

PERFORMANCE OF LARGE DIAMETER  
POLYVINYL CHLORIDE (PVC) PIPES  
IN 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 OF LARGE DIAMETER POLYVINYL CHLORIDE (PVC) PIPES IN WATER APPLICATIONS

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Polyvinyl chloride (PVC) pipes with diameters greater than 24" make up a small fraction of water utilities. Most of the research done on PVC pipes in water utilities focuses on diameters less than 24". Therefore, this thesis focuses on PVC water main pipelines with a diameter greater than 24" in an attempt to understand their performance in the water management facilities.

This thesis had several objectives, such as to evaluate 24" and larger diameter PVC pipes in water transmission and distribution applications, calculate failure rate per hundred miles of PVC pipes at water utilities, categorize age of PVC pipelines with 24" and larger diameter in water utilities and identify the different types of failures that have occurred in PVC pipe material.

The Center for Underground Infrastructure Research and Education (CUIRE) conducted surveys consisting of questions pertaining to PVC pipe material and installation practices to different U.S. water utilities. This study is focused on PVC diameters greater than 24" due to limited previous research on this topic.

PVC pipes with diameters greater than 24" are still not popularly used in water utilities in U.S. compared to diameters less than 24". Most common causes of PVC pipe failures are

operational/environmental failures (third party damage, improper installation practices, bedding concerns, and so on). Almost all PVC pipes with diameters greater than 24" are less than 25 years old. PVC pipes with diameters greater than 24" are not considered in some of the water utilities responded to survey questions, because they stated that large diameter PVC pipes material is not easily available, and some water utilities are still not comfortable with large diameter PVC as piping material, as compared to other pipe materials.

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## CHAPTER 1

### INTRODUCTION

#### 1.1 Pipelines in History

Construction of pipelines began thousands of years ago in countries such as Persia, China, Crete, Greece, etc. For instance, the people of Mesopotamia started using aqueducts around 2000 BC to transport drinking water from rivers through desert to housing communities. People of Egypt started using canals to divert the Nile River to irrigate farming fields and communities in 3000 BC. To reduce evaporation from the aqueducts, communities then started using clay pipes (Antaki, 2003). In the United States, settlers first invented log pipes and later adapted wooden pipes connected by steel hoops soon after migrating from Europe (Najafi, 2010). The increase in population and the need for efficient water transport demanded better and safer pipe technologies over time. Although, this thesis will focus on performance of large diameter polyvinyl chloride pipes in water applications, this particular chapter will focus on the comparison of different types of pipe materials.

##### *1.1.1 Different Types of Pipelines*

The transportation of fluids in our society takes place via complex pipeline networks. The role of pipelines initially was to transport waste materials away from inhabited areas to uninhabited areas. However, throughout the decades, the roles of pipelines have changed drastically. There are now different pipelines that perform different functions. For instance, oil and gas pipelines provide efficient transportation of fuel, while water pipelines manage safe water transfer. Pipelines can be mainly divided into transmission and distribution pipelines.

Transmission pipelines transport fluids from a facility to its respective distribution center or customer. These pipelines have large diameters and range from hundreds to thousands of miles. Furthermore, transmission mains are known to have minimal interconnections.

Transmission pipelines are designed to ensure efficient fluid transfer by taking into account forces such as internal pressure, longitudinal stresses and thrust forces. Additionally in hilly conditions, air valve placement in the pipes also ensures reduction of air build up in the pipe (Najafi & Gokhale, 2005).

As compared to transmission pipes, distribution pipelines have more complex networks which are made of smaller diameter pipes leading to unpredictable surge conditions. They are also long ranged and typically connect suppliers to their destination point. Furthermore, a distribution system needs to have acceptable internal pressure, longitudinal stresses and thrust forces just as a transmission pipeline does; in addition, fittings, back-fillings and other service-related connections must be properly installed and maintained. Methods to ensure proper maintenance and to decrease environmental damage such as corrosion should also be taken into account when installing these pipelines (Najafi & Gokhale, 2005). The following pipelines are divided according to the type of fluid they carry and can be either subcategorized as a transmission or distribution pipeline.

### *1.1.2 Water Pipelines*

Drinking water transportation is a critical component of any community. A properly operating pipeline ensures public safety and a healthy population. An operational water distribution system consists of pipes and hydraulic components to ensure efficient water transport mechanisms at optimal pressures. Water system activities depend on laws that dictate the flow mechanisms in these pipes and hydraulics, demands made by the residents and the layout of the infrastructure. According to a fact sheet provided by the University of Michigan (Center for Sustainable Systems, 2011), in 2005, water use in the U.S. was estimated at 410 billion gallons of water per day. According to the same report, the United States needs to spend \$334.8 billion over the next two decades to ensure clean and safe water transport. Out of the \$334.8 billion, 60% (\$200.8 billion) of the total national need is current need and 40% (\$134.1 billion) is estimated as future need which is further divided into: \$200.8 billion for transmission

and distribution, \$75.1 billion for treatment, \$36.9 billion for storage, and the remainder for other systems showed in Figure 1.1.

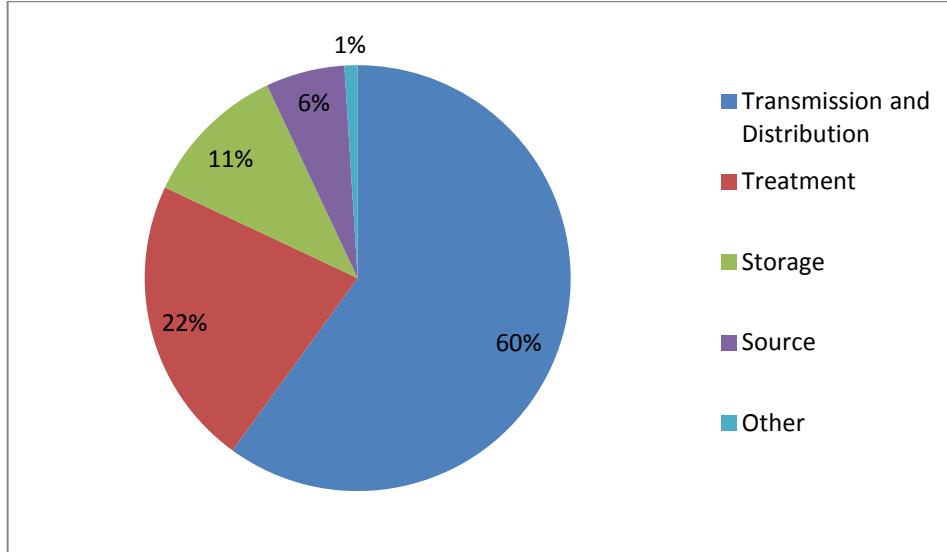


Figure 1.1 \$334.8 Billion Divided by Project Type for Safe Water Transport over the Next Two Decades (Center for Sustainable Systems, 2011)

The University of Michigan also reported that water systems maintain more than 2 million miles of distribution mains. In 2000, nearly 80% of systems were less than 40 years old, while 4% were more than 80 years old. Furthermore, from 2001-2006, over 56,000 miles of distribution mains were replaced and 225,000 miles were newly added. According to Walker (2005), there are an estimated 600 water main breaks per day in the United States leading to 15% (6.8 billion gallons) of water lost due to leakage.

Performance of a particular system decides the reliability of water distribution pipeline. For instance, an extremely reliable water system is one that delivers optimal water in a given time interval. The calculation of this reliability is critical in order to ensure proper and safe transport (Ostfeld, 2001).

### 1.1.3 Gas Pipelines

According to the American Gas Association (AGA, 2012) gas distribution pipelines run for more than 2 million miles while gas transmission pipelines run for 300,000 miles in the

United States presently. Gas pipelines are constructed from different types of pipe materials, have different diameters and are regulated by various sources. Gas transmission pipelines are operated by distribution companies and serve the appropriate commercial, industrial and residential facilities. They are installed in various locations including but not limited to downtown areas, highways and suburban localities. Because these pipelines are installed in public access locations, permits and licenses are required for officials to repair or examine them. Table 1.1 shows the miles of gas pipelines installed throughout decades.

Table 1.1: Mileage of Gas Transmission Pipelines by Decade of Installation (AGA, 2012)

Decade of Installation	Number of Miles
Pre-1940	11,860 miles
1940-1949	22,450 miles
1950-1959	70,585 miles
1960-1969	71,111 miles
1970-1979	30,206 miles
1980-1989	26,370 miles
1990-1999	31,477 miles
2000-2009	27,274 miles
Unknown	4,853 miles

#### 1.1.4 Sewer Pipelines

Sewer systems are an important part of any civilization for they assure transport of contaminated or dirty water away from housing communities. The first noted sewer pipeline was used in Rome around 800 B.C. and was made from stone and cement. Sewage is described as either domestic or industrial waste from public or private water supplies. Service laterals are sewer pipes that transport waste from houses to treatment plants after which the material is allowed to enter any main water stream. To ensure the proper flow from houses to treatment plants to the body of water, engineers design sewer pipes that have an operating velocity of 2 ft/sec to ensure proper flow of sewage material. To avoid clogging, the average diameter of sewer pipelines in the United States is 8" to 12" (Najafi & Gokhale, 2005). Table 1.2 below shows the minimum grades considered safe for smaller sewer pipeline diameters.



Table 1.2 Minimum Grades in Gravity Sewers (Metcalf & Eddy, 1930)

Diameter (inches)	Minimum Fall in Feet per 100 Feet
4	1.2
6	0.6
8	0.4
10	0.29
12	0.22
15	0.15
18	0.12
20	0.1
24	0.08

#### 1.1.5 Oil Pipelines

Oil pipelines are used to transport produced oil (from individual wells) to treatment and storage facilities. Crude oil, more commonly known as petroleum, is transported globally via intercontinental (within a country) and transcontinental (from one country to another) pipelines. Crude oil pipelines were used in the United States to transport petroleum from one state to another. During World War II, two pipelines, a 24" diameter pipeline covering 1,250 miles and a 20" pipeline covering 1,470 miles, were built to transport crude oil from the southwestern region to the east coast. In the 1960s, a 40" diameter pipeline was built to transport crude oil from Louisiana to Illinois (Kennedy, 1993).

