

PERFORMANCE COMPARISON OF HIGH DENSITY POLYETHYLENE PIPE  
(HDPE) IN MUNICIPAL WATER APPLICATIONS

by

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### Disclaimer

All pipe materials have advantages and limitations, and can deteriorate over time. Many project specific factors, operations and maintenance procedures of a specific utility, pipe manufacturing process, and site and soil conditions around the pipe affect the pipe performance. Since there is no national database of pipe inventory and performance in the U.S., and given the large number of utilities, it is difficult to gather data necessary for a comprehensive understanding of pipeline performance. Past literature do not consider all the factors affecting pipes, and, and the survey conducted as part of this thesis received limited responses. Therefore, this thesis cannot be used as basis for selection or rejection of any specific pipe material, and/or to make any design decisions on a project, which is responsibility of design professionals.

Abstract

PERFORMANCE COMPARISON OF HIGH DENSITY POLYETHYLENE PIPE  
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The current and forecasted major challenge faced by water utilities is delivering potable water efficiently with minimum loss to end users. Water pipe failure has negative impact not only local communities but also on the nation's economy. The American Water Works Association (AWWA) has estimated that it will cost over \$250 billion to replace and renew the nation's water pipes over the next 20 years. According to the 2009 American Society of Civil Engineers (ASCE) Report Card, seven billion gallons of water are lost in this country every day!

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. The very limited information on High Density Polyethylene (HDPE) pipes created the need for this research. This thesis is a preliminary step towards understanding the HDPE pipe performance for lower and larger pipe size diameters. To achieve the objectives of this research, a nationwide survey was carried out. For the respondent utilities, the average annual failure rate for the smaller diameter pipe is 0.5 per 100 miles. Most frequent causes of failures occurring in small

diameter pipes were due to joint failure. Due to lack of enough large diameter HDPE pipe respondents, the results were not conclusive.

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## List of Abbreviation

ABS - Acrylonitrile Butadiene Styrene

AC – Asbestos Cement

ASCE – American Society of Civil Engineers

ASTM – American Society of Testing Material

AWWA – American Water Works Association

B.C. – Before Christ

CAB – Cellulose Acetate Butyrate

CI – Cast Iron

CPVC – Chlorinated Polyvinyl Chloride

CSIRO – Common Scientific and Industrial Research Organization

CUIRE – Center for Underground Infrastructure Research and Education

DI – Ductile Iron

GRP – Glass Reinforced Pipe

HDPE – High Density Polyethylene Pipe

ICI – Imperial Chemical Industry

ISO – International Organization for Standardization

LDPE – Low Density Polyethylene

LLDPE – Linear Low Density Polyethylene

MDPE – Medium Density Polyethylene

NRC – National Research Council of Canada

PB – Polybutylene

PCCP – Prestressed Concrete Cylinder Pipe

PEX – Cross-Linked Polyethylene

PFA – Perfluoroalkoxy

PP – Polypropylene

PPI – Plastic Pipe Institute

PPFA – Plastic Pipe and Fittings Associations

PVC – Polyvinyl Chloride Pipe

PVDF – Polyvinylidene Fluoride

RCG – Rapid Crack Growth

RCP – Reinforced Concrete Pipe

SCG – Slow Crack Growth

UKWIR – U.K. Water Industry Research

USEPA – United States Environmental Protection Agency

## Chapter 1

### Introduction

This chapter introduces the history of pipes and their importance, the history of water distribution development, and problem statement, objectives and expected outcome of this research.

#### 1.1 History of Pipes

“Water is the basis of life on earth and the foundation of all civilizations” (Cech, 2005) and pipeline makes it available. Pipelines have their own history. Pipes were used in ancient times and have been modified extensively to make them more effective and efficient in the modern era. As early as 4000 B.C., the Egyptians used clay pipes in their drainage system. During 400 B.C., the Chinese used bamboo wrapped with waxed clothes to supply natural gas to Beijing for lighting purposes, Romans used lead pipes in its aqueduct system to supply water to its citizens (Liu, 2003). A breakthrough in pipeline technology occurred during the 18<sup>th</sup> century with the invention of the cast iron pipe which dominated all pipe materials until the invention of steel pipe during the 19<sup>th</sup> century which gained its popularity due to its increased wall strength regardless of size.

#### 1.2 State of Pipelines and Their Applications

According to Liu (2003), pipes are the most neglected, vaguely understood, and least appreciated means of transportation when compared to roads, railways and air transportation by the general public. The reason is pipes are often buried inside the earth. Despite of their minimal acknowledgment by the public, pipelines play a vital role in the nation’s economy and security.

The majority of pipelines are laid to transport products such as water, sewage, natural gas, crude oil and refined petroleum products (gasoline, jet fuel, etc.) from treatment plants as well as residential and commercial buildings and refineries for short

or long distances. In addition to transporting these major products, pipelines are also used to transport various other forms of liquid, gas and solid freight (Liu, 2003).

### 1.3 Pipe Classifications

The classification of pipes can be based on:

- Nature of their applications, such as: Commodity transported in pipeline like gas, water, sewer.
- Environment or topographical applications such as offshore, inland, mountain pipelines.
- Type of burial or support, such as underground, elevated and underwater.
- Based on the material used to manufacture the pipe such as cast iron, PVC, HDPE, concrete pipe.

Table 1.1 presents a summary of pipeline classifications.

Table 1.1 Classifications of Pipelines (Mays, 2000)

Classifications	Applications
Commodity Transported	Water, Sewer, Natural Gas, Oil, Product, Solid Pipelines
Environment	Offshore, Inland, In-plant, Mountain, Space Pipeline.
Type of Burial or Support	Underground, Elevated, Aboveground, Underwater Pipelines
Pipe Material	Steel, Cast-iron, Ductile Iron, Plastic (PVC, HDPE, etc.), Concrete, Others (Clay, PCP)



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 refers to the pipes, which share partial characteristic of both types. Table 1.2 classifies pipe materials as either rigid or flexible. Rigid pipes are resistant to longitudinal and circumferential (ring) bending and they do not deform under the applied loads. Flexible pipes are deformable pipes capable of deforming without causing any damage to the pipe. According to Najafi (2010), flexible pipe is defined as pipes capable of deforming more than 2 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 1.3 classifies pipe 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, plastics, are non-conductive and are classified as non-metallic pipes (Mays, 2000; Liu, 2002).

Table 1.2 Classifications of Pipe based on Material (Najafi, 2010)

Rigid Pipes	Flexible Pipes
Concrete	Steel
Vitrified Clay	Ductile Iron
Pre-stressed Concrete Cylinder	PVC
Reinforced Concrete	HDPE
Bar-wrapped Concrete Cylinder	Fiber Reinforced Plastic (FRP)
Asbestos-cement	—
Fiber-cement	—

Table 1.3 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

The Table 1.4 is a summary of timeline of the pipe material used to distribute water in United States along with American Water Works Association (AWWA) standards manual used for installation practices. The first pipe material to be used for the distribution of water was 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 1.4 Timeline of Pipe Material with AWWA Standards 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

#### 1.4 Water Distribution

Delivering a high quality and hygienic water to the public is the main objective of any municipality. Water distribution networks consist of pumps, pipes, junctions, tanks, reservoirs, and valves. To deliver the water, pumps and gravity systems are used to transport water from a reservoir through a series of pipelines. The pipe networks are designed to deliver sufficient quality water with under a desirable pressure (Austin, 2011).

Water usage is classified as follows (Clark, 2012):

- Domestic or Urban
- Agricultural
- Industrial

Primarily, municipal water distribution systems provide water to residential, industrial, and commercial locations. Although the bulk of water delivered is potable or drinking water, it is also used for toilet flushing, showering, clothes washing, landscaping, and industrial applications. Water is held to a standard that assumes the water will be

used for drinking. Much less frequently, but equally important, this water is used to fight fires; therefore, historically, water distribution systems have also been designed to carry the high flows needed for firefighting (Austin, 2011).

#### *1.4.1 History of Water Distribution*

Archaeologists unearthed the fact that early civilizations were built on the banks of rivers such as Sindhu, Tigris and Euphrates, Yellow and Nile had the knowledge of water distribution system (Cech, 2005). Reservoirs were used to store and developed means to transport the water from reservoirs and from the river for irrigation and drinking purpose (Bhave and Gupta, 2006). Archaeologists have confirmed the use of ceramic pipes for the distribution of water from the ruins of Harappa and Mohenjo-daro (Bhave and Gupta, 2006). Knossos currently located at Herakleion (capital of Crete, Greece) supplied water through an aqueduct and then distributed it by tubular conduits to the palace and city. Ephesus in Anatolia or Asia Minor (currently located in Republic of Turkey) was reestablished by the Romans during the 6<sup>th</sup> century B.C (Cech, 2005). "Water for the great fountain was diverted from dam at Marnss and conveyed to the city by a 3.75-mile system consisting of one large and two smaller clay pipelines" (Mays, 2000).

#### *1.4.2 History of Water Distribution System – USA*

Boston was the first city to operate a functional water supply system in United States, when in 1795, a private water supplier installed wooden pipes made from a tree trunk to deliver water from Jamaica Pond to the city (Wallace, Floyd Associates, 1984). During 1652, the Moravian community of Bethlehem, Pennsylvania, used bore logs to draw water from their water source. By 1754, the water was supplied by a network of pipes built on bored logs which served the entire community of Bethlehem. The water was pumped from a spring using horse-driven pumps (Mays, 2000). The first cast iron

pipe was used in the year 1817, to deliver water for citizens of Philadelphia (Bhave and Gupta, 2006).

### 1.5 Problem Statement

Pipes have been used extensively to transport water, gas, petroleum products and sewage since the beginning of 20th century. Pipelines have become the backbone of the nation's economy. The U.S. underground pipe infrastructure was installed 50 years ago, and it is nearing the end of its design life (Ékes et al., 2011). According to Rogers and Griggs (2009) most of the installed pipes are deteriorating due to pipe aging, negligence and underinvestment. The aging of pipe has added significantly to the water utilities' replacement or renewal costs followed by decreased flow capacity and water quality, with great social costs and economic losses due to service disruptions. Recent unexpected failures of drinking water systems are causes for concern for many reasons, the least of which is the major interruption to our public and private streets. The forecast of costs required to replace or rehabilitate existing water pipes is based on water loss and pipe failures reported by U.S. utilities. This has been a major concern of private and government organizations for several years. Estimates from the most prominent of these organizations are summarized in Table 1.5. The Water Infrastructure Network (WIN) included both potable water and wastewater in their study.

Table 1.5 Cost Estimates Forecast for Water Pipe Replacement in USA (EPA, 2007)

Professional Organization	Cost Estimate	Period	Comments
ASCE	\$11B	Per year	—
USEPA	\$151B	Next 20 Years	\$ 83B of this amount for transmission and distribution piping
AWWA	\$250B	Next 30 years	—
WIN	\$460B	Next 20 Years	Includes both water and wastewater

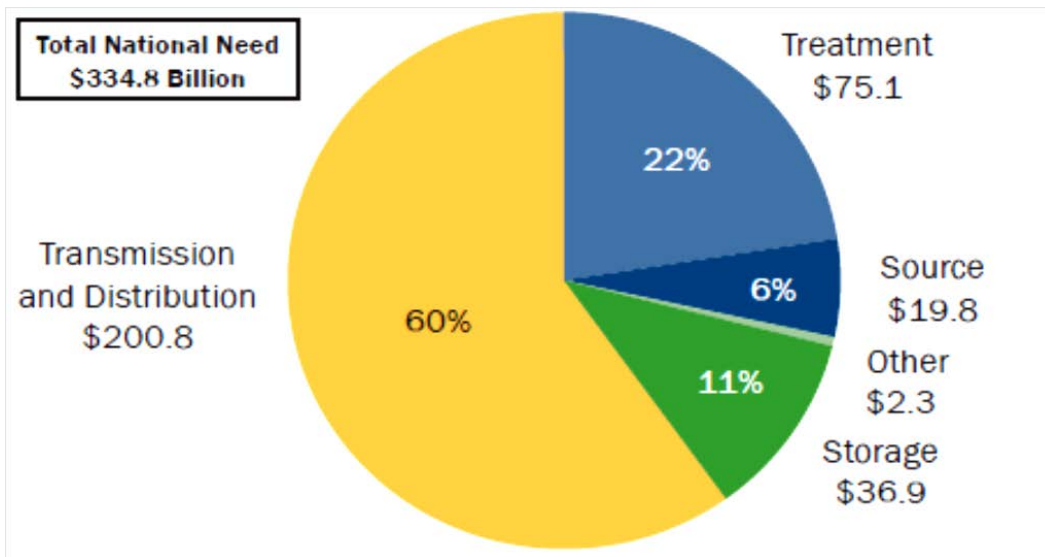


Figure 1.1 Estimated Cost for Drinking Water Projects for the Next 20 Years (EPA, 2007)

Figure 1.1 shows the estimated national water need cost breakdown forecasted by AWWA for the next 30 years. About 60% of the cost has to be invested on repair and replacement of the existing U.S. water transmission and distribution systems.

Table 1.5 and Figure 1.1, clearly show that underground pipelines (represented by the transmission and distribution segment of Figure 1.1), are the major hurdles to be

tackled in upcoming years, and conditions will worsen if the problem is ignored. ASCE 2009 report card, the "Infrastructure Factsheet," gave water infrastructure a grade of D minus. This report confirms a loss of 7 billion gallons per day of clean drinking water due to leaks in pipes, and estimates the repair and replacement cost at \$250 billion (ASCE, 2009). Hence, it is critical to the health and wellbeing of the nation that U.S. water utilities find a cost effective and efficient way to manage and maintain pipelines.

Research has been conducted and several reports have been published on the performance, failure modes and annual failure rates of different pipe material.\* Rajani and McDonald (1995) submitted a report for the National Research Council of Canada. This study found that the annual water main break rate per 100 miles of Cast Iron (CI) pipe is 57.4, DI pipe is 15.2, Asbestos Cement (AC) pipe is 9.3 and PVC pipe is 1.2. A similar study on water main break rates was conducted by Folkman (2012) for a total of 188 U.S. and Canadian utilities stating that Cast Iron Pipe is more susceptible to damage or failure. The annual failure rates per 100 miles for different pipe material are as follows: CI is 24.4, DI is 4.9, PVC is 2.6, Concrete Pressure Pipe (CPP) is 5.4, Steel is 13.5, AC is 7.1, and other pipes<sup>†</sup> are 21.

The failure rates of different pipe material\* from USA and Canadian utilities are discussed in above studies except for HDPE pipe. Davis et al. (2007), discussed the failure trends and annual frequencies of break encountered in HDPE pipes. Their findings are mainly from the survey conducted in Australia and United Kingdom utilities with only a few U.S. utilities participating. The annual failure rate of HDPE per 100 mile length for

---

\* Pipe Material refers to Cast Iron, Ductile Iron, Polyvinyl Chloride, Asbestos Cement, Concrete Pressure Pipe and Steel.

<sup>†</sup> As reported by Folkman (2012) other pipes refer to HDPE, Galvanized Steel and Copper Pipes.

Australian Utilities and U.K. utilities was 11.5 and 5.1 respectively. This study did not offer any robust conclusions for U.S. utilities.

The limited information on HDPE pipes created the problem statement for this research. How can water utilities address HDPE needs if they do not have adequate information concerning its performance? The information presented in this thesis will evaluate performance of HDPE pipes used in water utilities.

### 1.6 Objectives

The primary objective of this thesis includes comparisons of field performance of HDPE with DI and PVC pipes from previous research findings of Rajani and McDonald (1995), Weimer (2001), Folkman (2012) and Davis et al. (2012). This thesis evaluates the average annual occurrence failures of HDPE pipe per length and frequent causes of failures observed for particular diameter ranges. This thesis also makes available data on the age of pipe installed, population served, and inventory based on diameter size.

### 1.7 Methodology

The methodology adopted to accomplish the objectives of research is discussed in detail in Chapter 3. A quick overview of the steps used to conduct this research is shown below.

- Conduct an extensive literature search.
- Conduct a nationwide utility survey and collect the responses.
- Analyze and evaluate survey results to understand the performance of the HDPE pipe.
- Analyze results by:
  - Compare current research findings with Davis et al. (2007) study on HDPE pipe.



- Compare current research findings with similar studies conducted on Ductile Iron and PVC by Rajani and McDonald (1995), Weimer (2001), and Folkman (2012).
- Draw conclusions from analysis of results.

Provide limitations of current research and recommendations for future research. It should be noted that initially large diameter (more than 24 in. diameter) was targeted for this research, but since not much inventory for this diameter range was available, it was decided to target smaller diameters, 2-16 in. diameter range.

### 1.8 Expected Outcome

The outcomes of the research are discussed in details under Chapter 5. The expected outcome of this research was based on the conclusions drawn from the results obtained from the analysis of the survey conducted by the Center for Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington. The major key findings are average annual rate of pipe failures per length of pipe calculated for diameter ranges, frequent causes and types of failures. The expected results were compared with the failure rates of PVC and DI pipes obtained from previous research findings, Rajani and McDonald (1995), Weimer (2001), Folkman (2012) and Davis et al. (2012).

### 1.9 Chapter Summary

This chapter discussed the history of pipes, pipeline importance, and history of water distribution. In addition, this chapter presented problem statement, research objectives, methodology, and expected outcomes of the current research.

## Chapter 2

### Literature Review

This chapter introduces polymers, their classification, and the timeline of polymer development. The invention of the polyethylene (PE) manufacturing process is also included in this chapter. In addition, this chapter also discusses PE pipe joints and types of joints, different trends and causes of failure.

#### 2.1 Polymeric Material

The word polymer is derived from Greek, *poly* means *many* and *meros* meaning parts (Katz, 1998). A polymer consists of very large molecules made up of many smaller units called monomers which are joined together to form a long chain by the process of polymerization. Monomers are called the building blocks of polymers; monomers constitute mostly hydrogen and carbon. Sometime oxygen, nitrogen, chlorine, or fluorine is added to monomers to create different properties and grades of polymers (Farshad, 2006).

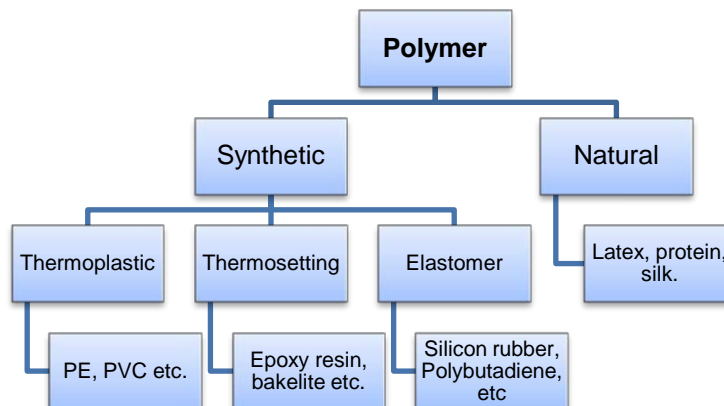


Figure 2.1 Classifications of Polymers (Farshad, 2006; Katz, 1998)

Figure 2.1 is the classification of polymers based on the type. From Figure 2.1 polymers can be broadly classified into two types:

- Natural Polymers

- Synthetic Polymers

Polymers such as latex from trees, protein from animals and silk from silk worm, are a few examples of naturally occurring polymers, which are appropriately called *natural polymers* (Katz, 1998).

Polymers, other than natural polymers, are called ***synthetic polymers***, which are manmade polymers, e.g., Bakelite, polyethylene, epoxy, PVC, silicone etc. Synthetic polymers are further divided into three categories *thermosetting plastics*, *thermoplastic*, and *elastomer* (PPFA, 2005; Katz, 1998).

*Thermoplastic Plastic* refers to a plastic that can be repeatedly softened by heating and hardened by cooling through a temperature range characteristic of the plastic, and that in the softened state can be shaped by flow into an article by molding or extrusion (PPFA, 2005).

*Thermosetting Plastic* refers to a plastic that, when cured by application of heat or by chemical means, changes into a substantially infusible product (PPFA, 2005).

Table 2.1 shows the timeline of polymeric evolution. The first type of polymer was discovered in the year 1868 and was called cellulose nitrate. In 1933 polyethylene was discovered and during 1948 polyethylene pipe was manufactured (PPFA, 2005).

