves and other pipe materials is the polyethylene flange joint. Typically, the joint uses a polyethylene flange adapter and a rotatable lap-joint metal bolt-ring. The polyethylene pie industry uses a contoured bolt ring against the back-face of the polyethylene flange hub, to squeeze the flange face and to seal the connection by facial pressure well exceeding the flow-stream pressure. The flange adapters are polyethylene, but the bolt-rings are metal, typically Ductile- Iron or stainless steel, and can be galvanized or epoxy coated. Guidance on making the flange connection by torqueing the flange-bolts is given in the bolt torque guidance document: http://plasticpipe.org/pdf/tn-38_bolt_torque_flanged_joints.pdf

Mechanical Joint Adapter: The polyethylene MJ Adapter (MJA) was invented in 1997, and has 18 years of very successful leak-free performance. This fitting spigot sockets into the standard 'mechanical joint' of all ductile-iron pipe and fittings from 2-inch diameter to 54-inch diameter, sealed by compression of the standard rubber MJ gasket. Typically, the MJ Adapter is delivered with a stainless-steel stiffener below the rubber gasket, internal to the ID of the MJ Adapter. This internal stiffener supports the gasket load and counteracts the effects of thermal diameter contraction induced by winter's cold waters. The hub of the MJ Adapter compresses the gasket under load from the standard gland ring, and seals the connection. The thickness of the MJA hub is sufficient to exceed the tensile strength of the pipe fused to the MJA, such that this joint connection is fully restrained, and will NOT pull out of the MJ bell.

Transition Fitting: The transition fitting is a permanent, factory-made joint which connects polyethylene pipe to any other pipe material, by use of an O-ring sealed, circumferential compressive fit of the polyethylene around or into the other pipe material such as steel pipe, ductile-iron pipe, PVC pipe, fiberglass pipe, stainless steel pipe, brass or copper pipe, etc. It can be engineered to resist full pressure and full tensile loading, or, just pressure sealing with reduced axial tensile load capacity.

Elbows: Elbows or 'bends' may be molded in diameters through 12-inch, and fabricated by heat fusion of mitered gore-pipe segments up through diameters of 63-inch. ASTM F2206, paragraph 1.3, specifies that the elbows shall be EDR fittings (Equivalent DR to the pipe main) so that the fitting is fully pressure rated the same as the pipeline itself. Because the miter joint removes material from straight pipe, a thicker-wall gore-pipe segment is typically used to reinforce the elbow geometry to provide full pressure rating. The increased wall thickness can be 'applied' to the pipe ID or to the pipe OD. Hence, the descriptive elbow language is: constant-OD EDR xx, or, constant-ID EDR xx Elbow. Elbows may be fabricated with 3 standard miter-cuts of: 11.25^0, 15^0, 22.5^0 miters. For a 90^0 elbow (1/4 bend), these miter cuts form 5-segment, 4-segment, 3-segment elbows. The 4-segment ells are the optimum of pressure capacity, size, and economics. 4-segment 90-degree elbows are used world-wide.

Line Tee; Cross: Equal Outlet 'Line-Tee' are typically molded in diameters up through 12-inch. The Equal outlet tees are fabricated from heavier wall pipe segments, in diameters 2-inch to 63-inch. Again, the ASTM F2206 language of 'Constant-OD, or, Constant-ID' EDR xx prevails, to assure full pressure rating of the tee equal to that of the polyethylene pipeline. Cross fittings are fabricated from mitered pipe segments, or pipe main with reducing massive base branch saddles.

Reducing Tees: Reducing tees typically use a branch-outlet that is smaller than the pipe main diameter for branch outlets less than 65% of the pipe main diameter, a massive base, side-wall fused branch-saddle is fused to the pipe main to form the reducing tee. For branch outlets larger than 65% of the pipe main diameter, typically a line tee is used, and reducers fused onto the line tee outlet to reduce the outlet diameter to the desired size. The large base or massive base branch saddles provide additional mass to surround and reinforce the outlet "hole" cut through the pipe main. The design of the branch- saddle base follows the guidelines of the ASME BPV Code, using the guidance rules of the 'area-replacement' method to provide full pressure rating. Sidewall fusion is a proven joining technology, basically being a curvilinear butt-fusion joint.

Reducers: There are so many reducer combinations involving diameter ranges and permutations and combinations of sizing systems such as IPS, DIPS, CTS, PIP. The design rules for reducers are simple, but still require sufficient mass to provide a pressure rating greater than that of the pipe itself. Conical reducers are used for pressure pipe systems. ASME pressure vessel design rules for conical components apply. Large size reductions may require flat-plate reducers, which are designed using ASME BPV design rules for "Blanks" or welded blinds. The thickness of the plate must be sufficient to 'blank' off or flat-plate 'cap' the pipeline while holding full pressure. The flow of liquid through the flat-plate type reducer stagnates in the circumferential corner, idling there, and forming a natural cone-of-flow in the central section tapering down to the outlet diameter, with minimal turbulence. While a conical reducer 'looks' good, both the flat-plate and conical reducers provide about the same resistance to flow due to trade-offs in the ratio of inlet to outlet diameter, overall length of the reducer, and resultant angle of taper.

Wyes: Wyes are a special case of angled branch outlets. The typical fitting is a 45-degree lateral WYE with equal or reducing branch diameter. For pressure pipeline systems, because of the 'wishbone' geometry of the lateral WYE, its strength is about 1/3rd to 40% of the pressure capacity of the pipe from which it is made. Hence to obtain an EDR xx, the WYE is typically fabricated from pipe that is 2.5 to 3 times the wall thickness of the pipe main itself. However, for gravity flow purposes, wall thickness increase does not apply. Hence, for fully pressurized WYEs, the WYE is usually made as a constant-ID EDR xx fitting, wherein the OD is enlarged, so as to not constrict the ID with extra wall thickness.

SLIP-JOINT Gasket Fitting: Polyethylene pipe can be joined with PVC pipe and Ductile-iron pipe by insertion into their bell gasket. This fitting is machined from heavy wall polyethylene pipe leaving a circumferential HUB in the middle, with an extended ‘nose’ on the insertion-end going into the gasketed ‘bell’ of the PVC or DI pipe, and with the other end being the butt-fusion end which joins to the polyethylene pipe main. A JCM Bell restraint kit can be applied to the joint to restrain the polyethylene hub and PVC bell from separating (fully restrained joint).

Wet-Tapping Tees: Water mains and natural gas pipe mains need to deliver fluids to homes, farms, factories. One method to do this is to sidewall fuse a self-tapping or a tap-able branch-saddle to the OD of the pipe main. The base of the branch-saddle / service saddle or tapping tee reinforces the pipe main and allows a hole to be cut to deliver the fluid as service to the user. Hot-tap or wet-tap tees are typically sidewall or electro-fused to the pipe main. Additional information on electro-fusion tap tees can be found at: http://www.georgfischer.hr/media/katalog/upute-Electro%20Fusion%5B1%5D.pdf
http://www.bing.com/videos/search?q=georg+fischer+video+electrofusion&FORM=VIRE6#view=detail&mid=14F90D9474FC0B48C70414F90D9474FC0B48C704

Electro-Fusion Couplings: Traditionally, polyethylene pipes are butt-fused. The fusion joint is leak-free. Occasionally, a repair or a new service requires the installation of a line tee or a new piece of pipe. The ordinary butt-fusion machine sometimes does not fit into the excavated ‘pit’. To join the new pipe and fittings, an electro-fusion coupler is used to complete the work, versus butt-fusion. More information on electro-fusion couplers can be found here: https://www.youtube.com/watch?v=RPsQhLrw-_0

Thrust Anchors / Water Stops: When thermal expansion or contraction is of interest. The potential movement of the polyethylene pipe can be constrained and managed by use of a thrust anchor fitting, which prevents axial movement, by transferring the active load through the HDPE fitting into a concrete thrust block, into the passive soil mass. The fitting is a monolithic component machined from a heavy-wall polyethylene pipe, having the same dimensions as the pipe-main on each end, with a central HUB radially larger than the pipe diameter. The hub is typically embedded in re-bar reinforce concrete to transfer expansion or contraction forces into the soil to hold the pipe in position, thus constraining and preventing movement. The thickness of the hub is sufficient to exceed, in shear, the axial tensile strength of the pipe itself. The pipe would pull apart before the hub would shear off.

Caps: The industry typically uses tori spherical domed end-caps molded in diameters from ½ -inch to 12-inch. In larger diameters, a flat-plate end-cap is used in diameters up through 36-inch. In larger diameters, a flange adapter with blind-flange is typically used to ‘cap’ a pipeline.

Pull Heads: Trenchless installation of polyethylene is frequently done. To pull the pressure main through the subterranean bore-hole or host pipe, a pull-head is required. High performance pull heads are designed for pull-strength equal to that of the pipe itself. Installation length from a few hundred feet to over a mile in length have been done using high integrity pull heads. Users should insure that the pull-head received is rated for the tensile requirements of the specific project.

Accessories: Mechanical clamps, mechanical tap saddles, and other mechanical connections are available and are discussed at length in the Plastics Pipe Institute Field Handbook, downloadable from: http://plasticpipe.org/pdf/mid-pe-field-manual-municipal-water-applications.pdf

CONCLUSIONS

The project workshops provided valuable input to the project and assisted the Project Team to improve upon the project scope and experimental approach. The structured approach utilized for the workshop allowed the critical topics to be identified in an efficient manner. The limited and valuable time of participants was mostly devoted to discussion of the most critical topics. The workshop enabled the project team to explore different perspectives and identify several studies and experiences brought up by the project participants. Specifically, the following areas were identified as deserving special attention during the course of this research project:

- Role of specifications, installer training and certification.
- Operation and maintenance.
- Pipe joints and connections.

FUTURE ACTIVITIES

All the participants were invited to two future workshops. These workshops will be at ACE 2013, in Denver, on Monday, June 10, 2013, from 1:00 PM to 5:00 PM, and at ASCE Pipelines 2013 Conference in Fort Worth, Texas, on Sunday, June 23, 2013, 9:00 AM to 1:00 PM, at Renaissance Worthington Hotel in Fort Worth, Texas.

B.2. WORKSHOP # 2

Agenda

1:00 – 1:10 p.m.	INTRODUCTIONS
1:10 – 1:45 p.m.	PRESENTATION BY P.I. ABOUT RESEARCH
1:45 – 2:30 p.m.	DISCUSSION ON TESTING
2:30 – 3:15 p.m.	DISCUSSION ON CASE STUDIES
3:15 – 3:30 p.m.	BREAK
3:30 – 4:30 p.m.	BRAINSTORMING (OPEN SESSION)
4:30 – 5:00 p.m.	CONCLUSIONS, REMARKS & FUTURE ACTIVITIES

Attendees

Twenty-one attendees including HDPE manufacturers/vendors, water utility representatives from larger utilities, design consultants, contractors, university faculty, representatives from PPI, and key project team members participated in the workshop. Table B.2.1 is a complete list of workshop 2 attendees.

Table B.2.1
List of attendees for project workshop # 2

Name	Organization	Category
Holly Link	Colorado Springs Utilities	Utility Representative
John Fishburne	City of Charlotte	Utility Representative
Chad Owens	Springfield, MO City Utilities	Utility Representative
Ken Morgan	City of Phoenix	Utility Representative
David Marshall	Tarrant Regional Water District (TRWD)	Utility Representative
Jason Gehrig	Tarrant Regional Water District (TRWD)	Utility Representative
Andrew De Graca	San Francisco Public Utilities Commission	Utility Representative
Sameer Mehta	Lyondell Basell	Consultant
Matthew Thistleton	ISCO	Pipe/Equipment Manufacturers
Mike Whitehouse	ISCO	Pipe/Equipment Manufacturers
Frank Lopez	MPS	Pipe/Equipment Manufacturers
Harvey Svetlik	Georg Fischer	Pipe/Equipment Manufacturers
Heath Casteel	Performance Pipe	Pipe/Equipment Manufacturers
Chase Avansnkul	Performance Pipe	Pipe/Equipment Manufacturers
Stephen Boros	Georg Fischer	Pipe/Equipment Manufacturers
Camille Rubeiz	PPI	Professional/Industry Association
Mohammad Najafi (Leader)	CUIRE	Project Team
Ahmad Habibian	Black & Veatch	Project Team
Joe Mantua	Black & Veatch	Project Team
Abhay Jain	CUIRE	Project Team
Jian Zhang	WRF	Research/Educational Organization

Introductions & Presentation by Principal Investigator (PI)

After a brief self-introduction of each Project Participant, the PI gave a PowerPoint presentation to introduce the project scope, objectives, workshop # 1 details, experimental details and case studies. The introductory session culminated in a forum for the participants to offer ideas and express their expectations regarding the research.

Survey

Survey has been sent to more than 100 U.S. utilities. Pipe manufacturers suggested project team to send survey to Tucson, AZ; San Antonio, TX, St. Petersburg, FL; Indianapolis, IN, Jacksonville, FL; and West Palm Beach County, FL. All these utilities have used 16 in. and larger HDPE pipe in their water system. Also project team will send the survey to pipe manufacturers so that they can forward it to their clients. This will help project team to get as much information about the large diameter (16 in. and larger) HDPE pipe.

Discussion on Testing

The high pressure cyclic loading fatigue test setup was shown to the workshop participants. Following are the suggestions given by them:

1. Proper literature review should be conducted to ensure the proposed test has not been done in the past. Literature search shows that to date, cycling loading fatigue test has been done on small diameter (4 – 12 in.) HDPE pipes only.
2. The test pipe should be instrumented with strain gages.
3. The test pipe should be given enough time to retract after each cyclic loading.
4. Once the test reaches 10 million cycles, the test piece should be tested for creep and other properties. It should also be visually inspected.
5. The test pipe should be brought to failure (burst test) after the test ends.
6. The test pipe should be bending and cyclic loading should be applied to see the behavior.

Discussion on Case Studies

The PI presented three case studies and requested the participants of utilities to provide them with case studies based on their experience with large diameter HDPE. The WRF project team will send the case studies template to Holly Links of City of Colorado Springs, Co; Chad Owens of City of Springfield, Mo; Ken Morgan of City of Phoenix, AZ; and Jason Gehrig of Tarrant Regional Water District (TRWD). David Marshall of TRWD mentioned that they installed 6,000 ft of 42 in. HDPE pipe (100 psi) in 2002 and have not experienced any problems as of the date of workshop (2013).