Today, crude oil pipelines are divided into two categories, i.e., gathering and trunk lines. Gathering pipelines are small pipelines (ranging from 2" to 8") which collect oil from oil wells and supply to larger trunk pipes. Trunk lines, on the other hand, have a larger diameter (up to 60"), which takes the crude oil from production lines to refineries. For example, the Trans Alaskan pipeline is 48" in diameter and travels for 800 miles. The United States has 55,000 miles of crude oil trunk lines as of today (Crude Oil Pipelines, 2012).

## 1.2 Types of Pipes

Pipes are an essential part of any society because they provide safe and efficient water transfer. These different types of pipes are yet further classified based on different material types—not just within different facilities, but also globally. Figure 1.2 shows the different types of pipes based on their material.

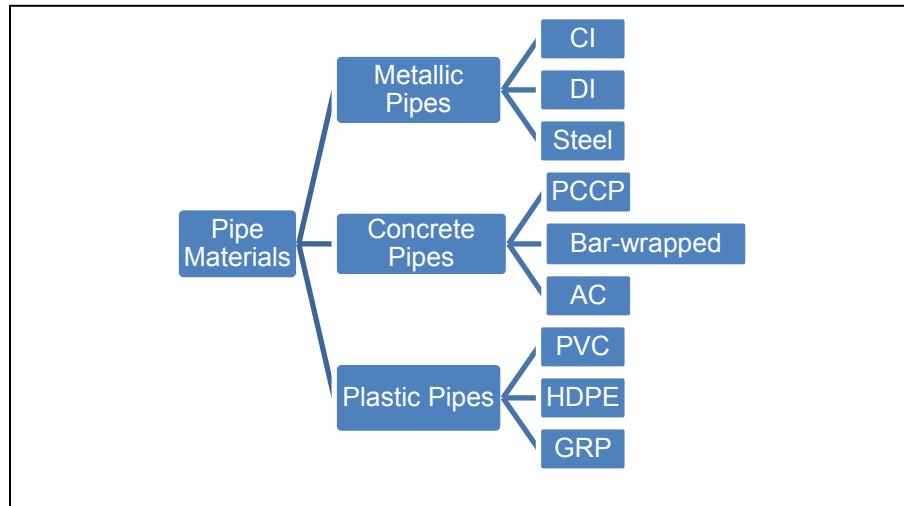


Figure 1.2 Different Types of Pipe Based on Material (Al-Barqawi & Zayed, 2006)

Figure 1.2 Acronyms: *CI*: Cast Iron, *DI*: Ductile Iron, *PCCP*: Prestressed Concrete Cylinder Pipe, *AC*: Asbestos Cement, *PVC*: Polyvinyl Chloride, *HDPE*: High Density Polyethylene, *GRP*: Glass Reinforced Polymer.

### 1.2.1 Metallic Pipes

#### 1.2.1.1 Cast Iron and Ductile Iron Pipes

According to Makar (2000), cast iron pipes were extremely popular in North America from the 1870s to the 1970s but are no longer in use. There are two types of cast iron pipes: the gray cast iron pipe and the ductile iron pipe. The gray cast iron pipe is made partly by graphite flakes while the ductile iron pipe is made of iron and carbon. The gray cast iron and ductile iron pipes are both lined with nonmetallic material on the inside of the pipe, which makes the pipe material resistant to internal corrosion. Cast iron pipes have experienced the greatest amount of failures per mile. The gray cast iron pipe experiences external corrosion causing

deformity of the pipe structure on the outside. For this reason, ductile iron pipes have replaced the gray cast iron pipes in previous decades. The ductile iron pipe comes with an additional advantage: because it is ductile, this material can handle stress (Makar, 2000). The gray cast iron and the ductile iron pipe are both used for sanitary engineering and especially for water transportation (Liu, 2003). Figure 1.3 shows the natural ability of cast iron pipes to undergo heavy corrosion-related degradation externally.

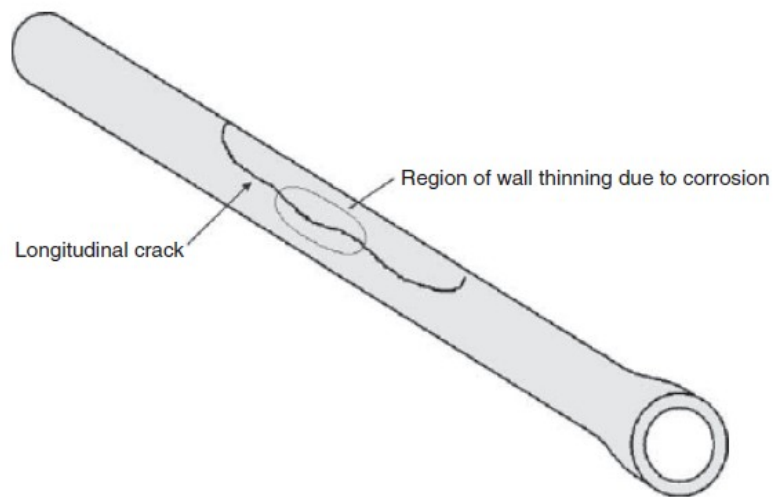


Figure 1.3 Longitudinal Failures in Cast Iron Pipes Caused by Corrosion (Najafi, 2010)

#### 1.2.1.2 Steel Pipes

Carbon steel pipes are most commonly used in the industry today. Steel pipes are manufactured in different ways to give them their respective characteristics. Steel pipes can be manufactured using seamless welds, butt-welds or spiral welds (see Figure 1.4). Seamless pipe is formed when a molten steel rod is combined with a clamp. Butt welded steel pipe is formed when hot steel is rolled into a hollow cylinder-like shape--giving the pipe a joint or a steel. Finally, a spiral welded steel pipe is formed when strips of steel metal are twisted and welded where the edges join each other. Steel pipes are known for their strength and ability to transport water at high pressures. The carbon steel material's drawback is the ability to corrode easily via

ferrous oxide formation on the inside of the walls, which can sometimes slow down the water flow (Parisher & Rhea, 2012). However, they are also economical and, therefore, are used in drainage systems where both water pressure and outside soil pressure are low. In other words, they are used in conditions where water leakage will not cause any severe problems (Liu, 2003).



Figure 1.4 Different Types of Steel Pipes: Seamless, Rolled and Spiral Weld (Parisher & Rhea, 2012)

### 1.2.2 Concrete Pipes

Concrete pipes are divided into low pressure and high-pressure categories. The low-pressure concrete pipes consist of simple concrete without any mixtures. The high-pressure concrete pipes are mostly used for water transport and can be further subdivided into prestressed concrete cylinder pipe (PCCP), asbestos cement pipe and bar-wrapped (Liu, 2003).

#### 1.2.2.1 Pre-Stressed Concrete Cylinder Pipes

Pre-stressed concrete cylinder pipes (PCCP) are more cost efficient than ductile iron pipes and do not undergo corrosion like steel pipes. This pipe has a cement mortar inside a steel cylinder mold. After the concrete hardens, the cylinder is again wrapped with a hot-rolled steel bar and then wrapped with a dense mortar layer of cement. However, in the 1990s, engineers noticed premature failures on pipes made out of this material. The first of many

symptoms of this degradation was brittleness, inefficient design; wire breaks due to soil corrosion and improper system operations (Zarghamee et al., 2012).

#### 1.2.2.2 Asbestos Cement Pipes

Asbestos cement pipes were heavily used around the world-- especially in the mid 1900s. These pipes are made up of a wet mixture (slurry) of cement (known as Portland cement) and asbestos fibers which is dewatered using a rotary sieve cylinder and a continuous felt which produces a thin layer of asbestos cement which is wrapped around a mandrel and pressed until the desired thickness is reached.. A/C Pipe Producers Association continues to give a detailed description of the manufacturing process on the [ecoasbestos.org](http://ecoasbestos.org) site which states that: "The mandrel is then extracted and the pipe is cured by passing through a tunnel-like low temperature oven followed by immersion in or spraying with water, or by autoclaving. After curing, the ends of the pipe lengths are cut and finished to receive couplings that are produced by cutting larger diameter pipe into sections" (A/C Pipe Producers Association, 2012). The pipes were especially popular for water transport and would last for up to 70 years. However, the pipes experienced degradation over time leading to chemically corrupted water. The AC pipes would lose free lime due to acidic pH which led to their eventual softening and a significant decrease in mechanical strength (Wang et. al, 2011). Due to the harmful effects of asbestos fibers to the human health, asbestos cement pipes are no longer used in the United States today (Najafi, 2010).

#### 1.2.2.3 Bar-wrapped Pipes

Before 1995, bar-wrapped pipes were also known as pre-tensioned concrete cylinder pipes and are currently used in high pressure water and sewer applications. These pipes are constructed by first forming a steel cylinder which is then lined with cement mortar. The cement mortar is steam cured and a steel bar is wrapped around it (Arnaout, 2000). Cement mortar coating allows for an alkaline environment which prohibits corrosion in the bar-wrapped pipe. However, this mortar is prone to damage due to handling stress and an unsuitable environment

which can then lead to corrosion and eventually a leak (that grows in time) of the steel cylinder (Pure Technologies, 2012).

