AN INVESTIGATION OF DURABILITY AND RELIABILITY OF HDPE PIPE FOR LARGE DIAMETER WATER TRANSMISSION APPLICATIONS

by

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Abstract

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The drinking water infrastructure in the North America requires a durable and reliable water transmission pipe material. Thus, it is important to study pipe performance, so that water utilities can benefit from cost-effective and efficient pipe installations and longer design life. All pipe materials deteriorate overtime and every pipe has unique properties with advantages and limitations. During a pipe's life cycle, failures occur due to numerous factors such as age, loading conditions, environmental conditions, installation quality, manufacturing procedures, operation and maintenance strategies and so on. This research focuses on reliability and durability of large diameter (16 in. and larger) high density polyethylene (HDPE) pipe and specifically its fatigue performance under cyclic loading, since limited information is available on resistance of this pipe under transient pressures.

To conduct this research, in addition to a comprehensive literature search, a national survey of water utilities in the North America was performed. Additionally a testing concept was developed to determine the performance of a HDPE pipe sample

with recurring surges for two million cycles. This specimen was subjected to a pressure of 1.5 times Pressure Class (PC) for a 16-in., 15-ft long, DR 17, 4710 HDPE pipe with a fused joint in the middle.

The results of this investigation showed that at this time, few water utilities use large diameter HDPE pipe. Those that use large diameter HDPE, majority are satisfied with the pipe performance; however, they had some concerns regarding joints and fittings as described in this thesis. Also, some utilities did not differentiate between 4710 HDPE pipe tested in this research, and older products such as 3408 and 3608. The results of testing showed that the pipe sample described above was able to withstand the 2 M cyclic loadings between 125 psi and 188 psi (1.5 times its pressure class).

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CHAPTER 1

INTRODUCTION

1.1 Introduction and Background

As per the “Report Card from American’s Drinking Water Infrastructure” (ASCE, 2013), the U.S. infrastructure is in poor condition and around 33 percent of drinking water is lost each year (Radoszewski, 2009). Due to leaks and breaks, water utilities in the United States lose 40 billion liters (10.6 billion gallons) of water between treatment plants and tap everyday out of 160 billion liters (42.3 billion gallons) of processed water. The U.S. spent approximately $1.2 billion on water rehabilitation in 2006 when the need was to spend $6 billion (Jeyapalam, 2007 and Najafi, 2013). The cost over the coming decades could reach more than $1 trillion (AWWA, 2013).

According to Mays (2000), based on the material used in manufacturing, pipes are classified into three types, such as metallic pipes, concrete pipes and plastic. Additionally pipes can also be classified as either rigid or flexible pipes based on their strength and stiffness. According to Najafi (2010), pipes can be classified as semi-rigid, semi-flexible or intermediate, which share partial characteristic of both types. Table 1.1 classifies pipe materials as either rigid or flexible. Rigid pipes are resistant to longitudinal and circumferential (ring) bending and they are considered to not deform under the applied loads. Flexible pipes are deformable pipes capable of deforming without causing any damage to the pipe under certain limits. Again, according to Najafi (2010), flexible pipe is defined as pipes capable of deforming more than two percent of their diameter size without undergoing any structural failure. Terminology used to characterize properties of rigid and flexible pipes is strength and stiffness.

Table 1.2 classifies pipes based on whether they are metallic or nonmetallic. Pipes manufactured from metals or mixture of metals, are conductive in nature and are classified as metallic pipes. Pipes, which are manufactured from material other than metals, such as concrete and plastics, are non-conductive and are classified as non-metallic pipes (Mays, 2000; Liu, 2003).

Table 1.3 is a summary of timeline of the pipe material used to distribute water in United States with related American Water Works Association (AWWA) standard manual used for installation practices (NRC, 2003). The first pipe materials to be used for the distribution of water were wood and pit iron. Even though the discovery of polyethylene pipes was made in 1933, and pipes were manufactured during the 1940s (Storm and Rasmussen, 2011), the actual application of HDPE pipes in the water distribution was not approved by AWWA until 1980 and installed the same year (Welton et al., 2010).

Table 1.1 Classification of Pipe based on Material[1] (Najafi, 2010)

Rigid Pipes	Flexible Pipes
Concrete (CP)	Steel (SP)
Vitrified Clay (VCP)	Ductile Iron (DIP)
Pre-stressed Concrete Cylinder (PCCP)	Polyvinyl Chloride (PVC)
Reinforced Concrete (RCP)	High Density Polyethylene (HDPE)
Bar-wrapped Concrete Cylinder (BCCP)	Fiber Reinforced Plastic (FRP)
Asbestos-cement (AC)	__
Fiber-cement (FC)	__

[1] See a complete list of abbreviations and acronyms on Page 90

Table 1.2 Classifications of Pipes based on Material (Liu, 2002; Mays, 2000)

Metallic Pipes	Non-metallic Pipes
Steel Pipe, Cast-Iron Pipe, Ductile-Iron Pipe, Stainless Steel Pipe, Copper Pipe	Concrete Pipe (PCCP, RCCP), Plastic Pipe (PVC, PE), Clay Pipe, Asbestos-cement Pipe

Table 1.3 Timeline of Pipe Material with related AWWA Standard Manual (NRC, 2003)

Pipe Material	Period of Installation	AWWA Standards
Asbestos Cement Pipe	1930 - 1980	C400
Concrete Pressure Pipe	1940 - Present	C300/301/302/303
Ductile Iron	1960 - Present	C151
HDPE	1980 - Present	C906
Pit Iron	1850 - 1950	C100
PVC	1970 - Present	C900/905
Spun Cast Iron	1930 - 1960	C100
Steel	1850 - Present	C200

A recent study by Utah State University's Buried Structures Laboratory recorded 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, ductile iron pipes was 4.9 failures/100 miles/year, PVC was 2.6 failures/100 miles/year, concrete pressure pipe was 5.4 failures/100 miles/year, steel pipe was 13.5 failures/100 miles/year and asbestos cement pipe was 7.1 failures/100 miles/year (Folkman, 2012). Folkman did not specifically include HDPE in his investigation, not considering the causes of pipe failures; these statistics show that some pipe materials have higher failure rates than others. Therefore, there is a need for reliable and durable pipe materials.

1.2 HDPE Background

According to PPI (2008), "High Density Polyethylene (HDPE) was first invented in England in 1933 by Imperial Chemical Company (ICI). The early polymerization processes used high-pressure (14,000 to 44,000 psi) autoclave reactors and temperatures of 200 ˚F to 600 ˚F. It was produced in a free radical chain reaction by combining ethylene gas under high pressure with peroxide or a trace amount of oxygen. Later in the 1950's, polyethylene (PE) with low pressure was introduced. Polyethylene as a density varying between 0.935 to 0.941 g/cc (58.37 to 58.74 pcf) for medium density polyethylene, and 0.941 to 0.945 g/cc (58.74 to 58.99 pcf) for high density polyethylene. Industry practice has shown that base resin densities are in the range of 0.936 to 0.945 g/cc (58.43 to 58.99 pcf). The polyethylene pipes with higher density, such as 0.952 g/cc (59.43 pcf), in combination with higher molecular weight and bimodal molecular weight distribution recognized higher levels of performance under ISO (International Organization for Standardization) standards for PE piping outside North America)."

According to AWWA (2006), "Polyethylene (PE) is a semi crystalline polymer composed of long, chain-like molecules of varying lengths and numbers of side branches." The above definition describes the structure of the polymer, which means that many parts are joined together (cross-linked) to make a whole. The structure of high density polyethylene is stronger when compared to two types of PE (i.e., LDPE & MDPE); the molecular weight is the main factor that determines the durability. The long-term strength, toughness, ductility and fatigue endurance improve as molecular weight increases. Also, the amount of crystallinity is 65% in high density polyethylene (HDPE) compared to medium density. As HDPE's crystallinity increases, its stiffness, modulus, and chemical resistance increases, while its permeability, elongation at failure, and flexibility decreases (Koerner, 2012).

According to Najafi and Gokhale (2005), “PE pipes in North America are classified into three groups, based on density and crystallinity, which is an indicator of the tensile strength. The higher the crystallinity, results in greater hardness, stiffness, tensile strength, and density. ASTM classifies Type I as a low-density PE (LDPE), Type II as a medium density PE (MDPE), and Type III as a high density PE (HDPE). HDPE displays the highest stiffness whereas LDPE is the most flexible.”

For the purpose of this thesis, “durability” can be defined as the ability of the pipe and its fittings to remain in service during its design life without significant deterioration, and “reliability” relates to consistency of performing the required function without degradation or failure (AWWA, 1994).

1.2.1. HDPE in Water Applications

The use of HDPE pipe in municipal water applications is much less than other pipe materials, mainly because unfamiliarity of water utilities about HDPE performance. Rahman (2003) reported data for pipe materials used for municipal applications in North America in 1999. The use of PE pipe for potable water applications was 3% of reported 310 million feet while that in the sanitary sewer was 11% or 290 million feet. The overall HDPE use in municipal applications was 6.87% of the reported 600 million feet of pipeline while that for DI and PVC Pipe were 20.82% and 69.38% respectively. Figure 1.1 illustrates North American municipal applications of piping material market.

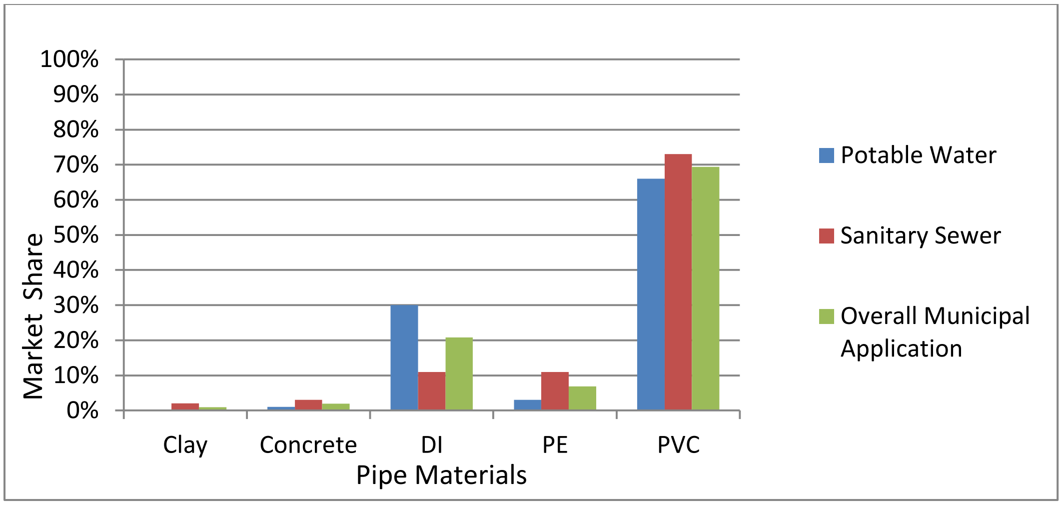


Figure 1.1 North American Municipal Applications Piping Material Market

(Source: Rahman, 2003)

While use of HDPE in U.S. water market is not significant, in the other parts of 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 Compound Annual Growth Rate (CAGR)[2] 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." According to Anon (1999), "PE pipe is light weight and available in various lengths, it is relatively easy to handle and install. PE is the material most frequently used in water supply applications in the UK. It is estimated that PE represents 4 to 6% of the potable water market in the U.S. and nearly 100% of the gas distribution market."

[2] The compound annual growth rate, or CAGR for short, measures the return on an investment over a certain period of time.

Table 1.4 presents use of HDPE pipe in various applications compared with other pipe materials.

Table 1.4 Application of Different Pipe Materials (Adapted from Najafi, 2010)

Pipe Material	Applications
Polyethylene pipe	1. Water systems 2. Gas distribution 3. Sewer systems 4. Nuclear and industrial process piping 5. Electrical and communication duct
Polyvinyl chloride pipe	1. Water systems 2. Sewer systems
Steel pipe	1. Transports fluids such as natural gas, crude oil 2. Potable water transmission 3. Casing pipe in micro-tunneling, jacking, boring and pipe-ramming
Cast/Ductile iron pipe	1. Mainly potable water distribution 2. Few sewer systems
Reinforced concrete pipe	1. Non-pressure applications 2. Low-pressure applications
Prestressed concrete cylinder pipe	1. High pressure applications 2. Sewer systems 3. Industrial cooling systems
Bar-wrapped steel-cylinder concrete pipe	1. Pressure applications 2. Treatment plants
Glass reinforced pipe	1. Water systems 2. Sewer systems

1.2.2. HDPE Pipe Limitations

While in the literature many benefits of HDPE pipes are listed, two major limitations are also described as follow:

Permeation is one of the limitations of HDPE pipe. If any ground contamination due to existence of hydrocarbons are found, then the pipe should be rerouted around the contaminated plume, or surround the pipe with good clean soil of class I or class II[3] materials to allow the hydrocarbon that may have contacted the pipe's wall to dissipate into the atmosphere (PPI, 2009).

Another limitation of HDPE pipe is oxidation. Oxidative degradation of polyethylene pipe is due to commonly present water disinfectants such as chlorine, chlorine dioxide and chloramines (Donald and Dale, 2009).

1.3 Thesis Objectives

The main objectives of this thesis are:

- To collect available information on the reliability and durability of large diameter HDPE pipe in water applications from various utilities around the United States.
- To identify features and benefits of HDPE pipe (design, installation, maintenance, etc.) as well as its limitations and issues in water mains.
- To develop a testing protocol for cyclic fatigue loading (transient pressures) of large diameter (16 in. and larger) HDPE pipe in water applications.

1.4 Research Needs

The existing drinking water pipeline is nearing the end of its useful life. There is an estimate of 240,000 water main breaks per year in the United States (ASCE, 2013). Large diameter transmission mains are the most critical element of a water supply system, since a failure can be disruptive to social life in addition to extended service

[3] Class I: Angular crushed stone or rock, dense or open graded with little or no fines (1/4 inch to 1.5 in. in size). Class II: (GW, GP, SW, SP, GW-GC, SP-SM) Clean, coarse grained materials, such as gravel, coarse sands and gravel/sand mixtures (1.5 in. maximum in size).

interruptions and property damage. Where rehabilitation by relining of a deteriorated large diameter water main is not feasible due to capacity concerns and structural integrity, replacement is necessary. Recent advancements in polymer science have resulted in production of high-strength and durable, large diameter (16-inch and larger) high density polyethylene (HDPE) pipes with thick walls (up to 4 inches). Since information on large diameter HDPE, especially relatively new PE 4710 is limited. As said earlier, while in the United Kingdom and other European countries use of HDPE pipe dominates water market at 65% to 85% share, in the North America, HDPE pipe holds a much smaller, though growing, share of the water piping market (Vibien et al, 2009). Therefore, this research is focused on durability and reliability of large diameter HDPE pipes in water main applications, as one of the main concerns of water utilities for its use.

1.5 Methodology

The methodology of this thesis is summarized below:

1. Conduct a literature research to identify and review the past research regarding the performance of durability and reliability of HDPE pipes. Also, refer to various publications, reports and other resources.

2. Conduct a nationwide survey of water utilities in North America to determine the performance of existing pipes, and issues or concerns related to HDPE pipes in water main applications.

3. To supplement the above literature research and survey, develop a testing protocol to evaluate a large diameter HDPE 4710 under cyclic fatigue pressures.

4. Finally, analyze the results of the literature search, survey and experimental work to draw conclusions and recommendations for future research.

Figure 1.2 illustrates an overview of the strategy behind this research.

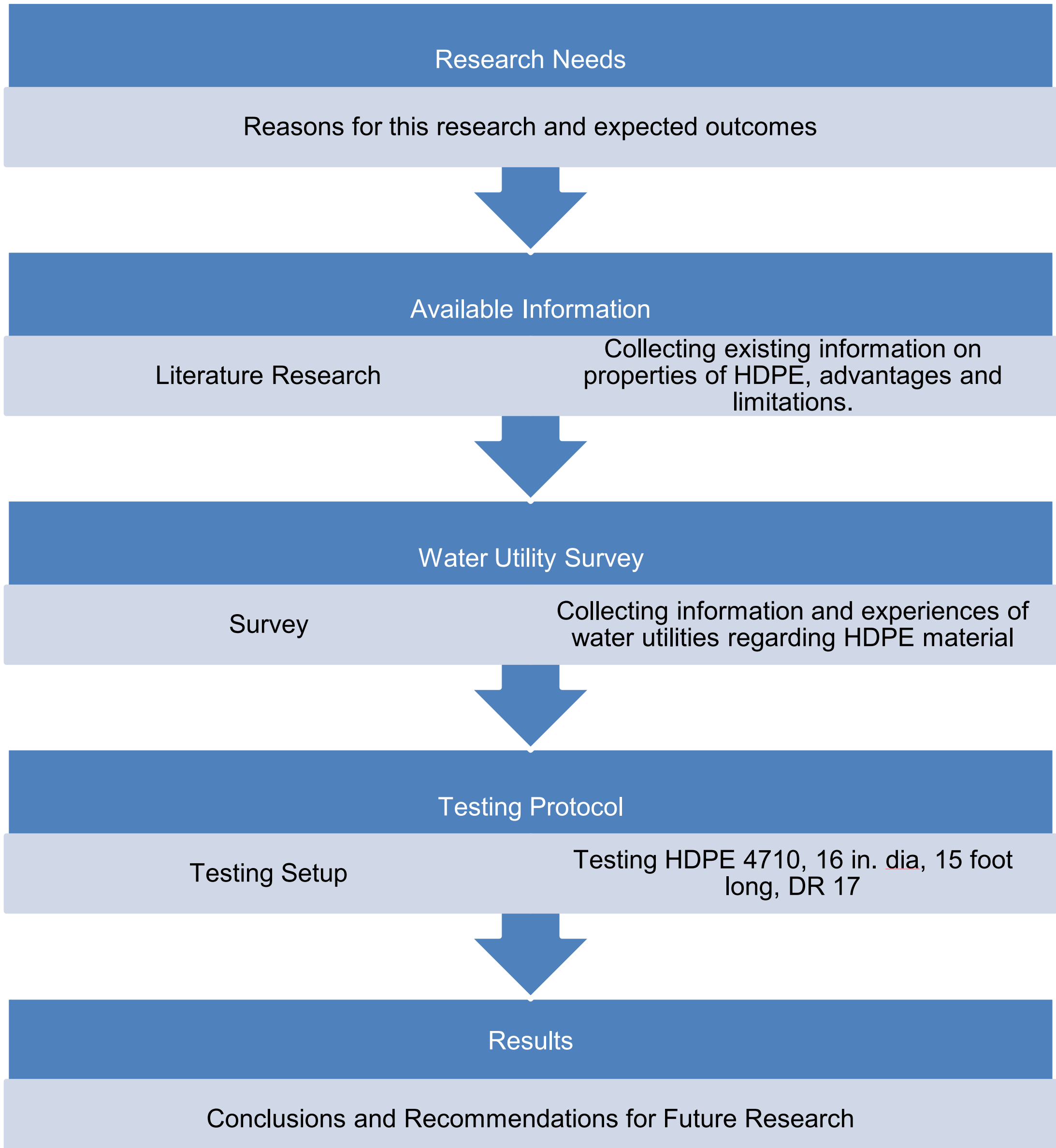


Figure 1.2 Research Methodology

1.6 Thesis Organization

This thesis is divided into 6 chapters. Chapter 1 presents instruction to the thesis and background of HDPE pipe material, objectives, research needs and methodology. The literature search is provided in Chapter 2. Chapter 3 discusses the survey results and summary of survey. Chapter 4 explains the experimental setup and equipment. Chapter 5 discusses the results of survey and experimental work. Finally, Chapter 6 concludes with the summary of thesis and provides recommendations for future research.