Table 2.1 Timeline of Polymer Evolution (PPFA, 2005)

Estimated Year of Discovery	Plastic Material	Estimated Year of Piping Usage
1868	Cellulose Nitrate (Celluloid)	First semi-synthetic plastic
1909	Phenol Formaldehyde (Bakelite)	First all-synthetic plastic
1927	Polyvinyl Chloride (PVC)	1940
1933	Polyethylene (PE)	1948
1938	Cellulose Acetate Butyrate (CAB)	1940
1938	Polytetrafluoroethylene (PTFE)	1960
1943	Chlorinated Polyvinyl Chloride (CPVC)	1960
1948	Acrylonitrile Butadiene Styrene (ABS)	1952
1955	Ethylene Chlorotrifluoroethylene (ECTFE)	1966
1956	Fluorinated Ethylenepropylene (FEP)	1965
1957	Polypropylene (PP)	1958
1960	Cross-Linked Polyethylene (PEX)	1965
1962	Polybutylene (PB)	1971
1963	Polyvinylidene Fluoride (PVDF)	1964
1968	Perfluoroalkoxy (PFA)	1972

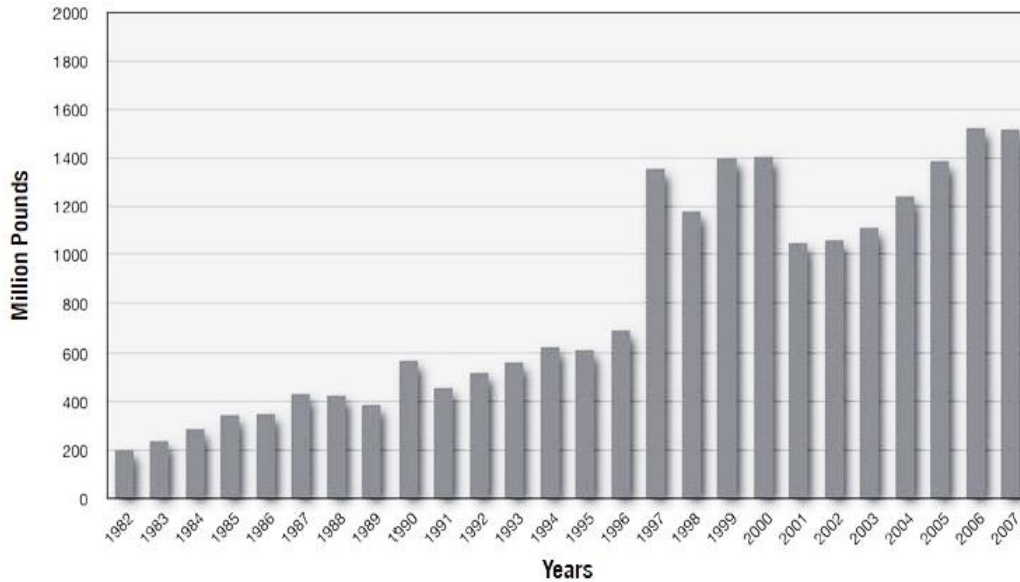


Figure 2.2 HDPE Pipe Manufacturing in North America (PPI, 2008)

The growth of HDPE pipe in North America is shown in Figure 2.2. Since 1982 the demand for HDPE pipe has grown from 200 million pounds production to over 1,500 million pounds in 26 years.

### 2.2. Discovery of Polyethylene

The discovery of polyethylene accidentally occurred during 1894 when an experiment by Hans von Peckmann yielded decomposition of diazomethane in the form of white powder. Further analysis indicated that the product was made up of hydrogen and carbon atoms forming a long chain of methylene (CH<sub>2</sub>) molecules which are known as polymethelenes. The second attempt to create polyethylene was made in 1929 by Fredrick and Marvel, who were successful in producing a polyethylene with lower molecular weight by heating butyllithium (BuLi) (Storm and Rasmussen, 2011).

In 1933, two English researchers at Imperial Chemical Industries (ICI) in England, namely Eric Fawcett and Reginald Gibson, were conducting an experiment on

an ethylene and benzaldehyde mixture at very high temperatures when a sudden loss of pressure in the experimenting vessel resulted in a waxy solid, which they called polyethylene. It was the first polymerization of the ethylene monomer. ICI began the commercial production of polyethylene in 1939. DuPont was the first industry to manufacture low density polyethylene (LDPE) collaborating with ICI to produce the first LDPE product for the U.S. Government in 1943 (Storm and Rasmussen, 2011).

### 2.2.1 Manufacturing of HDPE

There have been several manufacturing methods adopted by the plastic industries. One of the methods is discussed here, polymers are made up of hydrogen and carbon molecule called ethylene. Ethylene is obtained from oil refineries, and generally has a high molecular weight which can be separated from the other hydrocarbon in the crude oil by cracking over zeolite catalysts or by steam cracking of gaseous or light liquid hydrocarbons at 750-950°C. A further distillation and compression step separates the ethylene from other products. Once the ethylene is separated it is polymerized and polyethylene is obtained. The choice of polymerization technique is selected based on the physical property, density and application of the polyethylene. The catalyst is used to accelerate the process of polymerization and also to vary the structure of the polyethylene chains to manufacture the polyethylene so as to serve the intended purpose. The known techniques are *autoclave process* and *tubular process* which utilizes *free-radical* polymerization to manufacture LDPE and *Chromium Catalysis*, *Ziegler-Natta catalysts* and *Metallocene Polymers* which utilizes the coordination chemistry for manufacturing HDPE and LLDPE (Linear Low Density Polyethylene) (Storm and Rasmussen, 2011). Additives are added to the polymerized PE as antioxidants, the resulted polymers are dried, crushed to powder or granulated and stored (Denberg, 2009).

The extrusion of the polymerized PE into pipes is the final step of the manufacturing process. The PE granulates are added into the continuous mixers and this material is passed through a series of heated cylinders whereby a molten polyethylene is obtained. This molten polymer is then passed through the nozzles and slowly pushed through the extruders by a mixing screw. The pipe obtains the shape when the molten PE is passed under extrusion dies, followed by expansion of the material against a sizing sleeve. The sizing sleeve controls the outer diameter of the pipe. The resulting pipe is susceptible to collapse; to avoid collapsing it undergoes vacuum cooling. The pipe experiences a second cooling when it is pulled out of the vacuum tank and cooled by spraying water. The pipe is then processed for labeling and packing (Denberg, 2009; Hovland and Najafi, 2009).

#### *2.2.2 Polymerization Technology*

The technology used to manufacture polyethylene is called polymerization, and can be categorized as Reactor Technology and Catalyst Technology. Furthermore based on the type of reactor used for polymerization, reactor technology is further classified as gas phase process, solution process and slurry phase process. Similarly the catalyst technology used in PE manufacturing can be classified as the Ziegler – Natta catalyst process, Chromium catalyst process, and Metallocene Polymers (Plastic Pipe XVI 2012; Storm and Rasmussen, 2011).

### 2.3 HDPE

According to Hsieh et al. (2007), the plastic pipe system was introduced during 1930s and it was accepted globally during late 1950s and early 1960s. The confidence of usage of HDPE pipe in underground infrastructure has increased during every decade since the 1970s (Kuffer and Freed, 2009). Similarly, Watkins (2004) states the usage of HDPE pipe in underground infrastructure is significantly increasing due to its unique

properties such as its light weight and resistance to corrosion and abrasion as well as the fact that it is easily molded, extruded, machined and welded. “PE is the most widely used polymer in the world, and PE water pipes are increasingly being installed in buried and building plumbing applications globally” (Welton et al., 2010). “PE pressure pipes have excellent records of performance only some abnormal service loadings may result in field failures” (Yayla and Bilgin, 2006).

HDPE pipes are used to carry potable water (Whelton et al., 2011; Zhao et al., 2002), and the use of PE to supply drinking water has been increasing in the Danish market since 1960 (Denberg, 2009). PE has been successfully used primarily in water utilities and in the gas industry for over 50 years (Allwood and Beech, 1993, Haager et al 2006). There are several factors that have influenced the usage of HDPE pipe for water distribution. These include flexibility, cost of installation and manufacturing, resistance to oxidants, corrosion, and abrasion, long-term performance, low thermal conductivity and squeeze-off properties<sup>‡</sup> (Watkins, 2004; Welton et al., 2010; Yayla and Bilgin, 2006; Denberg, 2009; Frank et al., 2009).

Different terminologies are used to designate the HDPE pipe. Countries which use the metric system and follow ISO as standards designate HDPE pipe as *Polyethylene Pipe (PE)* and ASTM Standards nomenclature refers to it as *High Density Polyethylene Pipe (HDPE)*. Table 2.2 tabulates the grade of HDPE availability in the market as per ISO and ASTM standards. Column 1 in the Table 2.2 describes different types of HDPE based on the pressure used during the manufacturing process. For example, type I is designated for Low Density Polyethylene (LDPE) pipes which are manufactured mainly by high pressure. Application of type I pipes are limited; these are

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<sup>‡</sup> Squeeze-off is the emergency situation to stop or nearly stop the flow in PE by flattening the pipe between parallel bars. This is method is used when carrying repair or maintenance work of PE (Yayla and Bilgin, 2006).



typically used to carry liquid under low pressure. Type IV is manufactured and processed under low pressure, and application of the type IV pipes are used to carry liquid under high pressure (PPI, 2008).

Table 2.2 HDPE Grade as per ISO and ASTM Standards (PPFA, 2011; PPI, 2008)

HDPE Type	ISO Grade	ASTM Grade	Designation	Density
I	PE 32	PE 1404	LDPE	0.910 – 0.925
II	PE 80	PE 2708	MDPE	0.916 – 0.940
III	PE 80	PE 3608	HDPE	0.940 – 0.947
III	PE 100	PE 4710	HDPE	0.947 – 0.955
IV	–	–	–	0.955 & above

The standards used for HDPE pipes with a nominal diameter of ½ in. – 3 in. are covered under AWWA PE C–901 and ASTM 3035. HDPE pipes with a nominal diameter of 4 in. – 63 in. are covered by AWWA PE C–906 and ASTM F714.

Table 2.3, is the summary of the HDPE pipe standards used in water applications (PPI, 2008; Najafi, 2010).

Table 2.3 HDPE Pipe Standards for Trenchless Technology (Najafi, 2010)

Standard	Diameter
AWWA C901-08	½ in. – 3 in.
AWWA C906-07	4 in. – 63 in.
ASTM D3035-08	½ in. – 24 in.
ASTM F714-08	3 in. – 63 in.

## 2.4 Joints and Fittings in HDPE

The process of connecting the segments of pipes is joining. The joining procedure for HDPE pipe is shown in Figure 2.3.

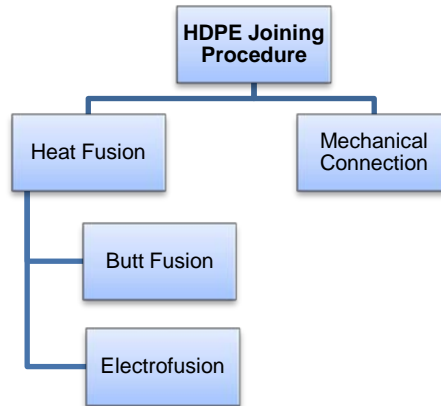


Figure 2.3 Types of HDPE Pipe Joining Procedure (PPI, 2008)

As Figure 2.3 shows, joining procedures of HDPE pipes can be mainly classified into Heat Fusion and Mechanical Connection. The heat fusion can be further categorized into Butt Fusion and Electrofusion.

### *2.4.1 Butt Fusion*

According to Zhao et al (2002) and Beamer and Kendall (2009), butt fusion is the most effective method for connecting HDPE pipes on job sites. The process of joining is explained as follows, the pipes to be joined are mounted on the clamps of the butt fusion equipment and this is checked for initial alignment. The pipes ends are then trimmed to remove any uneven surfaces, surface voids or any manufacturing defects. The hot plate is sandwiched between the pipe ends and pressure is increased to give a good thermal contact. The pipe ends melts to form weld beads on the inner and outer surfaces. This process is called bead up stage. Then pipes are slowly pulled away and hot plate is removed. The pipe ends are now pushed together and pressure is applied gradually. The process is called initial bead-up stage. When further more pressure is added to the pipe

the inner and outer surfaces of the pipes tend to curve outwards. The stage is called beadroll over stage. A leak proof joint is achieved when the weld is cooled (Davis et al., 2007). A typical standard butt fusion is shown in Figure 2.4 and Figure 2.5.

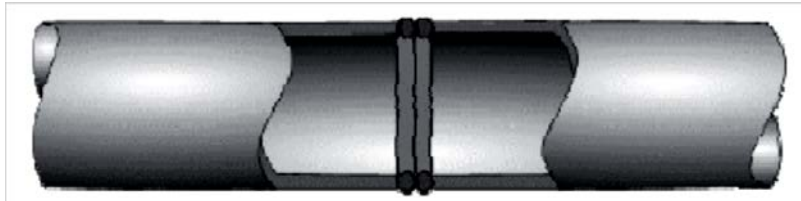


Figure 2.4 Standard Butt Fusion (PPI, 2008)



Figure 2.5 Butt Fusion

#### 2.4.2 Electrofusion

The electrofusion joining process can be achieved with the help of coupler. A coupler consists of resistance wires, stopper to prevent the meeting of pipe ends and this is connected to an electronic device. The pipe ends to be joined is slides into the coupling which has stopper. Controlled electric current is passed through the wires which heats the pipe surface. When sufficient heat is passed the pipe surface melts. Upon cooling the electrofusion joint is achieved (Davis et al., 2007). Typical electrofusion is as shown in Figure 2.6.

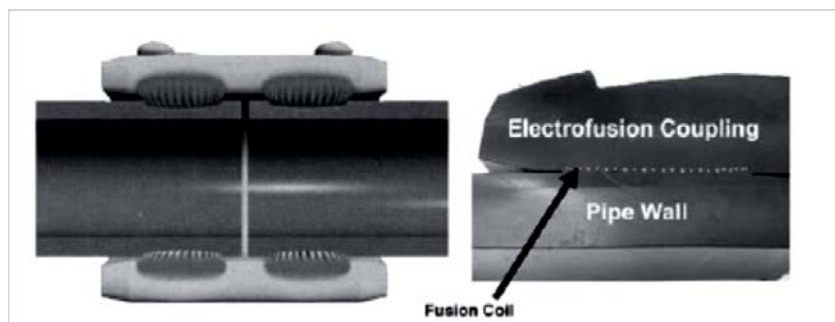


Figure 2.6 Standard Electrofusion (PPI, 2008)

For successful joining of pipes, three important pipe preparation stages must be followed (Davis et al., 2007):

- The pipe ends must have finished squared ends to ensure that the central cold zones function to contain the melt.
- The pipe surfaces to be joined must be properly scraped to reveal uncontaminated material. With the electrofusion joining process, there is little or no relative movement between the pipe and the coupler. Therefore, any contamination on the pipe surface is retained at the joint interface, which can significantly reduce the strength of the joint.

- The pipe and fitting should be clamped during welding to eliminate relative movement. This ensures that the molten polymer is contained at the fusion interface, allowing the development of a strong joint.

### 2.5 HDPE Pipe Performance

Pipes will deteriorate and fail overtime, but the rate of failure in pipes varies accordingly to the pipe material, operation, environment, loading conditions and several other factors. According to Farshad (2006), failure phenomenon of plastics can be categorized under two categories as shown in Table 2.4.

Table 2.4 Failure Phenomenon of HDPE (Farshad, 2006)

Sources of Potential Failure	Types of Failures
Material deficiencies	Mechanical
Insufficient design	Thermal
Problems related to processing	Chemical
Inappropriate storage, transportation and installation	Environmental
Unfavorable service conditions	Brittle and ductile
Third party damage	—
Ageing and deteriorations	—

#### *2.5.1 Failure Stage of HDPE Pipe*

According to Duvall and Edwards (2010) and a Technical Report submitted by Jana Labs (2011), the failure of HDPE pipe can best be described in three different stages based on the magnitude of the stress and the duration of time under stress. Figure 2.7 represents graphically the three stages of failure in HDPE pipe:

1. Ductile – Mechanical failure
2. Brittle – Mechanical failure
3. Brittle – Chemical failure or Brittle-oxidative failure

Stage I is purely mechanical failure as the material fails under stress that occurs due to loading. The material yields before failing indicating a brittle failure pattern. There is significant deformation of material during Stage 1 failure.

Stage II failure is the combination of a brittle-mechanical failure mechanism. This type of failure occurs due to Slow Crack Growth (SCG). When the material is under a point load for long duration, stress will cause the pipe wall to behave as brittle material and the wall may split developing a stress crack which propagates through the wall causing a longitudinal failure. Longitudinal failure and pinhole leaks are indications of Stage II failure pattern.

Stage III failure is referred to as brittle-chemical failure or brittle-oxidative failure. The indication of this failure is noticeable when the material degrades due to oxidation and also the action of stress induced due to the crack propagation corresponding to Stage II.

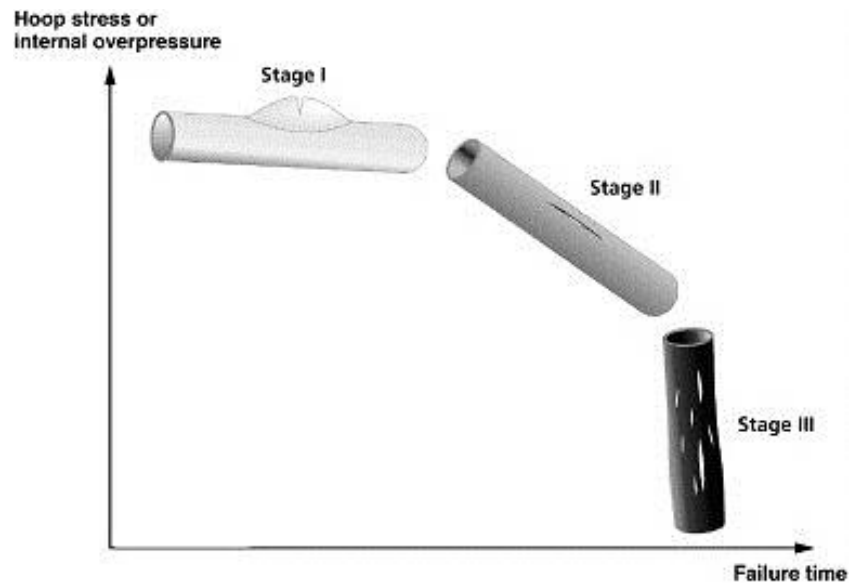


Figure 2.7 Failure Stages in HDPE Pipe (Duvall and Edwards, 2010)

### 2.5.2 Crazing

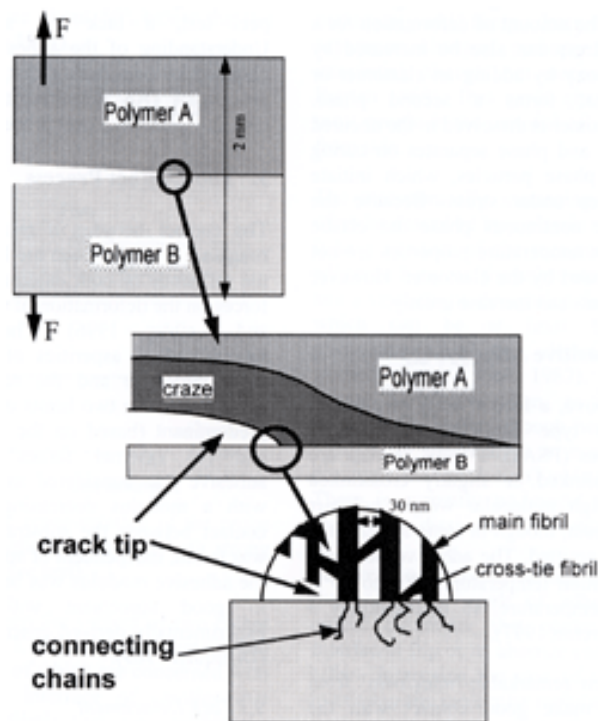


Figure 2.8 Schematic Representation of Crazing at the Crack Tip (Brown, 2000)

Crazing is a process of surface cracking which occurs in the amorphous polymer at the tip of the crack, and this is always normal to the direction of the tensile stress. The craze is comprised of voids and stretched fibrils. The schematic representation of the process is shown in Figure 2.8. When the load is applied, stress is induced on the polymer fibers, and they are stretched. The continuous contraction and relaxation of fibers initiates surface cracking or crazing. Once the craze is formed at the root of the notch, a plastic zone is generated due to the localized yielding of the material. The craze remains stable with the micro-fibrils sustaining the stresses. As time passes, the craze grows slowly by stretching the micro-fibrils. The rupture of the micro-fibrils near the base of the craze leads to a growing crack. When the remaining ligament reaches the critical size, complete failure occurs (Brown, 2000; Zhang, 2005; Farshad, 2006).

### *2.5.3 Cracking*

The premature failure of HDPE pipe due to cracking was most common type of failure seen in the 1<sup>st</sup> generation of HDPE pipes. The cracking of HDPE pipe can be categorized into three types, 1) third party damage, 2) joint failure and 3) material failure. Improper construction practices leads to third party damage, which occurs when the connection of pipes is not according to the standard specifications and practice manual. Poor design and quality of material used in manufacturing such as impurities and defects will promote material failure (Zhang, 2005; Lustiger and Corneliussen, 1987).