### 1.2.3 Plastic Pipes

The introduction of plastic pipes in the late 1950s revolutionized water and sewer systems. There are three main types of plastic pipes found in the U.S. - polyvinyl chloride (PVC), high density polyethylene (HDPE) and glass reinforced pipe (GRP). PVC and HDPE are considered to be thermoplastics; that is, the material's molecular structure can be heated and reshaped many times without physical changes to the material. GRP is considered a thermoset plastic formed by heat and chemicals and cannot be reshaped without permanent physical damage to the material. PVC and PE pipes are also considered rigid pipes (rigid meaning that the pipe does not contain any plasticizers) and are best suited for underground infrastructures. GRP pipes are mostly used in pressure and gravity applications (Najafi & Gokhale, 2005). All plastic pipes can damage easily, can expand and soften at high temperatures, and become brittle at lower temperatures (Liu, 2003). Due to their growing popularity, the focus of this thesis will be the growth of PVC material in the pipe industry focusing on its beginnings, advantages and disadvantages.

### 1.3 Pipe Failures

*"Pipe failure can be defined as situations in which a pipe can no longer perform its intended task; for example, the pipe is losing water, even though there is no catastrophic failure..."* (Cassa, 2011). While precautions are taken to make sure that pipe systems are maintained over time, pipe failure happens. This mostly depends on the type of material the pipe is made out of and the environmental conditions in which it operates. The pipe's operational capacity—that is how much water it carries and at what pressure—also determines its life. Pipe damage reflects upon the entire water main infrastructure because it decreases the efficiency and performance of the system (Al-Barqawi & Zayed, 2006).

To better understand pipe damages, researchers classified them into two categories: structural deterioration vs. internal deterioration. Structural deterioration occurs when pipes are no longer resilient and lose their ability to respond to applied stresses. Internal deterioration affects the water quality and hydraulic capacity and in turn affects the structural properties of the pipe (Kleiner & Rajani, 2001).

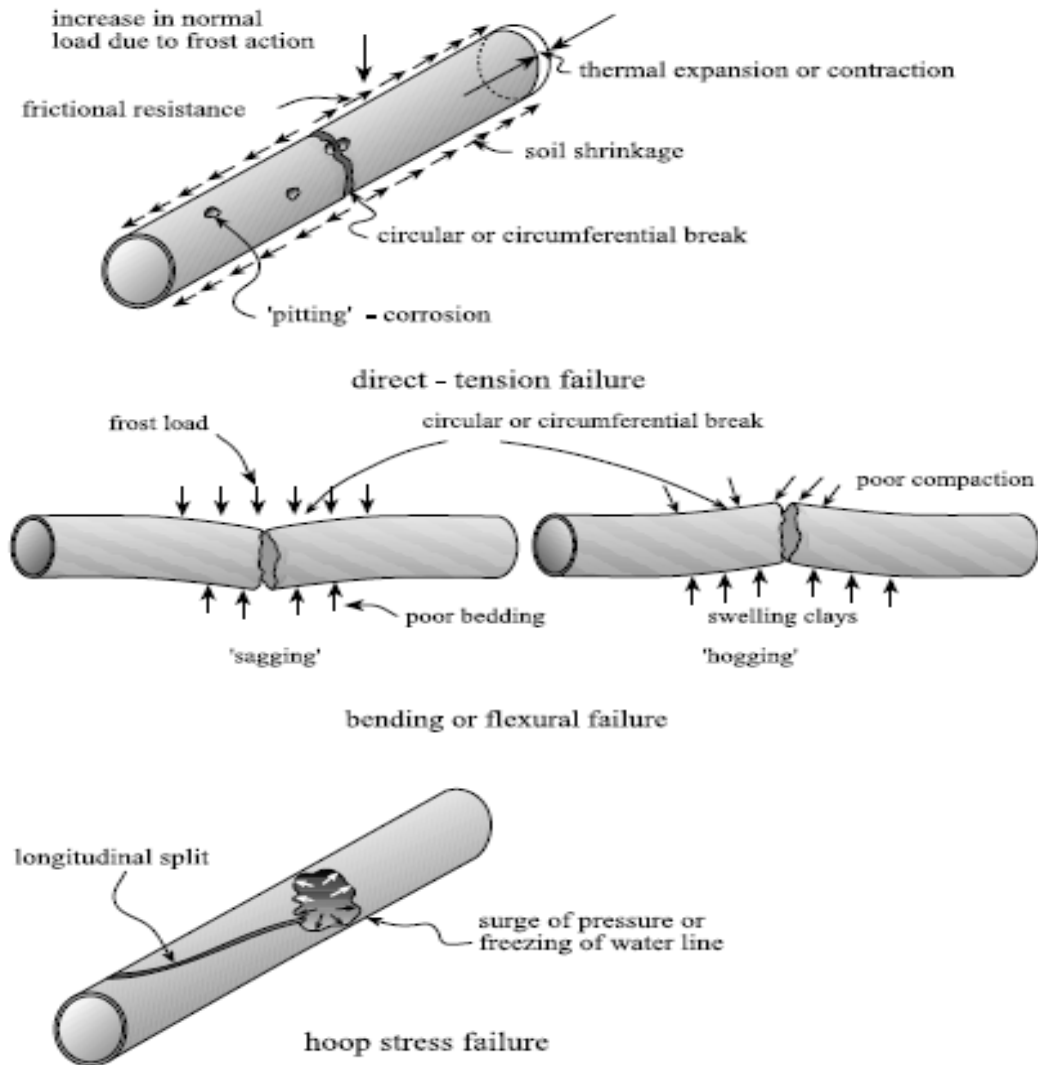


Figure 1.5: Different Failure Modes for Buried Pipes (Kleiner & Rajani, 2001)

Kleiner & Rajani (2001) published models of different types of pipe wall breaks caused by three different reasons: circumferential breaks, longitudinal breaks and split bell. Figure 1.5 above depicts these different breaks. Longitudinal stresses in the material cause circumferential breaks due to low water temperature in the pipes acting on the pipe, soil movements around the pipes and inappropriate bedding of the pipe. Transverse stress causes longitudinal breaks due to hoop stress caused by the intense pressure in the pipe, ring stress due to the soil above the pipe as well as any traffic pressure the pipe experiences. Hoop stress is mostly caused by frozen soil that permeates the ground during extreme winter conditions.

Finally the pipe's age is an important indicator of its failure. As shown in Figure 1.6, when the pipe is first installed it has a high probability of experiencing failure due to construction defects. During its midlife, the probability of pipe failure decreases. However, as the pipe approaches the end of its lifetime, the probability of failure increases again (Najafi & Gokhale, 2005).

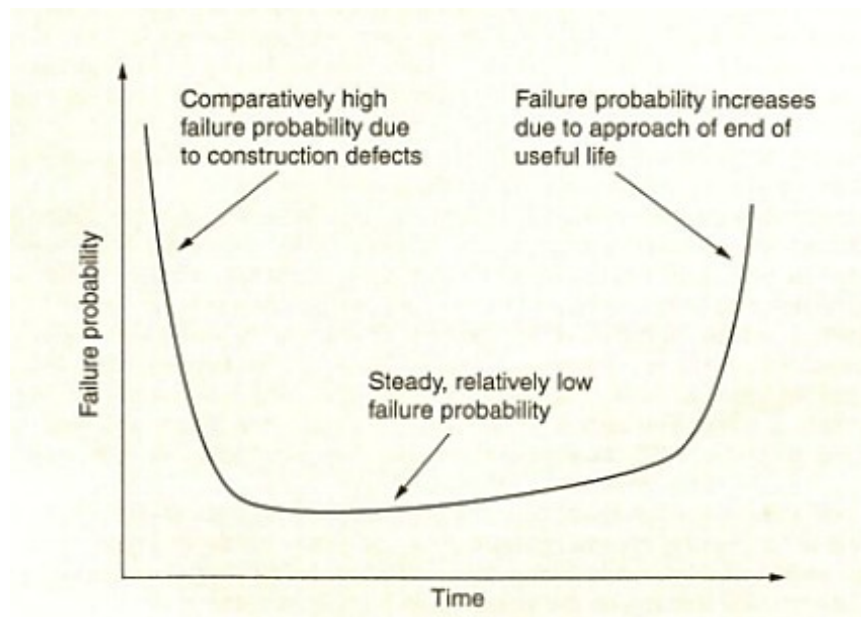


Figure 1.6: Bathtub Curve of Pipe Performance with Age (Najafi & Gokhale, 2005)



#### 1.4 Need Statement

It is estimated that 410 billion gallons/day of water is used in the United States alone and there are an estimated 600 water main breaks per day in the United States leading to 15% (6.8 billion gallons) of water lost due to leakage (Walker, 2005). According to a Utah State University study (Folkman, 2012), 66% of water mains are 8" or less in diameter and pipe diameters within the range of 10" to 14" make up another 18% of all installed water mains. This leaves less than 14% of water mains in the 24" or greater diameter range. The amount of water pipelines in the 24" or greater diameter range is limited and is further subcategorized into the different pipe materials. Polyvinyl chloride (PVC) pipes with diameters greater than 24" make up a small fraction of water utilities. Most of the research done on PVC pipes in water utilities focuses on diameters less than 24". Therefore, this thesis focuses on PVC water main pipelines with a diameter greater than 24" in an attempt to understand their performance in the water management facilities.

#### 1.5 Research Objectives & Scope

The main objective of this thesis is to evaluate the performance of PVC pipes with diameters greater than 24" in different water utilities through literature review and survey results. The following objectives were also considered to reach the main objective.

- Evaluate the use of 24" and larger diameter PVC pipes in water transmission and distribution applications.
- To calculate the failure rate per hundred miles of PVC pipes at the water utilities.
- Determine the different types of failures that have occurred in PVC pipe material.
- Incorporate these findings to predict future pipe development strategies.

## 1.6 Methodology

The methodology of this thesis is summarized below and also described in detail in Chapter 3:

- Read and study various literature articles related to PVC pipe material used in water utilities.
- Create surveys with questions pertaining to PVC pipe length installed, PVC pipe diameter, age of PVC pipes and causes of PVC failures and send to water utilities.
- Gather and compile responses to determine the usage of PVC pipelines greater than 24", their failure rate and the reasons for failure in water utilities.
- Summarize findings and formulate future recommendations for future research.