Brainstorming Session

Following the break, the workshop participants were engaged in a brainstorming session with the objective of developing a shorter list of issues from the topics of workshop (#1). Table B.2.2 presents the list of topics that was short-listed from the topics covered in Workshop #1 as listed in Table B.1.2.

Table B.2.2
Topics short-listed from Table B.1.2

Topic #	Topics
1*	**Design**
2	**Installation**
3	**Repair and Operations & Maintenance (O&M)**
4	Change of Surface Conditions
5	QA/QC of Manufacturers
6	Life Cycle Cost
7	**Perception**
8	**Connections/Fittings**

*The highlighted items were discussed in more details at Workshop #2

From the topics presented in Table B.2.2, the participants were asked to select five topics that were further discussed among them. The topics that were selected are highlighted in Table B.2.2. Further details of these activities are provided in Sections 21 through 25 of this report.

Perception

The participants mentioned the following perception issues and solutions:

The following issues were identified by workshop participants:

1. Not for Water
2. New to Market
3. Comfort Zone
4. New Equipment/Tools
5. Asset Management
6. Requires Training
7. Polybutylene
8. Inventory
9. Risks
10. Resistance to Change
11. Incomplete Specs (Flow, Cycles, Years)

The following potential solutions were mentioned by workshop participants to address the identified issued listed above:

1. Utilities that provide both Gas/Water
2. Simplification of Product
3. Center of Excellence
4. Provide Benefits like Life Cycle Costs, Life Expectancy
5. Leak Free
6. Usage in Right Applications
7. Work on Limitations like Capital Cost , Cost to Adopt

8. Energy Management
9. Collect Sample Specifications from Utilities

Connections/Fittings

The following issues were identified by workshop participants:

1. Availability
2. One Source for Pipe & Fittings
3. Develop One ASTM & AWWA Standards
4. Special Orders
5. DIP Size/IPS Size
6. Need for Industry Guidelines
7. Better Valve/Connections Options
8. Pricing Due to Lack of Competition
9. Education/Training Materials

Design

The following issues were identified by workshop participants:

1. Importance of Specs
2. Requirement of Experienced Designer
3. Training for Engineers
4. Rigorous Quality Based Selection (QBS) Process for Design Engineer Selection
5. Tools for Engineers
6. Level of Experience

Installation

The following issues were identified by workshop participants:

1. Experienced Contractor
2. Personnel Experience
3. Certification
4. Industry Guidelines, e.g. AGA
5. Equipment
6. Marketing to Gas Contractors – Distribution Size
7. Pipe Manufacturers Field Observations
8. Inspection – Full time
9. Inspector Training
10. Proof Testing
11. Groundwater Control
12. Acceptance Testing
13. Backfill

Repair, Operation and Maintenance (O&M)

The following issues were identified by workshop participants:

1. Ease of Repair
2. Standard Guidelines
3. Educational Materials
4. Experienced Repair Professionals
5. Tapping Process
6. Non-destructive Evaluation
    a. 10-15 Years Cycle?
    b. Development of Tools
7. Bathtub Curve Driven Inspection Schedule
8. Failure Forensics

CONCLUSIONS

This project workshop provided valuable input to the project and assisted the Project Team to improve upon the project scope and experimental approach. The structured approach utilized for the workshop allowed the critical topics to be identified in an efficient manner. The limited and valuable time of participants was mostly devoted to discussion of the most critical topics. The workshop enabled the Project Team to explore different perspectives and identify several studies and experiences brought up by the project participants. Specifically, the following areas were identified as deserving special attention during the course of this research project:

- Perception Issues
- Connection/Fittings
- Design
- Installation
- Repair and O&M

FUTURE ACTIVITIES

All the participants were invited to future workshop (#3) at ASCE Pipelines 2013 Conference in Fort Worth, Texas, on Sunday, June 23, 2013, 9:00 AM to 12:00 PM, at Bur Oak Room, Mezzanine Level of Renaissance Worthington Hotel in Fort Worth, Texas.

B.3. WORKSHOP # 3

Agenda

9:00 – 9:10 a.m.	INTRODUCTIONS
9:10 – 9:45 a.m.	PRESENTATION BY P.I. ABOUT RESEARCH
9:45 – 10:15 a.m.	DISCUSSION ON SURVEY RESULT AND TESTING
10:15 – 10:30 a.m.	DISCUSSION ON CASE STUDIES
10:30 – 10:45 a.m.	BREAK
10:45 – 11:45 a.m.	BRAINSTORMING (OPEN SESSION)
11:45 – 12:00 p.m.	CONCLUSIONS, REMARKS & FUTURE ACTIVITIES

Attendees

Twenty attendees including HDPE manufacturers/vendors, water utility representatives from larger utilities, design consultants, contractors, university faculty, representatives from PPI, and key project team members participated in the workshop. Table B.3.1 is a complete list of workshop attendees.

Table B.3.1
List of attendees for project workshop # 3

Name	Organization	Category
Dennis Abraham	Dallas County	Utility Representative
John Fishborne	City of Charlotte	Utility Representative
Abidur Khan	Dallas Water Utility	Utility Representative
James Thomson	Consultant	Consultant
Greg Scoby	Crossbore Consultants	Consultant
Ernest Lever	Gas Technology Institute	Consultant
Frank J. Blaha	WRF	Research/Educational Organization
Tom Iseley	Indiana University-Purdue University Indianapolis	Research/Educational Organization
Baosong Ma	China University of Geosciences	Research/Educational Organization
Mark Knight	University of Waterloo	Research/Educational Organization
Timmy Tipton	IPF Plasson	Pipe/Equipment Supplier
Dustin L. Langston	WL Plastics	Pipe/Equipment Supplier
Joe Castronovo	Retired	Consultant
Camille Rubeiz	PPI	Professional/Industry Association
Jian Zhang	WRF	Research/Educational Organization
Mohammad Najafi (Leader)	CUIRE	Project Team
Ahmad Habibian	Black & Veatch	Project Team
Firat Sever	Benton and Associates	Project Team

(Continued)

Table B.3.1 (Continued)

Name	Organization	Category
Abhay Jain	CUIRE	Project Team
Pejman Rezakhani	CUIRE	Project Team
Divyashree	CUIRE	Project Team

Introductions & Presentation by Principal Investigator (PI)

After a brief self-introduction of each project participant, the PI gave a PowerPoint presentation to introduce the project scope, objectives, workshop # 1 and #2 details, experimental details, and case studies. The introductory session culminated in a forum for the participants to offer ideas and express their expectations regarding the research.

Survey

Survey has been sent to more than 400 U.S. utilities including Tuscan, AZ; San Antonio, TX, St. Petersburg, FL; Indianapolis, IN, Jacksonville, FL; and West Palm Beach County, FL which have used 16 in. and larger HDPE pipe in their water system. Also project team has sent the survey to pipe manufacturers to be forwarded to their clients. Up to date, 49 replies to the survey have been received in which 44% of respondents mentioned that they have large diameter (16 in. and larger) HDPE water pipe in use. The survey results along with comments received by utilities were presented to the workshop participants.

Discussion on Testing

The high pressure cyclic loading fatigue test setup was presented at the workshop. Input provided by the participant included the following:

1. Fatigue test has not been conducted for large diameter (16 in. and larger) HDPE pipes in the past. Full-scale testing would be beneficial.
2. The test pipe should be instrumented with strain gages.
3. Using regular water with no additives is sufficient.
4. More than one sample should be tested to compare the results.
5. End caps should be designed with proper air and water release valves.
6. Air and water release valves should be installed on end caps to avoid their effect on pipe.
7. Test should be conducted in a controlled temperature environment.
8. The shape of the cycling load wave should be designed such that the pipe has adequate time to respond before the next cycle arrives.
9. Explore fatigue testing done by other researchers to determine the appropriate frequency of loading.
10. If the results are to be compared with previously available data, the test configuration should be compatible with previous testing. For example, restraining of end caps would be needed for this purpose. However, if the tests are to stand on their own, restraining of caps would not be necessary.

Discussion on Case Studies

The PI presented eight case studies and requested the participants of utilities to provide them with case studies based on their experience with large diameter HDPE. The information provided for each of these case studies included utility name, project name, pipe size, pipe length, construction cost, background, design parameters, construction challenges, project highlights, and conclusions. Participants suggested a case by case cost comparison of case studies with pipe materials other than HDPE.

Brainstorming Session

Following the case studies presentation, the workshop participants were engaged in a brainstorming discussion of the survey highlights including the ratings of durability and reliability of HDPE pipes, causes and modes of rupture of PE4710/PE3608/PE3408, installation methods, leakage, concerns/issues of using HDPE pipes and list of issues from the topics of workshop (#1 and #2). Table B.3.2 presents the topics that were brought up by the participants during the brainstorming session on the issues related to HDPE pipe in workshop # 1 and # 2. Table B.3.3 presents the list of topics that were brought up by the participants during the brainstorming session on the issues related to HDPE pipe in the workshop #3.

Table B.3.2
Topics discussed during brainstorming sessions of workshops # 1 and # 2

Topic #	Topics
1	Perception Issue
2	Third Party Damage (Outside Damage)
3	Comparison to Other Pipe Products
4	Installation Aspects/Contractor
5	Proven Track Record – EUROPE
6	Modes of Failure
7	Amount of Maintenance – Life Cycle Cost Analysis
8	Service Life
9	Life Reliability Curves
10	Specifications, Design, Installation/Contractor, Inspection, Maintenance
11	Asset Management Plan
12	Connection/Fittings
13	PE Material History/Variations
14	Permeations of Hydrocarbons
15	Disinfection Byproducts Impact
16	Seismic Activities
17	Regional Issues
18	Freeze/Thaw
19	Expansion/Contraction – Effects on Fittings
20	Trenchless Installation – Scoring
21	Jointing Methods/Fusion, Mechanical
22	Fusion at Colder Temperatures

(Continued)

Table B.3.2 (Continued)

Topic #	Topics
23	Change of Surface Conditions
24	QA/QC of Manufacturers
25	Life Cycle Cost

Table B.3.3
Topics discussed during brainstorming session of workshop #3

Topic #	Topics
1	Internal Abrasion
2	Life Time Prediction Curve
3	Training/Qualifications
4	Supply Chain Management
5	Tracking (Asset Management)
6	Learning from other Applications (Example: Book on use of HDPE for Ocean Outfalls)
7	Time to Repair & How to Repair
8	Lead Time for Fittings

In addition, the participants provided the following comments:

1. HDPE is offered in many sizes, wall thicknesses and cell classifications. While this versatility provides flexibility, it also can cause confusion. A simplification of production line items may be beneficial in this regard.
2. Molded fittings are not available on all sizes and fabricated fittings for large diameters are not always readily available. It appears that it is not cost-effective to make molded fittings if the demand is low.
3. The end user prefers to obtain the pipe and associated fittings and accessories (such as pipe stiffeners) from the same source, rather than going to different vendors.
4. Experience has shown that installation practices are very critical to the long term durability and reliability of HDPE pipe installations. Using certified workers can address this issue.
5. Utilities should consider performing forensic evaluation of failure incidents to learn from the failure and ensure the root cause of failure is established and eliminated from future design. During forensic evaluation, it is critical that the field personnel be interviewed as they are often most knowledgeable about what might have led to the failure.
6. Inspection during production, delivery and installation is critical for long-term success.
7. Procedures for tapping and repair of HDPE as well as how to properly connect to other pipe materials are not readily available. The latter issue is specially impacted for low DR pipes where the thick HDPE pipe may require a reducer to match the outer diameter of the cast iron, ductile iron or PVC pipe it is being connected to. Developing standard details, operating procedures, educational videos, etc. can address this issue. Such information should be developed with the end user in mind. Such documents are typically used by field personnel and not engineers and as such the language used should be clear and simple to the extent possible.

8. When connecting HDPE to another pipe, the end of HDPE pipe should be restrained by a thrust collar or otherwise restrained. If not, there is potential for the joint to pull open due to temperature effects.
9. The consequence of failure should be considered as a factor in pipe material selection. The consequence of failure should be quantified in dollar terms and should consider financial loss due to failure (for example if the water supply to a hotel is interrupted).

CONCLUSIONS

The project workshop provided valuable input to the project and assisted the project team to improve upon the project scope and experimental approach. The structured approach utilized for the workshop allowed the critical topics to be identified in an efficient manner. The limited and valuable time of participants was mostly devoted to discussion of the most critical topics of survey results and test set up. The workshop enabled the Project Team to explore different perspectives and identify several studies and experiences brought up by the Project Participants. Specifically, the following areas were identified as deserving special attention during the course of this research project:

- Validating the survey results
- Addressing connection/fittings issues
- Refining the test set up to ensure useful results are obtained
- Identifying and proposing tools which can help with the design of HDPE pipe
- Documenting the need for educational and technical procedures for installation
- Compiling available procedures for repair and O&M

APPENDIX C
EXPERIMENTAL WORK

Chapter 5 provided results of experimental work. Appendix C presents more details on testing equipment and the testing operation.

C.1. PROCEDURES

Initial Project Start-up Procedure

1) Make sure power to pump is off.
2) Make sure that water hose is properly secured, so that it does not cause flooding.
3) Reservoir should be full.
4) Open ball valve connected to reservoir.
5) The pump should be filled with water and bleed air from pump.
6) Open the inlet valve and fill up the tank.
7) Bleed air from specimen pipe.
8) Close the bleed valve until water comes out.
9) Open outlet solenoid valve using control board.
10) Partially open the bypass valve on the inlet side.
11) Open the gate valve on the outlet line which is near reservoir.
12) Close inlet solenoid valve.
13) Close outlet solenoid valve.
14) Close bypass valve on inlet side.
15) Turn on the pump and adjust backflow valve to 208 psi.
16) See procedure sheet on back-flow valve.
17) Adjust bypass valve, because if it takes too long to come to 188 psi.
18) Adjust the control board and see the procedure sheet for operation.