1.7 Expected Outcomes

The results from this thesis are expected to create awareness for future research on large diameter high density polyethylene pipes for water transmission applications. The survey questionnaire for water utilities was designed to provide answers about the field performance of PE4710 and PE3608/3408 pipe material. To supplement the survey results, a fatigue testing was conducted at CUIRE lab to determine the performance of large diameter PE4710, under transient pressures. The results of survey would provide a source of information for pipe manufactures to improvise on the concerns and issues explained by utilities. The experimental work is expected to provide a testing protocol for future fatigue testing of large diameter HDPE pipe.

1.8 Chapter Summary

This chapter presented an introduction to this thesis, some background information on HDPE pipes, and their benefits and limitations. In addition, thesis objectives, research needs, methodology and organization were presented.

CHAPTER 2

LITERATURE RESEARCH

2.1 Introduction

The previous chapter presented an introduction to this thesis and the some background information on HDPE pipe. This chapter consists of a detailed review of findings from an extensive literature search. Literature search was used as one of the tools to understand the performance of high density polyethylene pipes based on past papers, experiments and other work. The subjects covered in this chapter includes the pipe standard development, structural properties, manufacturing, leakage, fatigue resistance, thermal expansion, elevated temperature, permeability, and oxidation in HDPE pipe.

2.1.1. Background

According to PPI (2007), the advanced PE4710 is used in water piping applications because of higher hydrostatic design stress with the following designation codes:

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

According to ASTM standard specification D 3350, the pipe material designation codes for other PE materials are (PPI, 2007):

1. PE 3408 is a polyethylene (the PE abbreviation is in accordance with ASTM D 1600) with a density cell class of 3 and a slow crack growth (SCG) cell class of 4 (in accordance with ASTM D 3350). It has an 800 psi maximum recommended Hydrostatic Design Stress (HDS) for water at 73ºF (23ºC).
2. PE 3608 is a polyethylene (the PE abbreviation is in accordance with ASTM D 1600) with a density cell class of 3 and a slow crack growth (SCG) cell class of 6

(in accordance with ASTM D 3350). It has an 800 psi maximum recommended Hydrostatic Design Stress (HDS) for water at 73ºF (23ºC).

3. PE 4710 is a polyethylene (the PE abbreviation is in accordance with ASTM D 1600) with a density cell class of 4 and a slow crack growth (SCG) cell class of 7 (in accordance with ASTM D 3350). It has a 1000 psi maximum recommended Hydrostatic Design Stress (HDS) for water at 73ºF (23ºC).

Table 2.1 presents differences between PE 3408, PE 3608 and PE 4710.

Table 2.1 Differences between PE 3408, PE 3608 and PE 4710

(Adapted from: PPI, 2007)

<table>
<tr><th colspan="2"><u>PE3408 and PE3608</u></th><th><u>PE4710</u></th></tr>
<tr><td colspan="2">This resin is categorized as Class 3</td><td>This resin is categorized as Class 4</td></tr>
<tr><td colspan="2">Base resin density of PE3408 is 0.941 – 0.947 g/cc</td><td>Base resin density of PE3608 is 0.947 – 0.955 g/cc</td></tr>
<tr><td>The slow crack growth for Class 4 is atleast 10 hours</td><td>The slow crack growth for Class 6 is atleast 100 hours</td><td>The slow crack growth for class 7 is at least 500 hours</td></tr>
<tr><td colspan="2">Hydrostatic design stress (HDS) is 800 psi</td><td>Hydrostatic design stress (HDS) is 1,000 psi</td></tr>
<tr><td colspan="2">Pressure Class for PE3408 and PE3608 is lower for specified DR. The flow capacity is less.</td><td>Pressure Class is higher for specified DR when compared to PE3408 & PE3608. The flow capacity increases.</td></tr>
</table>

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. Table 2.2 presents pressure ratings for PE3608/PE3408 and PE4710 for specific DR's.

Table 2.2 Pipe Pressure Rating for Water at 80˚F for HDPE Pipe

(Source: Performance Pipe, 2007)

Pipe Pressure Ratings		
DR	PE3608 and PE3408	PE4710
	HDS - 800 PSI	HDS - 1000 PSI
7.3	255	317
9	200	250
11	160	200
13.5	130	160
17	100	125
21	80	100
26	62	80
32.5	50	63

[1]HDS – Hydrostatic Design Stress

2.1.2. HDPE Pipe Standard Development

According to Rubeiz (2004), "High density polyethylene piping systems have been available since 1948. In 1955, the American Society for Testing and Materials (ASTM) established the Plastics Pipe Committee. In 1978, the American Water Works Association (AWWA) approved HDPE for water tubes that were up to 3-in. in diameter. In 1990, AWWA developed the first edition of the AWWA Standard for HDPE water distribution pipes that range in diameter between 4-in. and 63-in. In 1992, the Indianapolis Water Company, now US Filter, adopted this technology and became one of the first municipalities in North America to install water mains using HDPE. In 2004, AWWA is expected to publish a new Manual (M55) to assist municipalities and consultants in the design and installation of PE pipes."

2.2 Research Findings

2.2.1. HDPE Pipe Manufacturing

HDPE resins are responsible for most of the material properties of HDPE pipes. Continuous research on HDPE resins has resulted in latest resin development for PE 4710. HDPE pipes are manufactured by extrusion process. Extrusion process of polyethylene pipe can affect its properties (Park et al., 1987). Residual stresses in HDPE pipe has been an interest of the researchers. Residual stresses have the greatest effect on the longitudinal direction of the liner with crack growth from the outer surface through the liner thickness. This implies that residual stress could be one of the factors that have led to pipe cracking in the field (Hsuan and McGrath; 1999). Annealing has been introduced as solution to the residual stress problems in HDPE pipe (Bhatnagar and Broutman; 1985). Bonds (2000) criticized the manufacturers' accuracy in extrusion, stating that it limits the pressure class of HDPE pipe. The PPI (2008) briefly explains the work of extrusion, stating that its function is to heat, melt, mix, and convey the material to the die, where it is shaped into a pipe section.

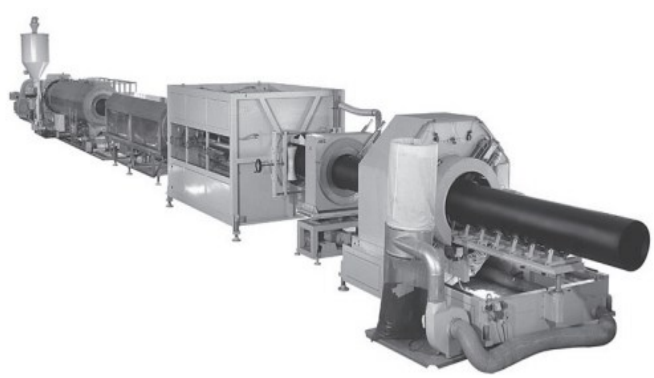


Figure 2.1 Typical Conventional Extrusion Line

(Sources: PPI Handbook, 2008)

Extruder screw operates on stick/slip principle. The design of screw is very important to produce high quality pipe. Figure 2.1 presents the typical conventional extrusion line.

In 2005, Paul et al prepared a novel high density polyethylene resins made in the loop-slurry process (single-reactor), using a catalyst of chromium on modified alumino-phosphate. This process developed a unique structure which is suitable for high performance pipe applications. In particular, pipes made from these ethylene I-hexane copolymers satisfy the performance requirements of PE4710 specifications. High density polyethylene pipes are extensively used for transportation and distribution of natural gas. Therefore, Chevron Phillips chemical company describes the development of a new catalyst and polymerization system capable of producing PE4710 (PE100)[4] resin in a single reactor from a single catalyst (Paul et al, 2005).

Again in 2005, Paul et al concluded that even though these polyethylene resins have a very broad molecular weight distribution; they exhibit good resistance to rapid crack propagation as indicated by the Charpy and S4 (see ASTM F1554 - 07ae1) results. The new multimodal, high density polyethylene resins made from chromium/alumino-phosphate catalysts compared well with the bimodal resins tested. The unique combination of primary structural properties met the requirements for a PE4710 (PE100) pipe resin.

2.2.2. HDPE Pipe Structural Properties

The PE pipe is known for its visco-elastic nature. Due to the molecular nature, PE is a complex combination of elastic-like and fluid-like elements. Figure 2.2 illustrates the small instantaneous elastic strain that is then followed by a time-dependent strain. As time increases, the strain increases, after some time the strain decrease with increase in time. This is related to fatigue resistance of surges in the pipe (PPI Handbook, 2008).

[4] PE4710 is called PE100 in Europe.

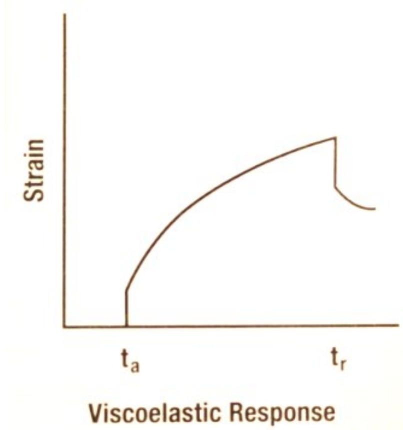


Figure 2.2 Visco-elastic Nature of PE (Source: PPI, 2008)

2.2.3. Leakage

In 2011, Donald et al prepared a “Chambers Report” regarding three stages of failures. He produced a schematic creep rupture curve in Figure 2.3. “The stage I failure involves a purely mechanical failure mechanism due to ductile overload of the material failure mechanism. Stage I failures on pipe testing manifest as ductile bursting of the pipe with yielding of the material. Stage II failure also involves a mechanical failure mechanism but manifests itself as non-ductile slit or pinhole cracks in the pipe wall permitting leakage from the pipe. Stage III failure also manifests itself as leakage from non-ductile cracking of the pipe wall but it is not purely mechanical. Stage III failure occurs at lower stresses that Stage II failure and requires some minimum level of oxidative degradation of the HDPE pipe material” (Donald et al, 2011).

Loss of water through leaks represents a significant cost for many networks that is often overlooked. Ambrose et al. (2010) estimated leakage cost based on two leakage models and those are:

- Background leakage, which occurs mainly through joints in the pipes and perforations.

• Leakage from burst failures such as longitudinal splits and circumferential breaks.

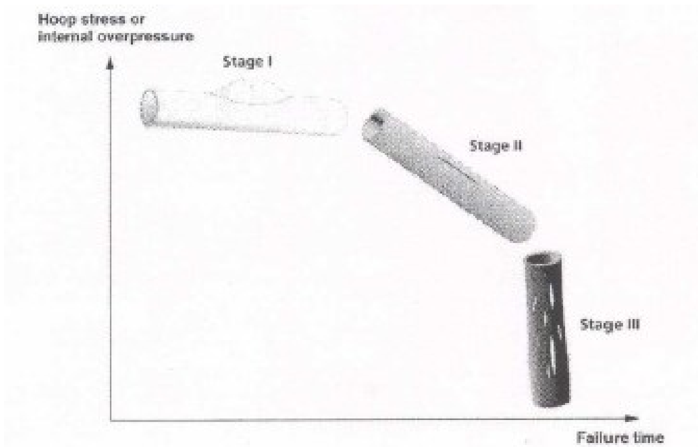


Figure 2.3 Three Stages of HDPE Pipe Failure

(Source: Donald et al, 2011)

Ambrose et al performed leakage cost simulation of PE, PVC/DI, DI and Mixed pipe material for a medium network of 100,000 costumers and concluded that PE has the lowest leakage cost. Figure 2.4 represents the Graph of Leakage Cost Simulation.

Based on American Water Works Association (AWWA) Manual M36, the largest leaks occur in the main line and can reach up to 1,000 GPM (AWWA, 1999). AWWA also mentions the cost for leak detection which can be added up to $800 per mile/main (in 1999 dollars). This cost will be in addition to the cost of leaking water, cost of treating water and the cost to repair the leak (Rubeiz, 2004).

For municipal applications, fused joints eliminate the potential leak points that exist every 10-ft to 20-ft when using the bell and spigot type joints associated with other piping products such as PVC or ductile iron. As a result of this, the allowable water leakage for PE pipe is zero as compared to the water leakage rates of 10% or greater typically associated with other piping products (PPI, 2008). This can considerably reduce the mentioned cost associated with leakage.

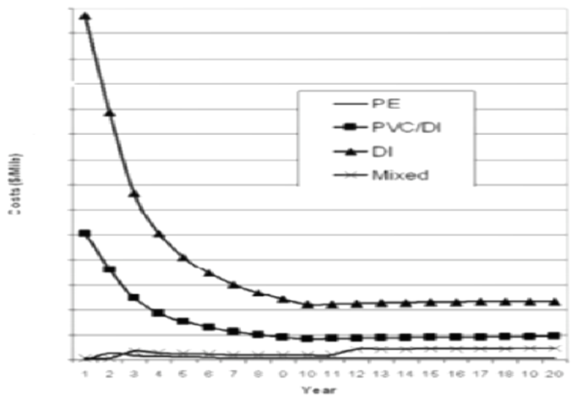


Figure 2.4 Leakage Cost Simulation

(Source: Ambrose et al, 2010)

<u>2.2.4. Fatigue Resistance</u>

There are three primary models for fatigue damage to thermoplastic materials, depending on the type of loading (Oliphant et al, 2012);

- Self-heating with induced localized melting
- A cumulative damage model
- A crack propagation model with acceleration by cyclic loading, which may be further subdivided into:
    - Pure fatigue
    - Combined creep and fatigue

In 2012, Oliphant presented paper on PE4710 which based on available data found resistance of PE4710 materials. He found both the approach for repetitive fatigue resistance and occasional surge resistance for PE4710 and PVC. Later he compared and concluded that PE exhibit superior fatigue resistance over PVC piping material.

In 1990, Jeremy presented fatigue response of polyvinyl chloride and polyethylene pipe systems. He concluded that fluctuating internal pressures induces fatigue stresses in pipes and fittings, also fatigue response of unplasticized polyvinylchloride (UPVC) pipe was well defined, whereas PE pipe systems failed at fittings and joints at elevated temperature. Therefore, the literature indicates that joints by butt fusion in particular, have the best projected fatigue lifetimes, and are capable of withstanding significant surge fatigue stressing at 68-73˚F (20/23˚C). Figure 2.5 presents the different loading profiles. The final wave pattern quantifies the fatigue damage pipe systems sustain in service. Same waveform pattern is used in this thesis, as presented in Chapter 5, Figure 5.1.

Velocity in HDPE Pipe:

Petroff (2013) presents the effect of flow velocity on surge pressure. As the velocity increases, lower dimension ratio (DR) (thicker wall) pipes may be required to handle the surge pressure. The paper also states that, AWWA-WaterRF “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.” The safe upper limit is 5 fps even though some of the utilities extend up to 8 fps.