## 1.7 Expected Outcomes

The current study will allow the performance of PVC pipes to be compared for a number of water utilities. This study will evaluate the use of 24" and larger diameter PVC pipes in water distribution utilities in the U.S. in order to calculate failure rate of PVC pipes per hundred miles, types of PVC pipe failures reported by water utilities, mileage and age of PVC pipes currently used.

## 1.8 Summary

This chapter discussed the different modes of pipelines, namely transmission and distribution. Different types of pipelines such as water, oil, gas and sewer were discussed. Different materials with which pipes are made of (metallic, concrete and plastic) were introduced. Finally, the thesis' objectives, scope of research and expected outcome were mentioned.

## CHAPTER 2

### LITERATURE REVIEW

To understand PVC pipe performance, it is necessary to understand its properties and its limitations. This chapter investigates PVC material's durability and life expectancy. The focus of this chapter is to first highlight other pertinent studies performed on PVC pipes in water utilities. The latter part of the chapter will then focus on PVC pipe materials' advantages and limitations which will be used to determine its influence in our water management facilities.

#### 2.1 The Discovery of Polyvinyl Chloride (PVC) Material

The history of pipe construction has its roots in the 1800s. PVC pipe was introduced by engineers with hopes of building stronger and longer lasting foundations for lavishly built infrastructures. However, just like any innovation, its critics are always looking for something better and its proponents want it to do more (Walker, 2011).

According to Mulder & Knot (2001), PVC was officially discovered and implemented in public utility systems in 1912. However, the compound was used by four Dutchmen named Dieman, Trotswyck, Bondt, and Laurverenburgh in 1795, a century before its official discovery. The substance was initially called "the oil of the Dutch chemists". The discovered compound had a complex yet delicate balance between ethane and chlorine, which was a mystery to many researchers at that time. Mulder & Knot also mentioned that in 1872, Baumann, a pronounced chemist, implemented the already existing compound—emphasizing the polyvinyl and chlorine components. This perfect mixture gave the scientist a milky white substance, which solidified after it cooled.

After several modifications by many other researchers, the polyvinyl chloride material was more stable and durable. PVC was then chlorinated during World War. Chlorination was

an important step in PVC development because it enhanced its processability. After the war, however, the demand for PVC dropped drastically—the material was considered low quality in comparison with its natural counterparts. This decline then led to its initial downfall since European countries, Russia being the first, terminated its production in 1917. Germany followed Russia and discontinued PVC usage in 1925 (Mulder & Knot, 2001).

While the production of PVC was completely halted—the scientific community continued their research on the fibers. The beginning of PVC polymerization occurred at the IG Ludwigshafen in a German laboratory. This laboratory took a keen interest in PVC polymerization, which included reduced melting temperature and allowed the product to uphold its flexible nature. These polymerizations led to yet another era in PVC development. Soon, companies invested billions and developed PVC systems. Products such as shock absorber seals and tank linings, which consisted primarily of this material, started showing up in markets all around the world. These innovations were followed by the cable insulation wires, followed by raincoats, shower curtains, paint, tank linings and most importantly, pipe systems. The flexibility by which PVC was being incorporated into the daily lives of people led to its growing popularity (Meikle, 1995). Table 2.1 demonstrates this increase in demand of PVC material specifically in the US and Canada.

Table 2.1: PVC Consumption in U. S. & Canada  
From 1997 to 2007 (Ackerman & Massey, 2003)

End Uses	Consumption (Millions of Pounds)				Annual Growth Rates (%)		
	1994	1999	2002	2007est	1994-1999	1999-2002	2002-2007
Pipes, Tubing, Fittings	4,875	6,685	6,494	7,350	7.0	-1.0	3.0
Construction	2,790	3,390	4,293	5,413	7.0	2.0	5.0
Sliding	1470	2,175	2,176	2,710	8.0	0.0	4.0
Windows & Doors	410	700	910	1,225	11.0	9.0	6.0
Profiles	225	400	525	775	12.0	9.0	8.0
Flooring	440	485	457	455	2.0	-2.0	0.0
Roofing	115	100	100	113	-3.0	0.0	2.0
Other Construction	130	130	125	135	0.0	-1.0	2.0
Consumer Goods	915	1,225	1,225	1,225	6.0	0.0	0.0
Packaging	820	885	839	935	2.0	-2.0	2.0
Electrical / Electronic	540	870	800	905	10.0	-3.0	2.0
Transportation	265	310	280	310	3.0	-3.0	2.0
Home Furnishings	185	240	240	240	5.0	0.0	0.0
Other & Inventory*	337	128	259	325			
Total	10,727	14,333	14,430	16,703	6.0	0.2	3.0

\* Other & Inventory Includes medical supplies (200 million pounds in 2002), coatings & adhesives (100 million pounds), and inventory changes for the industry as a whole, which can be positive or negative and which can also vary widely from year to year

PVC was praised initially but soon consumers criticized it because of its brittleness, foul odor, its tendency for degradability and the physical shortening and hardening of the products over time. Even though the research community was challenged by the critiques, researchers continued to work on PVC's progression. Suspension polymerization techniques were invented for better PVC quality and less degradability. This type of polymerization desired is when immiscible (non-mixing) compounds such as water and liquid vinyl chloride are mixed causing only vinyl chloride molecules to group together. This process is carried out in a pressurized system with the help of heat and catalysts (Polyvinylchloride (PVC) Suspension Polymerisation, 2008).

## 2.2 Improvements in PVC Material Over Time

Soon after the PVC material took over international markets, consumers began to notice some of the inherent flaws in the material. The material had harmful effects on public and environmental health which were addressed and resolved over time.

### *2.2.1 Effects of PVC on Human and Animal Health*

Vinyl chloride is a monomer which makes up polyvinyl chloride as shown in Figure 2.1. It was identified by the Environmental Protection Agency and other agencies as carcinogenic. The vinyl chloride can transport itself from the pipe into the water to residential and commercial areas. If the polymer is inhaled for a given period of time, it spreads first to the liver and kidneys and then to the lungs and spleen (Richardson & Edwards, 2009).

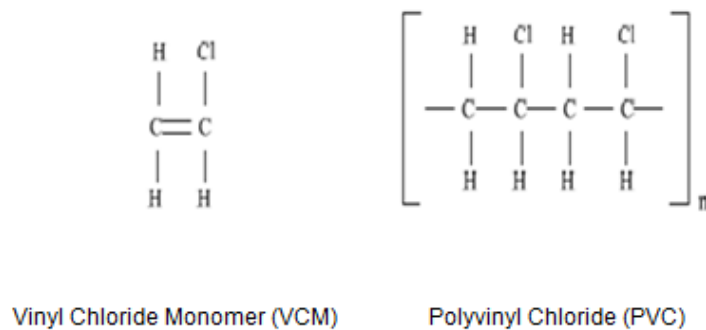


Figure 2.1: PVC is From Chloride Monomer (Richardson & Edwards, 2009)

In the 1960s, P.L. Viola, an Italian scientist, ran multiple tests on the effects of PVC on rats. While Viola initially only meant to induce acro-osteolysis in the rats, his results showed that PVC causes a rare form of cancer (angiocarcinoma) which affects the organism's liver, kidney and ears. To further affirm Viola's results, another scientist, B.F. Goodrich, declared that three of his employees—factory workers—died from angiocarcinoma in the span of two years. PVC was responsible for eight other deaths globally. The authorities took quick actions on the PVC facilities after the entire population was put into a state of panic (Viola, 1970). From this

point onwards, factories reduced VC emissions as shown in Figure 2.2 and controlled leakage by implementing better monitoring systems.

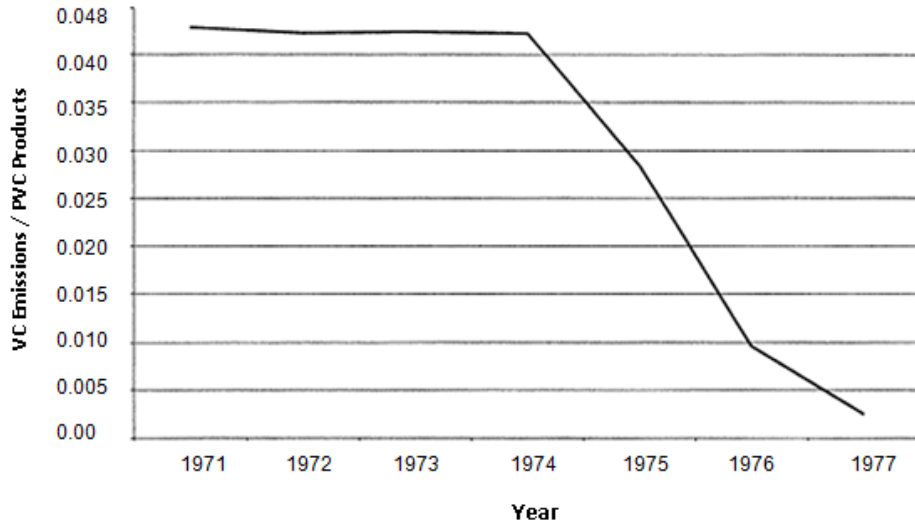


Figure 2.2: Decline in Amount of Vinyl Chloride Emissions From Factories (Mulder & Knot, 2001)

### 2.2.2 Effects of PVC on Environmental Health

PVC material has not only impacted individual health, but has also had deleterious effects on environmental systems worldwide. Specifically, the chloride release and recycling problems added to the damaging qualities of the material. Chlorine was excessively released during the production and processing of PVC. Chlorine is known to be an integral factor in environmental damage. However, reducing chlorine emissions would mean changing the PVC compound completely. Manufacturers seemed to think it was too late to change the compound since it was being used so widely around the world. Hence, there was no real resolution to the chlorine problem other than the fact the environmental groups heavily attacked PVC's influence and threatened to halt PVC sales (Thornton, 2002).