Routine Experiment Start-up

1) Make sure that tank is full.
2) Plug in control board switches.
3) Make sure that the pressure in control board is right.
4) Make sure that Roc-link[24] software is online.
5) Power the pump.
6) Bleed the air by opening hand operated valve.
7) Check the cycle time and water temperature.

[24] Roclink Software was installed on a desktop computer to operate the control board. It was used for data input.

C.2. EQUIPMENT DETAILS

Back-flow Pressure (BFP) Valve

Importance of BFP Valve

The back-flow pressure (BFP) control valve was necessary to; a) protect the pump from excessive water pressure due to water hammer, and b) to control excessive pressures from the pump as the inlet control valve to the pipe sample cannot sustain excessive pressures. Figure C.2.1 presents the Back-flow Pressure Valve.

Operation of BFP Valve

During the testing operation, the pump's head was about 480 ft, i.e., 208 psi. But the pipe sample is designed to withstand only 188 psi during each cycle of operation. Therefore, back-flow pressure control valve reduced pressure to 188 psi by assimilating the water head from multi-stage pump and reduced the surge on the inlet valve. The following steps explain how to set the valve;

Initial Procedures to set up BFP Valve

- Set pressure for Back-flow control valve at 188 psi.
- Pilot valve plug remained closed until pressure is below set pressure.
- Once the inlet pressure increases, then pilot valve plug opens.
- Loading pressure bleeds out the pilot exhaust faster than it can be replaced through the pilot restriction.
- Permit inlet pressure to balance the main valve plug and open the main valve.
- Once the inlet pressure drops below set pressure, then main valve plug closes.

Figure C.2.1 Back-flow pressure valve

Inlet and Outlet Solenoid Valves

Objectives

The inlet valve opens and induces pressure inside the pipe sample to reach 188 psi, whereas and the outlet solenoid valve reduces the pressure to 125 psi.

Working of Solenoid Valves

- These valves are normally closed (Figure C.2.2).
- When the pump is powered and control board is connected to valves, the inlet valves opens and let water to run into pipe sample.
- Once it reaches 188 psi, inlet valve closes and outlet valves open to reduce the pressure to 125 psi.
- This working pressure is set by the control board.

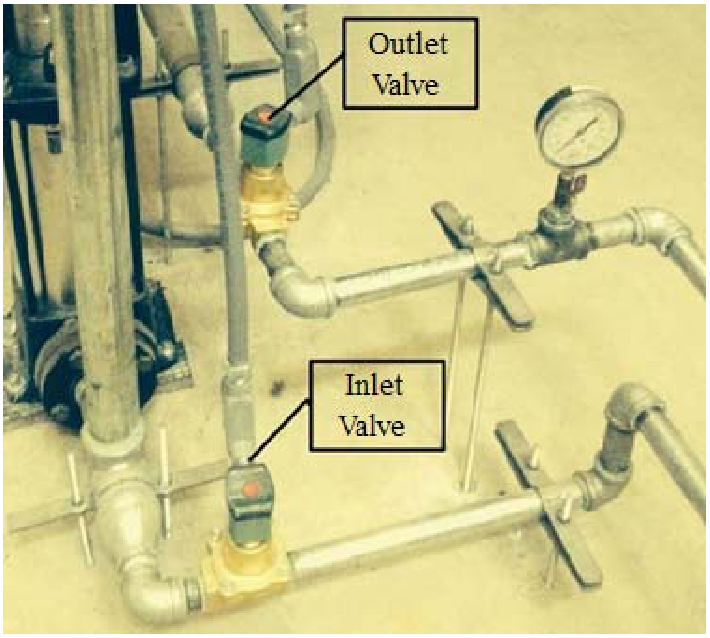


Figure C.2.2 Inlet and outlet solenoid valves

Control Board

Objectives

The Control Board (CB) signalizes both inlet and outlet solenoid valves to open and close. Also, it generates the data using Roc-link software. Figure C.2.3 illustrates the components of the Control Board. There are two types of operations at the board:

1. Read only
2. Edit information

Working Procedure of Control Board

- Enter pin code 1000 to enter into edit list
- Press user list
- Click on edit list
- Cycle run (0 = stop, 1 = start or reset the cycle counter, 2 = low cycle, 3 = high cycle) '2' keeps the cycle accumulation from 1 to 2 million cycles.
- High pressure set point (i.e., 188 psi for 16 in. pipe sample)
- Low pressure set point (i.e., 125 psi for 16 in. pipe sample)
- Inlet timer delay can be from one sec to 3 sec.
- Outlet timer delay can be same as inlet timer delay.
  (Note: Both inlet and outlet timer delay is to energize the inlet and outlet solenoid valves)
- Accumulator which counts number of cycles completed.

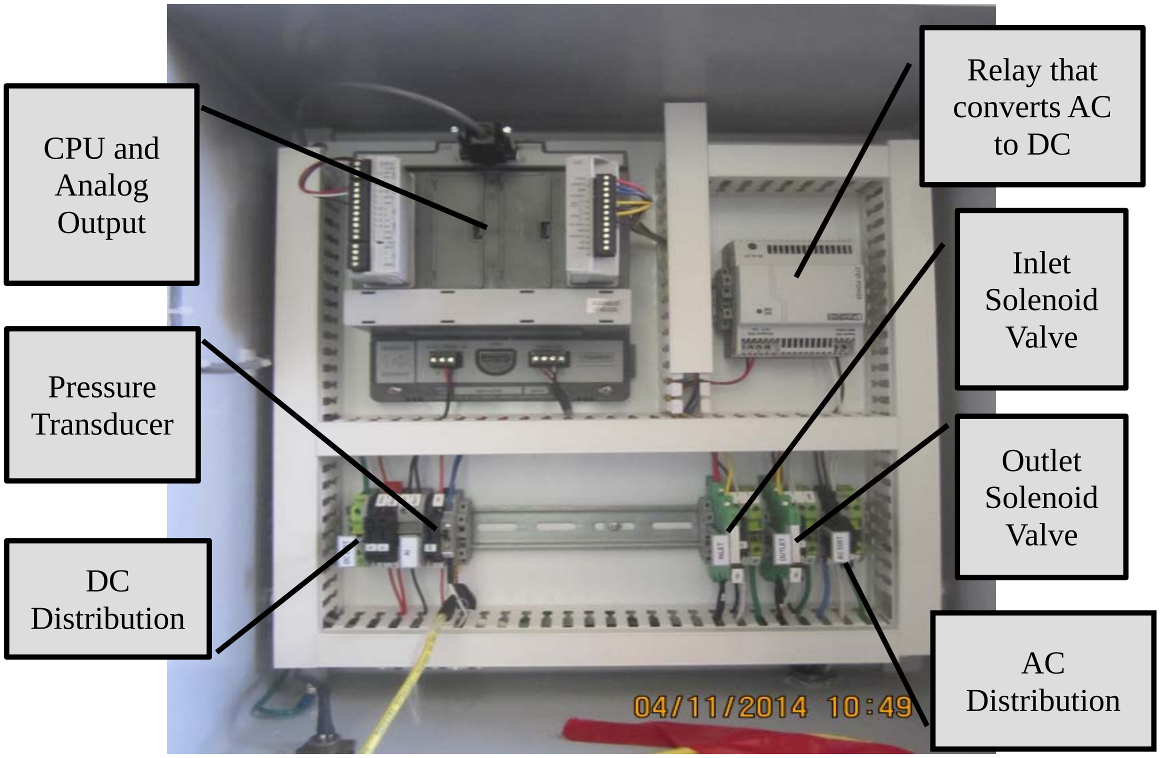


Figure C.2.3 Components of the control board

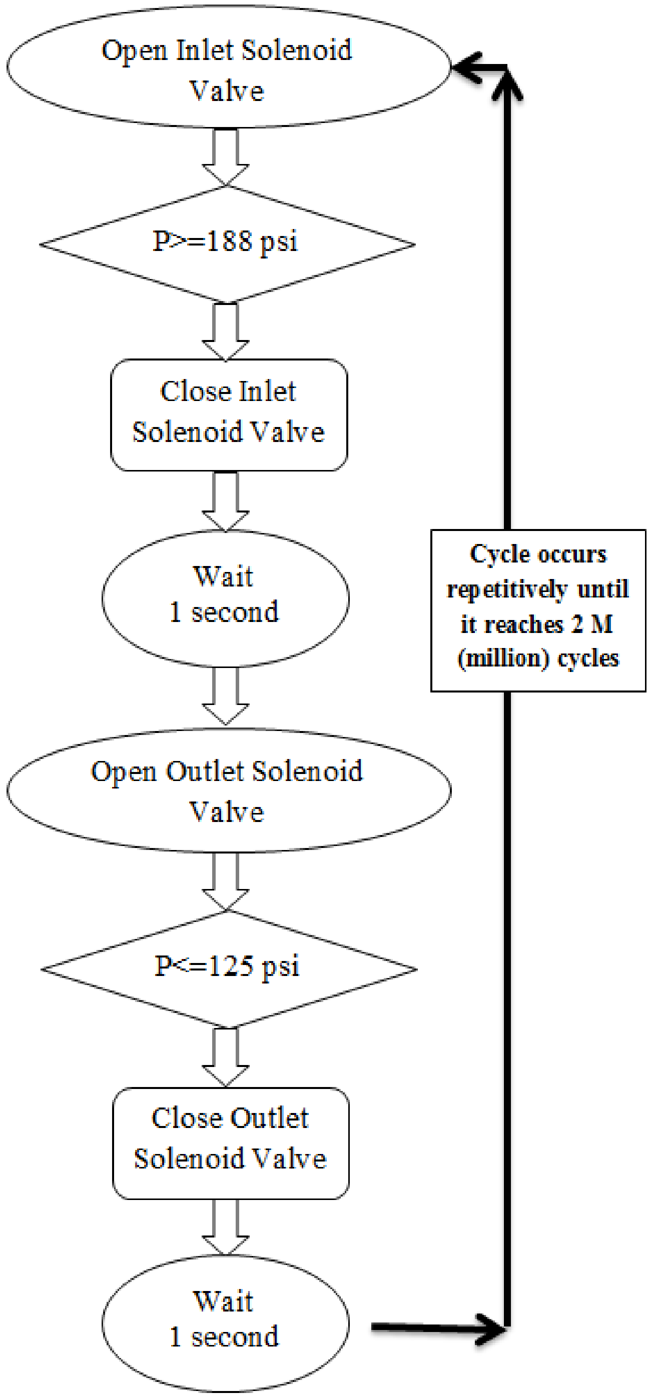


Figure C.2.4 Control board logic flowchart

Figure C.2.4 presents the logic flowchart of control board, and following represents the steps:

- Open inlet solenoid valve
- Pressure bigger or more than 188 psi
- Close inlet solenoid valve
- Wait one sec

- Open outlet solenoid valve
- Pressure smaller or less than 125 psi
- Close outlet solenoid valve
- Wait one sec if need time between each cycle, or we can make it zero (0) sec so that next cycle can start immediately.

Pressure Transducer

Objectives

1. To convert water pressure in the pipe into an analog electrical signal.
2. To regulate and convert pressure inside the pipe (125 psi - 188 psi).

Working Procedure of Pressure Transducer

- Two transducers are connected in the system, i.e., Transducer 1 & Transducer 2 (Figure C.2.5). One of these transducers is connected to the control board; and another one is occasionally connected to oscilloscope.
- The transducer 1 transmits signal to the control board, and control board operates the solenoid valves operation in the system.
- The transducer 2 is connected to oscilloscope to check the waveform pattern occasionally.
- Also, a transducer is used to adjust the Back-flow valve and adjusting screws of back-flow valve is adjusted to 4.7 V ~ 188 psi.

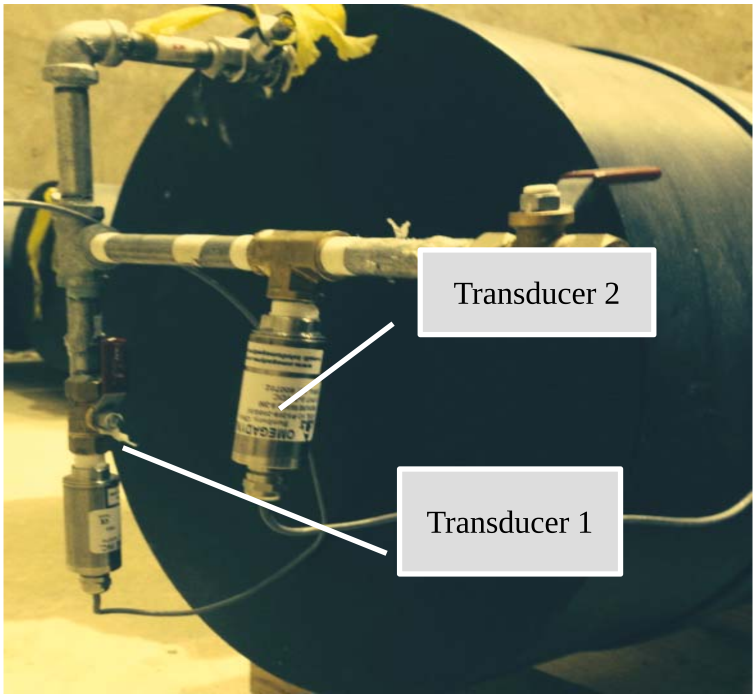


Figure C.2.5 Pressure transducer

Multi-Stage Centrifugal Pump

The pump was 10 HP. The water head on the pump was 10 ft and pump output pressure was 480 ft (208 psi). The head losses are calculated based on 2 in. and 1 in. galvanized steel pipes. Figure C.2.6 illustrates the multistage centrifugal pump.

Objectives

1. The pump inputs pressure to the solenoid valve.
2. Based on pump's head pressure the inlet solenoid valve and backflow valve open and close.

Working Procedure of Centrifugal Pump

- The pump was operating continuously, but needed to be stopped occasionally for maintenance purposes.
- The control board was powered before powering the pump, i.e., magnetic starter should be pulled down and on the button.
- The pump outputs 480 ft / 208 psi; where the pressure partly goes into backflow valve operation to cut down 208 psi to 188 psi.

Figure C.2.6 Multi-stage centrifugal pump (10 HP)

C.3. OTHER PROJECT EQUIPMENT

Water Reservoir

The Water Reservoir contains three inlet pipes at top and one outlet pipe at bottom that is connected to the pump which is 10 ft below. The dimension of reservoir is 3 ft height and 42 in. diameter with 450 gallon capacity.