Table 2.1 presents the DR 21 pressure design example for PE4710 pipe at 73˚ F, the PE 4710 DR 21 is designed based on design flow velocity, and surge pressure. Followed by Table 2.3, Table 2.4 presents number of cycles required to fail PE4710 and PE100 based on 55 surges per day and having a working pressure at 1.1 to 1.5 pressure classes. Using following equations (Eq.1 and Eq. 2) number of cycles and peak stress is calculated,

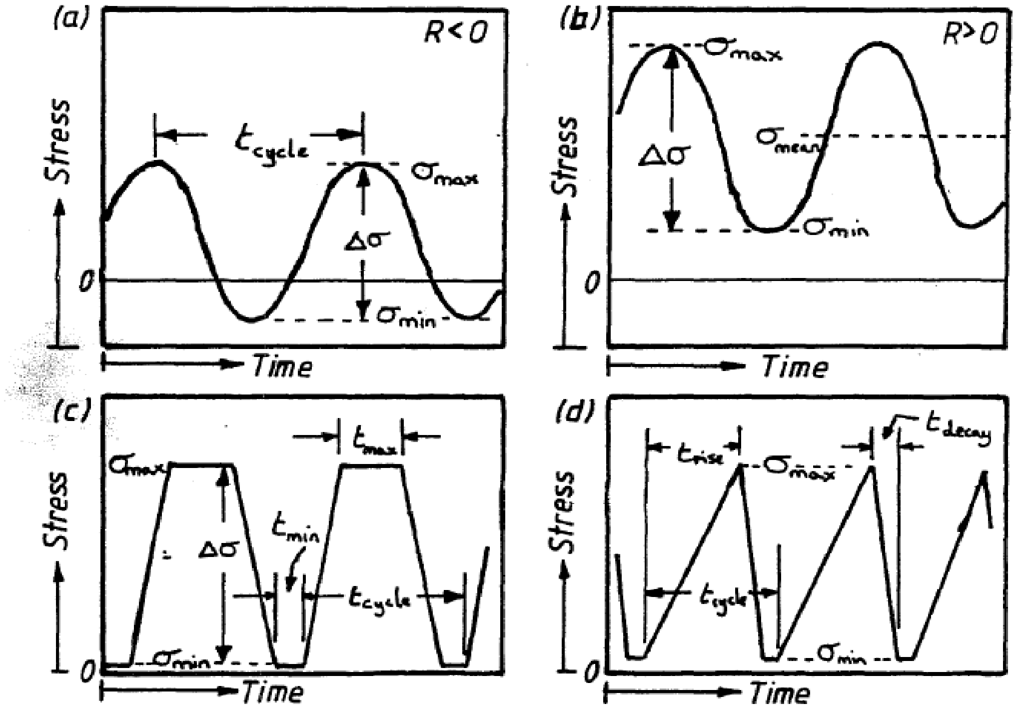


Figure 2.5 Schematic Presentation of Different Loading Profiles

(a) & (b) Sinusoidal, (c) Trapezoidal and (d) Saw tooth

(Source: Jeremy, 1990)

Number of Cycles = 10^ $\frac{1.708 - Log(\frac{Peak\ Stress}{145})}{0.101}$ Eq.1

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

Table 2.3 DR 21 Pressure Design Example for PE4710 pipe at 73 ˚ F

(Source: Petroff, 2013)

Working Pressure (psi)	DR	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)
100	21	100	4	40	140	200	150
	21	100	5	50	150	200	150
	21	100	6	60	160	200	150

Table 2.4 Cycles to Failure for PE4710 and PE100

(Source: Petroff, 2013)

Working Plus Surge Pressure (WP + PS)	Peak Stress (psi)	Cycles to Failure	Fatigue Life (Years) @ 55 surges/day	Safety Factor 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

2.2.5. Elevated Temperature

The geomembranes service life is influenced by the peak elevated temperature 140°-176°F (60-80°C). This can reduce the service life of high density polyethylene geomembranes by accelerating antioxidant depletion of geomembranes and polymer degradation. Jafari et al (2014) discuss possible temperature requirements for landfill.

They give a brief explanation about the estimated HDPE geomembranes service life based on 50% reduction in tensile strength at break for different temperatures. Table 2.5 presents service life of HDPE geomembranes, if the temperature is maintained at 68˚F (20°C) the life of HDPE increases to 565-900 years. As the temperature increases, the service life decreases or vice versa.

Table 2.5 The Service Life of HDPE Geomembranes Subjected to Elevated Temperature (Source: Jafari et al, 2014)

Temperature		Service Life (Years)	Temperature		Service Life (Years)
°F	°C		°F	°C	
68	20	565-900	104	40	80-120
86	30	205-315	122	50	35-50
95	35	130-190	140	60	15-20

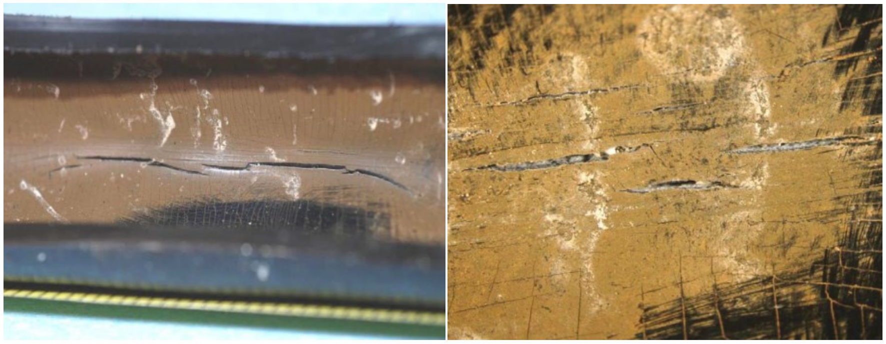
2.2.6. Thermal Expansion

Recently, research was carried out to determine the pipe property changing with time or temperature. Most of the papers neglected thermal expansion of HDPE pipe. Zheng et al (2012) investigated the combined effect of soil load and temperature on HDPE pipe with introduction of thermal expansion. The variation between stress and deflection was studied using ABAQUS finite element modeling software. The result showed that pipe temperature had great influence on buried HDPE pipe performance, and thermal stress was much larger than stress caused by soil load. Therefore, thermal expansion prevented pipe from deflecting due to soil load, which can protect HDPE pipe in application. The HDPE pipes expand and contract with change in temperature. The piping system should consider expansion and contraction coefficients, however, buried pipelines usually do not move due to soil friction. The unrestrained coefficient of thermal expansion for HDPE pipe is approximately $(9*10)^{-5}$ in. /in. / ˚F (PPI, 2008).

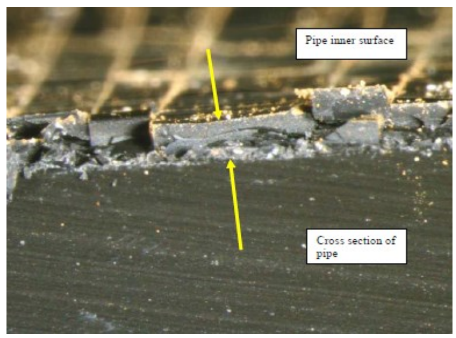
2.2.7. Oxidation

In 2009, a report was submitted by Donald and Dale regarding oxidation in HDPE pipe. Oxidative degradation of polyethylene pipe failure is commonly present in chlorinated water disinfectants such as chlorine, chlorine dioxide and chloramines. Studies in France by major utilities have linked factors such as type of disinfectant, average service temperature, disinfectant concentration and pressure to HDPE pipe oxidation and failure. Oxidation degradation of HDPE pipes has three failure stages (See Figure 2.6):

1. Initially in stage I, finite supply of anti-oxidants included in the HDPE pipe is washed by flowing water which contains chemical disinfectants.
2. When the protective anti-oxidants (AO) package is exhausted or depleted, the water disinfectants oxidants degrade the polymer at the pipe inner surface. In stage II, they reduce molecular weight and diminish mechanical properties of the polymer at that surface.
3. When degradation of inner surface is severe, cracks are developed which will propagate through the pipe wall, driven by internal pressure and other sources of pipe wall stress. This results in stage III non-ductile failure of the HDPE pipe.



(a) (b)



(c)

Figure 2.6 Oxidation Degradation of HDPE Pipes Failure Stages

(a) Inner Surface View of Fracture, (b) Partial Crack Opposite the Leak Site, &

(c) Thick Degraded Layer on Inner Surface of Failed Pipe

(Source: Donald et al, 2009)

2.2.8. Permeability

Water utilities want to maintain the high standards of water quality and protect water from contamination, WaterRF reported “Impact of Hydrocarbon on PE/PVC Pipes and Pipe Gaskets” which is susceptible to permeation of organic compounds. In 2009, Plastic Pipe Institute (PPI) commented that overall impact of hydrocarbon is very small, but measures need to be taken to limit the impact of hydrocarbon permeation. Meanwhile, Plastics Pipe

Institute also suggested the following three ways of addressing permeation of hydrocarbons:

1) To surround the pipe with good clean soil of Class I or Class II materials,
2) To sleeve the pipe in areas where active hydrocarbon contamination is known to exist, and
3) To reroute the pipe around the contaminated plume.

Ong et al (2008) suggested replacement of HDPE pipe if permeation is observed. Plastic Pipe Institute responded that permeation is not an issue in water mains as there is no stagnation of water. Plastic Pipe Institute also criticized applicability of Water-RF report because their research was conducted in temperature of 73˚ F without taking into account the effect of temperature on rate of permeation. However, an increase in density will result in a lower permeability (PPI Handbook, 2008).

2.2.9. Seismic Resistance

In 1995, there was a severe earthquake in Awaji (Kobe), Japan. Table 2.6 presents the failure rates of water pipes,

Table 2.6 Kobe Earthquake Failure Rates of Water Pipes

(Source: Rubeiz, 2009)

Type of Pipe	Water Pipe Damage/km (Damage/mile)
PE	0.00 (0)
Steel	0.437 (0.26)
DCIP	0.488 (0.303)
PVC	1.43 (0.88)
CIP	1.508 (0.937)
AC	1.782 (1.107)

The HDPE pipe for potable water and the piping system performed "very well with few failures" when compared to other pipe materials (Rubeiz, 2009).

The three recent earthquakes continue to show that the bulk of the total earthquake damage to water systems, and the resulting water outages to customers, are due to failure of hundreds to thousands of smaller diameter distribution pipes in zones of infirm ground. New technology in water pipeline joinery has been in place in Japan for nearly 20 years, and in 2012, it is estimated that more than 75% of new water pipes installed in Japan use seismic-resistant design. In comparison, California uses less than 1% of new water pipes with seismic resistant design. For common distribution pipes and service laterals (from under 1 in. to 8 in. diameter), HDPE pipe (either butt fused or electro-welded with clamped joints) appear to have excellent earthquake performance, as evidenced in all three recent earthquakes (WaterRF, 2012).

The toughness, ductility and flexibility of PE pipe combined with its other special properties, such as its leak-free fully restrained heat fused joints, make it well suited for installation in dynamic soil environment and in areas prone to earthquake. Table 2.7 illustrates the vulnerability of different pipe materials to ground deformation and shows that PE with fused joint type has low vulnerability to ground deformation comparing to other commonly used water pipeline materials.

Table 2.7 Commonly Used Water Pipeline Materials, Standards and Vulnerability to Ground Deformation (Source: AWWA, 1994)

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

Table 2.7—*Continued*

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. (203-mm) diameter	No designation	Bell-and-spigot, rubber gasket
Polyvinyl chloride	C900, C905	Bell-and-spigot, unrestraint
Steel	C200s series	Bell-and-spigot, rubber gasket, unrestrained
Moderate to High Vulnerability to Ground Deformation[1]		
Concrete cylinder	C300, C303	Bell-and-spigot, unrestraint
Steel	No designation	Gas welded
High Vulnerability to Ground Deformation[1]		
Cast iron	No designation	Bell-and-spigot, leaded or mortared

[1] Resistance of a pipe to ground movements due to seismic and dynamic loads

2.2.10. Trenchless Technology

Ortega et al. (2004) presented use of HDPE pipe in difficult installation conditions using trenchless technology. Rubeiz (2004) presented eight case studies, out of which at least five cases used trenchless technology. Usability with trenchless technology has been one of the major selling points of HDPE pipe. Cost savings due to use of trenchless methods and easy installation encourage the use of HDPE pipe. Table 2.8 summarizes the advantages and limitations of HDPE pipe.

Table 2.8 Advantages and Limitations of HDPE Pipe

(Najafi and Gokhale, 2005)

Advantages	Limitations
Resistant to both internal and external corrosion	May be subject to environmental stress cracking
Butt-fused joints effectively create a continues joint less conduit	Lower Hydrostatic Design Basis than other thermoplastic material, require thicker walls, which results in smaller flow area
Abrasion resistant not when used in sewer applications	Skilled labor and special equipment required for butt-fusion
High ductility, flexibility and toughness.	Chemical burial properties resist most ground contamination, unless excessively exposed.
Lightweight in smaller diameters	Cost/Benefit Ratio is different from other thermoplastic pipes of same pressure capacity
High flow coefficient, low frictional resistance to fluid flow.	Cannot be located unless buried with metallic wire or tape, except by Ground Penetrating Radar.
Highly resistance to rupture by impact, even at very low temperatures	Sensitive to temperature differentials, resulting in measurable expansion and contraction unless constrained by soil friction.
Resists shatter-type or rapid crack-propagation failure	High flexibility causes problems in retaining joints restraints, unless stiffener is inserted into pipe prior to attachment of restraints
Does not easily crack under expansive forces of freezing water	Degradation owing to ultraviolet light exposure has been seen in some HDPE pipes of low carbon black content

2.3 Chapter Summary

This literature search provided information on benefits and limitations of HDPE pipe compared with other pipe materials for water applications. The initial findings will help this research to conduct a survey of water utilities, and develop a testing plan.

CHAPTER 3

WATER UTILITY SURVEY

3.1 Introduction

To supplement the literature research, a survey was conducted with North American water utilities to find their experiences and concerns with HDPE pipe (16-in. and larger diameter sizes) used in water transmission. Appendix C includes questionnaire and detailed results of survey. The participants answered questions regarding amount of population served through large diameter pipelines, the footage of the pipelines in-use, leakage percentage, causes/modes of ruptures, and etc.

3.2 Survey Objectives

The objectives of the survey were to obtain as much as information from participating water utilities regarding HDPE pipe and its advantages and limitations.

3.3 Methodology

The survey questionnaire was prepared by Center for Underground Infrastructure Research and Education (CUIRE) and was sent to water utilities. The Plastic Pipe Institute (PPI) provided a database which listed HDPE pipe installed in the North America. Survey Monkey software was used to send questionnaires to more than 300 water utilities and more than 101 replies were received. Figure 3.1 illustrates the division of respondent utilities with regards to pipe diameter.

3.4 Questionnaire and Results

3.4.1 Availability of Large Diameter HDPE in Use

Q1: Do you have large diameter (16 in. and larger) HDPE water pipe in use?

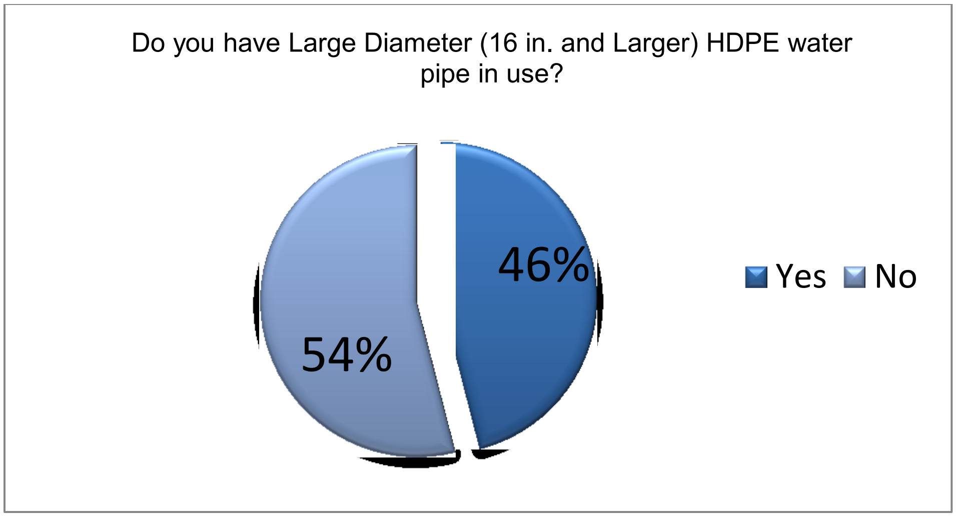


Figure 3.1 Availability of Large Diameter HDPE in Use

Figure 3.1 summarizes that most of the utilities did not use large diameter HDPE pipes in their transmission application, only 46% of utilities used larger diameters. Remaining 54% either used smaller diameters or never experienced usage of HDPE pipes. Therefore, survey analysis was restrained to 46 respondents only.

3.4.2 Amount of Served Population

Q2: What is the population of the area served by your organization?

The highest population served by utility using HDPE large diameter pipes was found in Tarrant Regional Water District Fort worth, Texas which is estimated at about 1.8 million people, and the lowest was recognized as Central Oregon Irrigation District from Redmond, OR, Oregon with an estimate of 4,300 people.

Based on Figure 3.2, on overall distribution the highest number of population served with HDPE pipes is in Texas, that is 4.6 million population and the second highest is

Colorado followed by California and Maryland. The lowest population served is in Oregon followed by Arkansas and Louisiana.

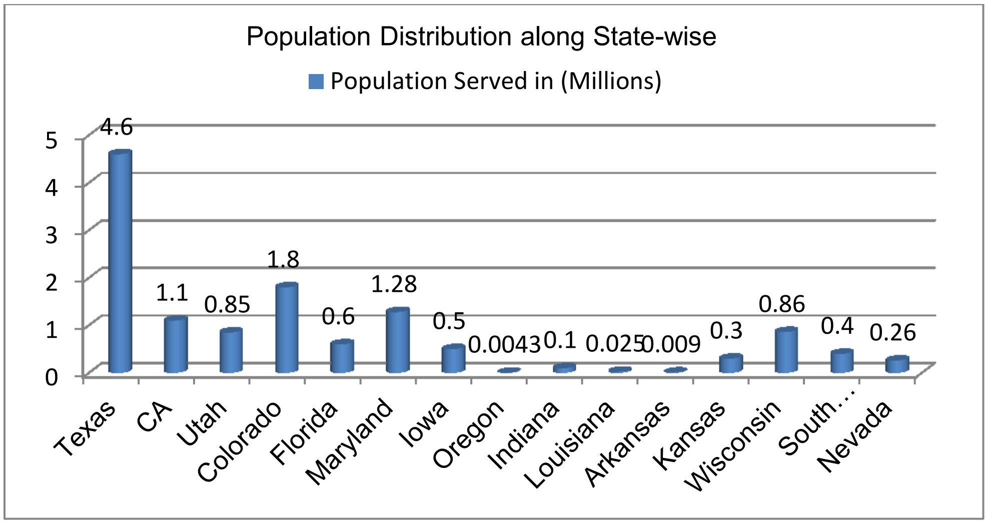


Figure 3.2 Population Distribution along State-wise

3.4.3 Age Distribution of HDPE Pipes

Q3: In your installed large diameter (16 in. and larger) HDPE water pipe in use, what length (miles) is:

Table 3.1 Age Distribution of HDPE Pipes[5]

Classification		Footage (miles)	No. of Responses
PE4710	Less than 5 years old	92	19
PE4710	Between 5 to 10 years old	609	10
PE3608/PE3408	Less than 5 years old	44	11
PE3608/PE3408	Between 5 to 10 years old	68	11
PE3608/PE3408	More than 10 years old	2,015	11

[5] Total No. of respondents were 30, however, they replied for different HDPE age classifications.