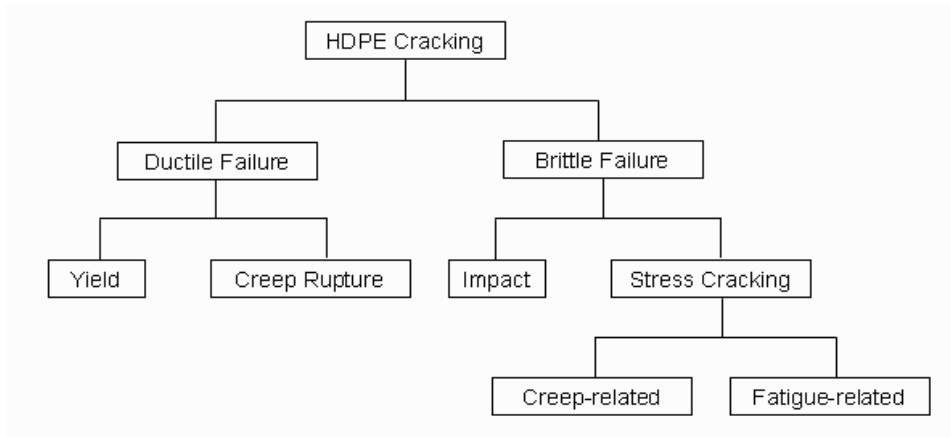


Figure 2.9 Failure Modes in HDPE Cracking (Zhang, 2005)

Figure 2.9 presents classification of HDPE pipe cracking. The Cracking can be primarily categorized into ductile failure and brittle failure.

#### 2.5.4 Ductile Failure of HDPE

The ductile cracking undergoes substantial yielding before undergoing failure. The growth of cracking in ductile failure occurs very slowly and is accompanied by a large amount of plastic deformation. Ductile fracture surface will have a larger necking. The microscopic phenomenon of ductile failure is shown in Figure 2.11 where initially all the polymeric fibers stretched creating a micro void. As the stress is continuously induced the deformation continues and the micro voids enlarge to form a crack. This crack is propagated in the direction of the tensile load and finally the necking of the material takes place and bonding between the polymeric fibers is decreased resulting in ductile failure (Lustiger and Corneliussen, 1987; Zhang, 2005; Davis et al., 2007).

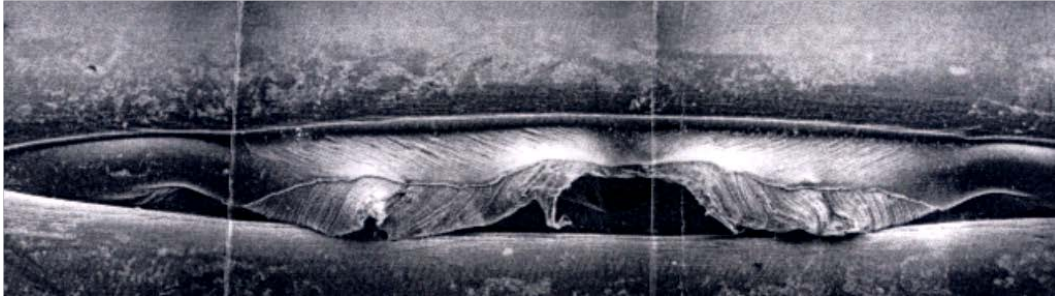


Figure 2.10 Macroscopic Ductile Failure of HDPE (Zhang, 2005)

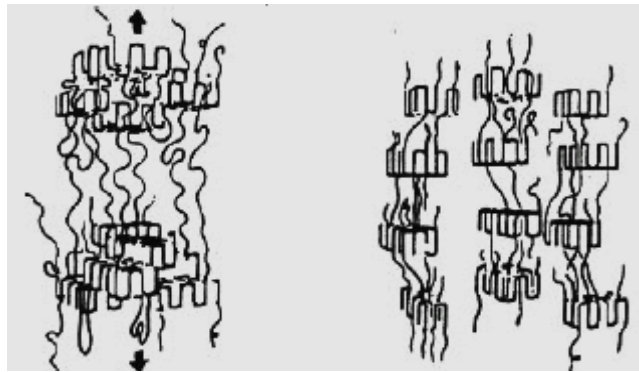


Figure 2.11 Microscopic Failure of Ductile Failure (Zhang, 2005)

### 2.5.5 Brittle Failure

In brittle failure, very little or no plastic deformation is observed before undergoing failure. Once the crack is formed, it propagates quickly in the longitudinal direction and fails without any deformation or elongation. Figure 2.13 explains the microscopic behavior of the material before undergoing the failure (Lustiger and Corneliusen, 1987). Brittle failure can be further classified based on the propagation of crack:

1. Rapid Crack Propagation (RCP)
2. Slow Crack Growth (SCG)



Figure 2.12 Macroscopic Brittle Failure of HDPE (Zhang, 2005)

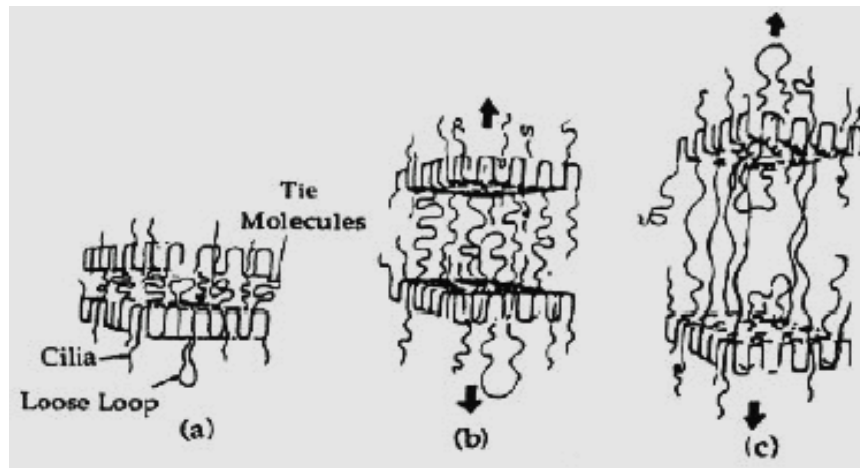


Figure 2.13 Microscopic Failure of Brittle Failure (Lustiger, 1985)

#### 2.5.5.1 Rapid Crack Propagation (RCP) and Slow Growth Propagation (SCG)

Rapid Crack Propagation (RCP) and Slow Growth Propagation (SCG) are the two types of brittle failure. RCP is also referred to as “fast brittle failure” and “linear split”. The initiation of RCP can be explained by several factors such as internal defects, pipe

material, internal pressure, temperature, joining techniques, and third party damage (Palermo, 2010). According to Frank et al. (2011), properties of HDPE such as ductility and semi-crystallinity resist the RCP in HDPE pipe when compared to other plastic material pipe such as PVC which are brittle in nature. According to Frank et al. (2011), very few failures were recorded under RCP in HDPE pipe for water application from various utilities in Europe and the U.S. In the typical RCP is as shown in Figure 2.14, the direction of the crack will be always normal to the surface of the pipe. Fast running crack rate can vary from 300 ft/s – 900 ft/s for an indeterminate length (Ivankovic and Venizelos, 1998).



Figure 2.14 Rapid Crack Propagation (Adapted from Performance Pipe, 2012)

According to Frank et al. (2011), the long-term HDPE pipe applications suffer crack initiation and SCG. The SCG can be accelerated by high temperature and presence of surfactant under cyclic loading conditions (Plummer et al., 2001).

#### 2.5.6 Failure Due to Oxidation

“Organic material reacts with molecular oxygen in a process called autoxidation” (Lundback, 2005). According to Lundback (2005) the process of autoxidation can be triggered by factors like heat, radiation, mechanical stress, catalysts residues or free

radicals. Although PE is a good corrosive resistance, it is vulnerable to oxidation due to chlorine actions when combined with oxygen (Eng, 2011). According to Duvall (2009) and Lundback (2005), the free radical chlorine is released when chlorine disinfectant is added to water. This reaction results in the polyethylene degradation. Even though HDPE inner walls are lined with anti-oxidants to avoid the reaction, over a period of time, these anti-oxidants are eroded due to continuous flow of water. When the HDPE inner walls are exposed to chlorine, no sufficient amounts of anti-oxidants will retard the oxidation or prevent the degradation initiation within the HDPE pipe.

Figure 2.15 represents PE degradation due to free radicals, i.e., chlorine. The steps involved in the oxidation process are initiation, propagation, and termination. The release of the free radical is the initial phase. The propagation phase involves reaction of free radical with oxygen and polymer forms another radical. The termination phase is when the radicals react to each other and form non-reactive products. In Figure 2.14, the process of polyethylene degradation and stabilization where  $R_o$  is the alkyl radical,  $RO^\circ$  is alkoxy radical,  $ROO^\circ$  is the peroxy radical and  $ROOH$  is the hydro-peroxide (Lundback, 2005).

The failure mode observed due to polymer degradation is brittle failure. Once the polymer degradation is initiated a brittle inner surface is commenced, and cracks are developed. Further degradation will propagate the cracks into the pipe wall and the pipe will fail due to brittle cracking (Duvall, 2009).

Figure 2.16 shows the wall surface cracking of HDPE due to the oxidation process, and Figure 2.17 shows a sample of HDPE degradation due to continuous reaction with the chlorinated water.

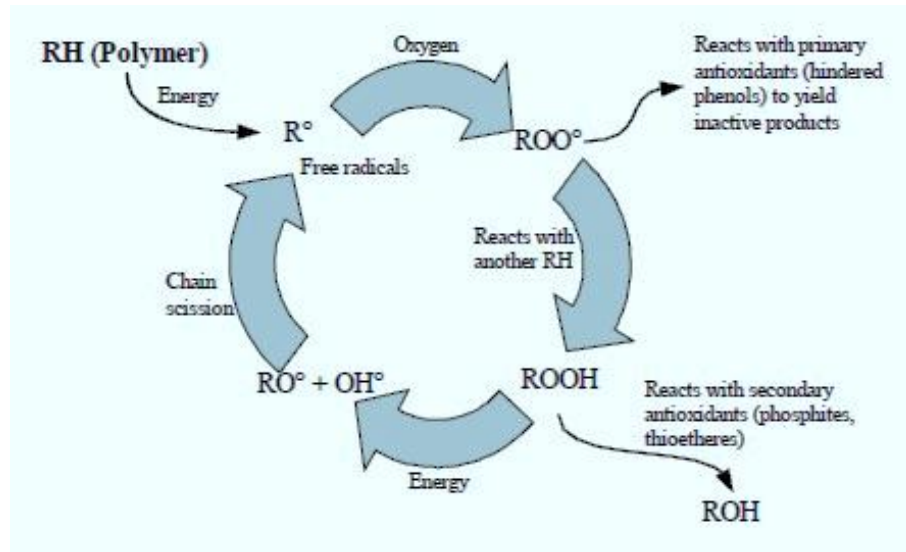


Figure 2.15 The Process of Polyethylene Degradation and Stabilization (Lundback, 2005)

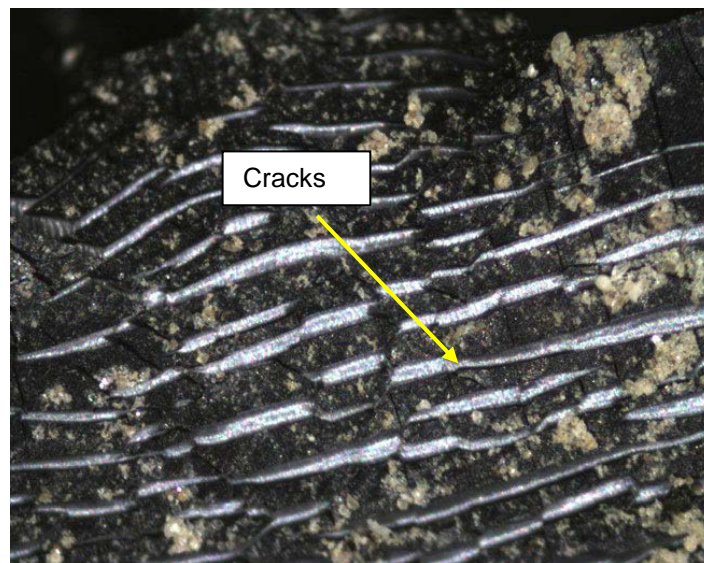


Figure 2.16 Cracks Due to Oxidation of HDPE (Chung et al., 2007)

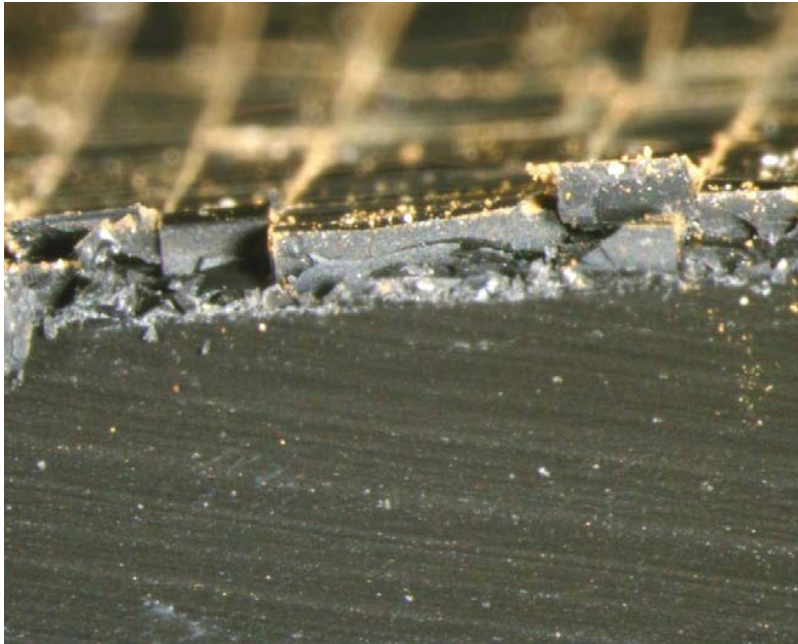


Figure 2.17 HDPE Pipe Wall Degradation Due to Oxidation (Duvall and Edwards, 2010)

### *2.5.7 Joint Failure*

HDPE pipes are connected by joining methods such as butt fusion, and electrofusion and fittings, such as tees and couplings. To avoid the failure of pipes at the joints standard joining procedure and preparation need to be adopted.

#### *2.5.7.1 Fusion Failure – Electrofusion*

The arrow in the Figure 2.18 is the electrofusion coupling failure of HDPE water pipe resulted due to bad workmanship. Separation is another type of failure that can be observed in electrofusion joints. The failure occurs when there is moisture trapped between the pipes and coupling. When the coupling is heated to high temperature for the joining purpose, the moisture vaporizes and attempts to escape, creating air bubble in the coupling during the joining process. Over a period of time the pipe is separated from coupling and fails (Davis et al., 2007).



(a)

(b)

Figure 2.18 Electrofusion Coupling Failure of HDPE Water Pipe

(Plastic Pipe Facts, 2012)

#### 2.5.7.2 Fusion Failure – Butt Fusion



Figure 2.19 Butt Fusion Failure Due to Contamination of Material (PPI, 2008)



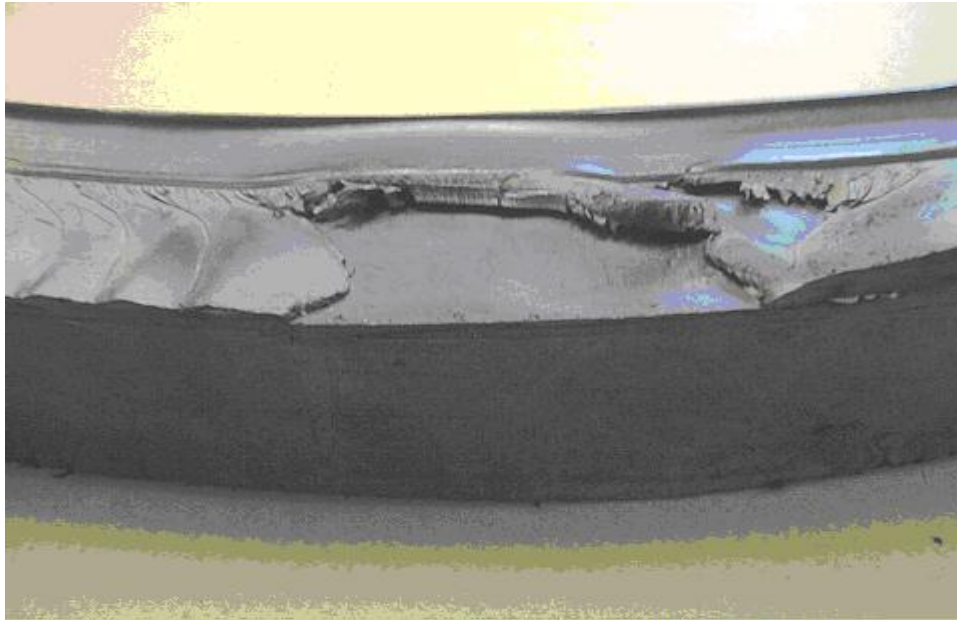


Figure 2.20 Butt Fusion Failure Due to Improper Trimming of HDPE Pipe Surface

(Plastic Pipe Facts, 2012)

Figure 2.19 and Figure 2.20 illustrates butt fusion failure in HDPE pipe. Figure 2.19 is the failure of pipe due to the presence of contaminant in the HDPE pipe wall and Figure 2.20 is the failure due to improper end trimming performed during the joining procedure.

#### 2.6 Past Study on HDPE Field Performance

It is important to know whether the pipes are performing as per the design as it pertains to flow capacity, whether it is able to withstand pressure, and if it is resistant to corrosion and so on. Periodic monitoring is very important to evaluate pipe performance. Several methods can be adopted to study water pipe performance, such as, conducting a survey and collecting responses from utilities. By conducting such surveys and studies, the limitations and advantages of the pipes can be understood. This benefits researchers

as they learn from the analysis of pipe limitations and find a better alternative or improve the product.

The AWWA Research Foundation, Commonwealth Scientific & Industrial Research Organization (CISRO) and U.K. Water Industry Research (UKWIR) made a similar study on HDPE field performance by conducting surveys and collecting responses from selected utilities in Australia, the United Kingdom and the United States. One of the objectives of this study was to find the annual rate of HDPE pipe failure per length. The summary of survey findings for Australian utilities is tabulated in Table 2.5.

Table 2.5 Annual Failure Rate in Australian Water Utilities

(Adapted from Davis et al., 2007)

Utility	Total Length of HDPE (Miles)	Number of Failure	Recording Period	Annual Failure Rate per 100 Miles
City West Water	175	132	1996 – 2003 (8 Yrs)	9.5
Yarra Valley Water	298	313	1996 – 2003 (8 Yrs)	13.1
South East Water	302	258	1996 – 2003 (8 Yrs)	10.7
South Australia Water	56	23	1995 – 2001 (8 Yrs)	5.9
Ipswich Water	46	29	2003 – 2005 (3 Yrs)	21.2

According to Davis et al. (2007), based on the UKWIR national failure database obtained from 17 water utilities for the years 1998 through 2002, the annual failure rate of PE per 100 miles is 5.6, 4.6, 5.3 and 4.8. Furthermore, the average rate of failure of HDPE per 100 miles for 5 consecutive years (1998 – 2002) is 5.1\*.

A similar study was conducted by Weimer (2001) in Germany collecting failure data from 500 water utilities to understand the water pipe failures which were used for water application. Table 2.6 is adapted by Weimer (2001); this study was concentrated mostly on the service connection pipe (2 in. and less diameter size).

Table 2.6 Water Pipes Failures Reported in Germany (Weimer, 2001)

Pipe Material	Length	Number of Failures	Annual Failure per 100 Miles
Cast Iron	13,233	5,658	42.8
Ductile Iron	8,724	375	4.3
Steel Pipe	3,000	1,602	53.4
PE	844	250	29.6
PVC	2,545	183	7.2
Galvanized Pipes	1,417	503	35.5

### 2.7 Chapter Summary

This chapter discussed the evolution of polymer, introduction to HDPE pressure pipe, joining procedures, failure modes of HDPE pipe and past survey findings of HDPE field performance.

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\*Only failures related to PE are considered and all the annual failure rates reported were per 100 km. To maintain the uniformity of the units, the values were modified from Kilometer (km) to miles.

## Chapter 3

### Methodology

This chapter will provide the methodology involved in achieving the objectives of the research explained in chapter 1.