Because the public was unhappy with PVC's harmful impact on human and animal health, the industry decided to improve factories' waste management systems. The Netherlands, for instance, improved recycling of PVC products with the goal of drastically

reducing chlorine emissions. In other words, their aim was to recycle the damaged products and then reuse it to make new products. In addition to material recycling, burning and chemical recycling processes were also implemented to ensure a drastic reduction in PVC waste production (Mulder & Knot, 2001).

### 2.3. The PVC Pipe Industry

The global water distribution system is composed of different types of pipes such as steel, ductile iron, PVC etc. Table 2.2 shows the different pipes and their usage through the years. The figure shows that very few types of original pipe material still exist. However, PVC which is still predominantly in use includes steel, ductile iron, reinforced concrete and prestressed concrete. What makes PVC pipes so different from the rest? That is the focus of this chapter.



Table 2.2 Ages of Different Pipes (AWWA, 2012)

Pipe Material	Joint type	Internal Corrosion Protection	1900s	1910s	1920s	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s
Steel	Welded	None	Commercially used	Commercially used	Commercially used	Commercially used	Predominantly used	Predominantly used					
Steel	Welded	Cement					Commercially used	Commercially used	Predominantly used	Predominantly used	Predominantly used	Predominantly used	Predominantly used
CI	Lead	None	Predominantly used	Predominantly used									
CI	Lead	None			Predominantly used	Commercially used	Commercially used	Commercially used					
CI	Lead	Cement			Commercially used	Commercially used	Predominantly used	Predominantly used	Commercially used	Commercially used	Commercially used		
CI	Lead	None			Commercially used	Commercially used	Commercially used	Commercially used					
CI	Lead	Cement			Commercially used	Commercially used	Predominantly used	Commercially used	Commercially used	Commercially used	Commercially used		
CI	Rubber	Cement						Predominantly used	Predominantly used	Predominantly used	Commercially used		
DI	Rubber	Cement							Predominantly used	Predominantly used	Predominantly used	Predominantly used	Predominantly used
DI	Rubber	Cement							Commercially used	Commercially used	Commercially used	Commercially used	Commercially used
AC	Rubber	Material				Commercially used	Commercially used	Predominantly used	Predominantly used	Commercially used	Commercially used	Commercially used	Commercially used
RC	Rubber	Material	Predominantly used	Commercially used	Commercially used	Commercially used	Commercially used	Predominantly used	Predominantly used	Predominantly used	Predominantly used	Predominantly used	Predominantly used
PC	Rubber	Material					Commercially used	Predominantly used	Predominantly used	Predominantly used	Predominantly used	Predominantly used	Predominantly used
PVC	Rubber	Material						Commercially used	Commercially used	Commercially used	Predominantly used	Predominantly used	Predominantly used

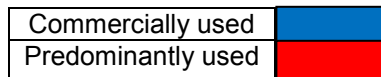


Table 2.2 Acronyms: *CI*: Cast Iron, *DI*: Ductile Iron, *AC*: Asbestos cement, *RC*: reinforced concrete, *PC*: Prestressed concrete, *PVC*: Polyvinyl Chloride

The pipe industry flourished during World War II. German engineers were the first to use PVC when the Allies damaged their pipelines during the War. During the 1950s and 1960s, the PVC era reached a new peak because it was during this period it was processed to achieve the required rigidity. The material became a global necessity, and in 1970s made its way into North America to become the “largest volume plastic piping material” (Handbook of PVC Pipes, 2001). Figure 2.3 shows PVC’s rapid growth in the years that follow. The reasons for the pipe’s popularity can be partially related to the fact that it is relatively cheaper than steel material, corrodes slower than metal and does not take much manpower for installation into water main networks because it is lighter than metallic pipes (Carroll, 1985).

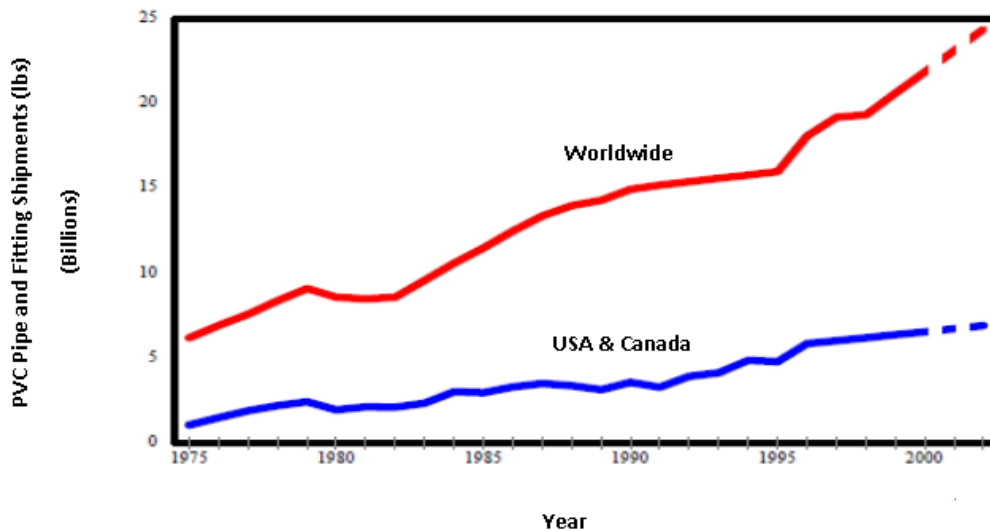


Figure 2.3 PVC's Increasing Popularity Globally & Nationally (Handbook of PVC Pipes, 2001)

#### 2.4 Limitations of PVC Pipes

While PVC is a popular material for pipe construction, it has its limitations. PVC is known to undergo thermal and photo-oxidative degradation. PVC is also prone to fractures due to environmental stress. As mentioned earlier, the PVC material is a known carcinogen and has detrimental effects on various species.

##### *2.4.1. Photo-oxidative and Thermo-oxidative Degradation*

PVC degradation can be classified into two different forms: photo-oxidative and thermo-oxidative. Photo-oxidative degradation occurs when the PVC pipe is exposed to extreme UV radiation from the sun. Thermo-oxidative degradation occurs when PVC pipe is exposed to extremely high temperatures for a continuous period of time. While the degradations are different in terms of how they are initiated, they undergo degradation due to similar, if not exact, chemical reactions. Degradation of the material yields free radical formation which yields hydrochloric acid, and this acid secretion into the environment proves harmful to plants and ecosystem growth. To prevent this degradation, heat stabilizers and inorganic fillers or UV-protective agents can be used (Burn et. al, 2005).

#### 2.4.2. PVC Pipe Cracks

As PVC pipes are known to be brittle, they experience cracks along their walls if left with high pressure internally. Their brittleness is caused by improper handling during processing or processing in higher temperatures. They can also be easily damaged if struck by tools during installation or rough handling by employees on site (Carroll, 1985).

PVC can also be damaged if it is improperly processed. The material is made from a gelation process by which it is melted and allowed to reform several times to strengthen individual crystallites into a strong polymer. Hence, hindering this process can alter its brittleness and make it more prone to cracks. Figure 2.4 shows a crack in a PVC pipe caused by stress due to high temperature processing (Burn et. al, 2005).



Figure 2.4: Noticeable Crack in PVC Pipe (Burn, et al., 2005)

PVC pipes undergo blown selection, which begins initially with a longitudinal split as shown below in Figure 2.5.

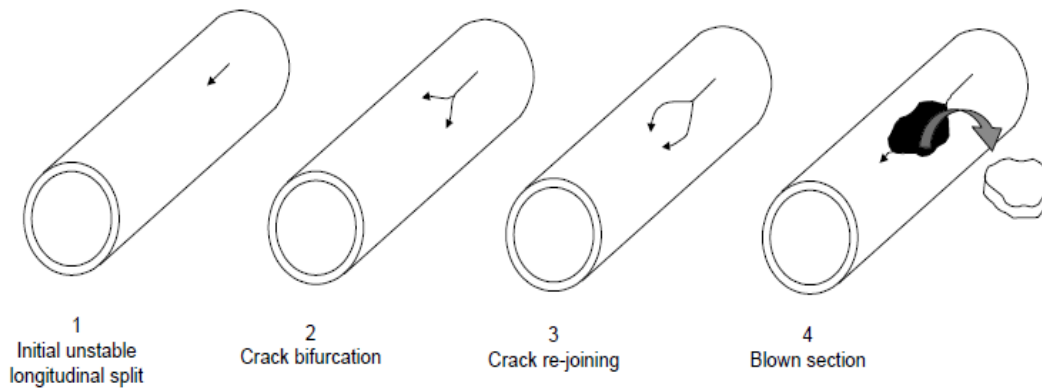


Figure 2.5 Events Leading to a Blown Section (Burn, et al., 2005)

### 2.4.3 Hydrocarbon Compounds and Their Effects on the Ecosystem

While PVC pipes are resistant to corrosion, they are less resistant to hydrocarbon compounds. Factory emissions, improper disposal of chemicals and other such pollutants in the environment have created a serious threat to the functionality of PVC pipes. The contamination takes place in a three step process as shown in Figure 2.6:

1. The contaminant makes its way from the source to the soil in which the pipe rests.
2. The contaminant then diffuses into the PVC material
3. It then makes its way into the water or the material that the PVC pipe carries.

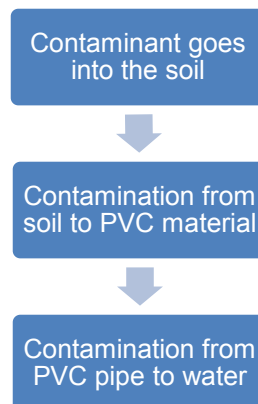


Figure 2.6 Process of Contamination (Ong et al., 2007)

This contamination poses a significant threat to the environment as the compounds can work their way through the drinking water and infect households and other public arenas (Ong et. al, 2007).