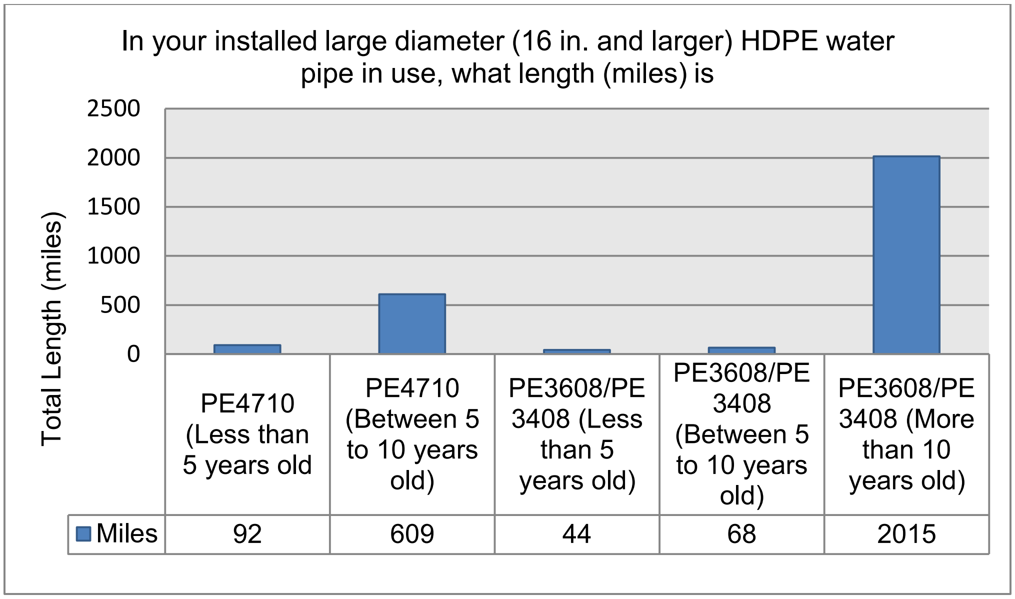


Figure 3.3 Age Distribution of HDPE Pipes

Table 3.1 presents age distribution of HDPE pipes in terms of miles. Figure 3.3 illustrates the distribution of length (miles) of water pipe in use. There was more of PE3608/3408 that had been installed more than 10 years ago when compared to PE4710. PE 4710 was installed mostly between 5 -10 years ago. This explains that most of the utilities are not familiar with PE4710.

3.4.4 Diameter Distribution of HDPE Pipes

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

Table 3.2 presents diameter distribution of HDPE pipes in terms of miles. Figure 3.4 illustrates the diameter distribution. Most of the utilities have used smaller diameters (4-in. to 12-in.) when compared to 16-in. and larger in spite of materials (i.e., PE4710/PE3608/PE3408). Based on the survey results, more 16-in. to 24-in. are used when compared to Larger than 24-in.

Table 3.2 Diameter Distribution of HDPE Pipes[6]

Classifications		Footage (miles)	No. of Responses
PE4710	16"-24"	155	16
PE4710	Larger than 24"	542	11
PE3608/PE3408	16"-24"	2,074	16
PE3608/PE3408	Larger than 24"	58	15

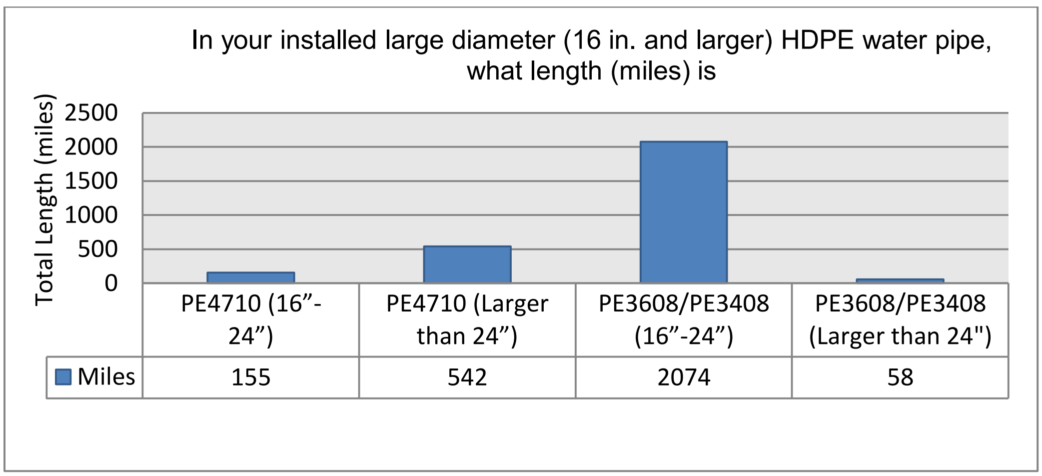


Figure 3.4 Diameters Distribution of HDPE Pipes

3.4.5 Restrictions in use of HDPE Pipes

Q5: If you have any restrictions in use of HDPE pipes, please provide reasons:

Following are some of the perceptions of restrictions in use of HDPE pipes specified by utilities:

[6] Total No. of respondents were 28, however, they replied for different HDPE diameter classifications.

- Using DR9 only in looped systems to allow back-feeding
- Using HDPE only in low pressure /gravity slip lines
- HDPE is to be used in areas of landslide or high corrosive soils with high pressure
- PE4710 is only HDPE material specified in areas of known contamination
- Not using HDPE for potable water service due to permeation
- 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 only used for transmission mains.
- 40 ft sections pose a problem in areas with a lot of services and other utilities to work around.
- Must be pressure class 125 psi
- Developers have to get permission from Public Works prior to installing HDPE Pipe
- Generally restricted to HDD installation

3.4.6 Types of Permitted HDPE Pipes

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

Table 3.3 Types of Permitted HDPE Pipes[7]

Pipe Type	4"-14"	16"-24"	Larger than 24"	No. of Responses
PE4710	18	19	17	23
PE3608/PE3408	13	14	12	17

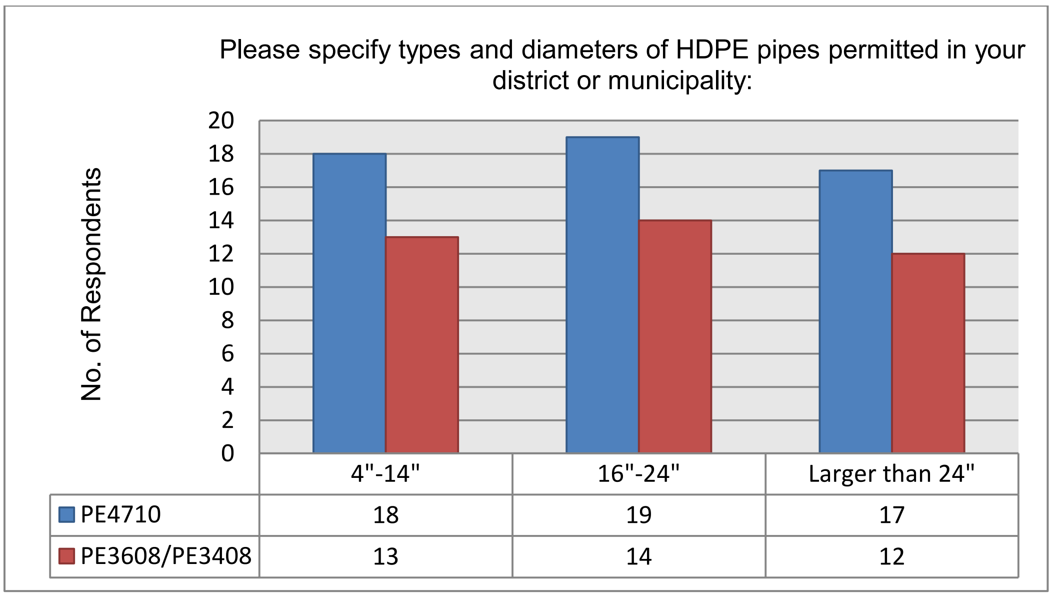


Figure 3.5 Types and Diameters of Permitted HDPE Pipes

Table 3.3 presents the types of permitted HDPE pipes in their districts. Based on Figure 3.5, most of the utilities have used PE4710 4-in. to 14-in. and 16-in. to 24-in. when compared to PE4710 larger than 24-in., as well as more number of utilities used PE4710 when compared to PE3608/PE3408. Other specific types and diameters permitted by utilities are discussed below:

[7] Total No. of respondents were 30, however, they replied for different type of permitted HDPE pipes classifications.

- DR17
- PE4710 limited usage due to special circumstances
- PVC up to 12 inches
- The PE3608/PE3408 has not been used in our system, though I believe that it is permitted.
- AWWA design factors apply
- Some of the pipe materials are PVC, ACP, DIP & CCP

3.4.7 Restricted Pipe Installation Methods

Q7: Please specify restricted HDPE pipe installation methods in your district or municipality:

Table 3.4 Restricted Pipe Installation Methods[8]

Pipe Type	Direct Buried (Open-cut)	Trenchless Application	No. of Responses
PE4710	9	10	12
PE3608/PE3408	7	8	10

Table 3.4 presents the restricted pipe installation method in their districts. Figure 3.6 illustrates that HDPE pipe installations are mostly done through Horizontal Directional Drilling than Open-cut method. Even though trenchless technology is an advanced method, cost for lying HDPE pipes are cheaper compared to Open-cut. Therefore, most of the utilities prefer HDD for HDPE pipes.

Following are comments from the utilities:

- Use of large diameter HDPE pipes is allowed only on a case by case basis. Mainly 6-in., 8-in. and 12-in. are used.

[8] Total No. of respondents were 17, however, they replied for restricted pipe installation methods.

- Many utilities use DR 9 and it is hard for them to find this DR in large diameter HDPE
- Both HDD and open-cut installation methods are allowed by most of the utilities
- Flange adapter HDPE to DIP application requires a specialist contractor to install and engineered bolt torque values

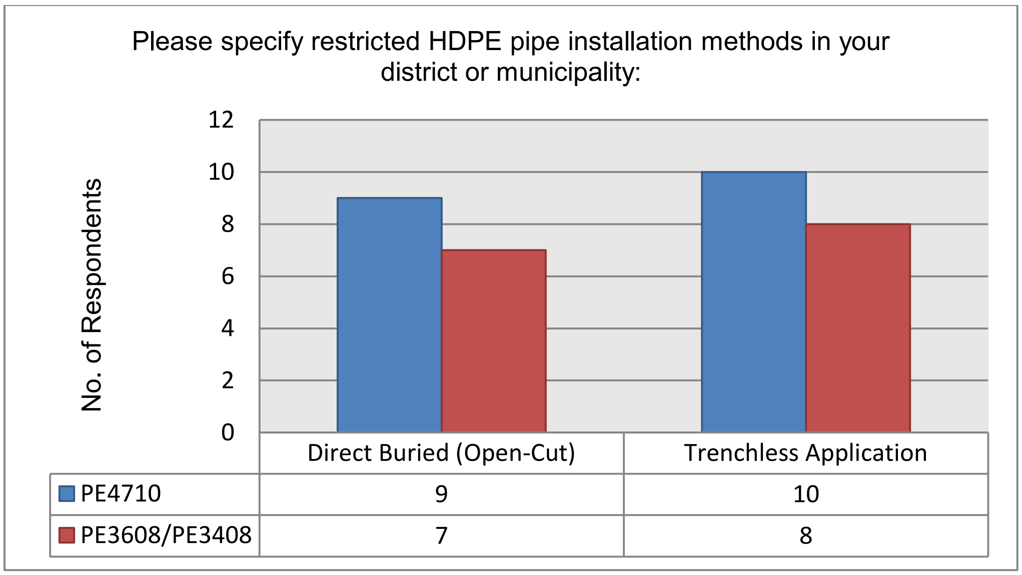


Figure 3.6 Allowed HDPE Pipe Installation Methods

3.4.8 Leakage

Q8: Have you had any leaks from your HDPE water pipe system (16 in. and larger)?

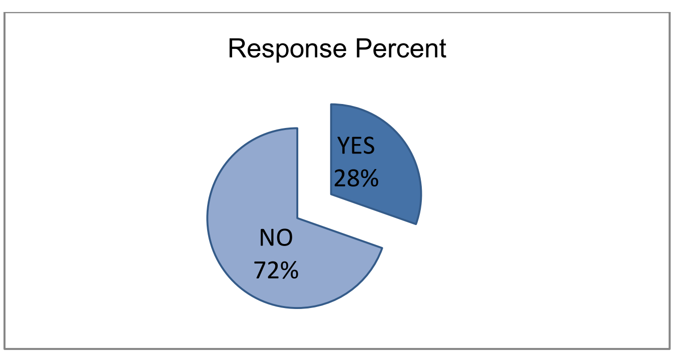


Figure 3.7 Leak Percentage

Figure 3.7 illustrates the percentage of leakage in HDPE pipe. About 72% of the utilities were satisfied with leak-free HDPE system, whereas 28% of the utilities had leakage due to expansion/contraction of HDPE pipes. The following is comments received regarding HDPE pipe leaks:

- At HDPE fitting's, joints and flanged adapter to DIP joints
- Poor fusion at some points
- Due to damage from other contractor equipment. Mainly from contractors and Mother Nature. Flooding and washing out a river crossing.
- Faulty service saddles
- Failure at manhole and service connections
- Failure at HDPE fused joints
- There was a pipe split when the new pipe was inserted inside of another old pipe
- Improper welding of joint
- A piece of 24-in. that was punctured during construction. The leak was quickly found at startup and then repaired by the contractor.

3.4.9 Causes/Modes of Rupture for PE4710

Q9: 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 3.5 Rating the Causes/Modes of Rupture for PE4710 (16-in. to 24-in.)[9]

PE4710							
16" to 24"	N/A	5	4	3	2	1	No. of Responses
Installation defects	9	2	0	4	1	2	18
Fittings	9	2	1	3	1	1	17
Electro-fusion	8	2	2	1	2	2	17
Expansion/Contraction	11	0	0	1	1	3	15
Permeation	11	1	1	0	0	2	15
Freeze/Thaw	11	0	1	0	1	2	15
Fusion	9	1	0	3	0	3	16
Seismic/Ground movement	11	0	0	2	1	2	16
Third party damage	9	2	2	1	2	2	18
Excessive internal pressure	11	0	0	1	2	2	16
Joint rupture	8	1	0	1	2	3	15
Ultraviolet radiation	11	0	1	0	1	2	15
Water temperature	11	0	0	0	1	3	15
Soil conditions	10	0	0	0	1	3	14
Circumferential rupture	11	0	0	1	2	2	16
Manufacturing defects	9	0	0	1	1	5	16

[9] Total No. of respondents were 19, however, they replied for different issues and utilities who did not face any issues replied not applicable

Table 3.5—*Continued*

Buckling/Collapse	10	0	0	0	1	4	14
Fatigue	9	0	0	1	0	4	15
Longitudinal rupture	11	0	0	0	1	3	15
Oxidation/Disinfection	10	0	1	0	0	3	14

As concluded from Table 3.5 and Figure 3.8, “Installation Defects”, “Third Party Damage”, “Electro-Fusion”, and “Fittings” have the highest frequency of occurrence and “Manufacturing Defects,” “Joint Rupture,” and “Buckling/Collapse” have the lowest frequency of occurrence for PE4710. However, most of the utilities said “Not Applicable” since they do not have any issues with these properties.

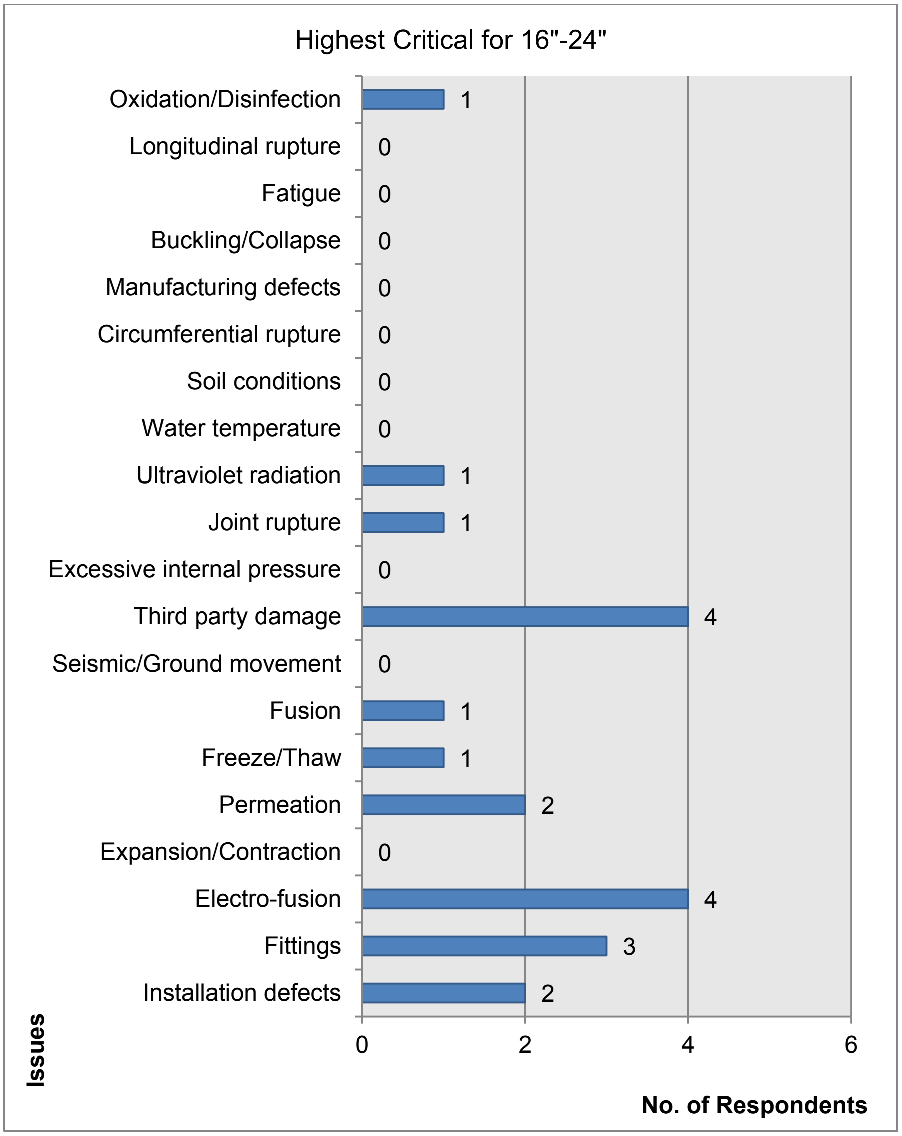


Figure 3.8 Critical Issues for Table 3.5

Figure 3.8 illustrates the highest critical issues in the HDPE 16-in. to 24-in. diameter. Also, on the scale of 1 to 5; 5 and 4 is considered highest critical and 1 to 3 is considered has lowest critical. For complete details refer to Table 3.5.