#### 3.1 Introduction

To analyze the performance of HDPE water pipe, it is necessary to gain the knowledge of material property, behavior of the pipe under different loading and environmental conditions, and its failure patterns. This knowledge is achieved by literature review. This chapter will provide the methodology employed to accomplish the objectives of the research.

#### 3.2 Methods

The methodology used to achieve the proposed research objectives are as follows:

1. Conduct an extensive literature search on HDPE pipe for potable water application. The study was mainly focused on types of failure, patterns of failure and factors causing failures.
2. Design the survey questions focusing on objectives.
3. Conduct nationwide survey and collect the responses.
4. Analyze and evaluate survey responses to achieve research objectives.
5. Discuss results and conclusions.
6. Recommend future research.

#### 3.3 Research

To achieve the primary and underlying objectives of this research, an extensive literature search was completed with the intention of gathering the information on the previous studies and findings on HDPE water pipe. With the knowledge gained from the

literature search, two national surveys were designed. Survey 1 was prepared and focused on the pipe diameter range of 2 in. – 16 in., and Survey 2 was targeted on pipe diameter range of 24 in. and Larger HDPE water pipes. The diameter size 18 in., 20 in., and 22 in., was not considered in this thesis study, since originally the survey was conducted to study the performance of HDPE water pipe for diameter 24 in. and larger. The limited and incomplete surveys responses, such as, no failure occurrence, and unavailability of HDPE for large diameters demanded additional survey to evaluate the small diameter HDPE performance. The second survey prepared focused on the diameter range 2 in.–16 in. and pipe diameter range between 18 in.-22 in. was not considered in the second survey.

### 3.4 Data Collection

The data collection is very important and plays a major role in research findings. In this research, the data collection method used was survey responses from selected utilities. The data collected focused on size, age, type of water (treated or untreated), installation and failure date, soil condition, and number of breaks. The collected data were then analyzed and conclusions were drawn based on the results obtained. The analysis of the survey is discussed in Chapter 4, and conclusions are discussed in Chapter 5.

#### *3.4.1 Survey*

Surveying was one of the methods employed to achieve the thesis objectives. The knowledge gained in the literature search was implemented to generate an efficient survey to evaluate HDPE water pipe performance. The survey is explained by the flowchart shown in Figure 3.1.



Figure 3.1 Flow Chart of Designing and Implementing the Survey (Hart, 2010)

The two surveys prepared were based on the flowchart that is illustrated in Figure 3.1. The first survey was developed for the HDPE water pipe focusing on the small diameter range of 2 in. – 16 in. and the second focused on 24 in. and larger. The survey contains both open-ended and closed ended questions. Very few open-ended questions were asked. Most of the questions were closed ended in order to make the respondents complete the survey easily spending less time so they could efficiently fill out the questions asked. Survey templates for both surveys are included in Appendix A (small diameter 2 in. to 16 in. diameter size) and Appendix B (24 in. and larger diameter size).

### 3.5 Analysis

Twenty one utilities participated in the surveys, out of which thirteen responses accounted for small diameter HDPE pipe and five responses accounted for large diameter HDPE pipe. The first few survey questions were generic and were answered by all twenty one utilities. Unavailability of data were assumed for the questions that were skipped or unanswered. From the generic questions, data was collected on inventory, population served, and pipe material used. The respondents were asked to report the number of failures, types of failure and frequent causes. The data collected was analyzed to obtain the desired results as per the objectives defined. The analysis of data, discussion of results and conclusions are presented in the following chapters.

### 3.5 Chapter Summary

This chapter discussed the methodology used to achieve the research objectives; survey design and data collection.

## Chapter 4

### Survey Results and Discussions

#### 4.1 Introduction

In this chapter the survey responses are discussed. The analysis is graphically represented and discussed in this chapter.

The survey was conducted by the Center for Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington. 200 Small Diameter Surveys were sent out and 332 Larger Diameter Surveys were sent out nationwide. There were 21 water utilities that responded to both. Of those 21, 13 water utilities could respond to questions about HDPE pipe on Small Diameter Survey and only 5 water utilities responded to Larger Diameter Survey. For confidentiality throughout the research the utilities are addressed by numbers instead of their individual names.

Section 4.2 discusses the data analysis for HDPE pipes with a diameter range from 2 in.-16 in. (Small Diameter Survey), Section 4.3 discuss the data analysis for HDPE pipes with a diameter range of 24 in. and larger (Large Diameter Survey). The results obtained are compared with previous research findings of Rajani and McDonald (1995), Weimer (2001), Folkman (2012) and Davis et al. (2012) and discussed in Section 4.5.

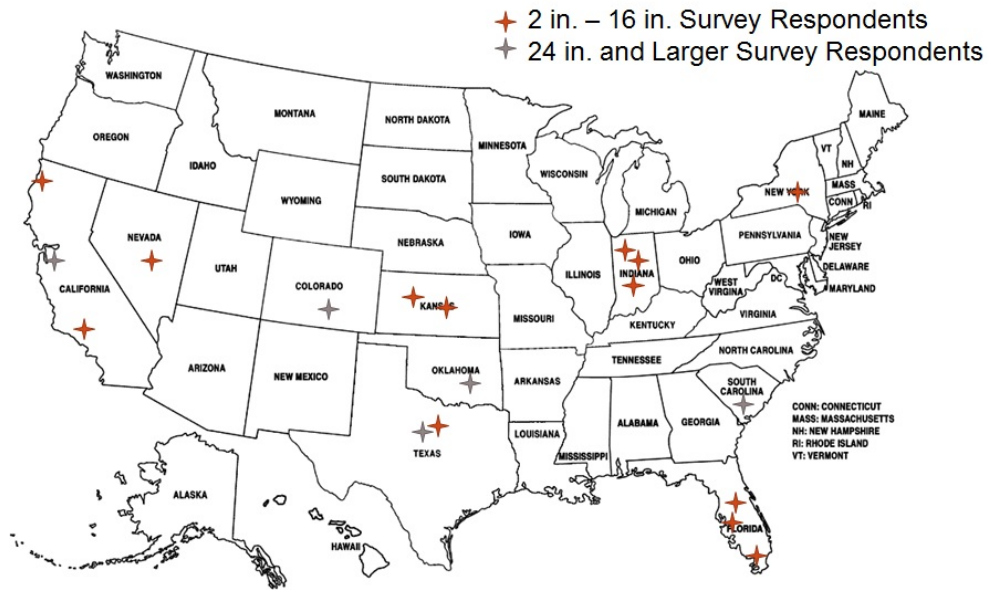


Figure 4.1 Utilities Responded to HDPE Survey Only

Figure 4.1 is the U.S. map indicating the states that replied for HDPE pipe survey only. The 13 utility responses received for Smaller Diameter Survey are spotted on the map by the orange colored star, and the 5 utility responses received for Larger Diameter Survey are spotted by silver colored stars.



#### 4.2 Discussion of Survey Responses – 2 in. to 16 in.

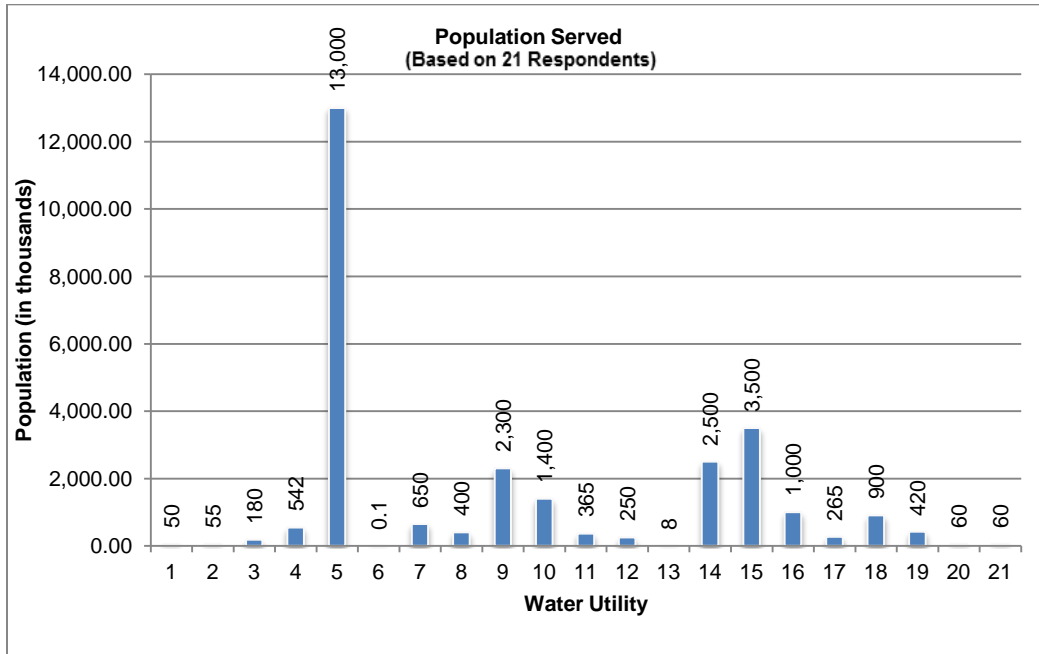


Figure 4.2 Population Served by All Pipe Material

The Figure 4.2 illustrates a wide range of population served. For example City 6 has the least population (100) and City 5 has the largest population served (13,000,000).

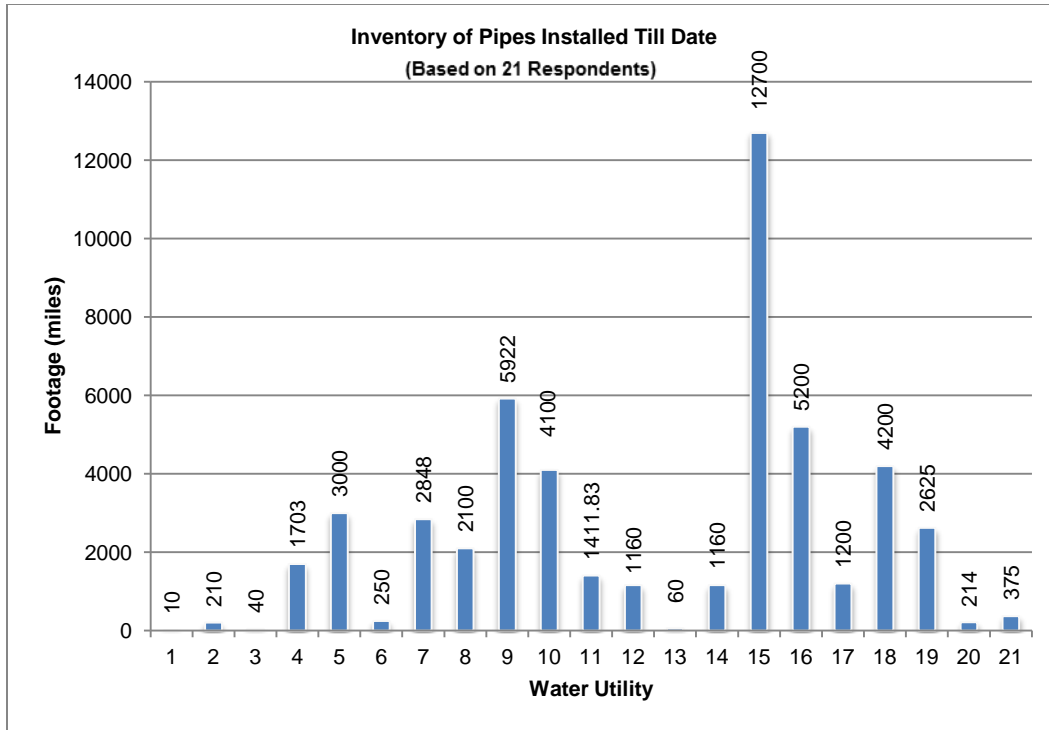


Figure 4.3 Pipe Inventory for 2 in. – 16 in.

The total length of pipe material<sup>§</sup> installed in the 21 utilities is represented in Figure 4.3. The bar graph illustrates that City 15 has the 12,700 miles of water pipe network laid, and City 1 has the least distance in miles of water pipe network with 10 miles.

<sup>§</sup> Pipe Material refers to Cast Iron, Ductile Iron, Polyvinyl Chloride, Asbestos Cement, Concrete Pressure Pipe and Steel.

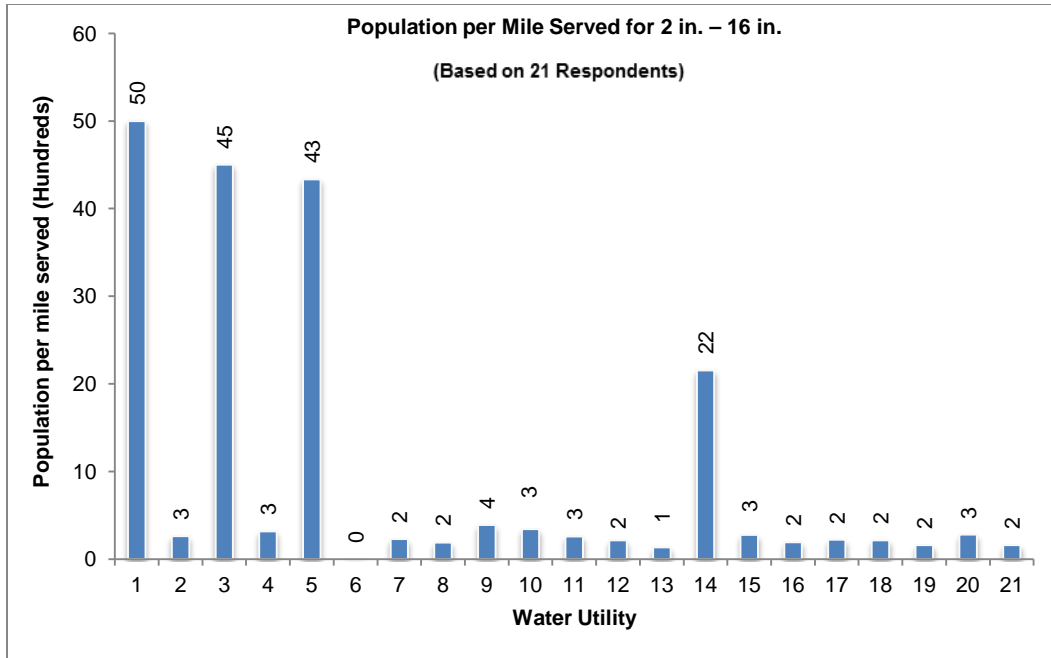


Figure 4.4 Population per Mile Served in the Utilities

Figure 4.4 represents the population per mile served in the utilities for surveyed pipe material. For example City 1 serves 5,000 persons per mile, and City 15 serves 280 persons per mile.

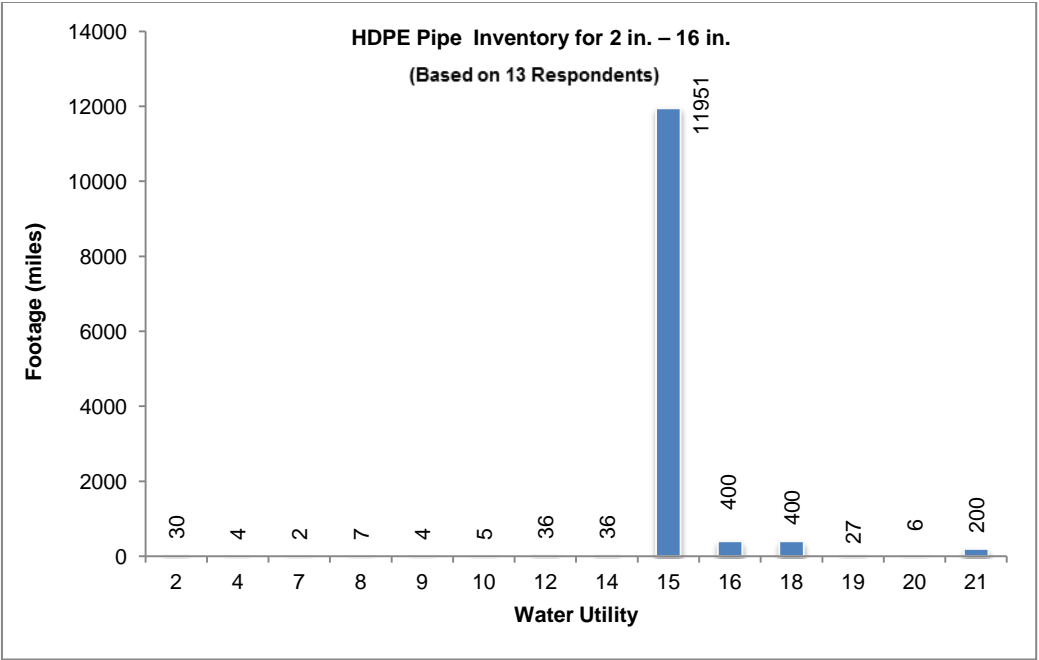


Figure 4.5 HDPE Pipe Inventory for 2 in. – 16 in.

Figure 4.5 is similar to Figure 4.3 illustrating the length of HDPE pipes installed. All the cities have less than 50 miles installed and cities 16, 18, and 21 have 400, 300, and 200 miles installed respectively. City 15 has the largest network of HDPE water pipes in the survey utility system with a total of 11,950 miles.

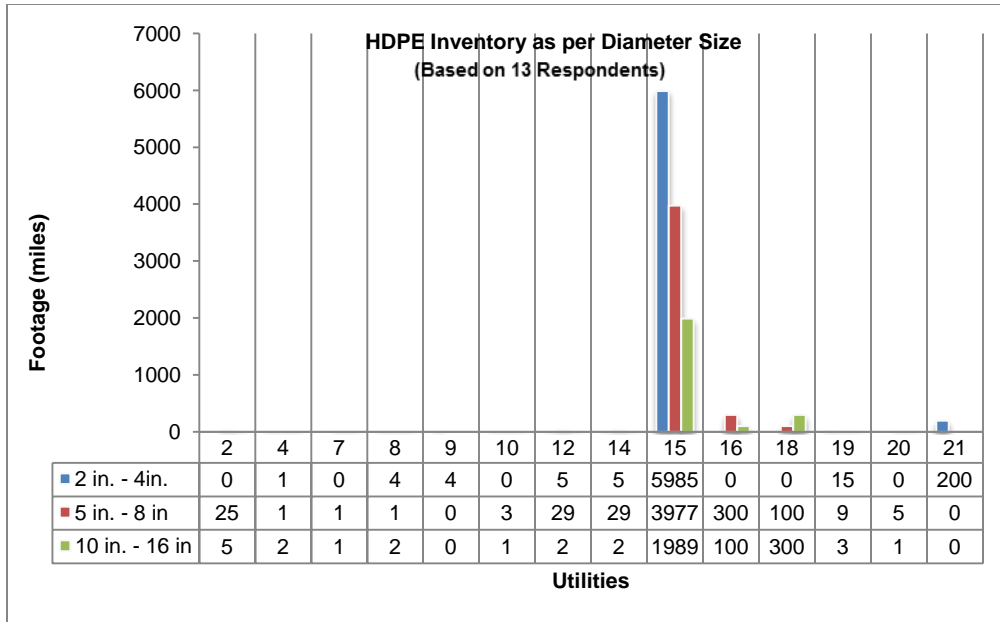


Figure 4.6 Inventory of HDPE Pipe Based on Diameter Sizes

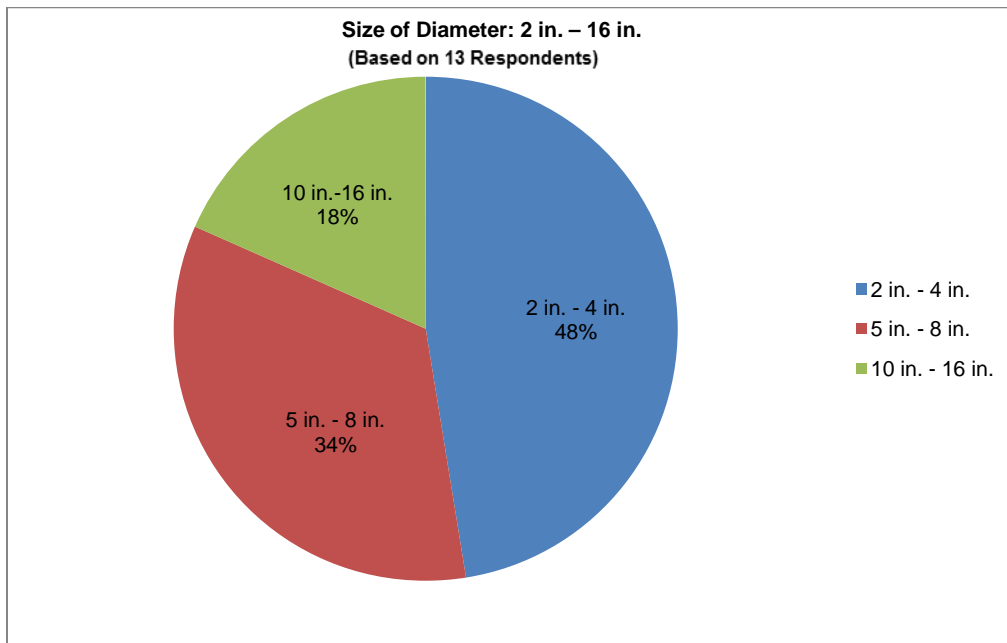


Figure 4.7 Distribution of HDPE Pipes Based on Diameter Sizes

Figure 4.6 is the HDPE pipe breakdown for individual utilities based on diameter sizes, and Figure 4.7 is the percentage breakdown of HDPE pipe based on the size of diameter for all utilities combined.