Butterfly Valve

This valve is used to turn on and off the water flow into the pump for maintenance purposes. The butterfly valve should be turned off when the pump is off; to prevent flooding of test area.

Hand Operated Valve

This valve is left open throughout the experiment. It is placed as a safety measure to initially reduce the pressure on the pipe sample.

Pipe Sample

The initial experiment setup is for 16 in. large diameter pipe (125 psi -188 psi). The pipe sample has inlet and outlet connections. Initially the pipe sample is filled with water and air bubbles are released through a nipple. The pipe sample is placed on a 1% slope.

Oscilloscope

The Pico-scope PS2200A (PP906) is used to convert output signal of pressure transducer to waveform pattern in terms of voltage. The oscilloscope receives signal from pressure transducer and displays the pressure waves on desktop screen. Also, it is used to adjust backflow pressure valve.

Air Conditioning Units (Coolers)

The main purpose of air conditioning unit is to maintain the water temperature at 70-73˚F. It was observed that water temperature impacts cycle time, i.e., as water temperature increases the duration to complete one cycle gradually increases. To maintain constant water temperature and cycle duration, two air conditioning units were installed.

APPENDIX D
CASE STUDIES

D.1. CASE STUDY 1 – LOS ANGELES

<table>
<tr><td>Utility/Owner Name
LA Dept. of Water and Power</td><td rowspan="5"></td></tr>
<tr><td>Project Name/Location
Silver Lake Trunk Line Slip Lining
On Coronado Street between Sunset Blvd and Bellevue Ave</td></tr>
<tr><td>Project Date
February 2006 ~ July 2006</td></tr>
<tr><td>Owner Contact
Kathie E. Hirata</td></tr>
<tr><td>Pipe Size
Host Pipe is 40 in. sliplined with 36 in. HDPE</td></tr>
<tr><td>Pipe Length
1,690 ft</td><td>Project Engineer
Eric J. Kim</td></tr>
<tr><td>Construction Cost
$941.5k</td><td>Contractor
J. Fletcher Creamer & Son, Inc.</td></tr>
</table>

Background

Los Angeles Department of Water and Power (LADW&P) used large diameter HDPE to slip line a 40 in. cast iron pipe. The basis of design and reasons why HDPE was the material of choice for the project are as follows:

- The smooth interior of the HDPE with high Hazen Williams friction factor made up for the reduction in the diameter and met the hydraulic requirement
- Trenchless (except the access pits) installation allowed fast construction
- Slip lining with HDPE cost less than 2/3 of the cost of replacement
- Minimum traffic impact (reduced social cost).

Design Parameters

Low cost installation method allowed LADW&P to install the 36 in. HDPE pipe with minimal traffic disruption for the residents. Los Angeles trunk lines are typically welded steel pipes (WSP); and therefore, replacing old riveted trunk lines usually involves installing a new WSP in parallel either in the same street (if there is space available) or in a parallel street, and abandoning the old trunk line. LADW&P implemented slip lining as an alternative approach for the subject project, thereby using the old steel pipe as the host pipe for new HDPE pipe to be inserted. This reduces time and cost involved with trenching the whole length of new pipeline as well as the time involved with welding each section of the steel pipe. LADWP also discovered fusion of HDPE is much faster than welding steel pipe segments. Overall construction was significantly reduced in comparison with replacing the old pipe with a parallel line because of reduced time involved with trenching, shoring, welding. Figure D.1.1 presents the 36 in. HDPE being inserted into the host pipe.

Figure D.1.1 The 36 in. HDPE being inserted into the host pipe

Construction Challenges

While LADWP experienced no major challenges or change orders during construction, it took more effort than expected to fuse the HDPE pipe segments in the trench due to limited space and access. The project required excavation at the access points and despite the flexibility of the HDPE pipe, the bends in the host pipe had to be removed prior to installation of the new 36 in. pipe.

Additionally, the new pipe required a delicate installation through the host steel pipe to avoid surface abrasion and bending under high winch loads and irregularities on the interior surface of the old pipe.

Project Highlights

Based on the previous experience with HDPE pipelines projects, LADWP required the contractor to hire a 3rd party fusion inspector to sign off on every fusion joints and turn in the data logger records for the first time on the Silver Lake Transmission Main project. LADWP is of the opinion that HDPE pipeline applications are as good as the quality of the fusion joints; and therefore, workmanship is a very important part of the overall success of an HDPE pipeline project. LADWP implemented the same approach on this project as a welded steel pipe installation; i.e., deployment of a certified inspector's inspection, thereby achieving the QA/QC in place by having a 3rd party fusion inspection.

Figure D.1.2 Fusing the joints in the trench imposed a challenge for the construction crew

Figure D.1.3 Access pit to the steel host pipe

Figure D.1.4 Flanged tee connected to the new HDPE pipe

Conclusions and Recommendations

LADWP thought sliplining with large diameter HDPE is a viable option where the conditions (hydraulic, pressure requirements, etc.) are met. LADWP states the following as chief advantages of using HDPE for large diameter pipes:

- Enables trenchless installation (or minimal excavation regarding the access pits) utilizing the existing pipe as a conduit. Accordingly, there is essentially no risk of damage to adjacent utilities or structures and it is quick to install.
- HDPE slip lining application requires minimal excavation with a few small access pits; this minimizes traffic disruption.
- HDPE pipes are not affected by metallic corrosions.
- It costs substantially less than replacement cost of welded steel pipe.

LADWP further points out the following as the cons of large diameter HDPE pipe for transmission mains:

- Difficulty in tapping future connections.
- Difficulty in locating leak origin should the liner fail, because the leak travels along the annular space to a point where the host pipe has holes or other types of openings.
- Must account for expansion and contraction of HDPE.
- Reduction in flow capacity due to annular space requirement for slip lining with respect to the thick HDPE pipe walls.

D.2. CASE STUDY 2 - SEMINOLE COUNTY, FLORIDA

Utility/Owner Name Seminole County, FL	
Project Name/Location Seminole County Regional Water Treatment Facility at Yankee Lake/ Seminole Co., Florida	
Project Date 2010	
Owner Contact Carol L. Hunter, P.E., Manager Utilities Engineering Environmental Services Dept. 500 W Lake Mary Blvd Sanford FL 32773 407-665-2040 407-665-2029 fax chunter@seminolecountyfl.gov	
Pipe Size 42 in.	
Pipe Length 41,100 ft	Project Engineer CH2M Hill
Construction Cost $40.5M (Pipeline: $2.9M)	Contractor Encore Construction Company (now Garney Construction)

Background

The HDPE pipe was selected for the project based on the limited accessibility throughout the raw water pipeline corridor, its flexibility, resistance to corrosion, a 50- to 100- year design life, low friction coefficient, no joints, and the close proximity to a high voltage overhead power lines.

Design Parameters

The main drivers for the design were to transport 45 mgd capacity, a 50- to 100- year design life, low friction coefficient , the environmental requirements; limited or no joints, bedding requirements, and flexibility.

Construction Challenges

Before installation of the pipeline could commence, a temporary construction road was installed adjacent to the pipeline corridor to allow access for equipment and materials for installation of the pipeline and the raw water pump station. Figures D.2.3 and D.2.4 show the temporary road construction. Excavation equipment was stationed along the construction road, allowing for easy loading of all-terrain haulers. Turn-out areas were spaced every 500 ft to 1,000 ft along the construction road to allow vehicles to pull off the temporary road and allow vehicular traffic to pass, thus providing access to both the pipeline and the pump station.

The intake and raw water pump station (RWPS) are located on a canal perpendicular to the St. Johns River. In addition to the remoteness of the site, significant portions of the corridor are within wetland areas that can be under water for significant periods of time.

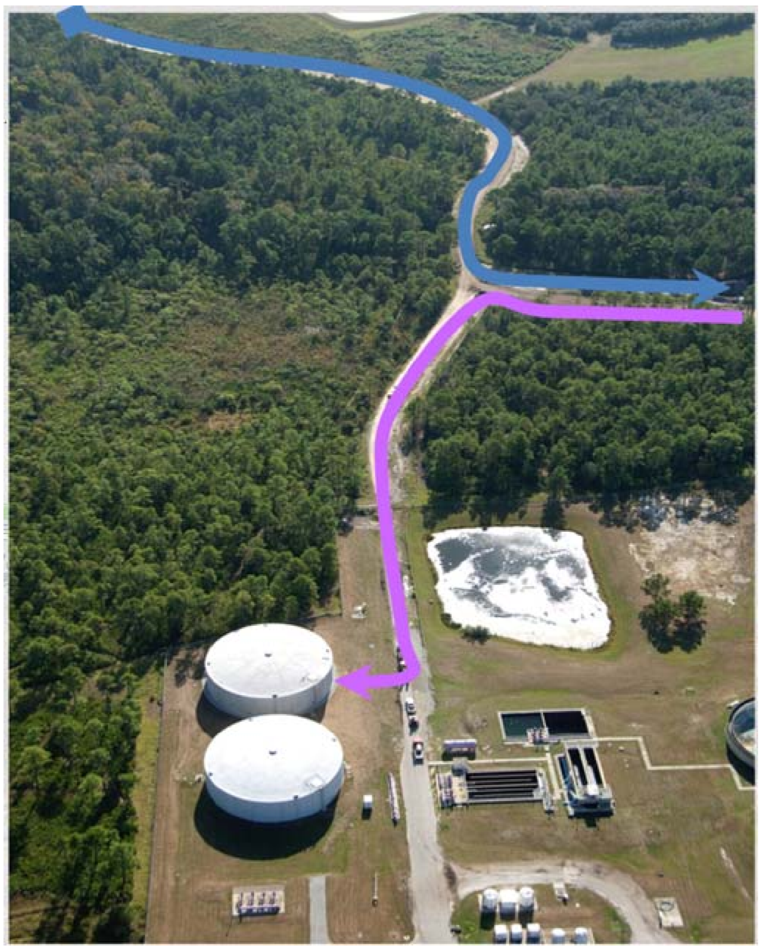


Figure D.2.1 Finished reclaimed water to ground storage tanks (Purple), raw water pipeline route from RWPS (Blue)

Figure D.2.2 Raw pipeline route looking over asphalt road and scrub jay PML

Figure D.2.3 Raw water pipeline route, turning onto berm road adjacent to FPL corridor

Figure D.2.4 Raw water pipeline, approaching RWPS

In addition to the considerations dictated by the accessibility and environmental constraints, several factors related to the technical approach greatly contributed to the success of the pipeline project. Among these were the ability to monitor the joint fusing process, use of a flexible pipeline material to successfully navigate bends along the pipeline route, elimination of corrosion protection requirements, and elimination of pipeline fittings except at the raw water pump station, treatment facility and pigging station, and the ability to install long lengths of pipe.

The pipe fusion machine utilized a monitoring process which allowed daily review of work. This provided the contractor with an increased ability to conduct onsite quality control by inspecting the fusing data logs, which recorded and graphed installation parameters such as fusing temperature, pressure, and time. In turn, this increased the ability to conduct onsite quality control and allowed for timely corrective action and decreased cost associated with rework. Since fusing took place mostly above-ground, daily inspection of the fusing logs allowed for repairs and replacement before the pipe was buried.

As summarized in Table D.2.1, a very small percentage of the fused joints (10 of 775 joints, approximately 1%) failed, mostly as a result of slight misalignments between the two pipe segments. Figure D.2.5 shows the heater plates being lowered between the two pipe segments that were about to be fused. Typically, the contractor was able to fuse 250 to 300 ft of HDPE pipe above-ground prior to fusing with the rest of the pipeline. On average, 400 to 500 ft of pipe were fused and installed per day. Figure D.2.6 shows the typical output for the fusing data logger. The County has retained a copy of these logs and was able to review them on a weekly basis during installation. Each joint was numbered and the joint identification number was branded into the pipe for identification.

Table D.2.1
Overview of installation quantities for HDPE raw water pipeline

Description	Amount	Units
Amount of Pipe Installed	41,100	LF
Number of Fused Joints	755	#
Number of Joint Fusion Failures	10	#
Quantity of Turbidity Barrier Installed	13,200	LF
Quantity of Silt Fencing Installed	26,200	LF
Quantity of De-mucked Material	18,200	CY
Quantity of land Fill	13,800	CY

Figure D.2.5 Lowering the heater plate between the pipes for fusing

The first portion of the fusing process involved lining up the two segments to be fused. Once that took place, the plate heater was lowered between the two segments, and allowed to reach a specified temperature, after which the two segments were placed against the plate heater at a specified pressure (630 psi) in this case. Once melting of the HDPE began, the pressure between the plate and the segments was decreased to 30 psi. At this point, heat was transferred until a ¼-in. “bead” formed around the outside of each pipe segment along the pipe-plate interface. The heater plate was then removed and the segments were fused and allowed to cool.

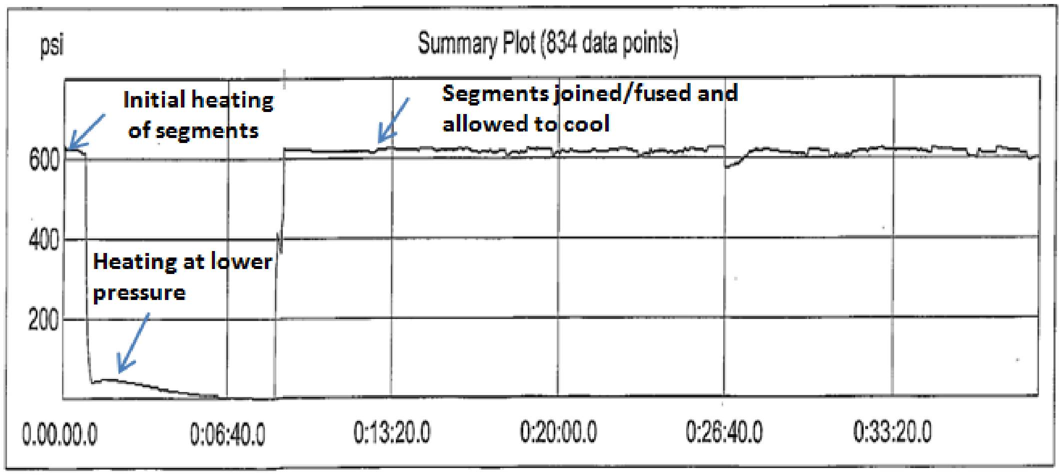


Figure D.2.6 Typical plot of fusing process

Bends and Tie-Ins

Two of the main challenges associated with the installation process were the bends along the corridor and the tie-ins to the raw water pump station. Figure D.2.7 shows one of the most challenging bends along the corridor. Not only was the installation restricted within the narrow corridor area called out in the Environmental Resource Permit (restrictions on placement of turbidity barrier), but the pipeline bend was located between the Florida Power and Light power poles (right side of Figure D.2.7) and the guide pole (left side of Figure D.2.7). The bend shown in Figure D.2.7 is approximately 60 degrees, and is one of the 5 bends placed in the pipeline at angles greater than 45 degrees. The bends were executed utilizing backhoes to place and bend the pipe while maintaining the 2 ft separation between pipes.