#### *2.4.4. Gasket Failures in PVC Pipes*

Joining of PVC pipes is done via welded joints mainly used in diameters less than 24" and bell and spigot gasketed joints mainly used in diameters greater than 24". There are two types of welded joints--heat fused and solvent cement. Heat fused joints are made by increasing heat and pressure causing the melting of two pipe surfaces together. Solvent cement joints are made by chemically bonding two pipes via a translucent chemical between the pipes (Rahman & Watkins, 2005). There is one more joint system which is used to connect PVC pipes known as Bulldog integral joint restraint system, but this joint is designed for pipe-to-pipe connections of only diameters 4" through 12" (Rahman & Farrell, 2012).

The bell and spigot joints are more commonly used in diameters greater than 24". In the earlier days, the gaskets were mostly made out of homogenous rubber or an elasticized sealing ring. Nowadays, they are made of a locked in gasket (Rieber joint). The reason for this transformation is that the steel ring ensures pipe gasket stability and formidability formability. The joint is compressed between the spigot (which is at the distal end of a smaller pipe that fits into a bigger component of another pipe to make a pipe joint) and the bell to form a tight seal. Insertion into the spigot disables leakages along the pipe which is explained through Figure 2.7 (Balkaya et.al, 2012).

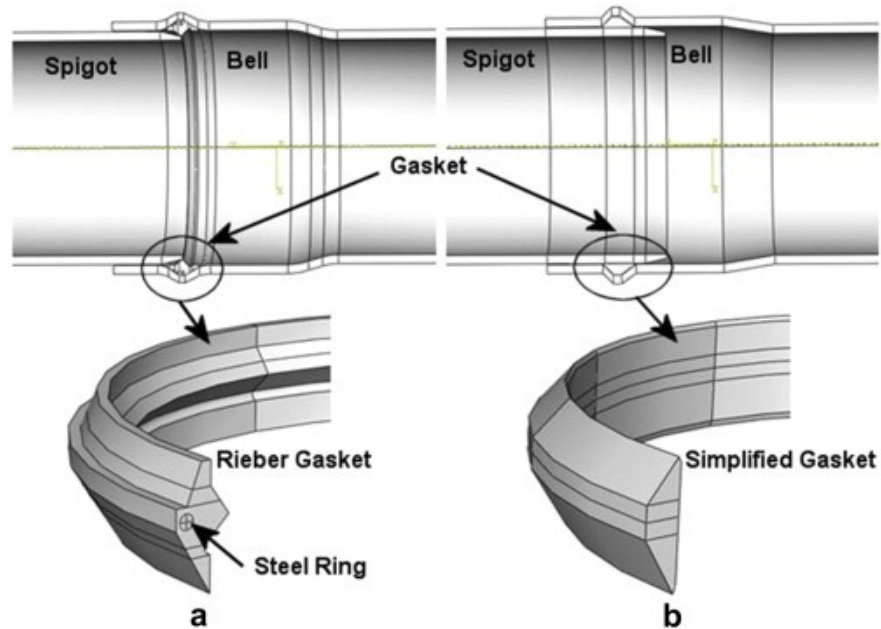


Figure 2.7: Left (a) Shows Newer Type of Gasket, While Right (b) Shows the Type of Gasket Used in Earlier Days (Balkaya et al., 2012)

While pipe design is based on its ability withstand the amount of internal fluid pressure, it is also partially determined by pipe joint systems. If the pipe joint systems are installed incorrectly or contain damage, then fluid can leak out of the pipes resulting in serious repercussions.

Leakage is an extremely common problem caused by improper installation of pipe joints. Leakage can cause serious damage to public water systems resulting in contamination of drinking water if sewage water enters by groundwater infiltration. The leakage can also cause dangerous chemicals to seep into the soil leading to hazardous levels of erosion. This erosion can alter the soil quality exerting pressure on the pipe system and causing pipe death. In order for the pipe to function efficiently, the soil bedding level must be uniform around the joint. If the bedding is not uniform, it can cause pipe bending which can alter the joint tightness (Balkaya et al., 2012).

#### *2.4.5 Examples of PVC Pipe Failures*

Literature can only allow for a basic understanding of PVC material and its usage. However, before any pipeline installation begins, failure data must be collected from different currently operational water management facilities and must be carefully scrutinized. This evaluation can allow new water managing establishments to avoid errors.

Along with PVC's negative impact on the environment, the material also experiences cracks along the pipe infrastructures via different mechanisms. One of the first incidents reported of PVC pipe failure was about a liquid-nitrogen carrying system where the PVC pipe was kept outside. The PVC pipes in this system failed due to the UV (ultraviolet) degradation and temperature fluctuations (Carroll, 1985).

Kent A. Lackey did a case study in 2010 involving 16" and 24" PVC pipes in a service station at an undisclosed location. The causes of the failures were attributed to many reasons. Firstly, the pipe bedding was uneven leading to an improper installation process which ultimately put unbalanced pressure on the pipe exterior. The continuous pressure led to pipe fatigue which caused the pipe to ultimately fail. Figure 2.8 shows the improper bedding conditions which led to the PVC pipe malfunction (Lackey, 2010).



Figure 2.8: Improper Bedding Conditions Leading to Uneven External Pressure on PVC Pipes (Lackey, 2010)

PVC is known to undergo rapid crack propagation (RCP). RCP is a rapidly occurring fracture that can impact pipelines over a long distance. The cracks occur when PVC pipes respond to impact behaviors, acid soil surroundings or the inability of bell and spigot joints to attach to each other properly (Long, 2012). The following case study discusses the different areas where RCP heavily impacted PVC pipeline health by causing accelerated fractures.

In Chatham, Illinois, an 18" DR<sup>1</sup> 25 pipe was held at a 60-psig<sup>2</sup> pressure without any known problems. However when the pressure was increased slightly, there was a crack formation which went on for 850 feet and through 21 PVC bell and spigot joints.

### 2.5 Advantages of PVC Pipes

Just like the philosophical saying goes "Every coin has two sides," the PVC story has two sides to its story. On one side, PVC is criticized for its impact on ecosystem health, while the other side cites proof that PVC material has other properties that keep its production going

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<sup>1</sup> DR/SDR- Both are the average outside diameter divided by the minimum wall thickness (defined by: <http://www.markturner.com/engineer/pvc.htm>)

<sup>2</sup> psig- Abbreviation for pounds per square inch, gauge ( defined by: [www.dictionary.com](http://www.dictionary.com))



globally, which include elasticity, the ability to form various polymers and immunity to corrosion (Ackerman & Massey, 2003).

#### *2.5.1 Flexibility and Strength of PVC Pipes*

According to the Handbook of PVC Pipes (Handbook of PVC Pipes, 2001), PVC is known to be fracture resistant, and it's this very quality that makes it impermeable to external stresses. It has the ability to withstand soil force and torsion even in places where pressure exists. The pipes are made from such compounds that they can withstand the harshest strength tests compared to metallic pipes. The pipes also work to the advantage of employers as they are easily transportable and do not take much manpower for installation. This quality makes them not only safe for workers but reduces collateral damage to the actual site of operation.

Compared to clay or asbestos cement pipes, PVC pipes are resistant to manual stress at most temperatures, but the material does face a reduction in its strength at extremely low temperatures due to its brittleness. Even then, PVC pipe strength compares favorably to other materials (Handbook of PVC Pipes, 2001).

#### *2.5.2 Immunity of PVC Pipes to Corrosion and Chemicals*

PVC material is mostly made from hydrocarbons and some other stabilizers; it exhibits an inherent nature of plasticity. That is, unlike its metallic counterparts, it is a poor electricity conductor. Hence, PVC material is naturally immune to reduction-oxidation reactions that take place in conductor material such as that of iron or steel. This makes PVC pipes efficient in transporting chemicals such as sulfur hexafluoride and others as these chemicals will not interfere with the pipe material.

Along with its ability to hinder reduction-oxidation reactions both inside and outside the pipe itself, PVC material is also resistant to different chemicals at different temperatures. This makes the material take on chameleon-like properties making it capable of multiple purposes (Handbook of PVC Pipes, 2001).

### *2.5.3. Joint Tightness of PVC Pipes*

Pipes made from PVC provide optimal and efficient water transport. This is because they provide unhindered joint tightness, thereby preventing water leakage. The types of joint are known as gasketed joints which perform well above standards compared to other pipe materials. The joints are also manageable and easy to fit due to PVC's flexibility (Handbook of PVC Pipes, 2001).

### *2.5.4. Insulation & Flame-Retardant Properties of PVC Pipe*

Due to its non-metallic properties, PVC is considered a valuable thermal insulator, mainly in colder temperatures. It is apparent that PVC can be used as a coating reagent due to this quality. It was determined that it works to decrease heat loss when the pipe is faced with drought-like conditions (Deeble, 1994).

Studies show that PVC material is heat resistant. Unless an external ignition source is present, PVC pipe will not ignite. The material is also known to self extinguish because after combustion takes place in it or near it, the resulting products combine with oxygen and retard the flame (Handbook of PVC Pipes, 2001).

### *2.5.5. Simplicity in Manufacturing Processes of PVC*

Ethylene and chlorine are combined to form ethylene dichloride which forms vinyl chloride monomer. Then, a polymerization step converts monomer to a polymer--known as polyvinyl chloride (Vinyl Institute, 2012). Because it is easily manufactured and transferred, the average cost for pipe production and disposability are significantly lower than those of other materials (Saeki & Emura, 2001).

### *2.5.6. Prevention From Oxidation*

Kim et al. (2008) determined that extremely high temperature can oxidize the PVC material and cause a reduction in its tensile strength. However, it was recently discovered that adding titanium oxide to the material can hinder the oxidation process and keep the material

more durable for longer periods of time. The titanium oxide does so through the following mechanisms:

- a. The material competes for UV light which disallows direct PVC degradation
- b. Scatters visible light which masks the loss of color and catalyzes surface photo-oxidation.

## 2.6 Previous Studies on Performance of PVC Pipes

The following studies were evaluated to determine the similarities and differences between the current study and other previous studies already done on the performance of PVC pipes in water utilities.