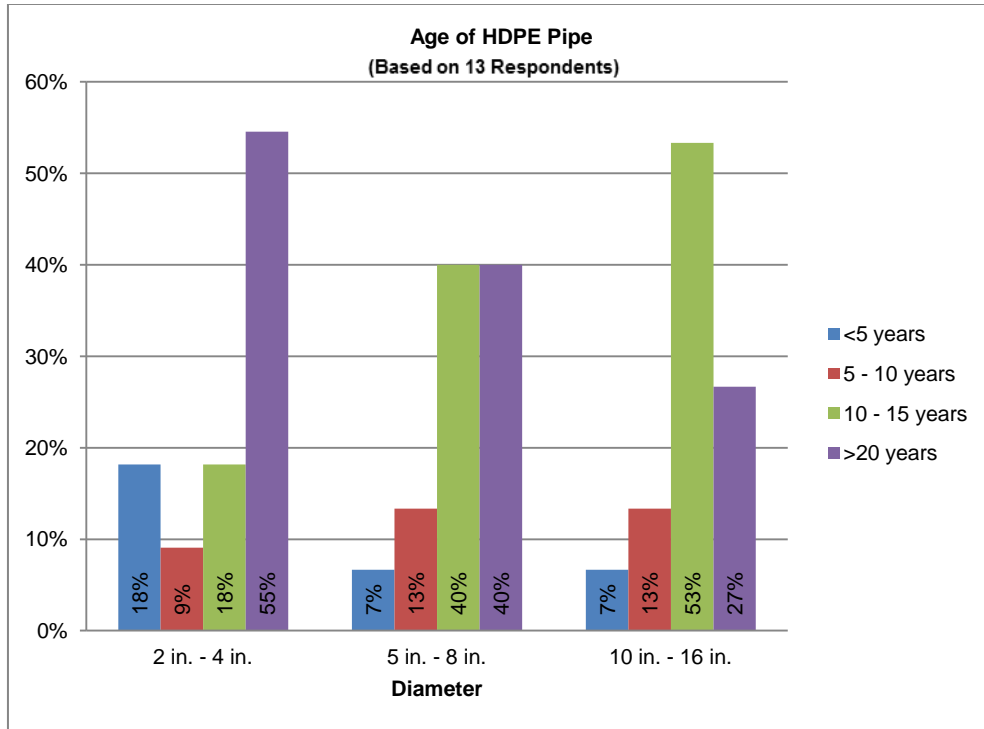


Figure 4.8 Percentage Age break-up of HDPE Pipe

Figure 4.8 illustrates percentage age breakdown of the HDPE pipe based on diameter range for the respondent utilities. For 2 in. – 4 in. diameter pipes, 55% are over 20 years old, while 5 in. – 8 in. pipe diameter pipes are 10-15 years old, and 5 in.-8 in. pipes are over 20 years old. Each age group shares 40% of the inventory. For 10 in.–16 in. diameter pipes, 53% of that inventory are 10–15 years old.

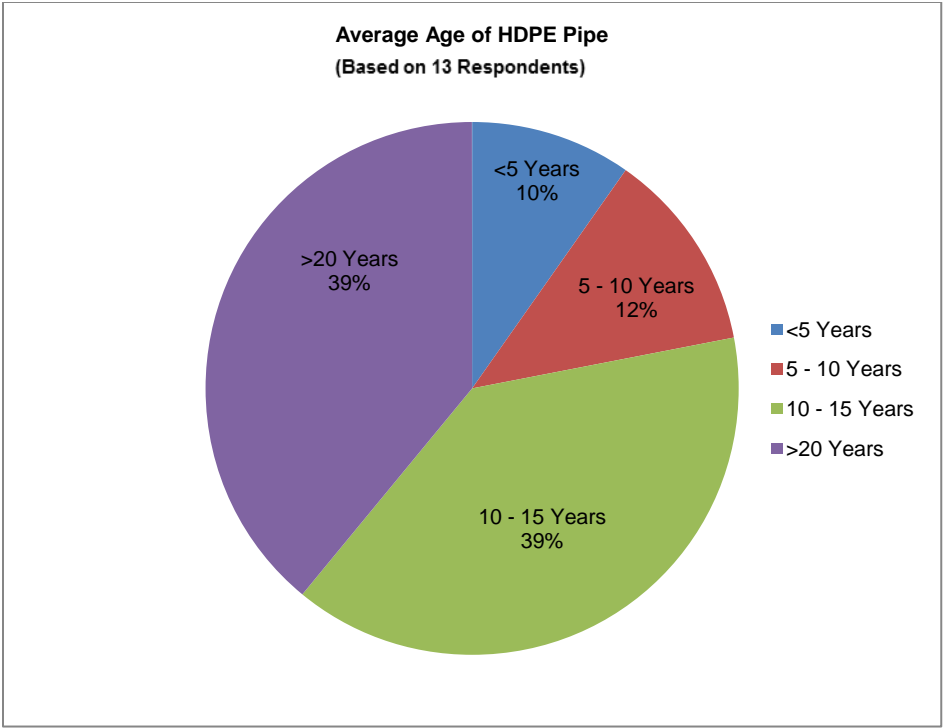


Figure 4.9 Average Age of HDPE Pipe

Figure 4.9 is the breakdown of the average age of HDPE pipe in the utilities, the age of pipe greater 20 years share 39% in the pipe inventory and pipe age between 10–15 years share 39% in the pipe inventory. The remaining 10% and 12% of the pipe inventory age is shared by pipes less than 5 years and pipe between 5–10 years.

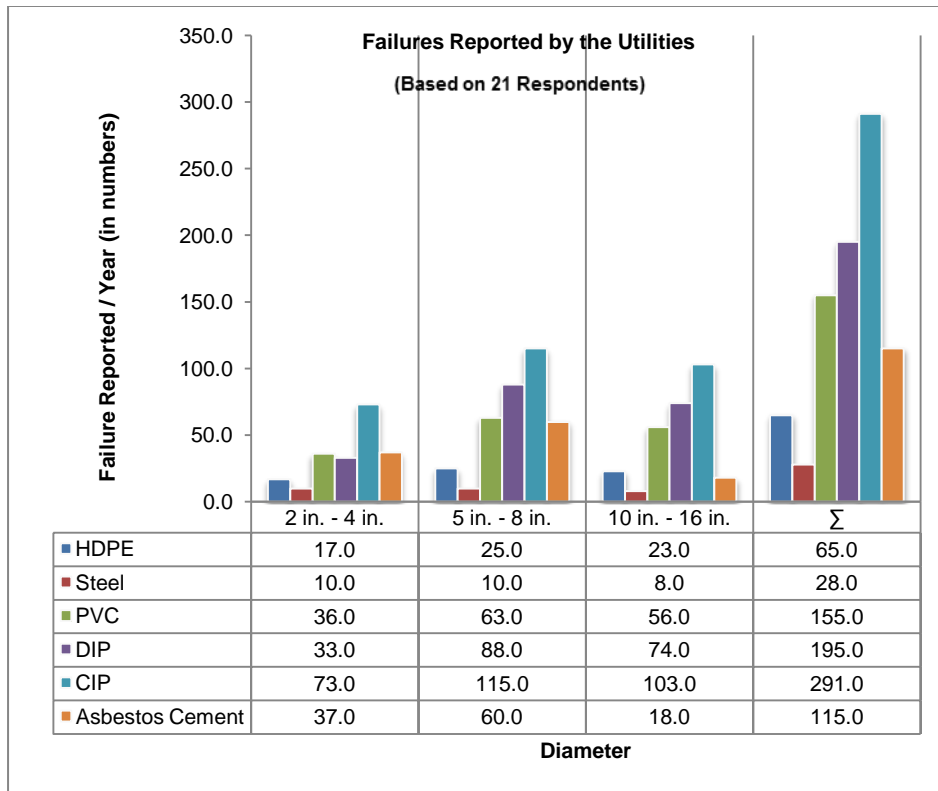


Figure 4.10 Failures of Different Pipe Material

Figure 4.10 represents the failures per year for different pipe material from the survey responses. These failure rates are, irrespective of the miles installed and total responses counts for each material.

From the Figure 4.10, steel has the least cumulative failures per year with 28 and Cast Iron pipe has highest cumulative failures per year with 291 irrespective of diameter. Cumulative failure of HDPE pipes per year for the surveyed utilities is 65.



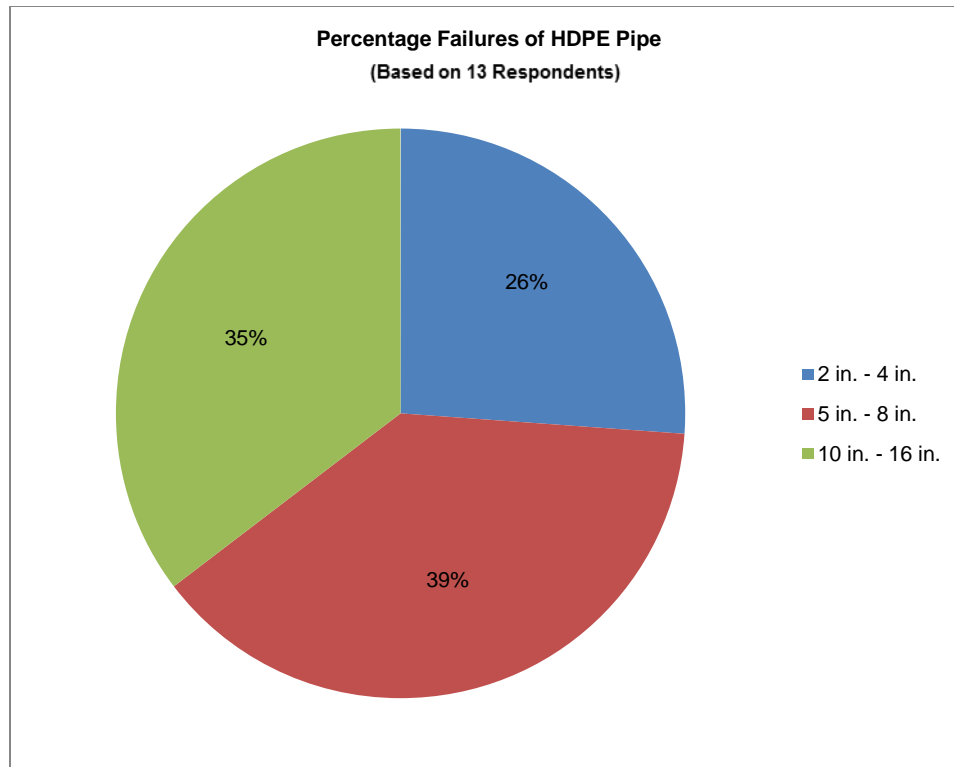


Figure 4.11 Percentage Failures of HDPE Pipe

The percentage failure for different HDPE pipe diameter sizes is illustrated in Figure 4.11. The failure rate for pipe size diameters 2 in.–4 in. is 26% with 39% of HDPE pipe failure occurring in pipes with diameters of 10 in.–16 in. Finally, 35% of pipe failures shown in the Figure 4.11 occurred for HDPE pipes with a diameter of 10 in.–16 in for the survey respondents.

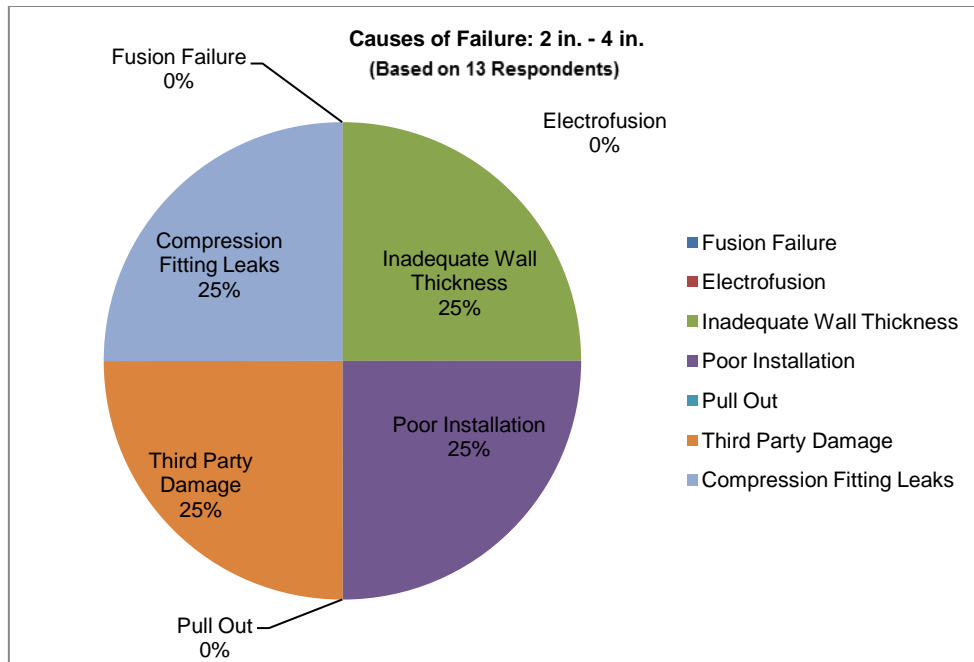


Figure 4.12 Causes of Failures for Diameter Range 2 in.–4 in.

Figure 4.12 is the pie chart with the cause of failure percentages for diameters ranging from 2 in.–4 in. Poor installation, third party damage, compression fitting leaks and inadequate wall thickness all share equally in the failure causation summary with 25% each. The rest of the possible causes for failure had not occurred in the surveyed utilities. For pipes with 4 in. diameters and below, the segments are joined using fittings such as tees and couplings; hence, electrofusion and butt fusion are not reported.

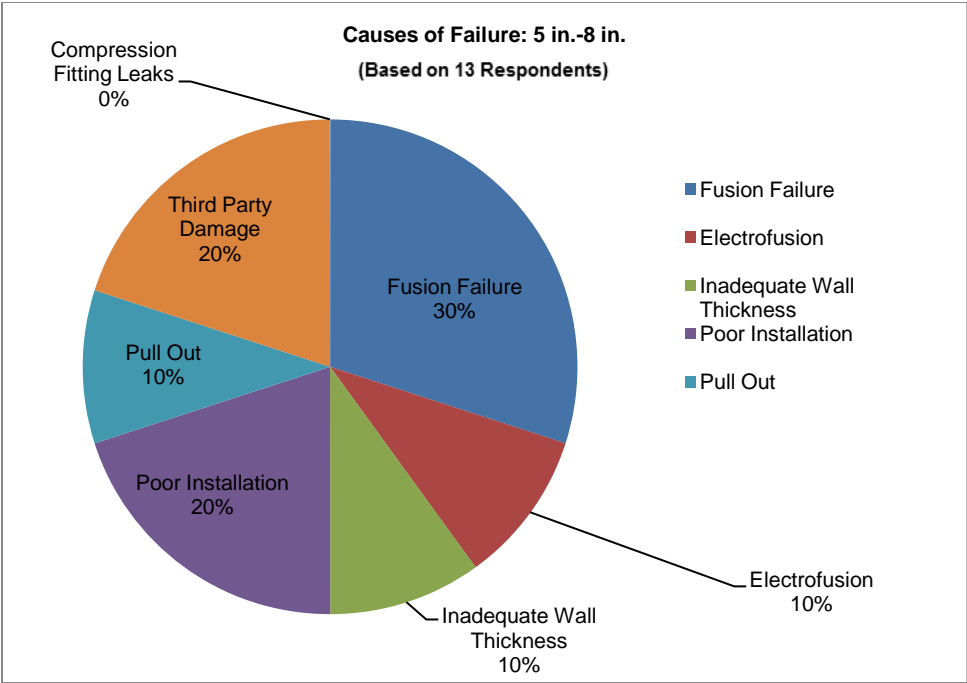


Figure 4.13 Causes of Failures for Diameter Range 5 in.–8 in.

Figure 4.13 is the graphical representation of failure causes occurring in utilities for diameters ranging 5 in.–8 in. Fusion failure accounted for 30% of the failure. Poor installation and third party damage shared 20% each. Electrofusion, inadequate wall thickness and pull out failure all share 10%. There were no compression fitting leaks reported for this diameter range.

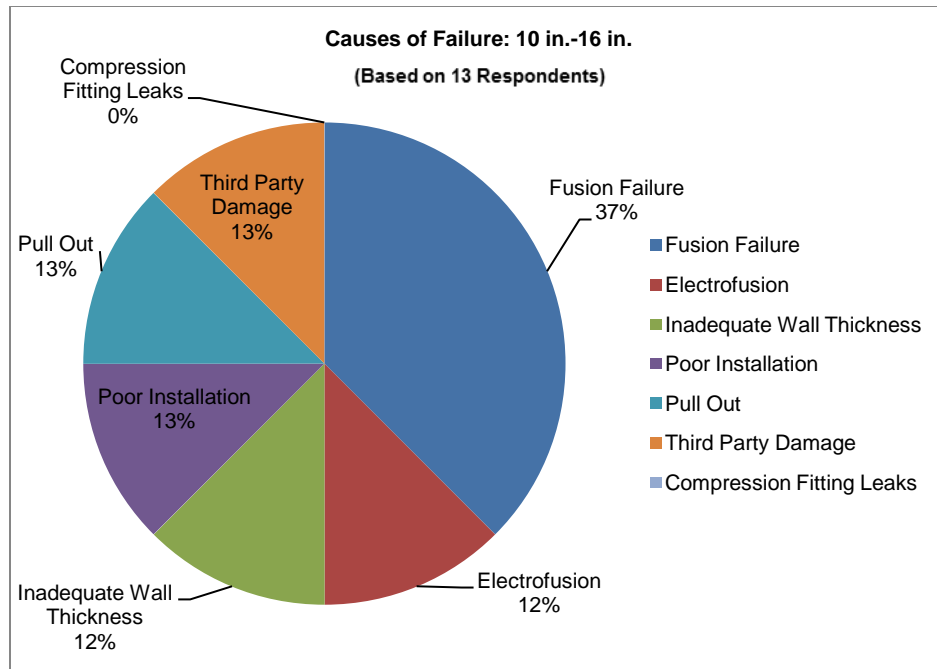


Figure 4.14 Causes of Failure for Diameter Range 10 in.–16 in.

Figure 4.14 is the graphical representation of causes of failure occurring in utilities for pipe diameters ranging from 10 in.–16 in. Fusion failure accounts for 37% of the failure. Poor installation, third party damage and pull out share 13% each and inadequate wall thickness and electrofusion failure all share 12% of the responsibility for failure. There were no compression fitting leaks reported for this diameter range.

The total number of failures that occurred in HDPE water pipes after being in-service for the different diameter ranges is summarized and shown in Table 4.1. The table is to be read accordingly. For example, from the 13 utility responses, 11 utilities confirmed their inventory of 2 in.–4 in. diameter HDPE water pipes, of eleven 11 respondents, nine 9 reported 0 or no failures occurred in HDPE pipes for size 2 in.-4 in. for the current year. The remaining two respondents had 4 failures and greater than 12 failures reported (15 reported) for the current year.