Figure D.2.7 Photograph of challenging bend

The transition from HDPE pipe to ductile iron pipe at the raw water pump station also presented a challenge. As depicted in Figure D.2.8, there is a tight bend of three pipelines just before the transition to ductile iron pipe. The HDPE pipes were guided and installed between the piles used to support the raw water pump station deck.

Figure D.2.8 Final pipe bend and tie-in

Another design and construction issue that had to be addressed was the thermal expansion of HDPE pipe. Due to the length of pipe, the expansion equaled several feet because of temperature fluctuations throughout the construction period. This was mitigated by sequencing the work to minimize temperature-induced misalignments and account for some expansion and contraction in the bends.

Project Highlights

The Yankee Lake project in Seminole County, FL, was one of the first to use the St. Johns River as an alternative water supply to meet the future drinking water needs of its customers.

It was one of the most important projects in Central Florida because it is a crucial part of the St. Johns River Water Management District's long-term water supply plan to reduce groundwater use and increase drinking water alternatives.

The new pipelines installed in Phase I of this project provided up to 5.5 million gallons of water per day for reclaim water augmentation. The treated water will be conveyed to the adjacent reuse facility, where it was blended with the reuse stream prior to distribution for irrigation (public access reuse).

Conclusions and Recommendations

The new HDPE material used for this project has increased density, thinner wall thickness, greater tensile strength, and greater resistance to slow crack growth. Because of these improved properties, the Yankee Lake project design allowed reduced wall thickness, better bending capabilities, increased hydraulic capacity, and better overall mechanical properties than the former PE3408 HDPE pipe material. Seminole County will continue to use/consider HDPE pipe on future projects.

D.3. CASE STUDY 3 - GLASGOW, SCOTLAND

Utility/Owner Name Scottish Water	
Project Name/Location Katrine Water Project/Glasgow, Scotland	
Project Date 2001-2007	
Owner Contact Augustus Watt	
Pipe Size 1,000 and 1,100 mm (39 and 43 in.)	
Pressure 4 bar (58 psi)	
Pipe Length 4,500 m (14,764 ft) 1,100 mm (43 in.) 550 m (1,804 ft) 1,000 mm (39 in.)	Project Engineer Kelton Bennet, MJ Gleeson (now Black & Veatch)
Construction Cost TBC	Contractor Gleeson

Background

Scottish Water, a utility firm that supplies water for Glasgow, Scotland, was required to build a water supply system to use Loch (Lake) Katrine as the primary source of water for the Mug dock Water Treatment Plant. The new water supply system included two parallel transmission mains that had to span the lake.

The 2-3 years' application development support by the pipe manufacturer (KWH Pipe) in advance of this project and the DWI (Drinking Water Inspectorate) approval obtained for the special large-diameter HDPE pipes and fittings in the UK market were key factors in the decision to use pipes and fittings made from Hostalen CRP 100 black for this project. Scottish Water and the general contractor, Gleeson, had been familiar with the economic and technical advantages of HDPE pipes for transporting drinking water for a number of years. Cost effectiveness of PE100 Pressure pipes and fittings made from PE 100 offer significant advantages in handling and installation because of their low density of 0.959 g/cm^3. This has a positive impact on installation costs.

During the planning stage, reference was made to relevant experience in various previous projects and the operator was duly persuaded. Good chemical resistance, high operational reliability, corrosion resistance, fused joints that enable leak tightness of the system were the other key factors for selecting PE100 (HDPE) for the project.

Design Parameters

The pipelines were designed for 4 bar (58 psi) internal pressure for a service life of up to 100 years.

Construction Challenges

Upon delivery, the pipe segments were first placed on a bed of sand beside the trench. This was followed by the on-site fusion process; and then, the assembled pipelines were lowered into the trench with suitable lifting equipment. The trench was backfilled with “stone chippings” and sandy excavated soil.

Figure D.3.1 A part of the Katrine Lake pipeline spanned a reservoir and fused pipe segments were sunk down the reservoir using anchoring weigh

Project Highlights

The Katrine Water Project was Scottish Water’s largest water treatment investment project in Scotland. The estimated cost of the work accounted 120 to 140 million Euros (154 to 179 million USD). At peak times, approximately 300 people were employed at the various sites.

Figure D.3.2 Hot tool butt fusion machine by welding contractor, A.G. Wilson, with (HDPE) PE 100 pipe segments made from Hostalen CRP 100 black

Conclusions and Recommendations

Scottish Water had been successfully using PE 100 pipes and fittings to transport drinking water for over 5 years (as of 2007). This project shows that engineering and nature conservation can be harmonized without any problems. On the basis of the positive experience that Scottish Water has had so far with HDPE (PE100), further use will be made of HDPE pipes in the Edinburgh Drinking Water Project.

D.4. CASE STUDY 4 - LUDINGTON-MANISTEE, MICHIGAN

Utility/Owner Name Martin Marietta Magnesia Specialties/Dow Chemicals	
Project Name/Location MTD Pipeline/Ludington-Manistee, MI	
Project Date 2003	
Owner Contact Dow – Dr. Dane Chang, Global Pipe Technology Scientist	
Pipe Size 20 in.	
Pressure 150 psi	
Pipe Length 30 miles	Project Engineer Martin Marietta
Construction Cost NA	Contractor Martin Marietta (Design-build)

Background

Dow and other PE producers have been touting the performance and cost benefits of HDPE for pipe applications versus traditional materials for years, citing improved strength, durability, and advantages related to installation and lifecycle cost. As such, they decided to use a bimodal HDPE pipe (DR 11) for the 20 in. pipeline that conveys brine from Martin Marietta plant to that of Dow Chemicals. The primary reasons for choosing bimodal HDPE were its durability and expected leak free performance achieved from the corrosion resistance of PE and its ability to be fused to create one continuous pipeline.

These advantages are recognized to impact installation and maintenance, as wells as service life, overall performance, and cost saving associated with materials. The Michigan Department of Environmental Quality (MDEQ) contributed to the ultimate decision to use PE for this project, but cites flexibility among the biggest advantages of PE. MDEQ regarded polyethylene as a durable and flexible material, which allows horizontal directional drilling to bore further distances with less concern for fracture.

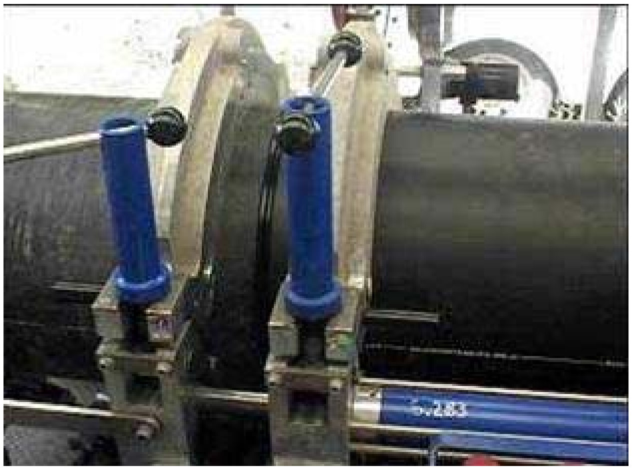


Figure D.4.1 Joints were butt-fused for the MDT pipeline project

Design Parameters

The design pressure was 150 psi and the pipe material had to be durable regarding high salt content in the brine solution that was to be conveyed between the two plants. Made from DOW CONTINUUM™ DGDA-2490 NT Bimodal High Density Polyethylene (HDPE) resin, which meets ISO PE100 qualifications, was specified for the 20 in. diameter DR 11 pipeline (1.8 in. thick wall).

Construction Challenges

In addition to the high-pressure requirements associated with transporting liquid chemicals an approximate distance of 30 miles, the MTD Pipeline project also presented several challenging engineering and environmental requirements.

Figure D.4.2 A view of the construction site, where the pipeline was installed open-trench

First, the pipe needed to be constructed from a material that could withstand the harsh Michigan climate and typical composition of the terrain adjacent to the sandy shores of Lake

Michigan. Cold-temperature toughness was a primary requirement, not only to enable the pipe to endure the frozen sandy environment once it was installed, but also to enable it to endure installation, which began in March when temperatures were still below freezing. In fact, temperatures were as low as minus 15°F when initial pipe shipments were unloaded at the site. While engineers would have preferred to begin installation during the warmer months of April or May, the scope of the project required that installation begin in March in order to be completed by October. While the course of the pipeline runs primarily along existing utility right-of-ways, the project also required extensive directional drilling under five rivers and scores of roads and highways. The longest drill of the project, under the Little Manistee River basin, required a pull of more than 3,200 ft – one of the longest North American projects with HDPE. Also, because the pipeline was being installed across nearly 30 miles of pristine country side between two popular resort towns (an area that sees its population increase by a factor of six during the summer), working life integrity associated with environmental impacts was also among the critical considerations.

Figure D.4.3 The 30-mile long was installed along a challenging terrain

Project Highlights

The project required the manufacture and installation of nearly 30 miles of pipeline to support the transport of brine solution from a plant in Manistee, operated by Martin Marietta, to a Ludington facility operated by Dow. In late 2002, Martin Marietta signed a long-term agreement with Dow Cal/Mag (Dow's calcium/magnesium business) to supply brine solution to Dow for use in the manufacture of its calcium chloride products.

The estimated total weight of the HDPE materials used is 6.3 million pounds, which represented the highest volume of PE100 material for any single design-build project in North America using this material at the time.

Conclusions and Recommendations

With detail designing & planning among pipeline engineers & designers, excellent coordination/cooperation between pipe producers and field installers and perfect execution, the MTD pipeline was completed on time and went on line during fourth quarter 2003. It marked a paramount advancement for HDPE pipe and the completion of the largest PE100 project for smooth wall pressure pipe in North America at the time.

Despite the challenges of the project, all parties involved confirm the benefits of working with a high performance ISO PE100 resin.

The MTD Pipeline project team is of the opinion that the project represents a significant step forward in the use of PE resins for pipeline development projects. Based on the positive experience achieved by the private sector on this project, the PE resin and HDPE pipe manufacturers expect a growth in the HDPE pipeline market in a number of industries including drinking water transmission mains.

D.5. CASE STUDY 5 - HOUSTON, TEXAS TRANSMISSION MAIN

Utility/Owner Name City of Houston	
Project Name/Location City of Houston – Pilot Project	
Project Date 1997	
Owner Contact NA	
Pipe Size 30 in.	
Pipe Length NA	Project Engineer NA
Construction Cost NA	Contractor NA

Background

The City of Houston (City), as the regional provider of drinking water, has had an interest in evaluating new products and materials for the water distribution and transmission system. Acceptance of new products must go through the City's Product Approval Committee. Based on the information provided and the subsequent evaluation performed by City engineers, the product may need to undergo further evaluation. Such was the case when Houston first considered the use of HDPE for water distribution and transmission main applications.

A 30 in. inside diameter (ID) high-density polyethylene (HDPE) water main was constructed as a pilot project under the City's Surface Water Transmission Program (CIP No. S-0900-26-3; File No. 10439). The HDPE water main was installed in the fall of 1997. The material specifications required the HDPE to be rated to 100 psi (DR 17) with surge pressure of 150 psi, undergo a field hydrostatic test of 150 psi and the use of heat fused butt joints. Special flanges for connections to bar wrapped concrete pressure pipe as noted below.

Provisions were included in the Contract Documents for WA10641 (Contract 17A) to perform an assessment of the existing 30 in. HDPE water main.

The criteria used for the HDPE assessment was the following:

- Evaluate performance of joints by visual inspection for leaks at butt-fused joints and special flanged connection to concrete pipe.
- Evaluate performance of HDPE material characteristics by direct measurement of the outside diameter (OD) of the pipe to quantify ballooning or elongation due to thrust at bends. This is done by verify that deformations in pipe material (if any) do not exceed allowable stress for HDPE material.

Two locations were identified as critical areas to be representative of the total length of HDPE installed; i.e., a 45-degree bend and a flanged connection to concrete pressure pipe at two road intersections. The HDPE water main was exposed at each of these locations for visual evaluation of the pipe's performance.

Figure D.5.1 Flanged connection between the 30 in. HDPE and bar wrapped concrete pressure pipe

No leaks were observed in the butt-fused joints or at the flanged connection. Also, the OD of the HDPE water main was measured at each of the exposed locations to determine if ballooning or elongation of the HDPE line had occurred as a result of thrust. The OD of the pipe matched the original OD prior to installation. However, if these phenomena occur simultaneously, they may have offsetting effects that are difficult to quantify individually. Based on the results of the limited assessment, the HDPE water main at each of the referenced locations was performing adequately under the current operating conditions.

D.6. CASE STUDY 6 - EASTERN NAVAJO

Utility/Owner Name Navajo Nation (Indian Tribe)	
Project Name/Location Eastern Navajo Water Pipeline Phase 2	
Project Date 2010	
Owner Contact Andrew Robertson, P.E. (consultant), 505-299-0942, andrew.robertson@soudermiller.com	
Flow Rate 3,050 gpm (192 L/s)	
Pipe Size 24 in.	
Pipe Length 13 miles (Phase 2)	Project Engineer Souder, Miller and Associates
Construction Cost $8 mil ($28 mil total)	Contractor BRB Contractors (Topeka, KS)

Background

The Eastern Navajo Water Pipeline project consists of installation of 24 in. transmission main to provide drinking water for eight rural communities of the Navajo Reservation in the desert southwest, where drinking water supply has historically been very scarce.