Table 3.6 Rating the Causes/Modes of Rupture for PE4710 (Larger than 24-in.)[10]

PE4710							
Larger than 24”	N/A	5	4	3	2	1	No. of Responses
Installation defects	8	1	1	1	2	2	15
Fittings	10	1	0	1	1	1	13
Electro-fusion	11	0	0	1	0	1	13
Expansion/Contraction	11	0	0	1	0	1	13
Permeation	11	1	0	0	0	1	13
Freeze/Thaw	11	0	0	0	1	1	13
Fusion	10	0	0	1	0	2	13
Seismic/Ground movement	11	0	0	0	1	1	13
Third party damage	10	2	1	0	0	0	13
Excessive internal pressure	11	0	0	0	1	1	13
Joint rupture	10	0	0	1	1	1	13
Ultraviolet radiation	11	0	1	0	0	1	13
Water temperature	11	0	0	0	0	2	13
Soil conditions	10	0	0	0	1	1	12
Circumferential rupture	10	0	0	0	2	1	13
Manufacturing defects	11	0	0	2	1	0	14
Buckling/Collapse	11	0	0	2	1	0	13
Fatigue	11	0	0	1	0	1	13

[10] Total No. of respondents were 19, however, they replied for different issues and utilities who did not face any issues replied not applicable

Table 3.6—*Continued*

Longitudinal rupture	11	0	0	0	1	1	13
Oxidation/Disinfection	11	0	1	0	0	1	13

From the above Table 3.6, it is concluded that "Third Party Damage" has the highest frequency of occurrence and all other properties have the lowest frequency of occurrence. Followed by Table 3.6, Figure 3.9 illustrates the No. of respondents with highest critical especially for diameters larger than 24 in. Also, on the scale of 1 to 5; 5 and 4 is considered highest critical and 1 to 3 is considered has lowest critical. For complete details refer to Table 3.6.

Responses from Utilities:

- No problem with all these factors in Utah.
- No leakage in HDPE 16-in. and larger pipe in Maryland.
- Our Large diameter HDPE pipe has been installed less than 5 years and we have had no failures in Austin Texas.
- No pipe failures in Kansas.
- No rupture appeared in Lago-Vista Texas.
- Pipe has been installed less than a year and no rupture/damage were observed in California.

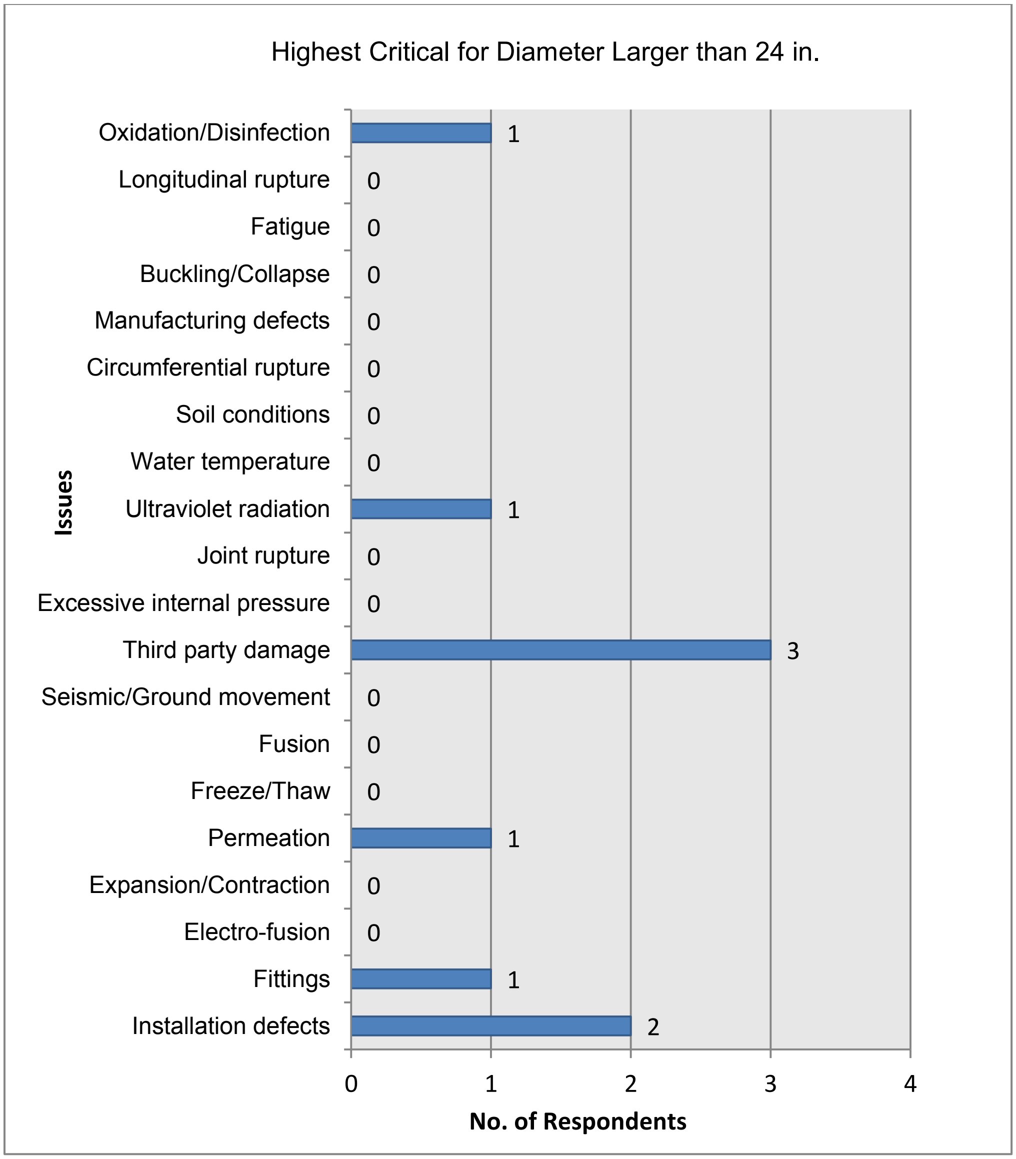


Figure 3.9 Critical Issues for Table 3.6

Some of the issues and comments from utilities about PE3608/3408 are “Fitting” has the highest frequency of occurrence and “Manufacturing Defects”, “Installation Defects”, and “Electro-fusion” has the lowest frequency of occurrence for PE3608/PE3408.

Responses from Utilities:

- Common failure mechanism is when one end of the pipe is firmly held in-place (attached or inside of 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. (California Utility)
- Flange adapter HDPE to DIP application requires a specialist contractor to install and engineered bolt torque values (Arizona Utilities).
- No Breaks or Failure (Maryland).

3.4.10 Concerns and Issues of Using HDPE Pipes

Q10: 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:

Table 3.7 Rating the Concern or Issues Using Large Diameter HDPE Pipes[11]

	PE4710						PE3608/PE3408					
	Responses	5	4	3	2	1	Responses	5	4	3	2	1
Cracking	13	1	0	1	1	10	12	1	0	3	0	8
Ease of use	14	4	1	2	2	5	13	3	2	1	3	4
Joints	15	3	1	5	1	5	13	3	2	5	0	3
Leakage	14	1	1	3	2	7	13	1	1	1	4	6
Oxidation	14	0	1	0	2	11	13	0	1	0	0	12

[11] Total No. of respondents were 21, however, they replied for different issues or concerns

Table 3.7—*Continued*

Permeation	13	1	0	2	1	9	13	1	0	2	1	9
Repairs	15	6	1	3	1	4	14	4	2	2	0	6
Tapping	15	6	2	3	1	3	15	5	2	4	1	3
Water Quality	14	0	0	1	4	9	13	0	0	1	2	10

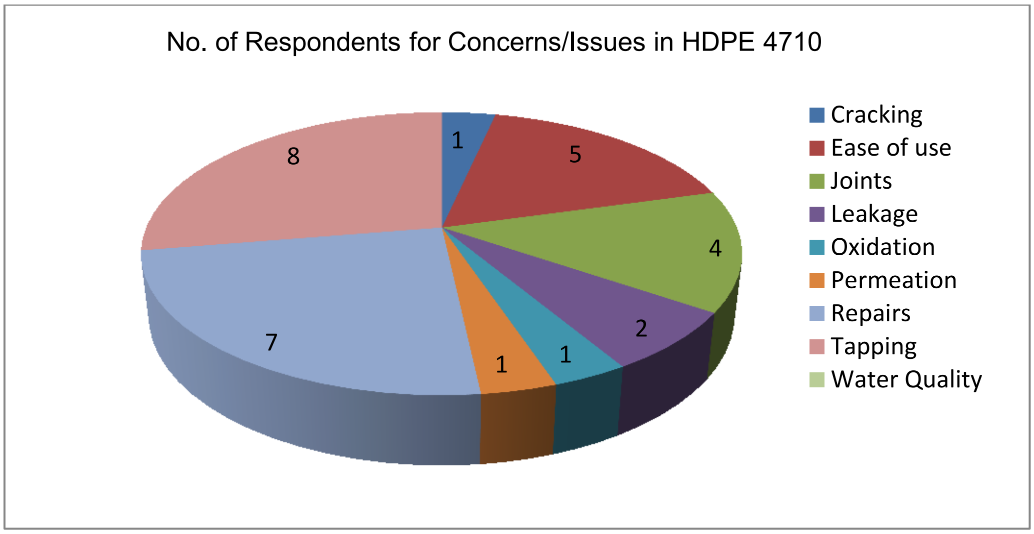


Figure 3.10 No. of Respondents for Concern and Issues in HDPE 4710

Table 3.7 presents that for PE4710, “Repairs” and “Tapping”, and for PE3608/PE3408, “Tapping”, “Repairs” and “Ease of Use” is the highest impacting factor on using the HDPE pipes. Followed by Table 3.7, Figure 3.10 illustrates the No. of respondents for PE4710.

3.4.11 Life Cycle Cost

Q11: 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:

Table 3.8 Rating the Factors Impacting the Life Cycle Cost of HDPE Pipes[12]

	PE4710						PE3608/PE3408					
	Responses	5	4	3	2	1	Responses	5	4	3	2	1
Asset management plan	15	0	2	3	3	7	14	2	1	6	4	1
Ease of joining	16	1	2	5	2	6	15	3	2	5	3	2
Ease of maintenance	18	7	4	4	1	2	16	6	4	3	1	2
Ease of Mechanical Joints	17	3	3	2	3	6	15	6	3	1	3	2
Ease of tapping	18	5	2	4	4	3	15	6	3	3	2	1
Leak-free joints	16	5	2	2	1	6	15	4	2	2	3	4
Life expectancy	18	4	3	3	0	8	16	7	0	3	2	4
Maintenance costs	17	5	3	2	1	6	16	6	1	2	2	5
Physical properties	15	2	3	2	1	7	14	2	0	5	4	3

Table 3.8 explains the factors impacting life cycle cost for large diameter HDPE. The most critical ones are Ease of Maintenance, Ease of Tapping and Maintenance costs. Figure 3.11 illustrates No. of respondents who had an impact on life cycle cost as also mentioned in Table 3.8.

[12] Total No. of respondents were 26, however, they replied for different factors impacting life cycle cost

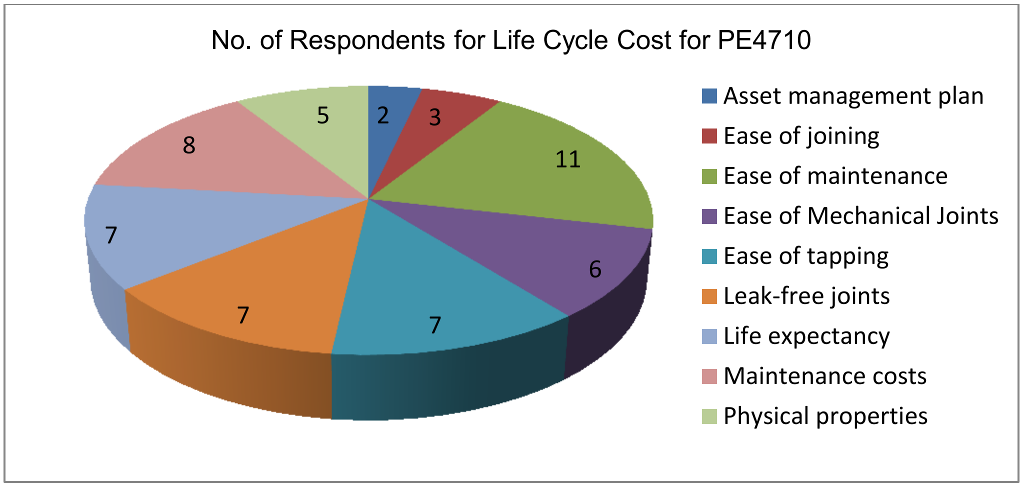


Figure 3.11 No. of Respondents for Life Cycle Cost for PE4710

3.4.12 Rating the Durability and Reliability of HDPE Pipes

Q12: 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 3.9 Rating the Durability and Reliability of HDPE Pipes[13]

	PE4710						PE3608/PE3408					
	Responses	5	4	3	2	1	Responses	5	4	3	2	1
Durability	20	10	2	7	0	1	16	6	5	3	1	1
Reliability	20	11	3	4	1	1	16	7	4	3	1	1

Table 3.9 presents most of the utilities were satisfied with the durability and reliability of 16 in. and larger HDPE pipes for water main application. Also, when compared to PE3608/3408, PE4710 is more durable and reliable.

[13] Total No. of respondents were 28, however, they replied for different pipe classifications.

3.4.13 Comments and Suggestions of Utilities

Q13: Please provide any comments/suggestions, such as, research topics or testing needs. Please send us any case study or pipeline rupture report.

- Molded fittings for pipes larger than 12-in. are not available and usage of fabricated fittings is the largest concern
- Additional permeation testing specially at joints is recommended
- External corrosion and water hammer/high pressure are major problems for C900 PVC, so HDPE was installed and most of them are 8-in. or 12-in.
- Problems in end caps, service connections, manhole connections and oxidation
- Some HDPE needs additional permeation testing
- Lack of molded fittings for large diameter pipes.
- Pressure rating is a problem for us. Often we have to resort to using steel pipe instead of HDPE. The cost of higher thickness HDPE is more than similar rated steel pipe; where we can always use steel.
- We are a transmission company and had an application to try using a 42-in. HDPE pipe. It was installed in 2000 and to date it had performed without a flaw. I always wonder about the life of the polymer. Verification through accelerated testing would help define expected life.
- Our water distribution system includes approximately 3000 ft of 16-in. HDPE pipe installed in 2012. The largest concern is lack of molded fittings for large diameter pipes.

3.5 Chapter Summary

This chapter presented that 64 percent of respondents were most satisfied with performance of HDPE, 32 percent had average response, and four percent (4%) expressed that durability of PE is poor. The majorities of respondents were concerned about the issues with service connections, end caps, testing required for permeation, and oxidation issues, and also mentioned that some of the measures are required to improvise the construction techniques.

CHAPTER 4

EXPERIMENTAL WORK

4.1 Introduction

This chapter will cover the experimental work to help in evaluating the reliability and durability of HDPE pipe. Currently, there is no known ASTM standard to evaluate large diameter HDPE performance under cyclic loads and recurring surge pressures. This thesis developed a testing protocol and successfully executed one test on a 16-in. diameter, 15-ft, DR 17 with a butt fused joint in the middle for 2 million cycles between 125 psi and 188 psi.

4.2 Objectives

The objective of the experimental task is to conduct high pressure cyclic loading fatigue test on new HDPE pipes with a joint. This test determines whether a 16-in. diameter HDPE (DR 17) can withstand cyclic loads that are 1.5 times higher than the long-term pressure rating of the pipe for an extended period of time, such as 2 million cycles.

4.3 Approach

The testing plan included testing one 15-ft long; 16-in. diameter HDPE pipe with a fusion joint in middle. The CUIRE Laboratory at UT Arlington was used to perform this experiment.

4.4 Methodology

The HDPE pipe samples were manufactured and delivered to CUIRE Laboratory on July 11, 2013. Table 4.1 presents pipe sample measurements. Figure 4.1 shows pipe samples.

Table 4.1 HDPE Pipe Sample Measurements

Diameter (in.)	Pipe Number	Inlet/Outlet Pipe Diameter			Length	
		Valve	Inner Diameter	Outer Diameter	cm	in.
16	1A	¼	0.995 in.	1.328 in.	456.4	179.69
16	2A	¼	0.996 in.	1.325 in.	456.8	179.84

Note: Modulus of Elasticity of HDPE Pipe, E = 125,000 psi

Figure 4.1 HDPE Samples

4.5 Experiment Setup

This section describes the experimental setup and role of each device. The setup comprises of a 450-gallon water Reservoir Tank, a Multi-stage Centrifugal Pump (10 HP), a Data Acquisition System, a Control Board, several Pressure Transducers, a DC power supply, one specimen (16-in. diameter), and Control Valves including one Back-flow Pressure Valve, two Solenoid/Pressure Ball Valves, and two Butterfly Valves. A galvanized steel pipe system with pipe diameters of one in. and 2-in. connects the equipment. Before the test setup is completed, it was important to design the test parameters based on the PE4710 HDPE. The discharge, temperature, and head loss were calculated and accounted for. Figure 4.2 illustrates a schematic diagram of experimental setup.

4.6 Procedures

Initial Project Start-up Procedure

1) Make sure power to pump is off.
2) Make sure that water filling hose to tank is properly secured, so that it doesn't flood water.
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 the specimen pipe from air.
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 software is online.
5) Power the pump.
6) Bleed the air by opening hand operated valve.
7) Check the cycle time and water temperature.