Table 4.1 Summary of Failures Occurrences per Year

Diameter (in.)	Occurrence of Failure (Nos.) / Year									Total Respondents
	0	1	2	4	5	6	8	10	>12	
2 in.–4 in.	9	0	0	1	0	0	0	0	1	11
5 in.–6 in.	8	1	0	0	0	1	1	1	0	12
10 in–16 in.	7	2	1	1	1	0	0	1	0	13

### 4.3 Discussion of Survey Responses – 24 in. and Larger

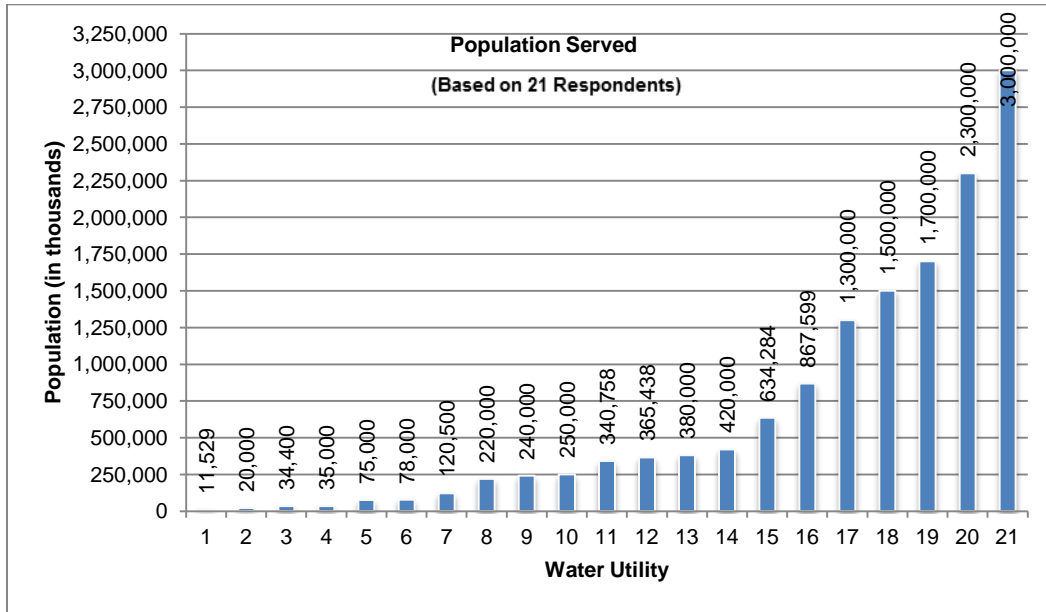


Figure 4.15 Population Served by All Pipe Material

Figure 4.15 is the graphical representation of the population served by the surveyed water utility respondents. City 21 serves a maximum population of close to 3 million, and City 1 utility serves a population of approximately 12,000.

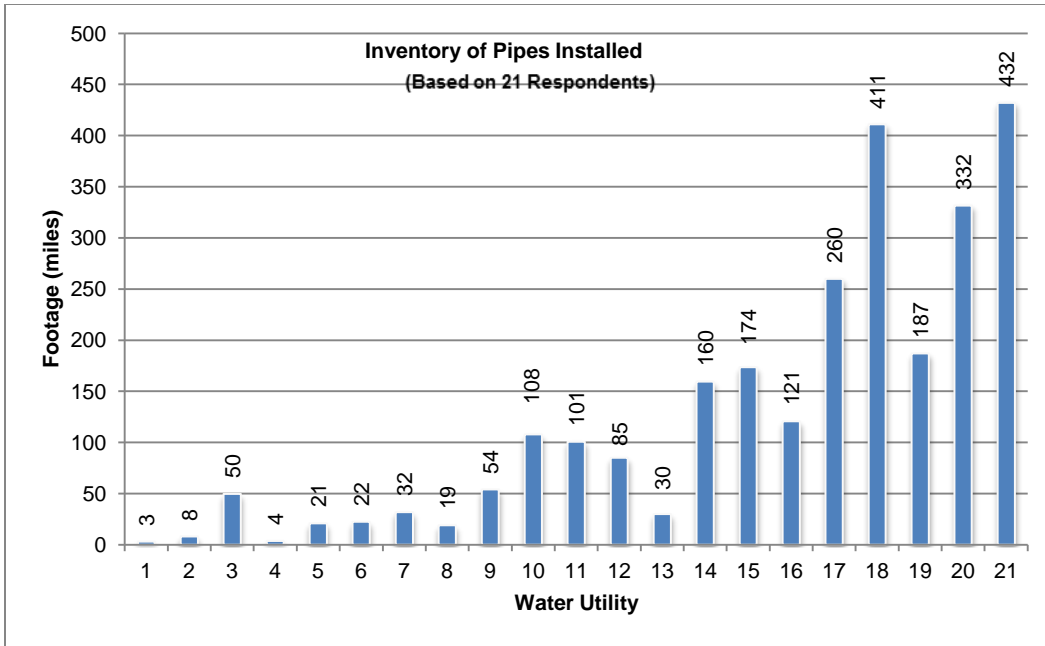


Figure 4.16 Pipe Inventory for 24 in. and Larger

The bar graph in Figure 4.16 is the total distance in miles of pipes installed in surveyed utilities. City 1 utility has the least miles of 24 in. and larger diameter water pipes in service, whereas City 21 has 432 miles of 24 in. and larger diameter water pipes in service.

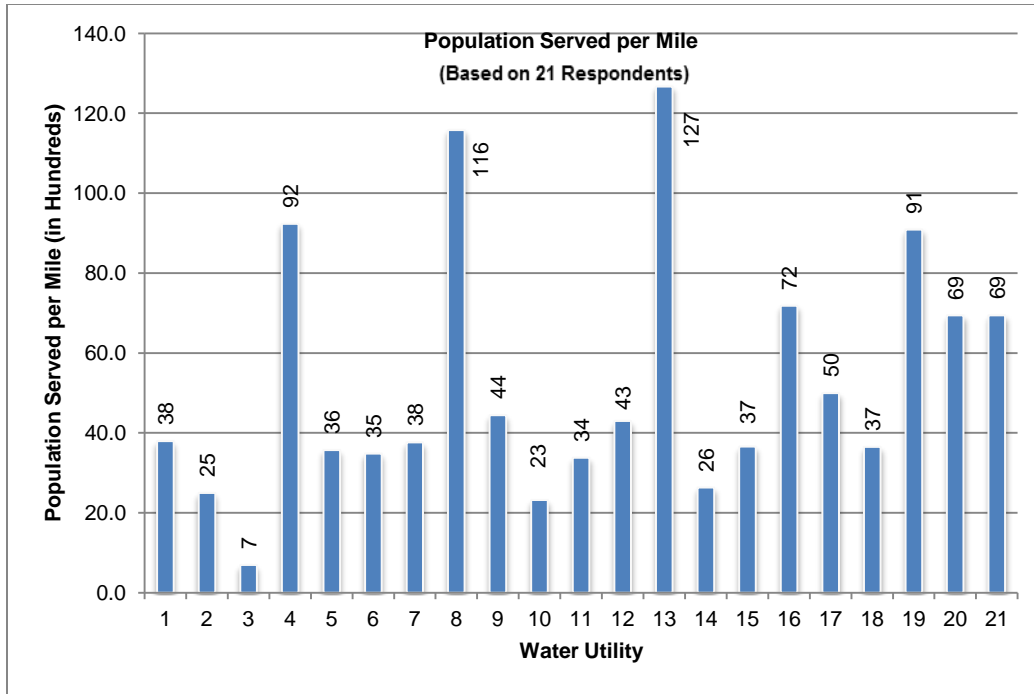


Figure 4.17 Population Served for 24 in. and Larger

Figure 4.15 and Figure 4.16 clearly show that City 13 had installed 24 in. and larger pipes (30 miles) with the population served (380,000) City 21 had the highest number of population served (3,000,000) and the highest number of miles installed (432 miles). When the graph was plotted against the population served per mile, from Figure 4.17 City 21 served the lowest number of people (approximately 6,940 people per mile) compared to City 13 (approximately 12,670 people per mile). From this graph it can be inferred that cities with highest number of miles for installed pipe need not serve a larger population.



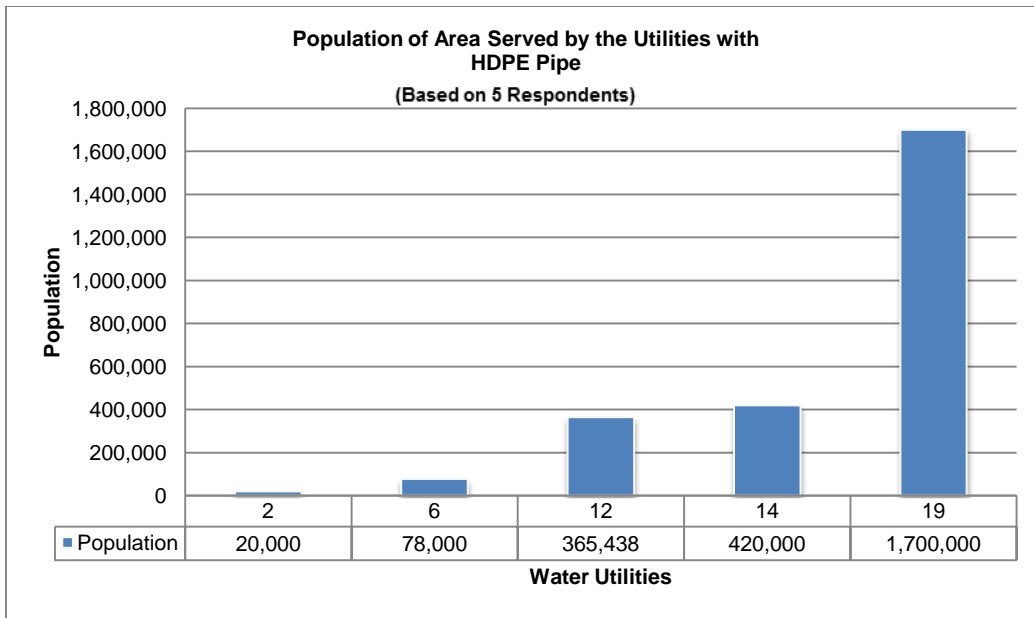


Figure 4.18 Population of Area Served by Utilities with HDPE Pipe in System

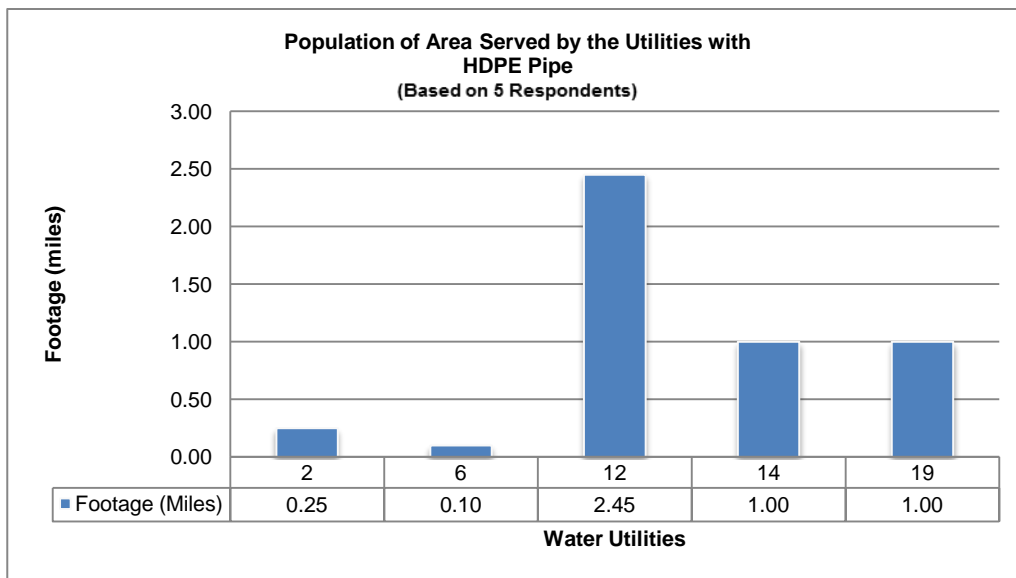


Figure 4.19 Mileage of HDPE Pipe Distributed in the Water Utilities

Figure 4.18 and Figure 4.19 represent the population served and mileage of HDPE pipe distributed in the utility system. For cities with HDPE pipes, they had a cumulative population of 2,583,438 served by 462 miles of water network, out of which

HDPE pipe makes up a cumulative of 1% usage in these water utilities for pipes with diameter 24 in. and larger.

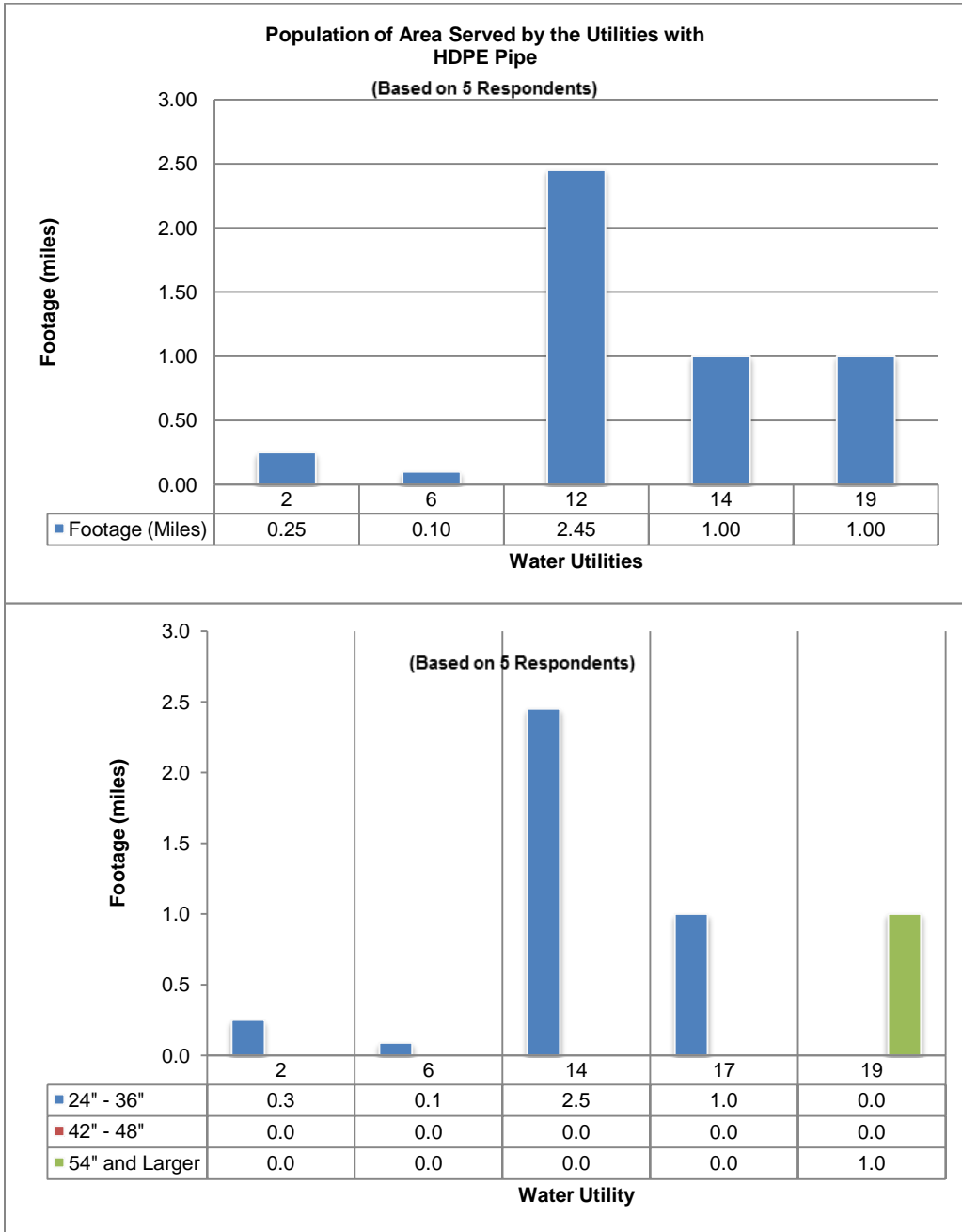


Figure 4.20 HDPE Mileage for 24 in. and Larger

Figure 4.20 represent the distribution of HDPE pipe from the responses obtained from the utilities for different ranges of diameters. For pipe diameters of 24 in. and 36 in., City 2 and City 6 have 0.3 miles and 0.1 miles of HDPE water pipes respectively. City 17 has 1 mile, and City 17 has 2.5 miles of HDPE water pipes installed for diameter size 24 in. –36 in. It can be observed from the graph that none of the utilities had installed HDPE water pipes with diameters of 42 in.–48 in. City 19 has 1 mile of 54 in. diameter range and larger.

Figure 4.20 summarizes HDPE water pipes installed (in miles) for the different ranges of diameter in the surveyed utilities. From the 5 utility responses, 4 utilities had a cumulative of 3.8 miles for HDPE pipe diameter range of 24 in.–36 in. and only 1 mile installed for 54 in., with zero miles for HDPE pipes with a diameter range of 42 in.–48 in.

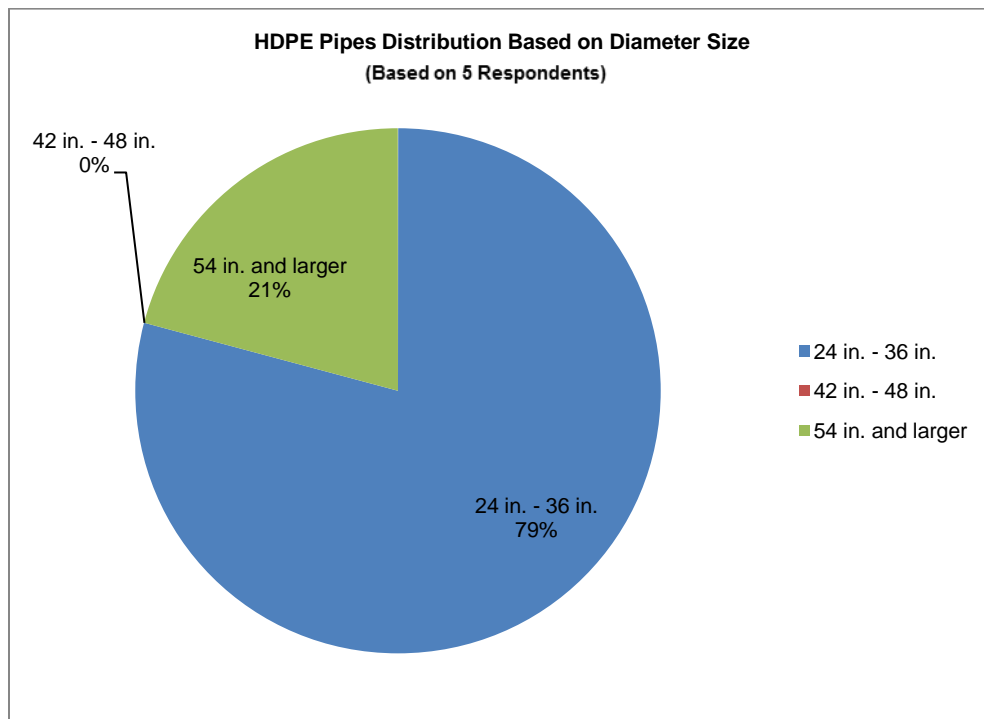


Figure 4.21 Relationship of Diameter Range and Miles Installed

Another graphical representation of the diameter of HDPE water pipes and diameter distribution is shown in

Figure 4.21. From the pie chart, 21% of the total HDPE water pipes were installed with 54 in. and larger diameters and 79% of the HDPE pipes were installed with 24 in.–36 in. diameters.

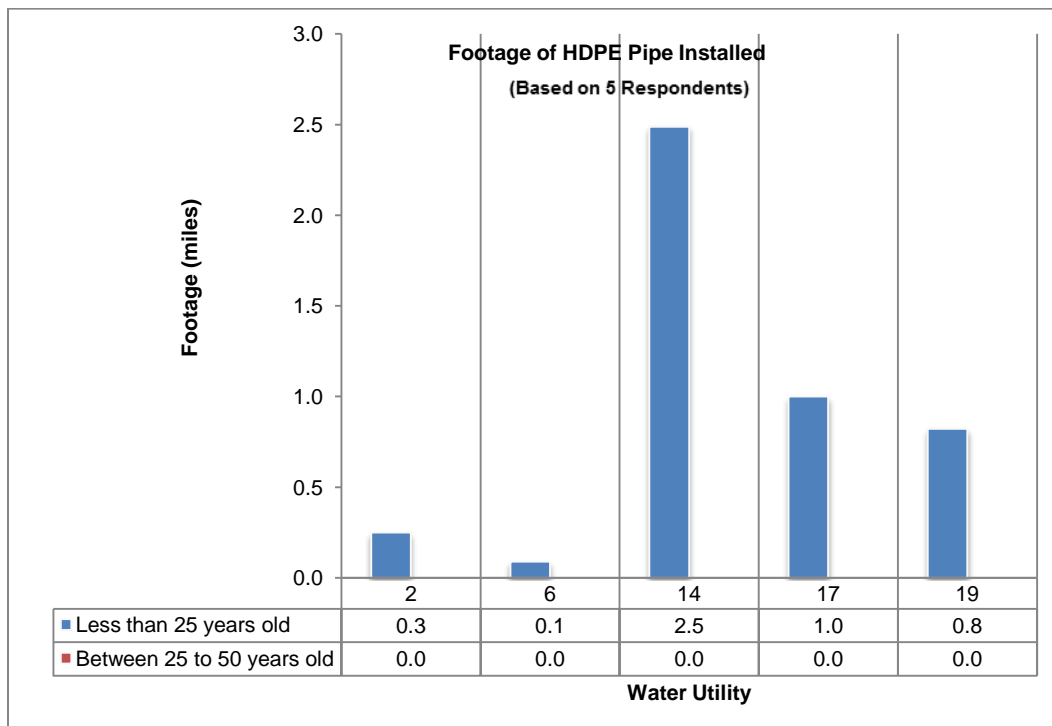


Figure 4.22 Relationship between Inventory and Age

The ages of installation for HDPE water pipes are shown in Figure 4.22. From the graph, the age of existing HDPE pipes in the system are less than 25 years old. There were no HDPE water pipes installed that were 25 years old or older.