Initially ductile iron pipe was specified for the project. Then the Bureau of Reclamation raised concerns about the corrosiveness of the soil; and therefore, the pipe material was changed to HDPE. The reason for choosing HDPE over PVC was that the project team felt it had more strength than PVC. Working pressures in the pipeline are as high as 290 psi. Moreover, the project area has many large seasonal waterway crossings with shifting soils and aggressive erosion. Fused joints and highly flexible pipe are preferred in this area to withstand pipe movement or even possible exposure caused by erosion. The ability to absorb surge pressures was among the other reasons listed for choosing HDPE for the project.

Design Parameters

The chief design parameter was durability of the selected pipe to normal operating and transient (water hammer) pressures. The design flow rate in the 24 in. transmission main is 3,050 GPM, which translates to an average velocity of 3.7 fps. A power failure could result in a significant surge along the 13 mile transmission main. Theoretically, the surge pressure could be as high as 360 psi. As such, the project team believed HDPE would have the flexibility and durability to withstand these potential surge pressures due to a water hammer. Moreover, the low modulus of elasticity of HDPE meant that surge pressures would be lower to begin with, reducing the system's reliance on surge tanks.

The other main design parameter was the resistance of pipe material to external corrosion as the soil in which was installed was deemed aggressive. This was the primary reason for choosing HDPE over DI pipe. Steel pipe was not considered for this project by the project engineer, because it requires cathodic protection in order to resist corrosion; the owner did not want the O&M burden of testing and maintaining cathodic protection systems.

Figure D.6.1 Sample fused fittings used for the Navajo transmission main project

The Project Engineer also pointed out the advantages of using HDPE as a fusible pipe material. Fused joints eliminated the need for joint restraints in addition to fast installation and flexibility. HDPE manufacturers claim that the butt-fused joints are as strong as the pipe itself.

Finally, the flexibility of HDPE allowed some alignment and grade changes to be made by pipe bending rather than ells, resulting in fewer fittings in comparison with more rigid materials such as PVC or ductile iron.

Construction Challenges

There was one major construction challenge, which was resolved during the course of the project. HDPE pipe was supplied by four different pipe manufacturers, each of which provided pipe in multiple pressure classes (DRs), as specified. One batch of pipe was later discovered to show embrittlement during the joint fusion process, which caused the fusion joints to fail the high-speed tensile impact test due to brittle, rather than ductile, failure. These joint failures were later found to be due to the pipe, not the fusion process, and were traced back to a single rail car of raw HDPE feedstock that was shipped to the pipe extruder. The apparently defective pipe was removed and replaced at no additional cost to the owner, and without adversely impacting the project schedule. Despite the initial difficulty, this problem was resolved to the full satisfaction of the owner and the engineer. No further problems with pipe material or joint fusion process were detected for the rest of this project, nor in the follow-on Phase 3 project (17 miles of 20 in. HDPE pipeline).

Project Highlights

The overall project will provide safe drinking water to approximately 10,000 people living in four counties in the region. Prior to the implementation of this project, nearly 4,000 people of the Navajo Nation people did not have access to any form of running water, and they were hauling water with their trucks prior to the Eastern Navajo Water Pipeline project.

This project is the first of several phases to be constructed. At the time of this writing, two other phases have been completed, include an additional 17 miles of 20 in. HDPE pipeline and 13 miles of 8 in. PVC pipeline. These follow-on phases were constructed upstream and downstream of Phase 2, respectively.

While the Navajo Tribal Utility Authority (NTUA) has utilized HDPE pipe for waterway crossings for many years, this project was NTUA's first major pipeline to be constructed entirely out of HDPE.

Conclusions and Recommendations

Based on the experience they had with HDPE along the second phase of the project, the Project Team decided to continue using HDPE for the following phase (17 miles of 20 in. pipe) of the Eastern Navajo Water Pipeline Project. The Project Team did not indicate any drawbacks or significant problems with HDPE pipe. In general, the Project Team sees benefits to a system that includes both HDPE and PVC pipe, with the option of using either material based on the specific needs of a particular reach of pipeline.

D.7. CASE HISTORY 7 – SAN ANTONIO, TEXAS

Utility/Owner Name San Antonio Water System	
Project Name/Location Regional Carrizo Project, San Antonio, Texas	
Project Date Water Supply Pipeline - 2013 (substantial completion September 2013)	
Pipe Size 36 in. diameter	Owner Contact Roger Placencia
Pressure 150 psi	Flow Rate 11.3 mgd (average)
Pipe Length 39,515 ft	Project Engineer Robert McCarty, P.E. Francisco C. Guerrero, P.E. Atkins North America, Inc. 6504 Bridge Point Parkway, Suite 200 Austin, Texas 78730
Construction Cost Supply Pipeline $12,512,949	Contractor SJ Louis Construction of Texas, Ltd. 9862 Lorene Street, Suite 200 San Antonio, Texas 78216

Background

San Antonio currently obtains more than 90% of its drinking water from the Edwards Aquifer. The Regional Carrizo Water Supply Project produces Carrizo Aquifer groundwater from Gonzales County, located approximately fifty miles east of San Antonio. This Project assists SAWS in diversifying its water sources thus reducing its reliance on the Edwards Aquifer. The Regional Carrizo project consists of a well-field with nine groundwater wells drilled to depths up to 2,200 ft which produces an average of 10.4 mgd. The nine production wells are connected by approximately 72,000 linear feet of HDPE pipe of varying diameter. The produced water is then transported from the well field to a regional partner's water treatment plant by approximately 40,000 linear ft of 36 in. HDPE pipe. The treated water will then be transported to the Northeast sector of the SAWS' distribution system using both the partner's existing pipeline and newly constructed SAWS pipeline and pump station.

HDPE pipe was chosen because of its durability, capability to fuse pipe sections to achieve a solid, fused pipeline, capability to withstand subsurface changing conditions (soil shifting, water table variations, etc.) and is essentially maintenance free. HDPE pipe is manufactured in a seamless operation, cut to size only because of shipping and handling criteria. The capability to fuse the pipe sections in the field to achieve an almost seamless solid pipe that can withstand moderate bending and flexing, allows this pipe material to have success in long distance projects. HDPE pipe is ground surface fused in long sections and then rolled into an open trench. Work in the trench is minimized by this process. This operation provides a safer working environment and reduces the risks associated with in trench pipe welding construction.

Design Parameters

The Regional Carrizo Project's design criteria was based on the distance of the Project from the SAWS' service area and the need to have an almost maintenance free pipeline. SAWS wanted a pipe material that would withstand rough handling over long haul distances, would withstand air temperatures in excess of 90 degrees for extended periods of time during storage and construction, would withstand source water temperatures at or above 98^{o}F, and would be constructed to achieve a seamless, joint free continuous pipe with minimum maintenance.

The project area is approximately 50 miles from San Antonio in rural ranch and farm land. SAWS does not have a presence in the area and the remote location requires an almost maintenance free system. HDPE pipe allows SAWS to have a pipe system which is almost maintenance free. The capability of HDPE pipe to be fused creating an almost seamless joint produces pipe joints that are leak free and fail safe. This reduces the maintenance requirements and limits the man-hours required for pipeline inspections.

Quality control was a huge concern for SAWS. The pipe supplier (ISCO) was able to provide highly trained and qualified field fusion technicians to fuse pipe on site.

Early in the design process, SAWS staff worked closely with their design partners and project managers in selecting the pipe material for the project. Important criteria such as ease of installation, durability (exterior for corrosive soils, interior for higher temperature water), longevity, and value were developed. HDPE was evaluated along with other pipe materials such as steel, FRP, and ductile iron. In addition, the use of a different resin (PE4710) was authorized that would allow the pipe to accommodate the higher temperature water.

SAWS construction specifications required the pipe supplier to provide proper material certifications from the pipe manufacturer (Performance Pipe), including the traceability of resin, McElroy Data Logger™ use and in-field tensile testing.

Location and specifications of the various components of the Regional Carrizo project are shown in the map below.

HDPE pipe was used in the Projects identified below as the "Water Supply Pipeline Project" and the "Buckhorn Well Field Project."

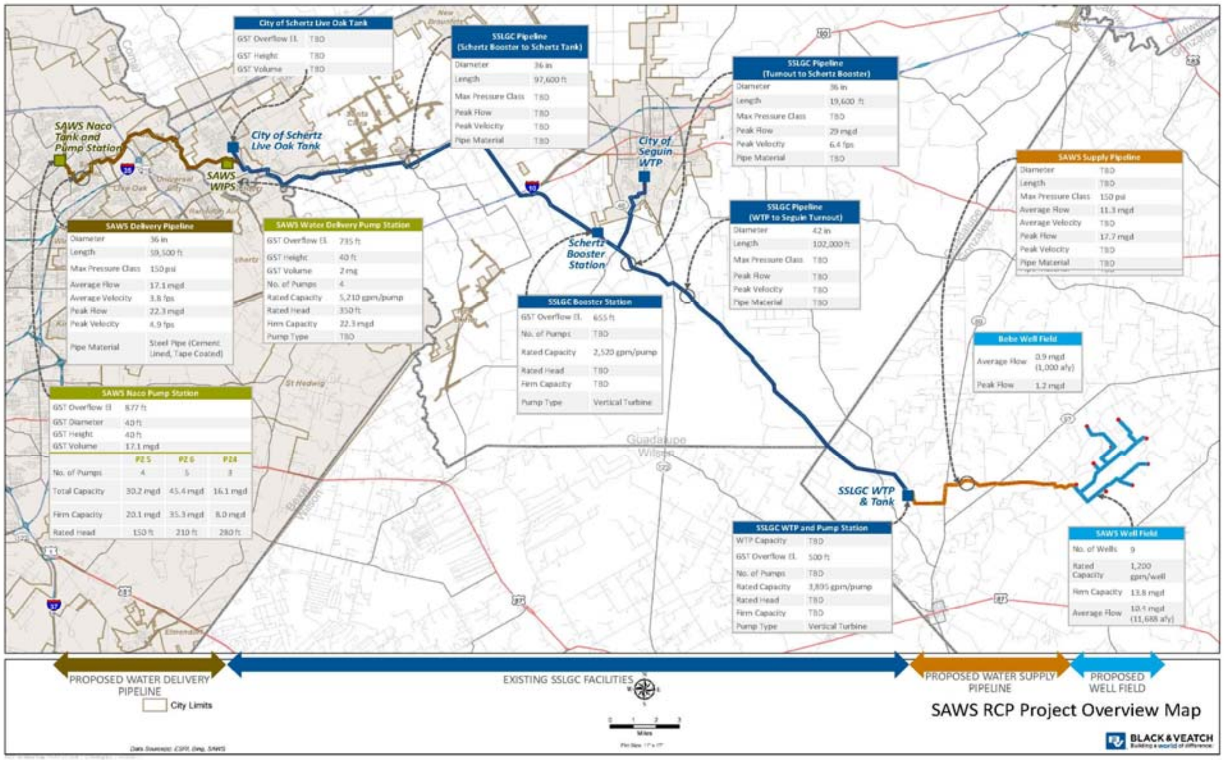


Figure D.7.1 Regional Carizzo project overview map

Construction Challenges

On the Water Supply Pipeline Project, there were no construction problems generated by the use of HDPE pipe. The rural, remote location and the need to stay within easement boundaries presented minor challenges, but were overcome in the end through the use of temporary construction easements, which gave the contractor and pipe suppliers more room to work. Any and all change orders were the result of other construction issues and not related to pipe selection.

Project Highlights

This project is, by far, the largest single use of HDPE pipe to date for SAWS. If the HDPE pipe utilized in the well field is included (smaller diameter from 18 in. to 36 in.), the total length was approximately 122,000 feet and consisted of approximately 328 truckloads of HDPE pipe, totaling more than 11 million pounds in various sizes. Up to 11.3 mgd of water supplied from Carrizo well field will be transported by pipeline to an integration point in northeast San Antonio where it will enter the SAWS distribution System.

SAWS Regional Carrizo project also represents the greatest volume to date of non-Edwards firm water supply. SAWS had positive results from its previous use of HDPE pipe, and expects to have the same results with the Regional Carrizo Water Supply Pipeline project.

Conclusions and Recommendations

Overall, the experience with large diameter HDPE pipe was positive. From the delivery, accountability, fusion, installation, and water delivery, the use of HDPE pipe improved the situation. There were no drawbacks on this project that would have injected doubts about the use of HDPE pipe. It is now being considered for use in future SAWS projects.

D.8. CASE HISTORY 8 – FISHER ISLAND (MIAMI), FLORIDA

Utility/Owner Name Miami Dade Water and Sewer Department (MDWASD)	
Project Name/Location Government Cut Utility Relocation Projects, Miami Dade County, Florida	
Project Date October, 2011	
Owner Contact Luis Aguiar	
Pipe Size 30 in.	
Pressure 70 psi	Flow Rate 4.2 mgd
Pipe Length 1,600 ft	Project Engineer Hazen and Sawyer
Construction Cost $13.4 Million	Contractor Design-Builder: Ric-Man Construction; Driller: Mears

Background

Fisher Island residents rely on a pipeline from the mainland through the Port of Miami for their fresh water supply. Additionally, because it is part of a water system loop, the pipeline enables the Miami Dade Water and Sewer Department (MDWASD) to maintain system pressure when cruise ships at the Port of Miami are filling prior to their departures. Age, leaks and the deepening of the Port of Miami's main shipping channels, and Fisherman's Channel, required this important pipeline to be replaced.

The replacement of the water main underneath Fisherman's Channel was originally proposed to be completed by micro-tunneling. In an effort to minimize project risks, reduce costs, minimize environmental impacts, expedite the schedule and cause less disruption to the community, the team proceeded with an alternate design for the 20 in. water main replacement that had an equal or greater hydraulic capacity than the existing pipeline and was designed for at least an 80-year design life. The alternate proposal utilized horizontal directional drilling (HDD) technology in place of the micro-tunnel technology. This new delivery system consisted of a 140 ft deep and 1,600 ft long and 30 in. diameter HDD (PE4710, DR 11) from the Port of Miami to Fisher Island to replace the existing 20 in. water main. Coordination with the Port of Miami was critical to minimize impacts to operations and other improvements projects. In addition, coordination with various permitting agencies had to take place prior to construction. All of the environmental resource and coastal construction permits were fast-tracked in order to maintain the project schedule. The HDD portion of the project was completed in October of 2011 and the pipeline was placed into service in April of 2012.