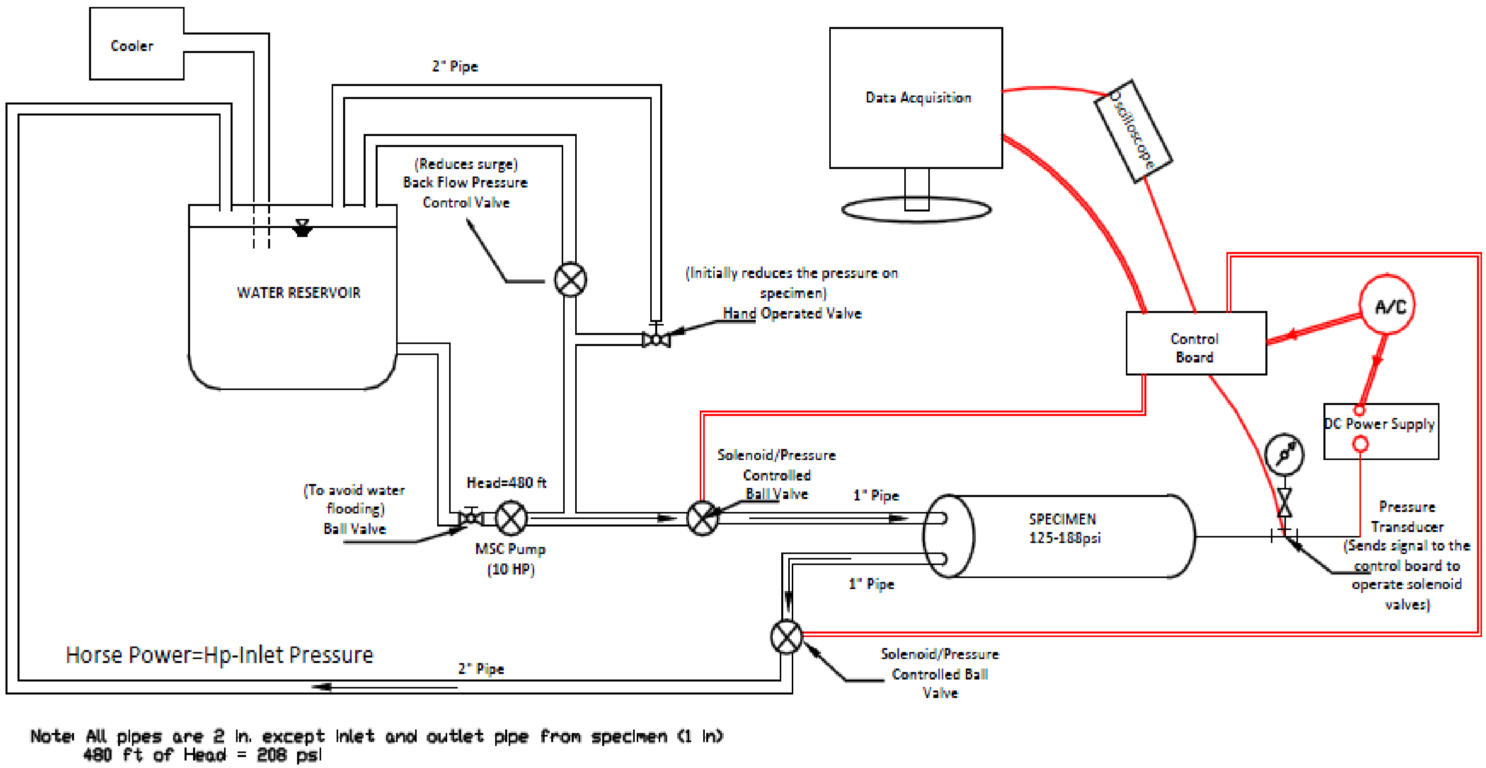


Figure 4.2 Schematic Diagram of Experiment Setup

4.7 Equipment Details

4.7.1 Back-Flow Pressure (BFP) Valve

Importance of BFP Valve

The back-flow pressure (BFP) control valve is necessary in the system to; a) protect the pump from excessive water pressure due to water hammer, b) to control excessive pressures from the pump as the inlet control valve to the pipe sample which cannot sustain excessive pressures. Figure 4.3 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 specimen 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 4.3 Back-Flow Pressure Valve

4.7.2 Inlet and Outlet Solenoid Valves

Objectives

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

Working of Solenoid Valves

- These valves are normally closed (Figure 4.4).
- When the pump is powered and control board is connected to valves, the inlet valves opens and let water to run into specimen.
- Once it reaches 188 psi, inlet valve closes and outlet valves open to reduce the pressure to 125 psi.
- This working of pressure is designed by control board.

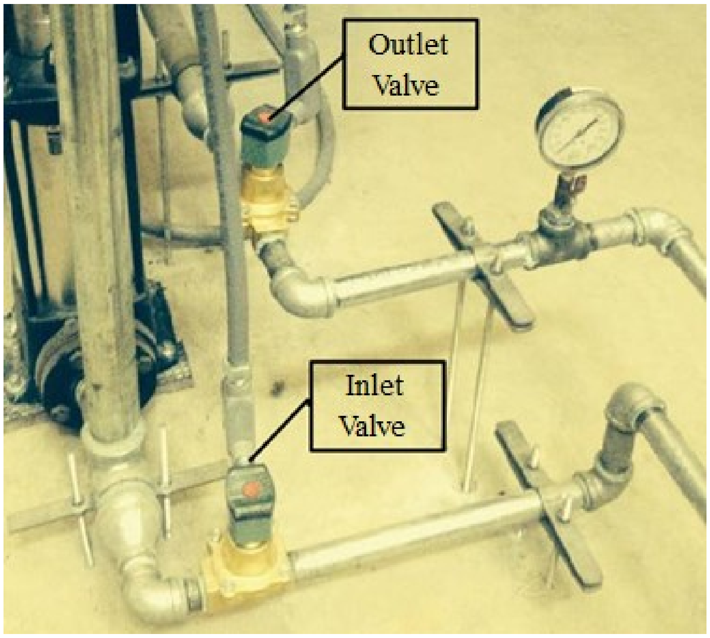


Figure 4.4 Inlet and Outlet Solenoid Valve

4.7.3 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 4.5 illustrates the components of the Control Board. There are two types of operations at the board,

1. Read only (BLM LCD)
2. Edit information (LIST LCD)

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. specimen pipe)
- Low pressure set point (i.e., 125 psi for 16 in. specimen pipe)
- 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 nothing but the time to energize the inlet and outlet solenoid valves)
- Accumulator which counts number of cycles completed.

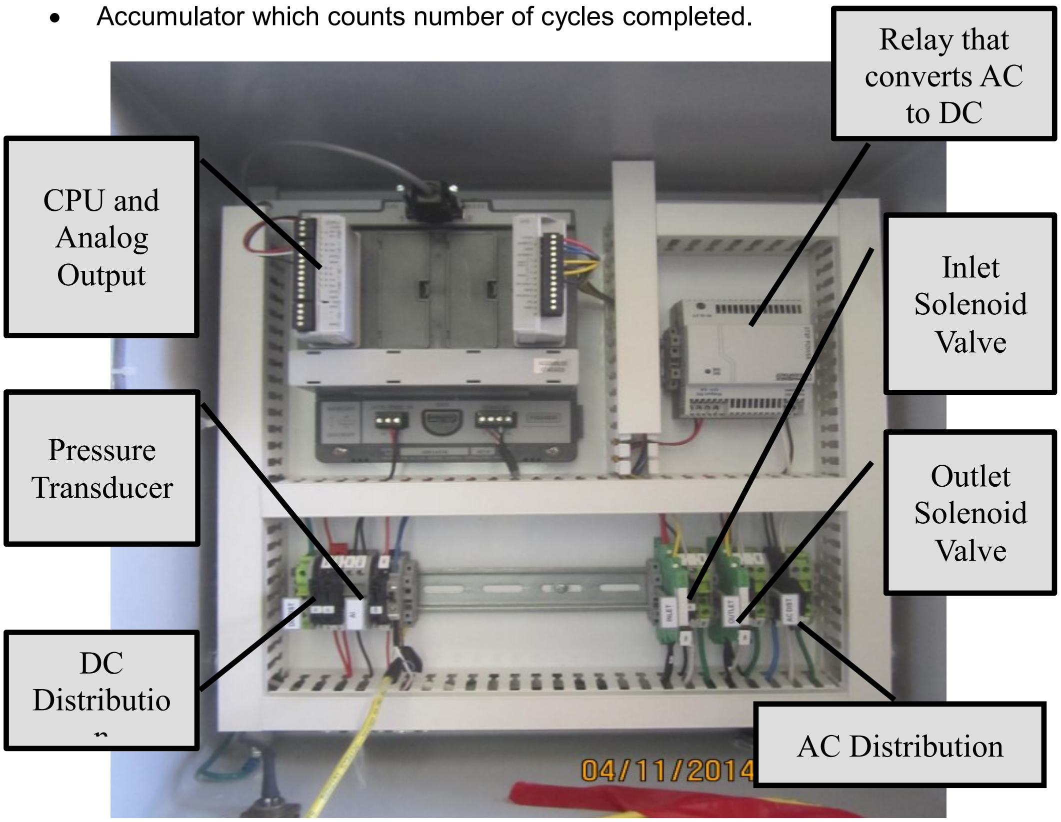


Figure 4.5 Components of the Control Board

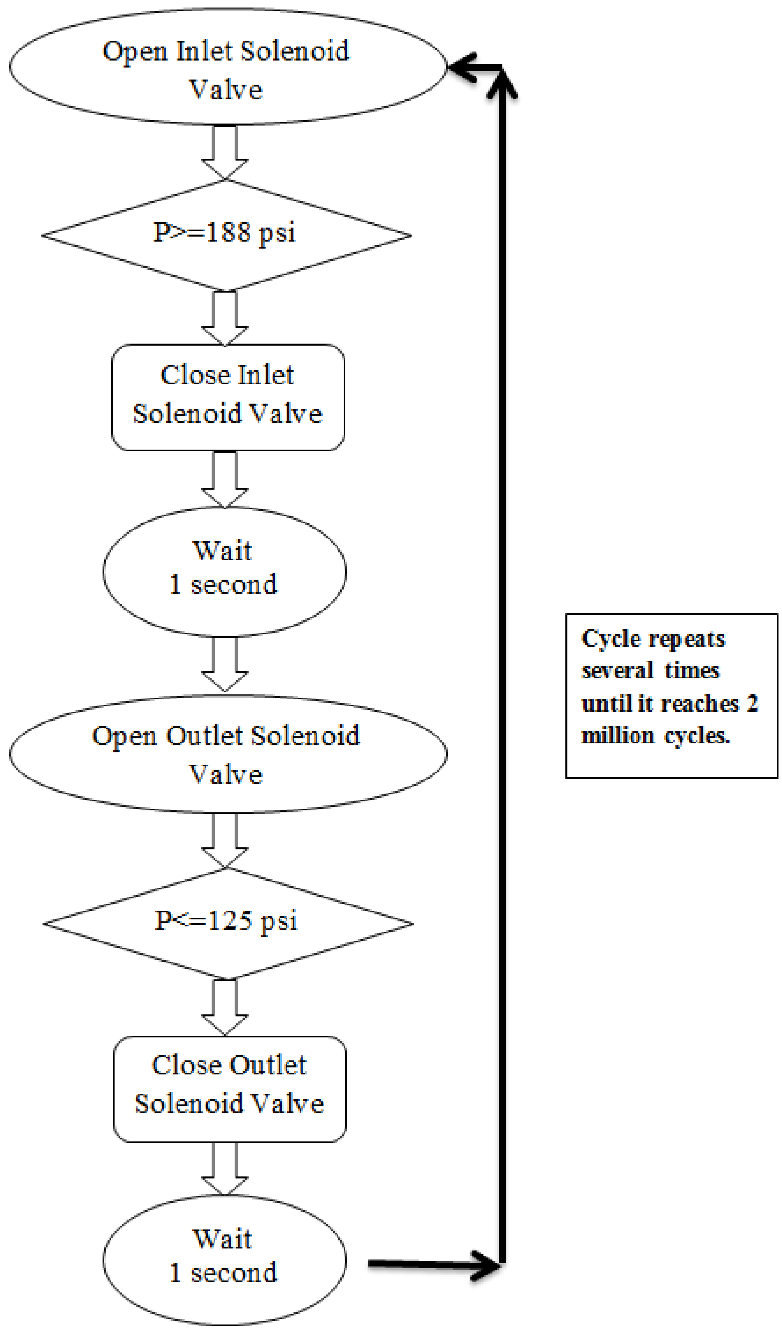


Figure 4.6 Control Board Logic Flowchart

Figure 4.6 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.

4.7.4 Pressure Transducer

Objectives

1. To convert water pressure in the pipe into an analog electrical signal.
2. To regulate 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 4.7). 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.

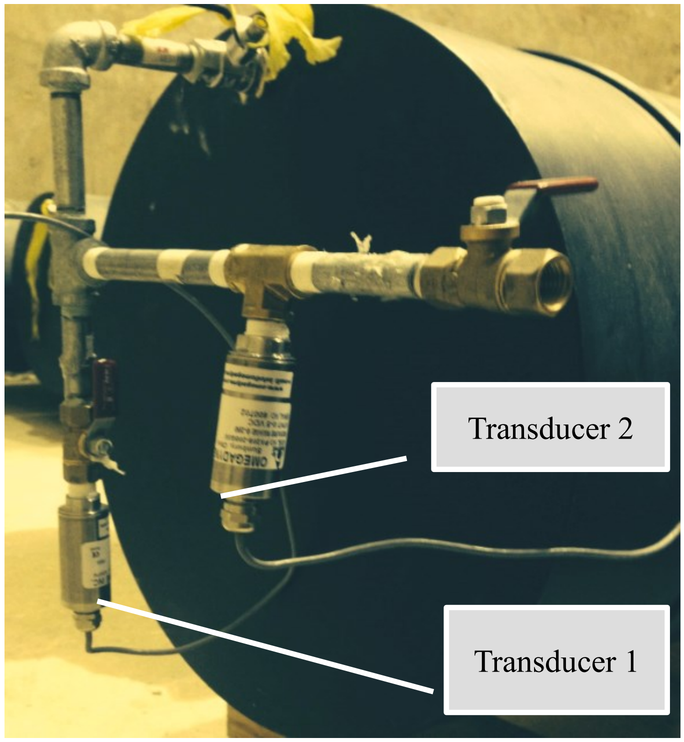


Figure 4.7 Pressure Transducer

4.7.5 Multi-Stage Centrifugal Pump

The horse power of the pump is 10 HP. The water head on the pump is about 10 feet and pump puts out pressure of 480 feet (208 psi). The head losses are calculated based on 2 in. and 1 in. galvanized steel pipes. Figure 4.8 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 will be performing continuous operation and may need to be stopped for maintenance purposes.
- Make sure that control board is powered before powering the pump, i.e., magnetic starter should be pulled down and on the button.
- The pump outputs 480 feet / 208 psi; where the pressure partly goes into backflow valve operation to cut down 208 psi to 188 psi.

Figure 4.8 Multi-Stage Centrifugal Pump (10 HP)

4.8 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 feet below. The dimension of reservoir is 3 feet 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 open throughout the experiment. It is placed to initially reduce the pressure on the specimen, i.e., 208 psi, whereas specimen can withstand up to 188 psi. Some amount of water runs through, i.e., approximately 5 GPM. Each cycle is 8-10 sec. This flow can either be continuous or stops at particular time.

Specimen

The initial experiment setup is for 16 in. large diameter pipe (125-188 psi). The specimen has inlet and outlet connections. Initially the specimen is filled with water and air bubbles are released through a nipple as the specimen is 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 demonstrates the pressure waves on desktop screen. Also, it is used to adjust backflow pressure valve.

Air Conditioning Unit (Cooler)

The main purpose of cooler 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 a cooler was installed.

4.9 Testing Operation

The water from reservoir flow to the pump which is located 10 feet below the reservoir to create a head pressure of 480 feet. The pump puts out a pressure of 208 psi. Since the specimen can handle pressure between 125 psi to 188 psi; therefore, a “backflow control valve” is used to back pressure the extra water from the pump to reservoir, which is about 20 psi. This 188 psi from the pump is used to pressurize the specimen using “inlet and outlet solenoid valves.” These valves are electrically operated using the “control board”. The pressure transducer is connected at the end of specimen. Once the water wave pressure hits the transducer, a signal is sent to the control board to operate solenoid valves.

Working of control board: Once the inlet valve opens, the pressure increases to 188 psi, the inlet valves closes. The pressure impacts the specimen for about one second, and outlet valve opens, and once pressure decreases to 125 psi, the outlet valve closes. At this time water from outlet valve goes back to reservoir. This process repeats for 2 million cycles (Figure 4.6). The control board is connected to data logger to obtain results from software. Also, oscilloscope is connected to control board to determine the actual pressure wave from the transducer. The cooler’s grid is immersed in the reservoir to maintain temperature range 70° - 73° F because temperature impacts the cycle time.

4.10 Chapter Summary

This chapter described the testing setup, operation, functions of individual equipment. During initial testing operation, some issues came up and needed to be corrected. The control board was designed to automatically operate the solenoid valves. The oscilloscope was to determine the actual pressure range of 125-188 psi, and obtain waveform from the software. Later on it was noticed that water temperature is impacting cycle time. Therefore, a cooling thermostat was placed inside the reservoir. Also, there was an issue with the control board scaling and it was rescaled to actual pressure and experiment continued for two million cycles. The experimental results and discussions are presented in Chapter 5.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter presents the results of this research. The testing results are based on biweekly analysis of specimen tested in the laboratory. The research was carried out by testing 16 in. (HDPE) large diameter under cyclic pressure, as was described in detail in Chapter 4.This chapter summarizes the results of this thesis.

The pressure cycle determined the cycle time of one full complete cycle (one complete surge) (see Figure 5.1). It is calculated by difference in time at the minimum stress (125 psi) and time at maximum stress (188 psi).