Table 4.2 is the summary of the average age of HDPE pipe installed in the surveyed utilities. The table demonstrates that all 5 utilities reported the age of HDPE pipe in their systems as less than 25 years old.

Table 4.2 Summary of Average Age of HDPE Water Pipe in the Utility

Pipe Material	Inventory (miles)					Total Inventory (miles)
	Less Than 25 Years Old	Between 25 to 50 Years Old	Between 50 to 75 Years Old	More Than 75 Years Old	Unknown Age	
HDPE	4.8	—	—	—	—	4.8

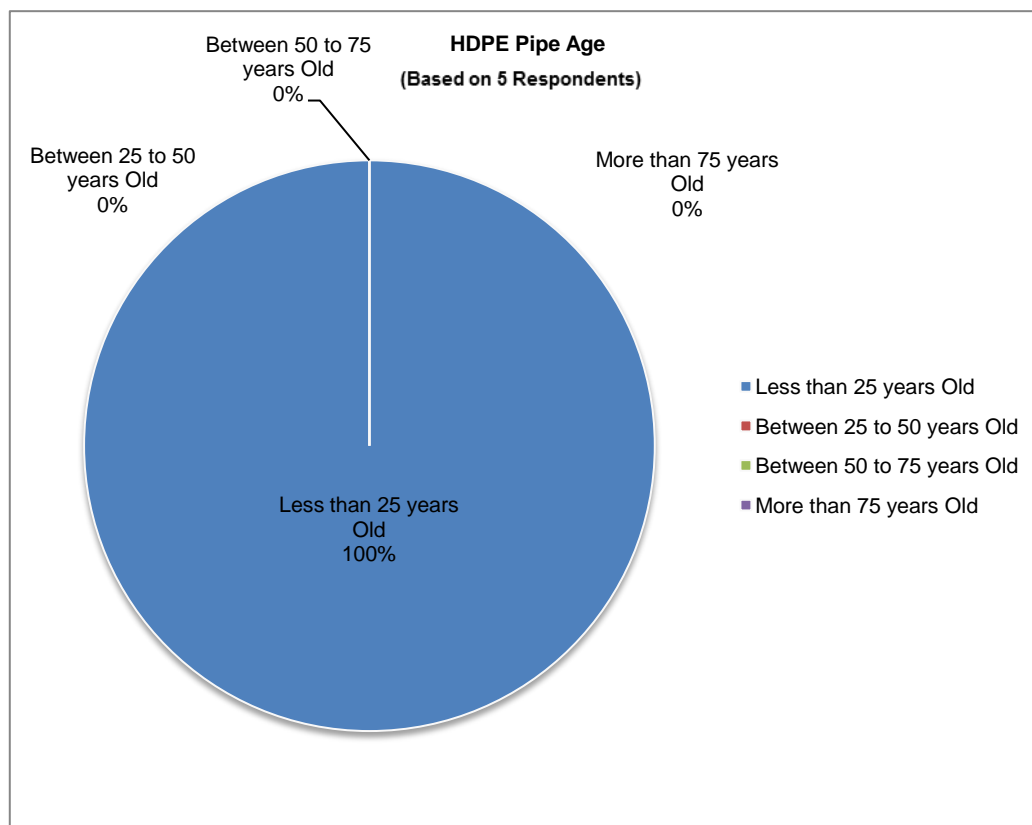


Figure 4.23 Relationships between Diameter Range and Miles of HDPE Pipes

Figure 4.23 shows 100% of HDPE pipes installed in the utility system as less than 25 years old.

#### 4.3.1 Considerations for Usage of HDPE Pipe

Table 4.3 Reasons for Considerations of HDPE Pipe Usage in Utilities

Respondents	Considerations
1	Pre-mature failure observed for 2 in.-4 in.
2	Hard to handle and install for 24 in. and larger pipe size
3	Cost
4	Large diameter don't meet pressure ratings
5	Being evaluated
6	Thermal co-efficient
7	Difficult to repair or tap
8	Pressure and depth

Table 4.3 summarizes survey responses on considerations for usage of HDPE water pipes. Most responses cited “difficult to handle” as reasons for avoiding 24 in. and larger size, and also stated that the larger pipes did not meet the pressure requirements needed for large diameter water transmission. Another respondent mentioned HDPE pipes were expensive and difficult to tap or pointed to their thermal coefficient. One utility responded the use of HDPE pipe is being evaluated.

#### 4.4 Failure Rates

In this section the failure rates of all the pipe materials from all the survey respondents from both 2 in.–16 in. diameter size and 24 in. and larger diameter size are discussed.

The failure rate is calculated using the following formula:

---

Equation 4.1: Average Failure Rate per Length

Note: The total footage in miles is the miles of the surveyed water utilities with HDPE pipe in their system.

##### *4.4.1 Failure Rates of HDPE water pipe for Diameter Size: 2 in. – 16 in*

From the surveyed utility responses the annual average failure per length is calculated and summarized in Table 4.4 As mentioned earlier in this Chapter, 21 cities responded to the survey and only 13 cities accounted for HDPE water pipes in their system. In Table 4.4 the average failures are calculated from Equation 4.1; for example the average annual HDPE pipe failure per 100 mile for diameter 2 in.–4 in. is calculated by simple division and multiplication  $(17 \div 6,218) \times 100 = 0.3$ .

Similar calculations are performed and average annual failure rate per 100 miles for diameter 2 in.–4 in., 5 in.–8 in. and 10 in.–16 in. are 0.3, 0.6 and 1.0, respectively. A total average annual failure rate of 0.5 per 100 miles was calculated for the responding utilities with HDPE water pipes in their system with a diameter range of 2 in.–16 in.

According to Folkman (2012), this method of calculation could eliminate biases towards large or small utilities. The pipe failures reported for individual utilities show that different utilities experience different failure rates for the same pipe material. This is due

to the influence of parameters which include pipe age, soil types (corrosive or noncorrosive), different installation practices, and climate and so on.

Table 4.4 Summary of Failure of HDPE Pipe per Year per 100 Miles

Diameter	Failure per Year	Total Miles	Average Failure per Year per 100 Miles	Average Failure per Year per 1000 Miles
2 in.–4 in.	17	6,218	0.3	3.0
5 in.–8 in.	25	4,481	0.6	6.0
10 in.– 6 in.	23	2,408	1.0	10.0
<b>Total</b>	65	13,107	0.5	5.0

#### 4.4.2 Failure Rates of HDPE Water Pipe for Diameter Size: 24 in. and Larger

The average failure rate of HDPE water pipe for diameter size 24 in. and larger can be calculated similarly using Equation 4.1. As mentioned in the earlier, only 5 responses accounted for HDPE water pipes and none of these utilities reported any failure of HDPE water pipe for diameters ranging 24 in. and larger.

#### 4.5 Discussions of Results.

In this section, results are discussed as per the above analysis and from the analysis conducted using the data collected from survey.

A total of 200 small diameter surveys for HDPE pipe with a diameter of 2 in.–16 in. and a total of 332 large diameter surveys for HDPE pipe diameters that are 24 in. and larger were sent to different utilities across the United States. The number of utilities that answered questions concerning HDPE pipes was, 13 regarding small diameter HDPE pipes and 5 regarding large diameter HDPE pipes. From the surveys, the population



served and total miles installed for utilities varied from 100 people to a population of 13 million with a variation in mileage from 10 to 12,700 miles for 2 in.–16 in. diameter pipe. Responses concerning large diameter pipe of 24 inches and large indicated a variation of population served from 12,000 people to 3 million with a variation in mileage from 3 miles to 432 miles. The total miles covering HDPE pipes were 131,097 miles for 2 in.–6 in. diameter and 4.8 miles for 24 in. and larger diameter.

#### *4.5.1 Discussions of results – 2 in.–16 in.*

For small diameter, there were 13 utilities reported a total of 65 annual failures and also the causes of failures. The percentage of occurrence are calculated and discussed as follows for diameter range of 2 in.–16 in. The average failure causes reported due to poor installation, inadequate wall thickness and third party damage were 19%, 15%, and 19% respectively. The compression fitting leaks are reported only for the diameter range or 2 in.–4 in. pipe size and those leaks constitute 25% for the pipe diameter range of 2 in.–4 in. only. It contributes to an 8% cause of occurrence when overall diameter ranges of 2 in.–6 in. is considered.

Similarly pull-out and fusion failures were not reported for pipe size 2 in.–4 in. because fusion joints cannot be achieved for 2 in.–4 in. due to the insufficient thickness of pipe wall. The average failure caused due to pull-out is 11.5% for the diameter range 2 in.–16 in. is 8% .The average fusion failure for pipe diameter range 2 in.-16 in. is 23 % and electrofusion is 8%. The graphical presentation of average failure causes reported for 2 in.–16 in. is shown in Figure 4.24.

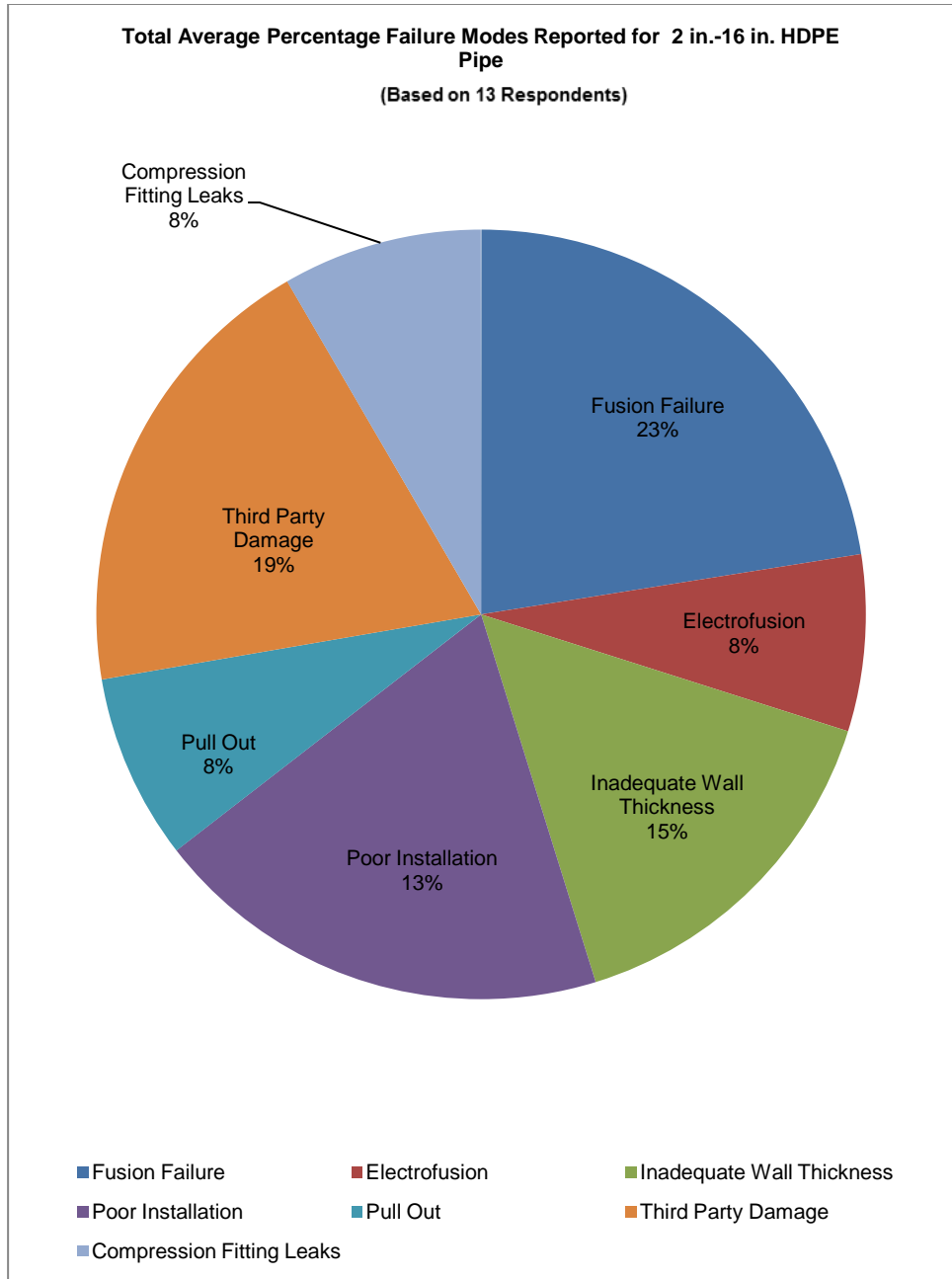


Figure 4.24 Average Percentage Failure Causes Reported

The average age of the HDPE pipe from the survey results are shown in the Figure 4.25 with 39% of the average age of HDPE pipes for respondent utilities shown as

10–15 years and greater than 20 years. About 10% of the 2 in.–16 in., HDPE pipe was less than 5 years, and 12% was between 5 and 10 years old.

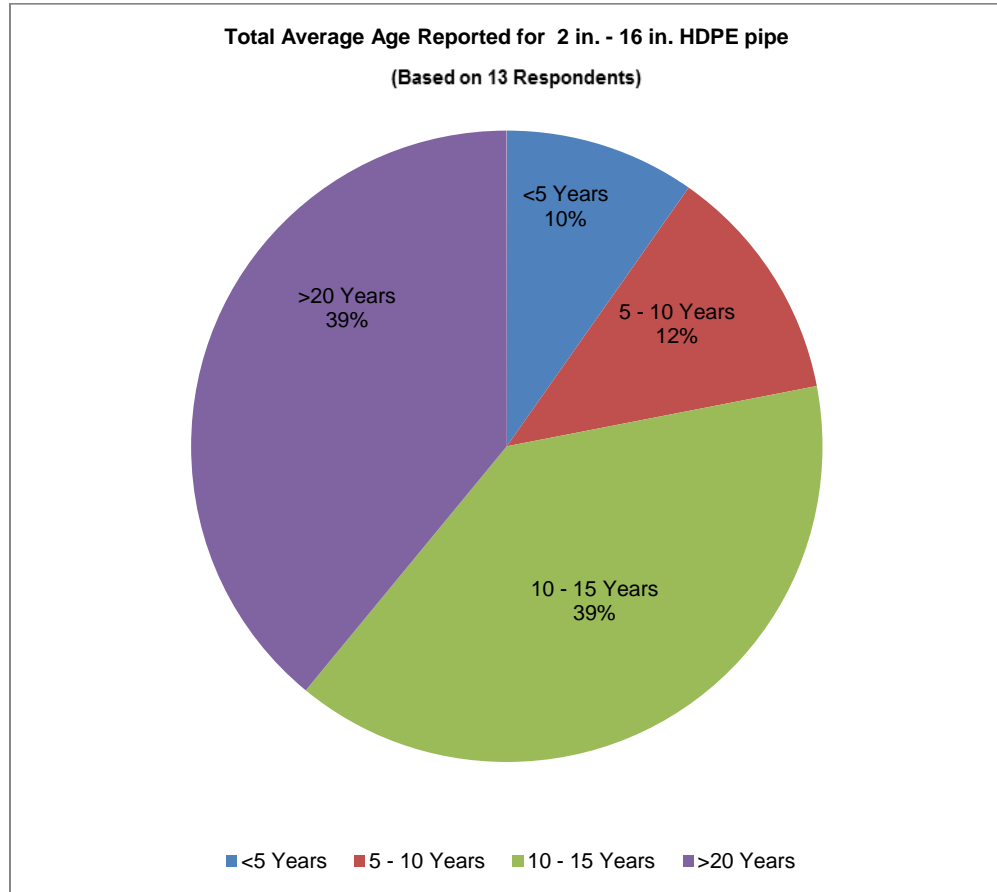


Figure 4.25 Average Age Reported for 2 in.-16 in. HDPE Pipe

There were total 65 failures reported for HDPE pipe diameter 2 in.–16 in., 17 failures reported for 2 in.–4 in. diameter, 25 failures reported for 5 in.–8 in. diameter, and 23 failures reported for 10 in.–16 in. diameter. From Figure 4.25 the pie chart illustrates the percentage failure for diameter 2 in.–4 in., 5 in.–8 in. and 10 in.–16 in. were 26%, 39% and 35% respectively.

Clearly from the survey responses, most of the HDPE pipe installed did not show any failures within one year of installation (See Table 4.1). For HDPE pipe diameters of

2 in.–4 in., utility reported 4 failures and greater than 15 failures occurred in HDPE pipe for current year. For diameter range 5 in.–8 in. utilities reported one, six, eight, and ten failure incidents occurred for the current year. For pipe diameter 10 in.–6 in., the utilities reported two, four, five and ten failure incidents for the current year.

Pipe diameters of 2 in. – 4 in. have an annual failure rate of 0.3 per 100 miles per year; 5 in.-8 in. diameter pipes have a failure rate of 0.6 per 100 miles per year and 10 in.–16 in. diameter pipes have a failure rate of 1.0 per 100 miles per year. The average failure rate of the HDPE pipe for diameter range 2 in.–16 in. is 0.5 per 100 miles per year (See Table 4.4). This extremely low failure rate represents a significant advantage for those using HDPE 2 in.-16 in., HDPE pipe.

#### *4.5.2 Discussions of results – 24 in. and larger diameter*

As mentioned earlier, the total responses received for the HDPE pipe with a diameter of 24 in. and larger were 5. The 5 responses received were not comprehensive in that most of the questions were either skipped or were not answered. The discussion of results for the 24 in. and larger diameter is based on an analysis calculated from the survey questions answered.

The total inventory of miles installed was 4.8 miles, with 3.8 miles installed for 24 in.–36 in. and 1 mile installed for pipes that were 54in. and larger. 79% of the inventory was installed with 24 in.–36 in. diameter HDPE pipe and 21% of the inventory installed constituted 54 in. and larger diameter pipe. Most of the pipes installed in the inventory were less than 25 years of old. There were no failures reported from the surveyed utilities and hence the failure rate of HDPE pipe for 24 in. and large could not be calculated. Since there were no failures reported, it is difficult to conclude that zero failure is representative of HDPE pipe with a diameter of 24 in. and larger.

There were 16 respondents reported consideration usage of HDPE pipe in their utilities due to its limitations. The number of respondents who gave substantial reasons for restricting considering the use of HDPE pipe is shown in Table 4.4.

According to Davis et al. (2007), the average annual failure rate of PE in Australia collected from 5 utilities regardless of the diameter size is 11.5 failures per 100 miles and the annual failure rate of PE in U.K. collected from 17 utilities is 5.1 failures per 100 miles installed (Table 2.5). The reason for the difference in failure numbers could be:

- U.K. utilities have maintained failure logs and the failure results obtained are more accurate.
- Australian utilities have pipe length installed that is relatively small when compared to U.K. utilities.
- Failure rate reported are more for Australian utilities when compared with U.K. utilities. It is greater due to the influencing parameters such as climate, soil conditions, length of HDPE pipe installed and installation practices followed.

According to Davis et al. (2007), 55 U.S. and Canadian utilities participated in the survey and 33 responses accounted for HDPE although the majority of the responses were *unreliable*. The responding utilities stated that they had used PE which was less than 2 in. diameter size (service connections), and some utilities replied the discontinuation of HDPE usage due to premature failure.

#### 4.5.3 Comparisons

The primary objective of current research was to make comparisons of HDPE performance results with PVC and DI pipe. This was achieved by comparing the research results from previous studies on failure of PVC and DI pipes. Figure 4.26 is the graphical representation of annual failure comparisons per 100 miles from different studies.