### *2.6.1 National Research Council of Canada (NRCC) Study*

Rajani & McDonald (1993) prepared a report for NRCC in 1992-1993 which consisted of data collected on water main breaks. Out of 31 facilities invited to complete specially prepared forms (surveys), 21 Canadian cities responded. This report analyzed the type of pipe material and proportional representation of the particular material in the total water distribution system per city. The total footage of PVC pipes in the 21 Canadian cities was 1818 km or 1130 miles. The NRCC found that PVC pipe represented 10% of the inventory and reported the average failure rate for 1992 and 1993 as 1.12 failures/100 miles. Because the failure rate was so small, the report could not determine a statistical trend in PVC pipe failure but mentioned that the predominant causes of failures were longitudinal split and joint failure.

Rajani & McDonald (1993) did not consider factors such as age of pipe and operational conditions which can have an impact in the breaks per year number mentioned. The size of PVC pipes that the water utilities used was also not specified. This study also focused only on major urban centers.

### *2.6.2 American Water Works Association (AWWA) Study*

According to Burn et al. (2005), 44 water utilities in Australia, Canada and the U.S. were contacted to participate in a survey. 17 water utilities (4 from U.S., 4 from Canada, 9 from

Australia) responded with information regarding the proportion of PVC pipes length compared to other pipes, the annual failure rate (events/length/year) of PVC pipes and the breakdown of the types of failures. Out of the 17 water utilities that responded to the survey, all supplied details of the total length of the pipe network, the percentage length of PVC pipes, and 13 provided estimates of the annual failure rate (per/length/year) in their PVC pipes out of which 6 supplied a breakdown of the failure types that make up the failure rate.

Burn et al. (2005) mentioned the highest average rate of failure being 10.9 failures/100 miles with the lowest average rate of failure being 0.5 failures/100 miles. The average rate of PVC pipe failures is 3.65 failures/100 miles. The failure rates of all cities were calculated at different periods.-For instance, some were calculated in the span of 5 years while others were calculated over the span of 2 years. The authors also stated that compared to other pipe materials, PVC experienced the least amount of failures. For example, one of the survey respondents had only 21 failures from 1996- 2002. The average age of PVC pipes recorded was 9 years with the oldest pipe being 20 years old.

Burn et al. (2005) also determined that joint leakages along with longitudinal and circumferential cracks were the most common causes of pipe failures and the highest to lowest occurrence was determined per city individually. This study did not specify the diameters of PVC pipes used in the different water utilities.

### *2.6.3 Utah State University Buried Structures Laboratory Study*

According to Folkman (2012), water utilities from the U.S. and Canada were invited to complete a survey consisting of questions regarding pipeline material, pipeline diameter and age of installation. A total of 188 water management facilities in the U.S. and Canada responded to Utah's survey, which covered 117,603 miles of water pipelines (with just above 9,000 miles of PVC pipeline alone). This data was collected over a span of one year and pipelines that mostly had diameters of less than 24". The Utah State study determined that 66% of water mains are 8" or less in diameter, and pipelines with diameters in the range of 10"

to 14" make up another 18% of all installed water mains and, therefore, are focused on pipelines that have especially smaller diameters ranging from less than 8" to 14"- leaving only 14% of water mains in the 24" or greater diameter range.

Furthermore, the study determined that 23% of facilities used PVC material as part of their water management facilities and 43% of the reported water mains are between the ages of 20 to 50 years while 22% are more than 50 years old. Folkman (2012) stated that "non-corrosive materials like PVC have an estimated life of over 110 years."

Folkman (2012) calculated the failure rate per hundred miles for pipe diameters less than 24" as:  $(\text{number of failures reported}) \div (\text{total number of miles})$ . The numbers were:  $(689 \div 26840.3) \times 100 = 2.6$  failures per hundred miles. The study focused on PVC pipes with less than 24" diameters. The study highlighted the most common causes of PVC pipe failure as longitudinal cracks, circumferential cracks, the lack of strength of the material, tapping difficulties, and bedding concerns.

## 2.7 Summary

This chapter discussed the discovery of the polyvinyl chloride material. Limitations and advantages of PVC pipes were discussed as well as remediation measures taken to offset a growing movement to increase regulatory consideration for PVC manufacturing.

## CHAPTER 3

### METHODOLOGY

This chapter explains the methodology used for this research. It also discusses the survey that was sent out to different water management facilities and utilities in an attempt to study PVC pipe failures.

#### 3.1 Introduction

To understand modes of failures for water pipe technologies, it is necessary to gain proper understanding of currently active pipe industries. Focusing on these industries will allow researchers to gain a complete understanding of PVC pipe failures. Understanding pipe failures will allow researchers to invent techniques that will overcome these failures to ensure better pipelines worldwide. Figure 3.1 summarizes methodology for this research study.

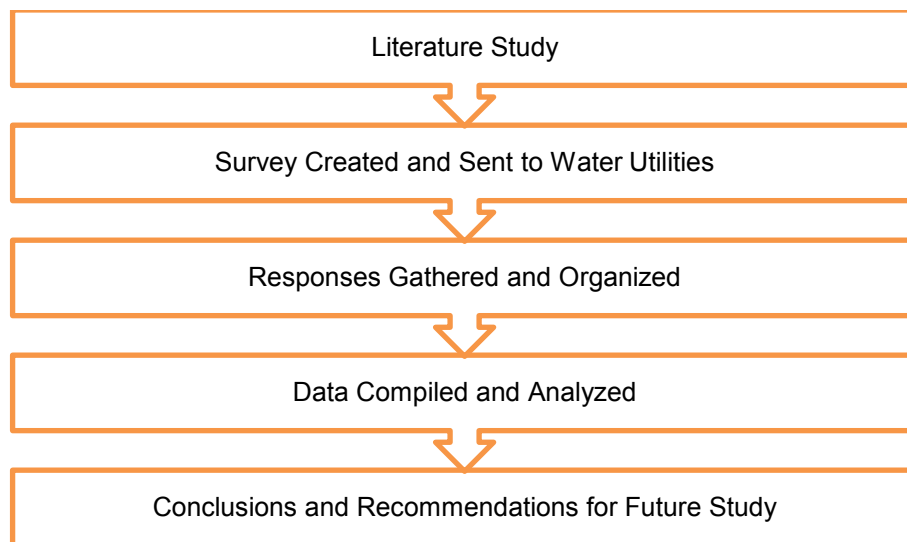


Figure 3.1: Research Methodology

### 3.2 Background Study

A thorough literature review was presented in Chapter 2 which was done through various databases such as Engineering Village, ASCE Database, Science Direct, Conference Proceedings, Web sources, and so on. The important data found in these sources was compiled and used to compare with the survey results for understanding PVC pipe failures.

### 3.3 Survey

As part of this research, a survey was sent out to different water utilities. These water utilities were given the choice of submitting their existing records regarding pipe failures instead of completing the survey. The survey prepared by Center for Underground Infrastructure Research and Education (CUIRE) included different pipe materials such as PVC, PCCP, cast iron, ductile iron, steel, HDPE, etc. This chapter will explain the reasoning behind each question on the survey and its implications on the overall research project concerning PVC in particular as it is the focus of this thesis. The original CUIRE survey contained 13 questions, but only 8 out of the 13 were used in this particular thesis because they pertained specifically to the PVC material and are explained as follows.

Question 1: “What is the population of the area served by your water pipes?”

Implication: The answer to this question will help researchers understand the vast or minor diversity and networks of PVC pipelines. It will also determine the importance of PVC water pipeline in that area and compare it to the different water pipelines.

Question 2: “What is the total length of your pipelines?”

Implication: The answer to this question will help determine the distances travelled by PVC pipes in order to reach target population.

Question 3: “Please provide the footage of the water system” (A table was provided for completion).

Implication: A table with different pipe materials was provided. This table determines the different types of pipe material being used and the lengths that each material was used for. It

will determine how much PVC was being used at a particular utility compared to other pipe materials.

Question 4: "In your large diameter water pipe (24" and larger), what footage is \_\_\_ years old?"

Implication: A table with different pipe materials and ages (ex. Less than 25 years old, between 25 and 50 years old, etc.) was provided. This table provides a sufficient age analysis of PVC material in an attempt to understand the wear and tear that it might have experienced throughout its lifetime.

Question 5: "Please provide information for past water pipe failures (24" and larger)."

Implication: A table was provided with several columns labeled: Pipe ID, Pipe Type, Pipe Diameter, Location, Date of Installation, Date of Failure, Causes of Failures, Modes of Failures, Type of Joint, Type of Coating, Type of Water (treated/untreated), Cathodic Protection (Y/N), Soil Conditions. Many rows were provided for facilities to fill out the information. This question compiles all the qualitative and quantitative information together for efficient analysis.

Question 6: What, if any, type of pipe material (24" and larger) is not considered? Why?

Implication: This question attempts to investigate the reason for considering pipe material associated with a larger diameter pipe length. The answer to this question will allow researchers to understand if, for instance, PVC pipe of a larger diameter is not considered. Is it because it is expensive or unmanageable in terms of installation?

Question 7: "List the most frequently observed causes of failures for each of the pipe materials in your water utility."

Implication: A table with pipe materials is provided for completion. This table provides a detailed account for the conditions under which particular PVC pipe failure occurred. If more than one survey, for instance, indicates that PVC experienced pipe failures in winter and at a location where the soil was loose, then it will be easier to deduce the problems associated with the material and eventually fix these problems by changing some properties of the material.



Question 8: Please provide any comments/suggestions, or feel free to send us any case study or pipeline failure report.

Implication: The establishments were allowed to comment and give examples of any case studies or specific examples that might come in handy when conducting the study.

### 3.4 Survey Results & Analysis

Survey results are presented in Chapter 4, and Chapter 5 presents discussion of results.

### 3.5 Summary

This chapter discussed the methodology for this research performed to understand PVC pipeline failures at different water facilities and utilities. This chapter will allow for understanding the results attained from survey questions' analyses.