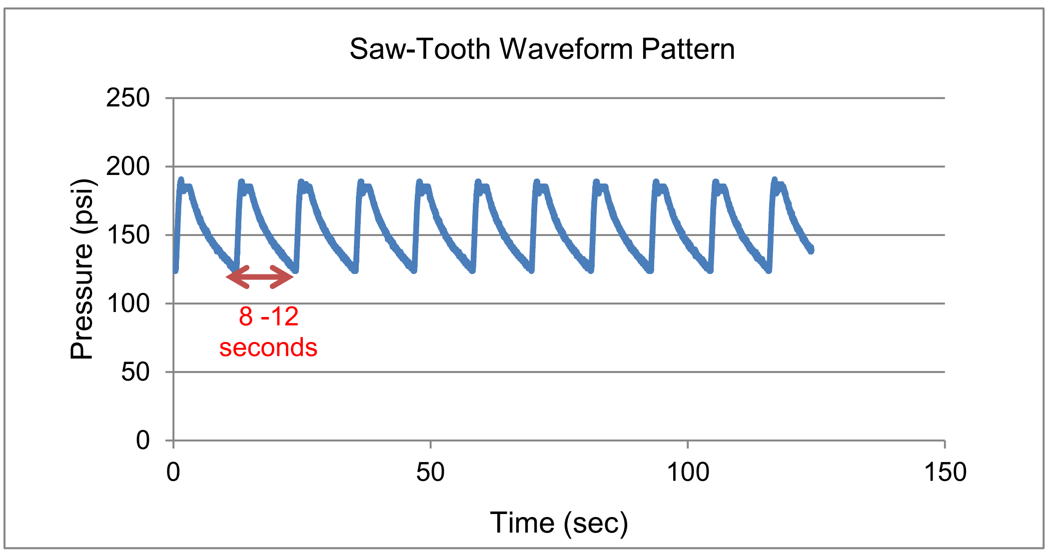


Figure 5.1 Saw-Tooth Waveform Pattern

Figure 5.1 illustrates the cycle time of each surges (i.e., 8 to 12 seconds). Since the saw-tooth waveform has very less impact time, the life of specimen increases (Refer to Section 2.2.4 and Fig 2.5).

5.2 Project Issues

The pressure transducer was dynamically tested using oscilloscope, and the software determined that there was an issue with the control board. This was due to false scaling of control board which was set by manufacturer, therefore; because of this the maximum pressure obtained was 156 psi and minimum was 63 psi. About one million cycles were accomplished with each cyclic pressure surges of 6-7 sec/cycle. Then the control board was rescaled to 188 psi and continued the test to complete 2 million cycles. The results are summarized in the section 5.3.

5.3 Project Results

Polyethylene material is known for its viscoelastic nature (Section 2.2.2). Based on the experimental results, the diameter of the HDPE is increasing over the time due to the continuous impact of surges. These dimensional changes are taking place near the butt joint, but with no variations at the end caps. The specimen was under pressure for 3 months with a maximum pressure of 156 psi and 188 psi. The temperature range was between 63°– 70°F (Section 2.2.5). Similarly, when the specimen was impacted with the highest pressure of 188 psi, the temperature range was 70° - 73°F, and surge time increased to 10 seconds.

Table 5.1 presents the changes in the pipe diameter with surge pressure and also changes in diameter under cyclic pressure of 156 psi.

Table 5.1 Variation of Diameter between 3 Months

Month	Diameter of Pipe	Duration of Cycle	No of Cycles Completed (Millions)
May 31st	15.99 in. (406 mm)	0 (start of test)	0
Sep 2nd	16.27 in. (413 mm)	8 sec	1.06

Figure 5.2 Pipe Bulge near Butt Joint

Figure 5.2 illustrates the bulged specimen near the butt fused joint. The pipe diameter is evenly increased by one inch when compared to bare sample. It represents the performance of specimen with 156 psi. The specimen diameter increased evenly along the length.

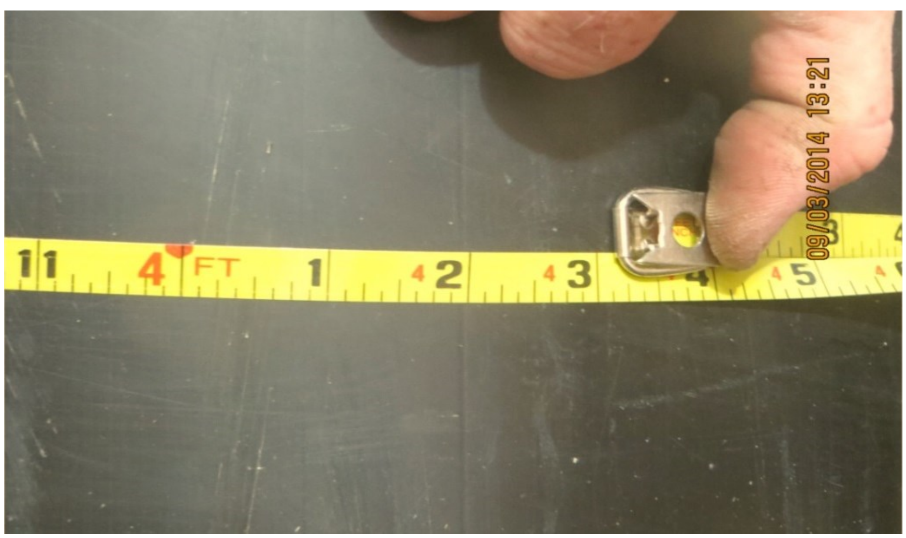


Figure 5.3 Bare Sample Measurement

Figure 5.4 Specimen Measurement after 3 Months

Figures 5.3 and 5.4 illustrate the bare sample and specimen measurements in detail, and comparison is made before and after of cyclic pressure. This resulted in one inch increase in circumference of specimen.

After 3 months, the specimen was no longer expanding linearly along the length; also, the variation is decreasing along the diameter. Therefore, the diameter check was made in three different locations to find the variations, Figure 5.5 illustrates 3D model of specimen and their locations. Location A is the point where pressure is exerted first and then it travels along the pipe to point C.

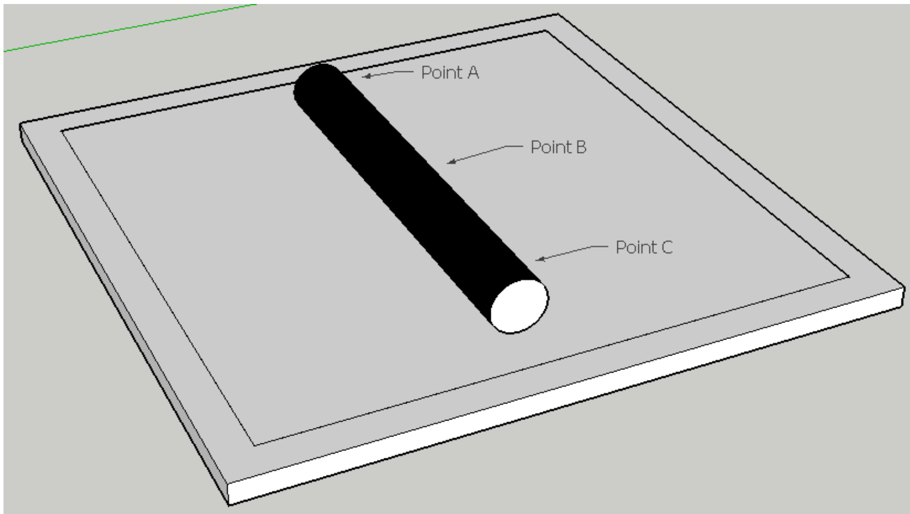


Figure 5.5 3D Model of Specimen

The difference in the diameter is noted in Table 5.2, which presents changes on the diameter along the pipe. This was observed within 15 days after the control board was set to 188 psi.

Table 5.2 Pipe under Constant Pressure of 188 psi (Sept 19th 2014)

Specimen Points	Diameter of Pipe	Breathing Diameter of Pipe
Point A	16.71 in. (424 mm)	Pipe measurements consider that pipe is breathing (cyclic changes in diameter) up to 1/8 in. for every 12-sec cycle
Point B	16.68 in. (423 mm)	
Point C	16.62 in. (422 mm)	

Figure 5.6 illustrates the different locations which measures length along the specimen. Table 5.3 presents the biweekly measurements. Initially, no expansion along the length was determined. After three months the specimen was subjected under poisson effect, as the diameter increases slowly the length started decreasing, and vice versa. But these variation are based on number of cycles completed. These changes were determined after 1.52 million cycles, and after that pipe length remained constant.

Figure 5.7 illustrates the different locations which measures the diameter of specimen pipe. Table 5.4 presents the variation of diameter of specimen due to its continuous cyclic pressures.

Variation along the Length of Specimen

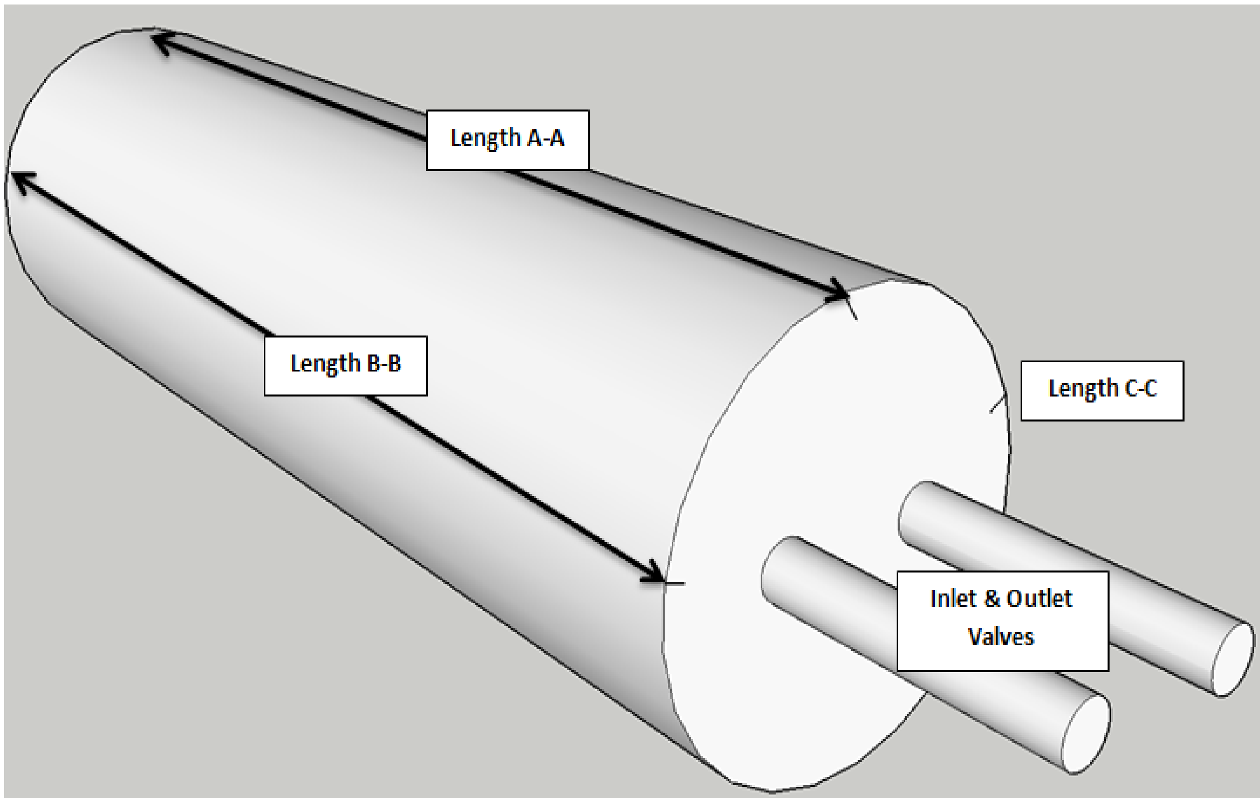


Figure 5.6 Length Measurements along the Specimen Pipe

Table 5.3 Variations along the Length of Specimen Pipe

Bare Sample length – 14.97 ft (179.69 in.)

Month	Specimen						No of Surges Completed (Millions, M)
	Point A (North)		Point B (East)		Point C (West)		
	ft	in.	ft	in.	ft	in.	
Monday, Oct 6th	15.05	180.6	15.05	180.6	15.08	180.96	1.52
Monday, Oct 20th	14.99	179.96	14.99	179.98	15	180	1.62
Wednesday, Nov 10th	14.98	179.85	14.96	179.60	14.90	178.8	1.76
Thursday, Nov 25th	14.99	179.96	14.98	179.85	14.98	179.85	1.95
Sunday, Nov 30th	14.99	179.96	14.98	179.85	14.98	179.85	2.00

<u>Variation along the Diameter of Specimen Pipe</u>

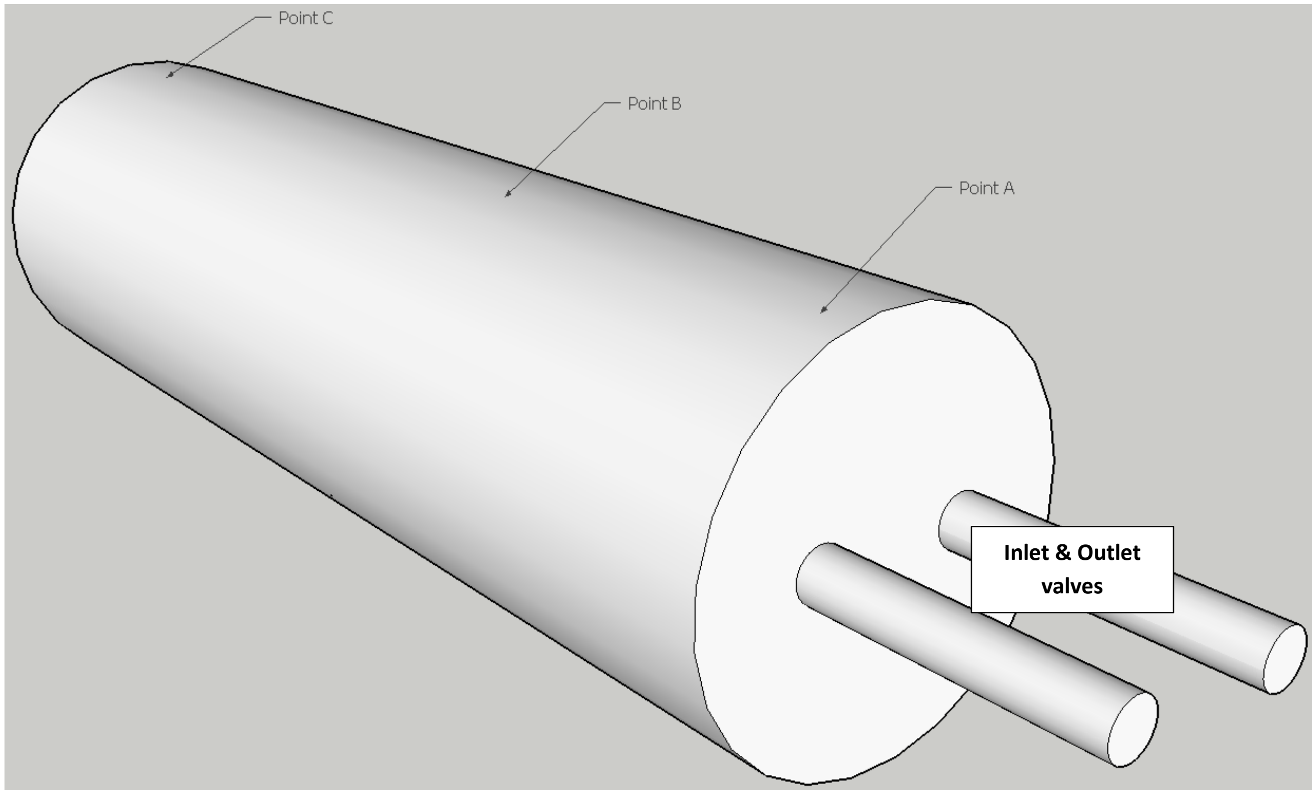


Figure 5.7 Diameter Measurements

Table 5.4 Variation along the Diameter of specimen pipe

Bare Sample – Diameter – 16 in. (406 mm)

Month	Diameter of Specimen						No of Surges Completed (Millions, M)
	Location A (Start of Pipe)		Location B (Center of Pipe)		Location C (End of Pipe)		
	in.	mm	in.	mm	in.	mm	
Tuesday, Sept 2nd	16.27	413	16.27	413	16.27	413.	1.06
Friday, Sept 19th	16.35	415	16.32	414	16.27	413	1.39
Saturday, Oct 4th	16.43	417	16.40	417	16.40	416	1.51
Monday, Oct 20th	16.54	420	16.49	419	16.44	418	1.62
Wednesday, Nov 5th	16.52	420	16.49	419	16.46	418	1.76
Thursday, Nov 20th	16.52	419.8	16.49	419	16.49	419	1.89
Sunday, Nov 30th	16.52	419.8	16.49	419	16.49	419	2.00

The Results of Fatigue Performance of 16 inch HDPE 4710

The fatigue performance of PE4710 pipe is determined by its occasional and recurring surges created in the actual field conditions. The utilities will have surges due to sudden shutdown of pump, valves, or due to consumption changes. Therefore, assuming 50 surges per day, an estimate of the design life will be:

Example: 50 surges X 365 days X Number of years …………………Eq.1

Table 5.5 Number of Surges for 50 and 100 years

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

The above example determines that PE4710 is capable of withstanding 2 million cycles for 100 years without any failure in material.

Using equations from Petroff (2013),

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

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

Table 5.6 presents the peak stress for DR 17 16-in diameter HDPE pipe, and also cycles to failure.

Table 5.6 Cycles to Failure for PE4710 for 16-in. Diameter

Working Plus Surge Pressure (WP + PS)	Peak Stress (psi)	Cycles to Failure	Fatigue Life (Years) @ 50 surges/day	Safety Factor for 100 years @ 50 surges/day
1.2*PC	1,246	45,907,200	2,515	25
1.5*PC	1,504	7,123,000	390	4

Results of Rate of Expansion along the Circumference/Longitudinal:

The rate of expansion/contraction is determined using Table 5.3 and 5.4 from chapter 5. The rate of expansion is due to continuous recurring surges and the impact time of each cycle.