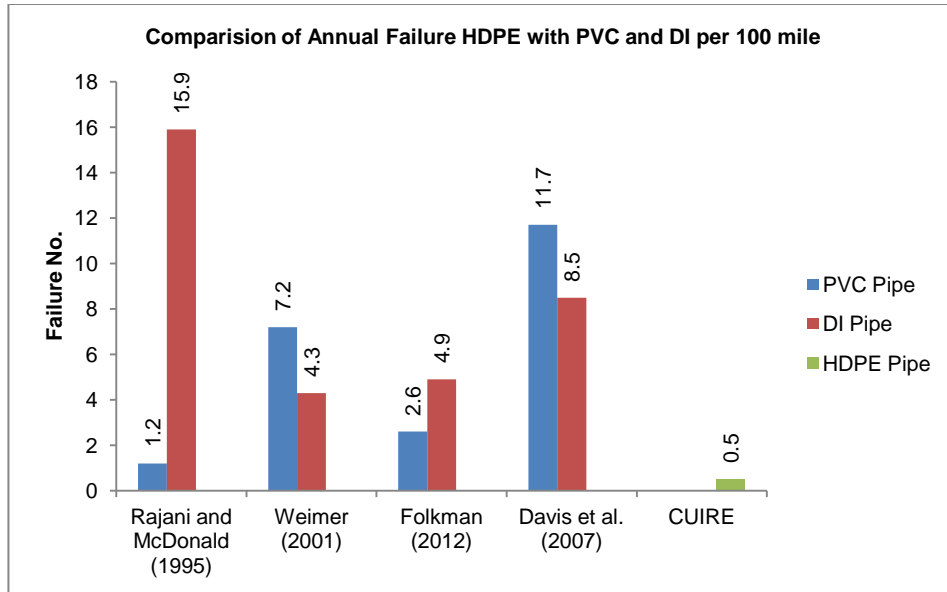


Figure 4.26 Comparisons of Annual Failure of HDPE, PVC and DI per 100 Mile

According to Rajani and McDonald, the total length of PVC and DI installed as reported by 21 utilities are 1,136 miles and 2,648 miles respectively, and the annual failure rate for PVC and DI are 1.2/100 miles and 15.9/100 miles.

According to Weimer (2001), the total length installed as reported by German utilities for PVC and DI was 2,545 miles and 8,724 miles respectively. And the annual failure rate for PVC and DI was 7.2/100 miles and 4.3/100 miles respectively.

Folkman (2012) reported the total length installed from 188 utilities for PVC and DI as 26,840 miles and 33,239 miles respectively, and the annual failure rate for PVC and DI are 2.6/100 miles and 4.9/100 miles respectively.

According to Davis et al. (2007), the annual failure rates for PVC and DI from 17 water utilities are 11.7/100 miles and 8.5/100 miles respectively. However, the length of PVC and DI were not mentioned in the report.

The current research conducted by CUIRE has an annual failure rate of 0.5/100 miles for HDPE pipe for a length of 13,107 miles from 13 utility responses. One of the

limitations could be the influence of City 15 impacting the results. City 15 has an installed length of 11,951 miles of HDPE pipe, which constitutes 91% of the overall HDPE pipe length. Also, City 15 had the highest failure reported, 44 numbers annually. The annual failure rate per 100 miles for City 15 is  $(44 \div 11,951) \times 100 = 0.4$ , and the annual failure rate per 100 miles excluding City 15 is  $(21 \div 1,157) \times 100 = 1.8$ . This calculation certainly shows an influence on City 15's rating.

The previous study conducted on PVC and DI did not include its individual length of pipes and distributed failure rates based on utilities. Since there is no information available to understand if any particular utility could have influence the overall results in previous studies conducted. However the result obtained from Rajani and McDonald, has reported the individual length of the water pipes installed in utilities, two cities including Calgary and Edmonton contributes 1,227 miles of 1,818 total miles reported for PVC pipe by 21 utilities. It can be assumed that the results could have been influenced by these two cities. As discussed earlier in the current study, City 15 has an influence on the overall results. To make an unbiased comparisons with PVC and DI pipes the influence of one city are not considered for the conclusion purposes.

#### 4.4 Chapter Summary

In this chapter responses to two surveys were analyzed and results discussed. The results were compared with the past surveys conducted on the field performance of HDPE water pipe.

## Chapter 5

### Conclusions, Limitations and Recommendations for Future Research

In this chapter the conclusions are discussed based on the results obtained and from the literature review. The future scope for the research is also discussed in this chapter.

#### 5.1 Conclusions

The conclusions of this thesis listed below are based on 13 survey respondents for the diameter range of 2 in.-16 in. and 5 survey respondents for 24 in. and larger diameter HDPE water pipes:

- The failure modes of HDPE water pipes include cracking, joint failures, third party damage, poor installation and inspection, and failure due to oxidation.
- Based on the results of this study, the annual failure rate per 100 miles for size 2 in.–in. is 0.3, for 5 in.–8 in. is 0.6 and 10 in.–16 in. is 1.0, which is comparable to available literature.
- The average annual failure per 100 miles for 2 in.–16 in. is 0.5.
- Field performance of HDPE pipe is better than PVC and DI pipes. Since the failure rate per 100 miles is less compared to PVC and DI pipes, increase in usage of HDPE pipe can be expected in future.
- Joint failure is the most frequent causes of failure occurred when compared to other failures.
- Compression fitting failure was observed only for pipe size 2 in.–4 in. Third party damage, poor installation and inadequate wall thickness were the commonly observed failure pattern for 2 in.–16 in. diameter.



- Joint failures can be minimized by proper installation procedures and practices, proper equipment and thorough knowledge of equipment operation. Additionally, experienced workers must be involved during the job execution in field.
- Average age of the pipes for respondent utilities includes:
  - 39% of existing installed pipes are 10–15 years old
  - 39% of existing installed pipes are over 20 years old
- 76% of responding utilities expressed that the consideration over usage of HDPE pipe for 24 in. and larger diameter HDPE pipe is due to insufficient pressure rating, cost and difficulty in handling.

#### 5.2 Limitations of Research

- Incomplete surveys from most of the utilities were major limitations to this research. Most of the questions regarding soil conditions, type of water (treated or untreated) and date of installations in the survey were either skipped or not answered. Sample size was small, as 14 responses were received for small diameters and five responses for large diameters (24 in. and more).
- Date of failure and condition of soil were not reported in larger diameter surveys.
- Utility 15 had highest miles installed which could have skewed results.

#### 5.2 Recommendations for Future Research

The following are the recommendations for future research:

- The research results are based on the limited survey responses conducted across the U.S. To understand comprehensively long-term research study, targeting more utilities is recommended to validate the annual number of failures of the pipes per length installed.

- Future research can be performed on pipe failures based on parameters such as soil conditions, weather conditions, environmental conditions, operating pressure, pH of soil, soil cover, pipe bedding and embedment material used.
- The use of HDPE pipe is limited for diameter range 24 in. and larger. To understand the performance of HDPE pipe in water industry, more data needs to be collected and a database created.
- According to literature search, the designed life of HDPE pipes is 100 years and most pipes installed currently are less than 25 years old, which accounts for 20-25% of their design life. A similar study should be conducted in the future to understand the influence of age on pipe failure.

Appendix A

Survey Questionnaire 2 In.–16 In.



The University of Texas at Arlington



**Center for Underground Infrastructure Research and Education (CUIRE)**

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High Density Polyethylene (HDPE) Water Pipe Questionnaire

<b>Project Overview</b>							
<p>The Center for Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington is working on a major project regarding failure modes, causes and rates of HDPE water pipelines. The primary objective of this project is to gain an understanding of pipe material performance under different environmental, loadings and operational conditions.</p> <p>The below national survey is critical as a first step to achieve these objectives, since it will provide valuable information regarding the inventory and conditions of HDPE water pipes. To show our appreciation for your time and efforts to complete this survey, we will send you a copy of the research findings upon completion, scheduled for Summer 2012.</p> <p style="text-align: center;"><b><u>Alternatively, instead of completing the survey; you may send us a report or a database file of your water pipe inventory, conditions and failure rates</u></b></p>							
<p>If you have any questions or concerns, please feel free to contact CUIRE at 817-272-9177 or Chandan Venkatesh, CUIRE Graduate Research Student, at 817-682-4404 or <a href="mailto:chandan.venkatesh@mavs.uta.edu">chandan.venkatesh@mavs.uta.edu</a> or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or <a href="mailto:najafi@uta.edu">najafi@uta.edu</a></p>							
a) Contact Person's Name					Position:		
b) Name of the organization		City		State		Zip	
c) Address							
d) E-mail							
e) Phone:				Fax			

1. What is the population of the area served by your water pipes? \_\_\_\_\_

The above answer is accurate within:  +10%  +20%  other

2. What is the total length of your water pipelines? \_\_\_\_\_ ft. or \_\_\_\_\_ mi.

The above answer is accurate within:  +10%  +20%  other

3. Please provide us the HDPE footage of your water pipeline system.

The below answer is accurate within:  +10%  +20%  other

Type of Pipe	Footage (mile)		
	2 in. – 4 in.	6 in. – 8 in.	10 in. – 16 in.
HDPE			

4. Regarding the age\* of your installed water pipe (2 in. – 16 in.), what percentage is:

Type of Pipe	% Total Inventory			
	Less than 5 years old	Between 5 to 10 years old	Between 10 to 20 years old	More than 20 years old
HDPE				

5. For water pipe (2 in. – 16 in.), what are the frequency\* of repairs\*?

The below answer is accurate within:  +10%  +20%  other

Types of Pipes	Frequency of Repairs (number per year)		
	Diameter* 2 in. – 4 in.	Diameter* 6 in. – 8 in.	Diameter* 10 in. – 16 in.
HDPE*			
Steel*			
PVC*			
DIP*			
CIP*			
Asbestos Cement*			
Other (Please Specify):			

6. For HDPE water pipe diameter\* (2 in. – 16 in.), please provide causes\* of failure, modes\* of failure, types of joints\*, and type of water (treated\* or untreated\*).

Nominal Pipe Diameter	Date of Failure	Cause of Failure	Mode of Failure	Type of Joint	Type of Water (Treated or Untreated )

7. What different types of couplings & fittings do you normally stock for repair of HDPE pipe?

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8. For the failure types mentioned in Question 6, please provide repair method for HDPE (mechanical\* or fusion\*), average repair time\*

<b>HDPE</b>			
<b>Causes of Failure*</b>	<b>Soil Conditions</b>	<b>Repair Method (Mechanical or Fusion)</b>	<b>Repair Time (hrs.)</b>

9. Please provide us any comments/suggestions regarding long-term reliability or repair of HDPE pipe, or feel free to send us any HDPE pipeline repair case study or failure report.

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Once again, thank you very much for your time. We will get back with you with the survey results in Summer 2012.

If you have any questions or concerns, please feel free to contact Chandan Venkatesh, CUIRE Graduate Research Student, at 817-682-4404 or [chandan.venkatesh@mavs.uta.edu](mailto:chandan.venkatesh@mavs.uta.edu) or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or [najafi@uta.edu](mailto:najafi@uta.edu)

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## Definitions

- **Age of the Pipe:** The number of years the pipe has been installed.
- **Asbestos Cement Pipe:** A concrete pipe made of mixture of Portland cement & asbestos fiber.
- **Cast Iron Pipe (CIP):** A hard, brittle, nonmalleable iron-carbon alloy, cast into shape, containing 2 to 4.5 percent carbon, 0.5 to 3 percent silicon, and lesser amounts of sulfur, manganese, and phosphorus.
- **Cause of Failure:** Basic cause for pipe leakage or breakage (e.g., third-party, improper fusion, pull-apart at fittings)
- **Clean and dry environment:** Conditions acceptable for making a reliable fusion joint
- **Diameter:** Nominal outer dimension of the pipe.
- **Ductile Iron Pipe (DIP):** Ductile Iron Pipe is an improvement to the Cast Iron Pipe. In DIP, the majority of the pools of graphite are in the form of spheroids. This distinctive shape significantly reduces the occurrence of points of stress concentration.
- **Ease of Application:** Convenience of completing repair, considering required training, time and effort.
- **Failure of Pipe:** Fracture, Breakage, Upset, Lining/Coating problems, Loss of Capacity, Leakage.
- Frequency of repair: Number of pipe failures per year.
- **Fusion Repair:** Connection accomplished by heating and melting HDPE material.
- **High Density Polyethylene (HDPE):** A plastic resin made by the copolymerization of ethylene and a small amount of another hydrocarbon. The resulting base resin density, before additives or pigments, is greater than 0.941 g/cm.
- **Installation Problems:** The difficulties faced during the laying of pipe in the ground, and making required connections.
- **Joint:** The interface between sections or lengths of a pipeline system, using various methods and materials (e.g., fusion, mechanical).
- **Maintenance:** The activity performed in an attempt to avoid pipe failures, unnecessary water loss and safety violations.
- **Mode of Failure:** A way or manner in which failure of the pipe occurs.
- **Mechanical Repair:** Method to connect pipe or stop leak by means of clamps, sleeves, bolts, etc.
- **Population:** The number of people or inhabitants in a specified region.
- **Polyvinyl Chloride (PVC):** 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.-
- **Reliability:** Length of time before failure or need to repair.
- **Repair:** Fixing a section of pipeline to restore the pipeline to working condition without increasing the design life.
- **Repair Time:** Interval (hours) required to restore service, not including travel time.
- **Treated Water:** Water that has been chemically or biological polluted, but after having been treated is now safe to be reused or discharged to the environment<sup>5</sup>.
- **Untreated Water:** Non potable water that has not been subjected to any process designed to remove contaminants or organisms<sup>6</sup>.

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<sup>5</sup> <http://www.sswm.info/glossary/2/lettert>

<sup>6</sup> <http://medical-dictionary.thefreedictionary.com/Untreated+Water>

Appendix B

Survey Questionnaire 24 In. and Larger



The University of Texas at Arlington



**Center for Underground Infrastructure Research and Education (CUIRE)**

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High Density Polyethylene (HDPE) Water Pipe Questionnaire

<b>Project Overview</b>						
<p>The Center for Underground Infrastructure Research and Education (CUIRE) at The University of Texas at Arlington is working on a major project regarding failure modes, causes and rates of HDPE water pipelines. The primary objective of this project is to gain an understanding of pipe material performance under different environmental, loadings and operational conditions.</p> <p>The below national survey is critical as a first step to achieve these objectives, since it will provide valuable information regarding the inventory and conditions of HDPE water pipes. To show our appreciation for your time and efforts to complete this survey, we will send you a copy of the research findings upon completion, scheduled for Summer 2012.</p> <p align="center"><b><u><i>Alternatively, instead of completing the survey; you may send us a report or a database file of your water pipe inventory, conditions and failure rates</i></u></b></p>						
<p>If you have any questions or concerns, please feel free to contact CUIRE at 817-272-9177 or Chandan Venkatesh, CUIRE Graduate Research Student, at 817-682-4404 or <a href="mailto:chandan.venkatesh@mavs.uta.edu">chandan.venkatesh@mavs.uta.edu</a> or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or <a href="mailto:najafi@uta.edu">najafi@uta.edu</a></p>						
a) Contact Person's Name				Position:		
b) Name of the organization		City		State	Zip	
c) Address						
d) E-mail						
e) Phone:				Fax:		

1. What is the population of the area served by your water pipes? \_\_\_\_\_

The above answer is accurate within:  ±5%  ±10%  ±15%

2. What is the total length of your water pipelines? \_\_\_\_\_ ft. or \_\_\_\_\_ mi.

The above answer is accurate within:  ±5%  ±10%  ±15%

3. Please provide us the footage of the water system.

The below answer is accurate within:  ±5%  ±10%  ±15%

Type of Pipe	Footage (mile)		
	24" – 36"	42" – 48"	54" and larger
PCCP*			
Steel*			
PVC*			
HDPE*			
DIP*			
CIP*			
Bar-wrapped*			
Asbestos Cement*			
Other (Please Specify)			

4. In your water pipe inventory, what percentage is:

HDPE*	% Total Inventory			
	Less than 25 years old	Between 25 to 50 years old	Between 50 to 75 years old	More than 75 years old

**5. In your water pipe inventory, what percentage is:**

The below answer is accurate within:  ±5%  ±10%  ±15%

HDPE*	% of Total Inventory		
	24" – 36"	42" – 48"	54" and larger

**6. Check (✓) the following pipe material which are limited or restricted\* for use in your water system?**

Pipe Material	Range of Diameter		
	24" – 36"	42" – 48"	54" and larger
PCCP*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Steel*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
PVC*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
HDPE*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
DIP*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
CIP*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Bar-wrapped*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Asbestos Cement*	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Other (Please Specify):			
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

**7. Why is the type of pipe material mentioned in the Question #6 banned or restricted\*?**

Pipe Material	Reason for Consideration
PCCP*	
Steel*	
PVC*	
HDPE*	
DIP*	
CIP*	
Bar-wrapped*	
Asbestos Cement*	
Other (Please Specify):	





**13. Please provide any comments/suggestions, or feel free to send us any case study or pipeline failure report.**

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Once again, thank you very much for your time. We will get back with you with the survey results in Summer 2012.

If you have any questions or concerns, please feel free to contact Chandan Venkatesh, CUIRE Graduate Research Student, at 817-682-4404 or [chandan.venkatesh@mavs.uta.edu](mailto:chandan.venkatesh@mavs.uta.edu) or the Principal Investigator of this project, Dr. Mohammad Najafi at 817-272-0507 or [najafi@uta.edu](mailto:najafi@uta.edu)

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## Definitions

- **Age of the Pipe:** The number of years the pipe has been installed.
- **Asbestos Cement Pipe:** A concrete pipe made of mixture of Portland cement & asbestos fiber.
- **Bar Wrapped:** Bar-Wrapped Cylinder Concrete Pipe combines the strength of steel with the corrosion resistance and durability of concrete. It is comprised of a welded steel cylinder that serves as a watertight membrane and works together with steel reinforcing bars wrapped under tension around the cylinder to provide strength.
- **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.
- **Cast Iron Pipe:** A hard, brittle, nonmalleable iron-carbon alloy, cast into shape, containing 2 to 4.5 percent carbon, 0.5 to 3 percent silicon, and lesser amounts of sulfur, manganese, and phosphorus.
- **Diameter:** Diameter here refers to the outer dimension of the pipe.
- **DIP:** Ductile Iron Pipe is an improvement to the Cast Iron Pipe. In DIP, the majority of the pools of graphite are in the form of spheroids. This distinctive shape significantly reduces the occurrence of points of stress concentration.
- **Excessive Dead Loads:** Weight of all materials on pipe. Generally expressed in terms of weight per unit length. Static load throughout the design life of the pipe. For large pipes with full flow, the contents can be considered to be dead loads because their weights and locations are very predictable. E.g. Soil load. Excessive term is used if the dead loads result in pipe failure.
- **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.
- **Excessive Live Loads:** Live loads change in position or magnitude. E.g. Vehicular loads. Excessive term is used if the live loads result in pipe failure.
- **External Corrosion:** Corrosion observed in pipe due to external sources like soil, groundwater.
- **Failure of Pipe:** Fracture, Breakage, Upset, Lining/Coating problems, Loss of Capacity, Leakage.
- **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.
- **Installation Problems:** The difficulties faced during the laying of pipe in the ground.
- **Joint:** The means of connecting sectional length of pipeline system into a continuous line using various type of jointing materials.
- **Manufacturing Defects:** An error or flaw in a pipe, introduced during the manufacturing rather than the design phase.
- **Oxidation:** The erosion damage observed in the pipe due to its surrounding environment.
- **PCCP:** Pre-stressed Concrete Cylinder Pipe (PCCP) consists of a concrete core, a thin steel cylinder, high tensile pre-stressing wires and a mortar coating.

- **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.
- **Pipe ID:** Unique identity of pipe.
- **Population:** The whole number of people or inhabitants in a region or country.
- **PVC:** A polyvinyl chloride (PVC) is made from a plastic and vinyl combination material. The pipes are durable, hard to damage, and long lasting.
- **Repair:** Fixing a section of pipeline to make the pipeline back in working condition without increasing the design life.
- **Replacement:** The act of installing a new pipeline in the place of old pipeline or renewing the pipeline with new design life.
- **Restricted:** The pipe material could not be used due to certain difficulties.
- **Steel Pipe:** Steel pipe is a material made from an alloy of iron and carbon.
- **Third Party Damage:** Damage caused by someone other than pipeline operator and owner.

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Mr. Chandan Venkatesh has received Bachelor of Engineering degree in Civil Engineering from Visvesvaraya Technological University and is in pursuit of a Master of Science in Civil Engineering at the University of Texas at Arlington. Mr. Chandan Venkatesh was employed with M/s JSW Steel Ltd, for 3 years; his latest position was Assistant Manager at the time of resignation. Mr. Chandan Venkatesh has worked for the Center for Underground Infrastructure Research and Education (CUIRE) and held treasurer position for North American Society for Trenchless Technology (NASTT) UTA Student chapter. His diligent and strong academic skills have paid off and Mr. Chandan Venkatesh is currently working as intern for Utility System Solutions, Inc., in Dallas, Texas.