Design Parameters

The primary driver of the design was the installation method. A trenchless method was selected to minimize the environmental nuisance and also allow for deeper installation beneath the seabed. This increased depth is warranted to enable dredging of the shipping channel in the Port of Miami for deeper draft vessels which travel through the Panama Canal.

DR11 HDPE with PE4710 resin was selected in lieu of PE 3608 resin due to its inherent ability to withstand higher tension loads and greater service life for an HDD installation this critical in nature. Steel was also considered for this HDD water main, but not implemented into design due to cost, high susceptibility to corrosion in salt water environment, and additional QA/QC time required for analyzing and testing of welded joints.

Figure D.8.1 HDD Pilot hole drill with starter casing

Construction Challenges

The calcareous soil and limited space in the Port and on Fisher Island for the drill entry and exit sites imposed a challenge for drilling the pilot hole during construction. This required careful selection of the drilling equipment as high stresses were exerted on the drilling rod.

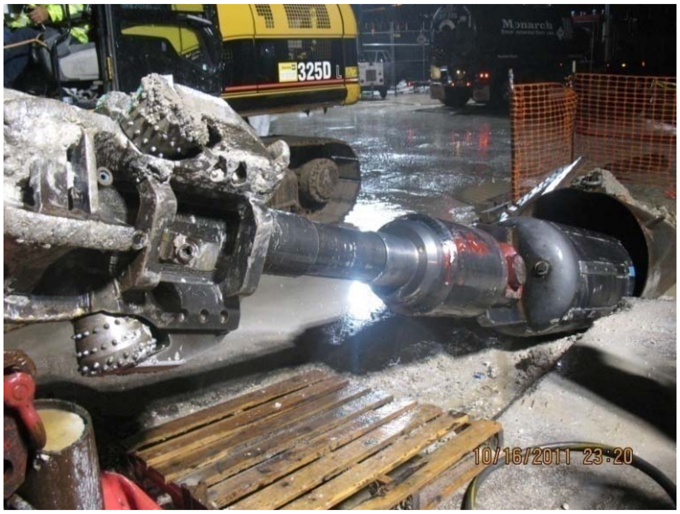


Figure D.8.2 Pulling of HDPE pipe following drill and reaming operations

Project Highlights

The project enables safe and reliable delivery of drinking water to the Fisher Island residents and allows MDWASD to maintain pressure in the system on days when cruise ships are taking on water for their voyages. It is designed around the proposed dredging at the Port of Miami. This will turn the Port of Miami into one of the only three ports on the East Coast that can harbor the Panamax ships with 13,000 container capacity.

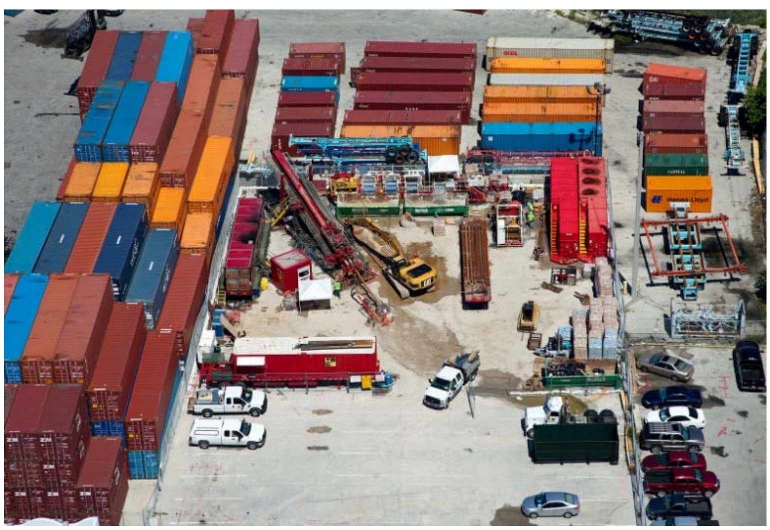


Figure D.8.3 Aerial view of port of Miami HDD drill site during construction

The project was completed on time and under budget, which enabled the owner to install two bidirectional meters at the Port. By using the new meters, the MDWASD will be able to measure the total quantity of water sold to the Port; without going through the individual meters at the warehouses, terminals, and buildings.

According to the owner, the project was very well received by the environmental groups due to the installation technique (HDD) used, which enabled minimum nuisance to the residents and environment.

Conclusions and Recommendations

The project was regarded successful by the MDWASD, and the Department continues to use HDPE for its transmission mains.

D.9. CASE HISTORY 9 - GATE HAMPTON BORE HOLE

<table>
<tr><td>Utility/Owner Name
Thames Water</td><td rowspan="5"></td></tr>
<tr><td>Project Name/Location
Gatehampton Bore Hole,
Gatehampton-Oxford/Swindon,
UK</td></tr>
<tr><td>Project Date
2009</td></tr>
<tr><td>Owner Contact
Thames Water</td></tr>
<tr><td>Pipe Size
14 to 31 in.</td></tr>
<tr><td>Pressure
87 psi</td><td>Flow Rate
Up to 105,000 m^3/d (28 mgd)</td></tr>
<tr><td>Pipe Length
1 mile</td><td>Project Engineer
Black & Veatch</td></tr>
<tr><td>Construction Cost
$7.5 million</td><td>Contractor
Black & Veatch</td></tr>
</table>

Background

Forming part of a suite of eight projects that were undertaken to provide resilience to the South Oxfordshire and Swindon Catchments and part of a suite of six projects for the GATOX (Gatehampton to Oxford) scheme to address the shortfalls in the supply of potable water into the Oxford area, the objectives of the GATOX - Gatehampton Borehole Upgrade Project (9LLF/A1) were to:

- allow the full licensed abstraction flows from boreholes at Gatehampton to be delivered to Cleeve Water Treatment Works/Plant (WTW),
- significantly reduce the risk of further pipe bursts with the installation of surge protection measures (via a new control system) and the replacement of the existing GRP pipeline with a PE solution,
- protect two of the boreholes against flood damage to allow normal supply levels from the site to resume after flooding with minimal disruption.

The scope of the 9LLF/A1 Project involved the uprating of the Gatehampton Borehole site to increase the output to the maximum licensed flow of 18.7 mgd (23.1 mgd peak), improve the resilience of the water supply to Cleeve WTW and to undertake “Burst Mitigation” measures.

The project scope included the following pipeline construction items:

- The installation (and subsequent removal during the PE mains installation detailed below) of a temporary overland PE pipeline that linked the existing boreholes GRP main with the 1000 mm (40 in.) dia. ductile iron transmission main to Cleeve WTW (at a point adjacent to the statutory works flow meter), which essentially bypassed a section of the existing GRP mains (which had a recent history of failures) and improved resilience until the existing GRP pipeline was replaced.
- The installation and staged commissioning of a new 630 mm (25 in.) to 800 mm (31in.) dia. PE ring (transmission) main that connected to the seven existing boreholes (including a connection point for a future borehole (ABH8) and replaced the existing, problematic GRP pipeline the majority of which was removed.
- The installation of a replacement, larger capacity air valve assembly located on the high point of the 1000 mm (40 in.) diameter, ductile iron trunk main to Cleeve, at an offsite location (Lockstile Way) between Gatehampton and Cleeve WTW, including the construction of the associated chamber.

Design Parameters

HDPE was determined to be a viable and economical option for the Gatehampton project due to its flexibility and constructability, which enabled the project team to minimize the number of thrust blocks and fittings. The groundwater table at the project site is high; and therefore, easier construction with minimal excavation was an important parameter in pipe material selection. A DR-17, PE100 (PE4710) was used for this project.

Figure D.9.1 A view from the construction site

Construction Challenges

The GATOX pipeline was effectively installed on a large flood plain that was used for agricultural purposes. The biggest challenge encountered was to install the new main on the same route as the existing (for archaeological purposes) whilst ensuring the site was delivering full output at all times. This meant careful planning by completing a section first to create a bypass main, from which this gave the facility to isolate sections, remove the existing GRP main and install, connect and commission each section as the construction progressed throughout the works.

Project Highlights

Gatehampton is the largest groundwater withdrawal project in Europe. The project has substantially increased the raw water supply for the Cleeve WTW.

Conclusions and Recommendations

The project was completed with success, and no failures have been reported to date. On the other hand, the owner has assumed the risk of maintaining and operating a type of pipe material they are not familiar with. This means, should a failure occur in the future, the owner will have to rely on an outside contractor to repair and return the pipeline back to service.

D.10. CASE HISTORY 10 – HOWARD COUNTY, MARYLAND

<table>
<tr><td>Utility/Owner Name
Howard County DPW</td><td rowspan="5"></td></tr>
<tr><td>Project Name/Location
Broken Land ParkwayTransmission Main, Howard County, Maryland</td></tr>
<tr><td>Project Date
May 2014</td></tr>
<tr><td>Owner Contact
Paul Di Marco</td></tr>
<tr><td>Pipe Size
30 in.</td></tr>
<tr><td>Pressure
N/A</td><td>Flow Rate
N/A</td></tr>
<tr><td>Pipe Length
2,182 LF</td><td>Project Engineer
O’Brien & Gere</td></tr>
<tr><td>Construction Cost
$2.3 Million</td><td>Contractor
Cossentino Contracting Company</td></tr>
</table>

Background

Due to the low soil resistivity and stray currents caused by an impressed current system protecting gas mains, HDPE was the material of choice for the project. Additionally, the project team liked the flexibility of HDPE in comparison with the other materials.

Design Parameters

The main drivers of the design were the corrosive conditions of the area. Howard County required a completely noncorrosive material to be installed.

Construction Challenges

- Limited work area (Approximately 40 ft.) that paralleled a river
- Rock was encountered at 4 ft and required 30 day of blasting
- Installation was 20 ft from an existing 36 in. PCCP (pre-stressed concrete cylinder pipe) transmission main that was corroding
- There was one major river crossing
- Located in a flood plain – A 200- year storm hit during construction

- Jointing 400 ft pipe segments with butt fusion.

Figure D.10.1 Flexibility was among the reasons for selecting HDPE pipe

Figure D.10.2 The project involved one river crossing

Project Highlights

This project is the first large diameter HDPE transmission main installed by Howard County. It will make a significant impact on the water transmission system management and level of service provided to the utility customers by providing a noncorrosive reliable material. Using HDPE as opposed to PVC allowed Howard County to get a completely nonmetallic pipe installed (utilizing fusible HDPE joints). Construction will be completed approximately 45 – days ahead of schedule and will not exceed the bid price. Certified inspection was performed through a third party consultant inspector.

Conclusions and Recommendations

Overall, the experience with large diameter HDPE installation for Broken Land Parkway Transmission Main went well. The pros are the installation is fast. A noncorrosive and relatively flexible material was beneficial for this particular installation. The cons are that the contractor required a large area in order to install the transmission main. Fusion of the 400 – FT sections of pipe together was a challenge. Howard County will continue to use HDPE after this project.

D.11. CASE HISTORY 11 – SOUTH CATAMOUNT, COLORADO

<table>
<tr><td>Utility/Owner Name
Colorado Springs Utilities</td><td rowspan="5"></td></tr>
<tr><td>Project Name/Location
South Catamount Reservoir Transfer Pipeline/Teller County, Colorado</td></tr>
<tr><td>Project Date Completion
January 2014</td></tr>
<tr><td>Owner Contact
Bob Bass</td></tr>
<tr><td>Pipe Size
36 in.</td></tr>
<tr><td>Pressure
100 psi</td><td>Flow Rate
20 mgd</td></tr>
<tr><td>Pipe Length
Approximately 3,000 ft.</td><td>Project Engineer
Theresa Weidmann- AECOM</td></tr>
<tr><td>Construction Cost
Non Disclosed</td><td>Contractor
Garney Construction</td></tr>
</table>

Background

The objective was to replace two leaking pipelines, 16 in. and 14 in. steel placed in the early 1950s, that fed the South Catamount (South) storage reservoir. In the late 1950s the dam for the North Catamount Reservoir was built. The North Catamount (North) reservoir then sat on top of the existing pipelines (Figure D.11.1). The two pipelines had developed many leaks due to corrosion, and this resulted in insufficient water supply to the South reservoir for storage.

Design Parameters

The issue was how to place a pipeline across the North reservoir to feed the South one without draining the North reservoir completely. Time and seasonal constraints were also in play as this reservoir sits at a 9,000 ft elevation, and the new pipe elevation reaches as high as 14,000 ft at Pikes Peak. Another challenge imposed upon the project team was short construction windows short due to the weather. The project was executed as a design-build in an effort to accommodate material procurement and combat the erratic weather conditions. The project involved intense collaboration with the design-build team and Colorado Springs Utilities (CSU) in order to make rapid technical decisions and develop design concepts.

The control valves on both sides of the North reservoir were reconnected to the existing steel pipe. The Design Engineer presented the option to lay 3,000 ft of 30 in. DR 11 HDPE pipe across the North reservoir using a float sink method.