1. The rate of expansion along circumferential:

The total difference between the initial and final diameter measurement is “0.5 in.” at 1.76 million cycles and the variation of diameter is decreasing along the length. After 1.76 million cycles the diameter is almost constant and remains constant. Figure 5.8 illustrates the variation of deformation in HDPE pipe with time.

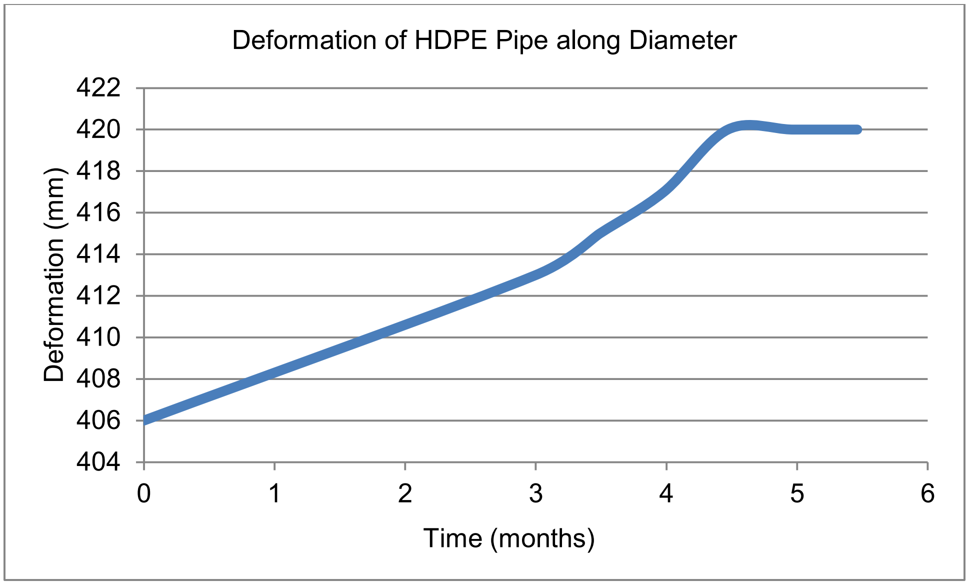


Figure 5.8 Deformation of HDPE Pipe along Diameter

Table 5.7 presents expansion of specimen in mm for one million and two million surge cycles.

Table 5.7 Deformation of Specimen for Number of Surges Completed

Surges	Expansion	
	in.	mm
1,000,000	0.28	7.112
2,000,000	0.49	12.7

2. The rate of expansion along longitudinally:

The expansion/contraction of specimen along the length is very small. By referring the Table 5.4, it is seen that pressure impact along the length is less when compared to diameter of the specimen.

5.4 Summary of Testing Operation

This experiment was conducted to determine the fatigue performance of 16-in. HDPE. It was determined that the specimen can withstand two million cycles without failure. Apart from fatigue performance, due to high pressure the specimen expands due to its visco-elastic nature (discussed in chapter 2) but after sometimes the rate of expansion stabilizes.

Some of the comments are discussed below:

- In CUIRE laboratory, about 9,000-13,000 surges/day were obtained. These recurring surges occurred continuously 24 hours a day 7 days a week, which may impact the rate of expansion. But in other words, utilities have 50 surges /day and this may not occur every day. Therefore, in real scenarios the rate of expansion for DR 17 (16 in. diameter) is slow and a chance of failure is less.

- Based on survey results from chapter 3, some of the failures occurred due to the leakage. These failures are due to expansion of pipes. But, proper selection of pipe is needed during installation of pipelines, i.e., proper DR with specified pressure. Probably this may avoid the failure rate.

- It is always good to have flow rate below the specified range of pressure to reduce expansion of pipe. Therefore, for 16-in., 188 psi is highest pressure, and it is designed to withstand the sudden surges and reduce the failure rate.

- Other reasons for failure mentioned in the survey was due to manufacturing defects, methods of installing pipes, selection of pipes for specific projects, lack of knowledge regarding butt fusion and trained labors.

The specimen with continuous recurring surges for 6 months, accomplished about 2 million cycles without failures at end caps, and the joint. The dimensional variations were not uniform along the pipe from the Table 5.4. The impact time of surge is important. This experiment accomplished two million cycles without failure.

5.5 Summary of Results and Discussions

This paragraph summarizes the entire thesis from the results of literature research, water utility survey and experimental work. As seen from literature research, the polyethylene is semi crystallinity polymer with several long chains and side branches (AWWA, 2006). Therefore, as molecular weight increases, long term strength, toughness, and fatigue endurance improves, and this determines that molecular weight is the main factor in determining the durability of HDPE (Koerner, 2012). Some of the other researches like Jana Laboratory have determined that smaller HDPE pipes have fatigue resistance to occasional and recurring surges. According to AWWA, the velocity of water in pipes is strictly between 5 fps to 8 fps. Therefore, with lower velocity the pipes can withstand occasional/recurring surges without failures (Petroff, 2013). If water temperature is maintained at 68-73°F, then life of HDPE geomembranes extend up to 565 years (Jafari, 2014). Also, according to AWWA, the water temperature should be strictly maintained at 73°F (~23°C). The HDPE pipe is known for its seismic resistance (Rubeiz, 2009). Due to its visco-elastic nature, the expansion takes place but once it reaches its ultimate stage, they remain constant with no changes in dimensions (PPI Handbook, 2008). Apart from the advantages, HDPE is also known for its limitations in permeation and oxidative degradation. A water utility survey was conducted to find out the experience water utilities with HDPE pipe.

The water utility survey was conducted through the Survey Monkey Website and sent to over 300 water utilities around the North America. About 101 replies were received, out of which 45 water utilities used large diameter HDPE. Most of the utilities failed to differentiate the advanced PE4710 and PE3608/3408; but results were summarized for larger diameter HDPE pipes. The summary of survey results are as follows:

- Most of the utilities did not use large diameter HDPE pipes in their transmission application, only 46% of utilities used larger diameters. Remaining 54% either used smaller diameters or never experienced usage of HDPE pipes. Therefore, survey analysis was restrained to 46 respondents only.
- The highest population served by utilities using HDPE large diameter pipes was found in Fort worth, Texas, which is estimated at about 1.8 million people, and the lowest was recognized as Redmond, Oregon with an estimate of 4,300 people.
- There was more of PE3608/3408 that had been installed more than 10 years ago when compared to PE 4710. PE 4710 was installed between 5 -10 years ago. This explains that most of the utilities are not familiar with PE4710.
- Most of the utilities prefer smaller diameters (4 in. to 12 in.) when compared to 16 in. and larger in spite of materials (i.e., PE4710/PE3608/PE3408). Based on the survey results more 16 in to 24 in. are found when compared to Larger than 24 in.
- Some of the utilities restricted the use of HDPE pipes due to permeation, issues with taps due to expansion and contraction of the pipe which affects the saddle and sleeves, and need permission from public works prior installing and restricted to HDD installation.
- Most of the utilities preferred PE4710 4 in.-14 in. and 16 in.-24 in. when compared to PE4710 larger than 24 in., as well as more number of utilities prefer PE4710

when compared PE3608/PE3408, because most of the utilities have stopped using PE3608/PE3408 due to fatigue issues.

- The HDPE pipe installations are mostly done through Horizontal Directional Drilling than Open-cut method. Even though trenchless technology is an advanced method, cost for laying HDPE pipes with HDD is less compared to open-cut. Therefore, most of the utilities prefer HDD for HDPE pipes.
- About 72% of the utilities were satisfied with leak free HDPE system, whereas 28% of the utilities had leakage due to expansion/contraction of HDPE pipes. Other issues were poor fusion, faulty service saddles, improper welding of joints or due to contractors fault.
- “Installation Defects”, “Third Party Damage”, “Electro-Fusion”, and “Fittings” has the highest frequency of occurrence and “Manufacturing Defects”, “Joint Rupture”, and “Buckling/Collapse” has the lowest frequency of occurrence for PE4710. However, most of the utilities said “Not Applicable” since they do not have any issues with these properties.
- Concerns and issues of using HDPE pipes; for PE4710, “Repairs” and “Tapping”, and for PE3608/PE3408, “Tapping”, “Repairs” and “Ease of Use” are the highest impacting factor on using the HDPE pipes.
- The most critical ones are Ease of Maintenance; Ease of Tapping and Maintenance costs are the factors impacting for life cycle cost.
- Sixty Four percent (64%) of respondents said performance of PE is excellent, thirty two percent (32%) had average response about PE, and four percent (4%) expressed that durability of PE is poor. Majority of respondents were concerned about the issues involved and measures needed to improvise the construction techniques.

Based on survey results, it was found that most utilities are satisfied with HDPE performance, since no failure was found in most of the states, such as, Utah, Maryland, Texas, Kansas, and California. But other utilities mentioned the issues and concerns regarding HDPE pipes. Also, it is important to educate most of the utilities regarding advanced polymer performance. Therefore, a testing concept was setup in CUIRE to determine the durability and reliability of HDPE 16 in., 15 foot long, DR17.

The HDPE pipe accomplished 2 million cycles with "0.5 in." variation in diameter at inlet end and decreased along the length to "0.2 in." at the other end (Figure 5.5). It was seen that dimensional changes remained constant after 2 million cycles. The longitudinal variation is minimal when compared to circumferential variation. The surge cycle time for each cycle is about 10 second; each cycle impacts a pipe for every 10 seconds with a pressure range between 125-188 psi. By assuming utilities having about 50 surges in a day, maximum surges for 50 years would be 912,500 and for 100 years would be 1.8 million; from this, the results were concluded that the pipe can withstand 2 million cycles for 100 years without failure. In a real scenario, if utilities have only 50 surges with velocity of 5 to 8 fps, a failure with expansion/contraction will not be developed. But utilities concluded issues with leakage in the system, which may have been for PE3608/3408, and not for PE4710, and those who used PE4710 were satisfied with a leak free system. Therefore, advanced PE4710 is reliable and durable based on the results from experimental work and the survey.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

6.1 Conclusions

The main aim of the thesis was to determine the durability and reliability of large diameter (16 in. and larger) HDPE pipe. In this chapter the conclusions are discussed based on the results obtained from the literature search, water utility survey and the experimental work.

6.1.1 Literature Review

- Most of the papers in this literature research are related to general HDPE pipe material.
- It was found that most of the testing's were conducted for smaller diameter PE pipes. Based on the smaller diameter results; the theoretical analysis was made to determine the performance of large diameter pipes (PE4710). Therefore, from these analyses larger diameters were concluded as durable and reliable in water application.

Apart from advantages, HDPE is also known for its limitations. Some of the limitations are listed below:

- The HDPE pipe is perceived for its permeation, therefore, if any permeation found, then the pipe should be rerouted around contaminated plume, or surround the pipe with good clean soil of class I or class II materials to allow the hydrocarbon that may have contacted the pipe's wall to dissipate into the atmosphere.

- The HDPE pipe could fail due to its oxidative degradation. This failure is mainly due to presence of chlorine in water, which acts as water disinfectants.

6.1.2 Survey

- Most of the utilities used only smaller diameter pipes or did not use HDPE pipe in their utilities. From the survey results, 45 out of 101 utilities used larger diameter pipes. Therefore, survey analysis was conducted based on 45 respondents.

- It was determined that most of the utilities could not differentiate between older PE material and advanced PE4710. Most of the utilities lacked the knowledge about performance of advanced PE4710. Therefore, this thesis will benefit and educate the utilities.

- Sixty Four percent (64%) of respondents were satisfied with performance of larger diameter PE pipes, thirty two percent (32%) of respondents had average response about PE, and four percent (4%) expressed that durability of PE is poor.

- Most of the HDPE pipe failed due to expansion and contraction; that is due to sudden surges in the system. This expansion/contraction caused leakage in the system, and 28% of utilities faced leakage issues. Apart from these utilities, others utilities were satisfied with the leak free systems.

- There were no failures like rupture, leakage or issues found in Utah, Maryland, Texas, Kansas, and California.

- Some of the utilities were concerned about perception issues, and also suggested to test pipe with elevated temperature, and for permeation.

6.1.3 Experimental Work

- The pipe specimen was subjected to 188 psi to determine the fatigue performance of 16 in. diameter for advanced polymer PE4710. From the results, it was determined that HDPE pipe can sustain 2 million cycles without failure.

- The specimen was tested for continuous application of cyclic pressure. The rate of expansion along circumference and longitudinal direction was determined for 50 and 100 years life span. No failure is found in joints or end caps of the pipe sample.

6.2 Recommendations for Future Research

The unaddressed studies that are of interest for future research are included below:

1. Specimen can be tested with fittings attached to it. This can be either done with two ways: a) one with polymer fittings, and b) other with non-polymer fittings, and then compare the results. Therefore, the results reveal any leakage issues in the system which may be due to rapid expansion/contraction of HDPE pipes.
2. The specimen can be tested by doubling the pressure from 125 to 250 psi for DR 17, to determine if the pipe fails.
3. The specimen can be subjected under compacted soil load and testing should be conducted to determine the load impact on the pipe and its expansion.
4. An experiment can be conducted with same DR and diameter for PVC and HDPE and compare the results for fatigue resistance.
5. The physical properties of HDPE pipe sample after 2 M cycles can be compared with physical properties of a new HDPE pipe.
6. The pressure for fatigue testing can be increased until the HDPE pipe fails and maximum failure pressure and total No. of cycles in fatigue can be determined.

APPENDIX A

LIST OF ABBREVIATIONS

ACP - Asbestos Concrete Pipe

AC – Asbestos Cement

AO - Anti-Oxidants

ASCE - American Society of Civil Engineers

ASTM - American Society for Testing and Materials

AWWA - American Water Work Association

BFV - Back-flow Pressure Valve

BCCP – Bar-wrapped Concrete Cylinder Pipe

CAGR - Compound Annual Growth Rate

CB - Control Board

CCP - Cement Concrete Pipe

CP – Concrete Pipe

CUIRE - Center for Underground Infrastructure Research and Education

DIP - Ductile Iron Pipe

DR - Dimension Ratio

FC – Fiber Cement

FRP – Fiber Reinforced Pipe

HDD - Horizontal Directional Drilling

HDPE - High Density Polyethylene Pipe

HDS - Hydrostatic Design Stress

HP - Horse Power

ICI - Imperial Chemical Company

ISO - International Organization for Standardization

LDPE - Light Density Polyethylene Pipe

MDPE - Medium Density Polyethylene Pipe

PPI - Plastic Pipe Institute

PCCP - Prestressed Concrete Cylinder Pipe

PVC - Polyvinyl Chloride

RCP – Reinforced Concrete Pipe

SCG - Slow Crack Growth

SP – Steel Pipe

UPVC – Unplasticized Polyvinylchloride

VCP – Vitrified Clay Pipe

APPENDIX B

SURVEY DEFINITIONS

EPA/WRF Project 04485 – Durability and Reliability of Large Diameter (16 in. and Larger) HDPE Pipe for Water Mains

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 *(AWWA, 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. In 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 1980's. 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): PE is a thermoplastic material produced from the polymerization of ethylene. PE plastic pipe is manufactured by extrusion in sizes ranging from ½" to 63". PE is available in rolled coils of various lengths or in straight lengths up to 40 feet. Generally small diameters are coiled and large diameters (>6" 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)* 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) 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 *(AWWA, 1994)*

APPENDIX C

SURVEY QUESTIONNAIRES FROM SURVEY MONKEY

EPA/WaterRF 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"-24") [ ]

PE4710 (Larger than 24") [ ]

PE3608/PE3408 (16"-24") [ ]

PE3608/PE3408 (Larger than 24") [ ]

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

	4"-14"	16"-24"	Larger than 24"
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 forPE4710 HDPE pipe material according to its frequency of occurrence?

	16"-24"	Larger than 24"
Third Party Damage	▾	▾
Installation Defects	▾	▾
Manufacturing Defects	▾	▾
Buckling/Collapse	▾	▾
Fatigue	▾	▾
Circumferential Rupture due to Bending	▾	▾

	16"-24"	Larger than 24"
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		
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"-24"	Larger than 24"
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		
Freeze/Thaw		
Fusion		
Electro-fusion		
Water Temperature		
Seismic/Ground Movements		

	16"-24"	Larger than 24"
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.

APPENDIX D

DAILY REPORT TEMPLATE

Daily Report Template

<table>
<tr><td>Date</td><td colspan="4"></td></tr>
<tr><td>Start time</td><td colspan="4"></td></tr>
<tr><td>End time</td><td colspan="4"></td></tr>
<tr><td rowspan="2">Activities</td><td>Time</td><td>Room Temperature(˚F)</td><td>Water Temperature(˚F)</td><td>Cycle Duration</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Issues</td><td colspan="4"></td></tr>
<tr><td>No of Cycles Accomplished @ end of the day</td><td colspan="4"></td></tr>
</table>

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BIOGRAPHICAL INFORMATION

In June 2012, Divyashree graduated with a Bachelor of Civil Engineering Degree in Civil Engineering from M.S. Ramaiah Institute of Technology at Bangalore, India. She started her Master's Degree in Civil Engineering with a focus in Construction Engineering and Management at the University of Texas at Arlington in spring semester 2013. While pursuing her Master's degree, she obtained a merit scholarship, and also she worked as a Graduate Research Assistant at UTA's Center for Underground Infrastructure Research and Education (CUIRE) for three consecutive semesters from Fall 2013 to Fall 2014. Her research assignment was the Water Research Foundation project - Innovation and Research for Water Infrastructure for the 21st Century: Durability and Reliability of Large Diameter (16 in. and Larger) HDPE Pipe for Water Main Applications (Project #4485). She has two internationally published papers while working on her bachelor's degree, and one at the ASCE Pipelines 2014 during her Master's degree. She has submitted three more papers which are under review for Pipelines 2015 and for the Texas Water Conference 2015. Divyashree served as the Vice President of the UTA Student Chapter of the North American Society of Trenchless Technology and also Secretary for Texas Society of Professional Engineers (TSPE). She volunteered at the ASCE Pipelines conference 2013 and Underground Construction Technology (UCT) Conference 2014 in Houston as well as she has been an active member of Construction Management Association of America (CMAA) Student Member.