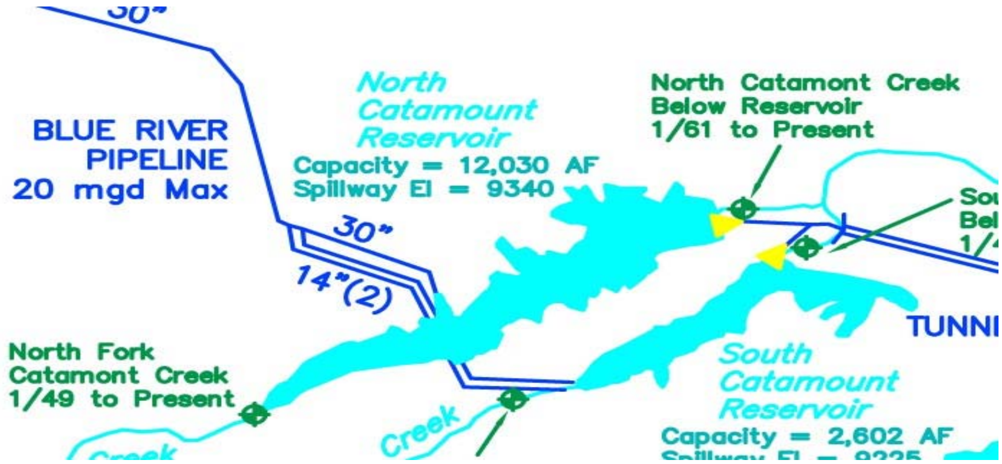


Figure D.11.1 Transfer pipeline schematic

Construction Challenges

One of the biggest challenges was getting material and equipment to the job site. Weather was a bigger challenge as construction did not start until August as the contractor had to wait until the reservoir was drawn down to its possible lowest point. Weather in Colorado can change in an instant at high elevations. As the project progressed the weather was turning colder with the threat of snow and the possibility of the reservoir freezing. After the bathymetric survey was completed it was determined that the pipeline has to be completely reconfigured to accommodate a natural riverbed, avoid tree debris and avoid crossing a deep ravine on the south side of the reservoir floor. The updated configuration is representative of the large radius of "s" shape of the pipeline, which the increased the total length. The proposed pipe was to be 30 in. HDPE DR 11 pipe. After much discussion and the possibility of future additional flow it was determined to change the pipe size to 36 in. HDPE DR 11. Additional Challenges were born by the divers who helped ensure the correct placement of the pipe on the reservoir floor and had to deal with short dive times and decompression chamber time due to the high altitude.

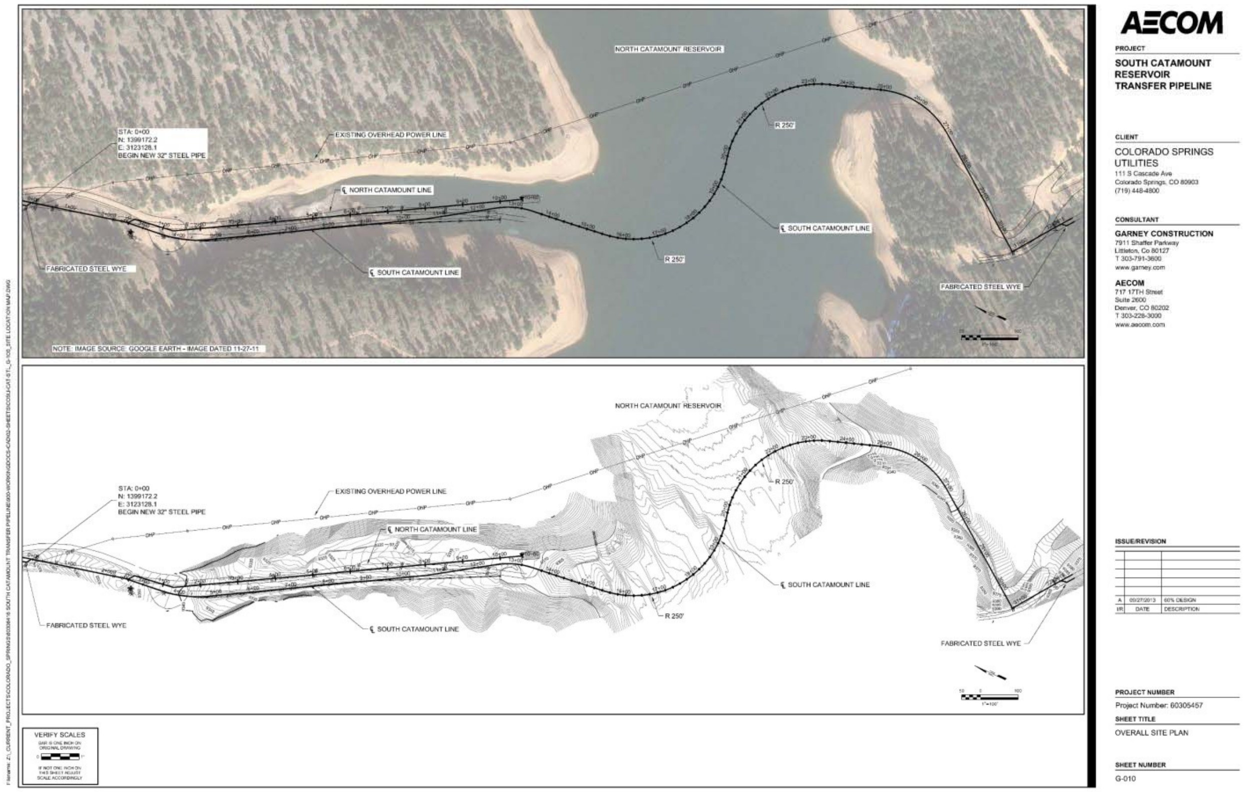


Figure D.11.2 Proposed HDPE pipe alignment

Project Highlights

This was a first for Colorado Springs Utilities. Although familiar with the use of HDPE pipe which is used in the Colorado Springs distribution system, CSU had not done a project of this caliber or method. The project did make a significant impact on the ability to get much needed water to available storage, which feeds through the transmission system to the treatment plant and then to the customers. There were many environmental benefits realized by using HDPE and placing the pipeline in a more direct route with a couple of curves and not having to plan a totally different route to dig and bury a new pipeline around the reservoir, which would entail many delays and damage to Forest Service land as wells as to the watershed due primarily to the geotechnical structure of the area. The HDPE pipeline should also have a longer lifecycle than the previous steel pipeline provided.

The access road to the construction site was the perfect staging area as the total length of the pipe could be fused together and laid along the road which was private access and not open to the public. Once the staged pipe was fused together it did create access issues to some materials and equipment. Before they could apply the concrete ballasts and start the initial floating of the pipe out on the reservoir, the contractor had to be sure that all equipment was placed on the correct side of the pipe as there was no way to cross over the pipe with equipment until the majority of the pipe had been floated out on the reservoir.

Conclusions and Recommendations

The project went well with minimal delays in the HDPE pipe placement. Once the HDPE pipe was placed in the reservoir, the construction continued to connect the ends of the HDPE pipe to the steel pipe could without worrying about any frost over the reservoir.

Using HDPE for this application has proven to be a good solution so far. CSU is considering using this type of application in other reservoirs for bypass or piping replacements. CSU thinks that there are also significant advantages for using HDPE in boring applications, and they will use HDPE pipe in the future when feasible.

Additional Photos

Uphill from launch site pipe staged

Looking towards launch site

Ballasts attachment area

Ballast attached ready to launch

Looking at launch area North side of reservoir

South side of reservoir

Boat tender pushing the end of the pipe across the reservoir

Sinking of pipe on 11-15-2013

Reservoir frozen 12-2-2013

APPENDIX E
CONVERSION TABLE

From	To	Multiply by
Length		
mil	in.	0.001
in.	mm	25.4
ft	m	0.3048
yards	m	0.9144
ft	in.	12
mile	km	1.609
mile	ft	5280
Area		
in.^{2}	mm^2	645.16
ft^2	m^2	0.0929
sq yards	m^2	0.8361
sq mi	km^2	2.5889
acres	km^2	4.0469×10^{-3}
Ha	km^2	0.01
acres	ft^2	43,560
m^2	Ha	10^4
Pressure		
psi	kN/m^2	6.895
psi	atm	0.0680
psi	kg/m^2	9.80665
psi	Pa	6894.757
psi	lb/ft^2	144
N/m^2	Pa	1
atm	psi	14.696
atm	Pa	101.325
bar	psi	14.5

From	To	Multiply by
Specific Weight (Weight/Unit Volume)		
lb/ft^3	N/m^3	157.1
lb/in^3	lb/ft^3	1728
Forces		
lb	kN	0.004448
tons	kN	9.96401
kN	kg(f)	102.0
Velocity		
mi/h	km/h	1.609
ft/s	m/s	0.3048
ft/min	m/s	0.00508
ft/min	m/min	0.305
Volume Flow Rate		
ft^3/s	gal/min	449
m^3/s	ft^3/s	35.3
m^3/s	gal/min	15,850
gal/min	L/min	3,785
m^3/s	L/min	60,000
m^3/s	ft^3/min	2120
m^3/hr	L/min	16.67
ft^3/s	m^3/hr	101.9
Temperature Conversion		
F to C first deduct 32, multiple by 5 then divide by 9		
C to F multiply by 9, divide by 5, add 32		

GLOSSARY

Abrasion – Wear or scour by hydraulic traffic.

Base Resin – Plastic materials prior to compounding with other additives or pigments

Butt Fusion – A method of joining polyethylene pipe where two pipe ends are heated and rapidly brought together under pressure to form a homogeneous bond.

Critical Pressure – the minimum internal compressed gas pressure at which rapid crack propagation (RCP) can be sustained along a section of plastic pipe.

Dimension Ratio – The ratio of pipe diameter to wall thickness. It is calculated by dividing the specified outside diameter of the pipe, in inches, by the minimum specified wall thickness, in inches.

Ductile Failure – A failure mode that exhibits material deformation (stretching, elongation, or necking down) in the area of the break

Fatigue – The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than tensile strength of the material.

High-Density Polyethylene (HDPE) – A plastic resin made by the copolymerization of ethylene and a small amount of another hydrocarbon. The resulting base resin density, before additives or pigments, is greater than 0.941 g/cm.

Hydrostatic Design Stress (HDS_{HDB}) – The estimated maximum tensile stress (psi) in the wall of the pipe in the circumferential orientation due to internal hydrostatic pressure that can be continuously applied with a high degree of certainty that failure of the pipe will not occur. HDS_{HDB} = HDB *DF (Design Factor)

Long-Term Hydrostatic Strength (LTHS) – The hoop stress that when applied continuously, will cause failure of the pipe at 100,000 hours (11.43 years). This is the intercept of the stress regression line with the 100,000 h coordinate as defined in ASTM D2837.

Molecular Weight Distribution – The ratio of the weight average molecular weight (M_w) to the number average molecular weight (M_n)

PE3408 – High density polyethylene with ESCR in accordance with ASTM D1693 equal to or greater than 600 hours or a PENT value per ASTM D1473 equal to or greater than 10 hours and a hydrostatic design basis of 1,600 psi

PE100 – A polyethylene classified by the ISO MRS system as having a minimum required strength of 10.0 MPa (1450 psi) in accordance with ISO 12162.

PENT – The common name given for a test to determine the slow crack resistance of PE materials by placing a razor-notched tensile bar under a constant tensile load of 2.4 MPa at 80ºC in accordance with ASTM F1473.

Permeability – Penetrability

PEX – Cross-linked polyethylene

Pressure Class – (AWWA C906) The design capacity to resist working pressure up to 80º F (27º C) maximum service temperature, with specified maximum allowances for reoccurring positive surges above working pressure.

Pressure, Surge - The maximum positive transient pressure increase (commonly called water hammer) that is anticipated in the system as the result of a change in velocity of the water column

Pressure, Working – The maximum anticipated sustained operating pressure, in pounds per square inch gauge, applied to the pipe or tubing, exclusive of surge pressures.

Slow Crack Growth (SCG) – The slow extension of the crack with time.

Stress Crack – An internal or external crack in a plastic caused by tensile or shear stresses less than the short-term tensile strength of the material. The development of such cracks is frequently related to and accelerated by the environment to which the material is exposed. More often than not, the environment does not; the environment does not visibly attack, soften or dissolve the surface. The stresses may be internal, external, or a combination of both.

Stress Relaxation – The decay of stress with time at constant strain.

Working Pressure – The maximum anticipated and sustained operating pressure applied to the pipe exclusive of transient pressures.

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ABBREVIATIONS

ACP	Asbestos Concrete Pipe
AC	Asbestos Cement
AO	Anti-Oxidants
AGA	American Gas Association
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
BCCP	Bar-wrapped Concrete Cylinder Pipe
BFV	Back-flow Pressure Valve
BTEX	Benzene, Toluene, Ethyl benzene and Xylene
CAGR	Compound Annual Growth Rate
CB	Control Board
CCP	Cement Concrete Pipe
CI	Cast Iron
CLSM-CDF	Controlled Low Strength Material-Controlled Density Fill
CP	Concrete Pipe
CUIRE	Center for Underground Infrastructure Research and Education
CPVC	Chlorinated Polyvinyl Chloride
DIP	Ductile Iron Pipe
DR	Dimension Ratio
DWI	Drinking Water Inspectorate
DI	Ductile Iron
EPA	U.S. Environmental Protection Agency
FC	Fiber Cement
FRP	Fiber Reinforced Pipe
GPM	Gallon Per Minute
MGD	Million Gallon Per Day
HDD	Horizontal Directional Drilling
HDPE	High Density Polyethylene
HDS	Hydrostatic Design Stress
HP	Horse Power
ICI	Imperial Chemical Company
ID	Inside Diameter
ISO	International Organization for Standardization

LADWP	Los Angeles Dept. of Water and Power
LDPE	Light Density Polyethylene
LHTS	Long-Term Hydrostatic Strength
LPM	Liters per Minute
MDPE	Medium Density Polyethylene
MDWASD	Miami Dade Water and Sewer Department
NTUA	Navajo Tribal Utility Authority
OD	Outside Diameter
PAC	Project Advisory Committee
PE	Polyethylene
PEX	Cross-linked Polyethylene
PC	Pressure Class
PI	Principal Investigator
PPI	Plastics Pipe Institute
PCCP	Prestressed Concrete Cylinder Pipe
PPFA	Plastic Pipe and Fitting Association
PVC	Polyvinyl Chloride
PSI	Pounds per Square Inch
QA	Quality Assurance
QBS	Quality-based Selection
QC	Quality Control
RCP	Reinforced Concrete Pipe
SAWS	San Antonio Water System
SCG	Slow Crack Growth
SP	Steel Pipe
TRWD	Tarrant Regional Water District
UKWIR	UK Water Industry Research
UPVC	Unplasticized Polyvinylchloride
UTA	The University of Texas at Arlington
VCP	Vitrified Clay Pipe
WRF	Water Research Foundation
WP	Working Pressure
WSP	Welded Steel Pipe
WTW	Water Treatment Works/Plant