## CHAPTER 4

### SURVEY RESULTS

This chapter presents compiled data put together after survey responses were received. Visual tools such as graphs, tables and charts allow for a better understanding of the PVC pipe material in the different water management facilities. The data collected focuses on PVC pipe diameters greater than 24" and of all ages.

As explained in the previous chapter, the Center for Underground Infrastructure and Research (CUIRE) at the University of Texas at Arlington sent out surveys to different water management facilities in an attempt to collect data on various pipe materials. Approximately 300 surveys were sent out to various facilities in the northern, southern, eastern and western regions of United States of America. Out of the 300 surveys sent, CUIRE received 30 replies. Out of these 30 surveys, 10 surveys were useful in analyzing the PVC material.



Figure 4.1 Survey Respondents Identified on Map of U. S.

In Figure 4.1, the survey respondents' respective regions are highlighted on the map above. However, the cities are not mentioned for confidentiality purposes.

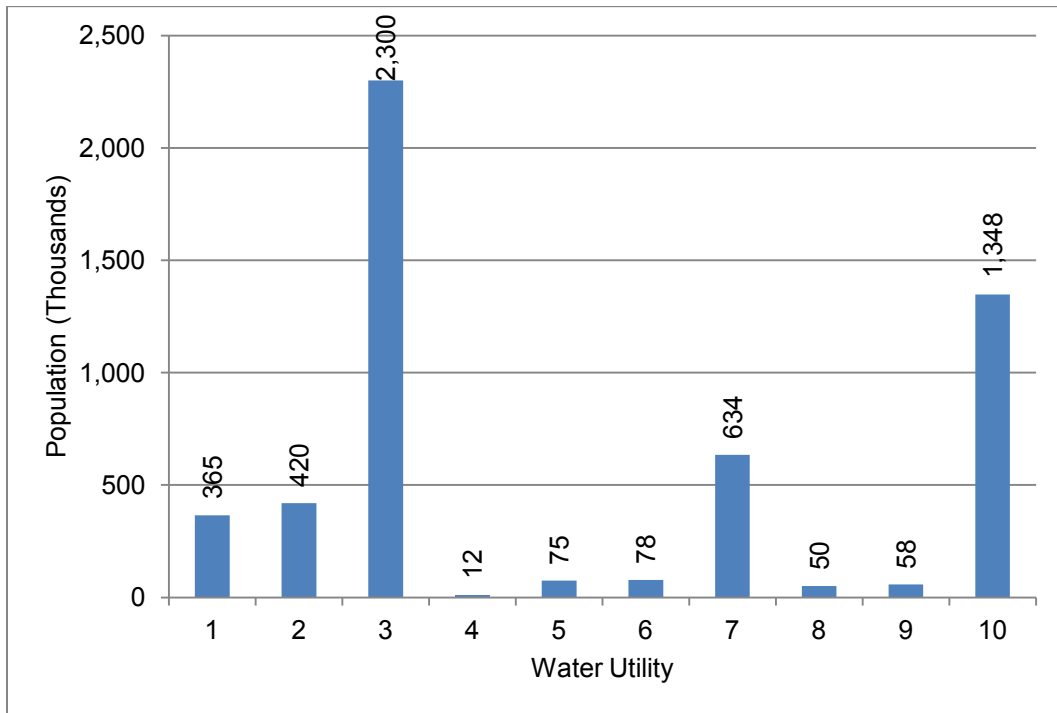


Figure 4.2 Population of Area Served by Water Utilities with 24" and Larger Pipe Diameter (Based on 10 Respondents)

Figure 4.2 shows the population breakdown per water utility. The combined population of all utilities is 3,884,251 with utility 3 reporting the highest population (2,300,000) and utility 4 reporting the lowest (11,529). The average population of the 10 utilities is 533,980.

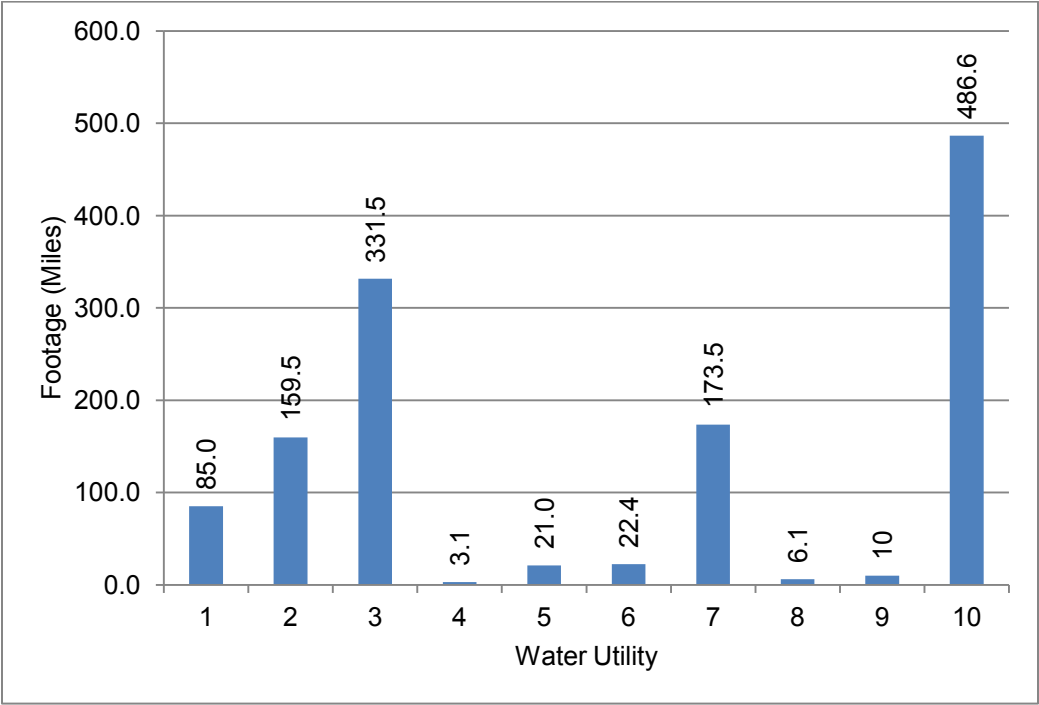


Figure 4.3 Total Length of Water Pipelines for 24" and Larger Pipe Diameter (Based on 10 Respondents)

Figure 4.3 shows the total footage of water pipelines that provides for each utility. The combined length of the pipelines is 1,298.7 miles. Utility 10 has the highest footage (486.6 miles) while utility 4 has the lowest footage (3.1 miles).

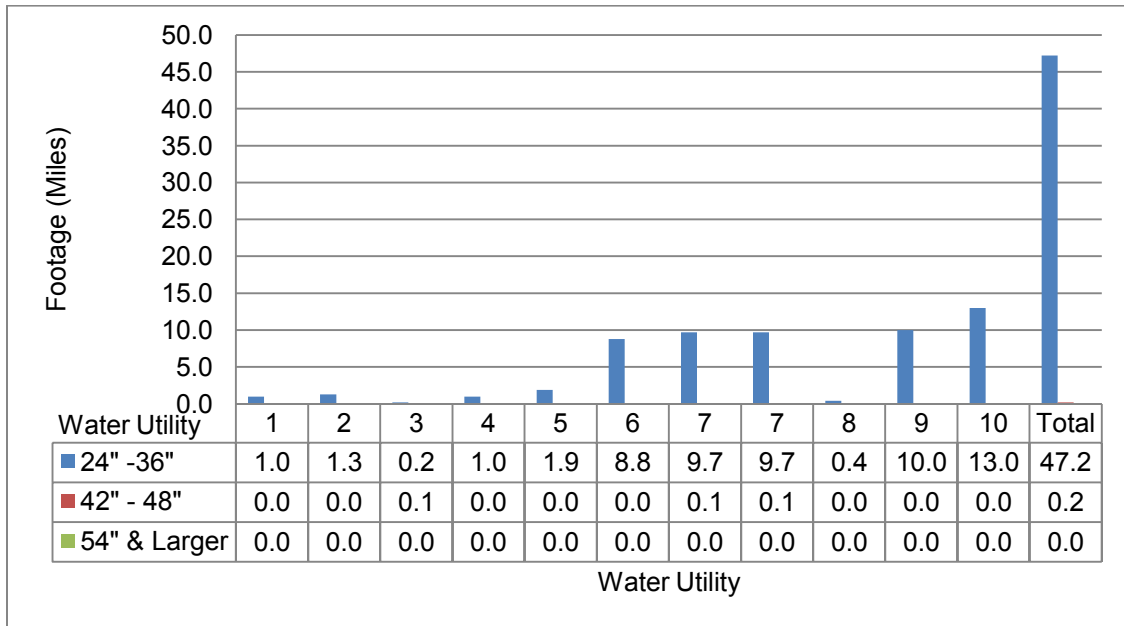


Figure 4.4 Footage of Water System for PVC Pipes with 24" and Larger Pipe Diameter (Based on 10 Respondents)

Figure 4.4 breaks down the footage of the pipelines per diameter length. Utility 1 and utility 4 have 1 mile of PVC pipelines ranging in the 24" to 36" diameter only. Utility 2 has 1.3 miles of 24" to 36" diameter only. Utility 3 has 0.2 miles of 24" to 36" diameter and 0.1 miles of 42" to 48" diameter. Utility 5 has 1.9 miles of 24" to 36" diameter only. Utility 6 has 8.8 miles of 24" to 36" diameter only. Utility 7 has 9.7 miles of 24" to 36" diameter and 0.1 miles of 42" to 48" diameter. Utility 8, 9 and 10 have 0.4 miles, 10 miles and 13 miles respectively all in the 24" to 26" diameter category. The total length of PVC pipes of diameter 24" to 36" is 47.2 miles and of diameter 42" to 48" is 0.2 miles with 0 miles in the 54" and larger diameter range as per the 10 utilities.

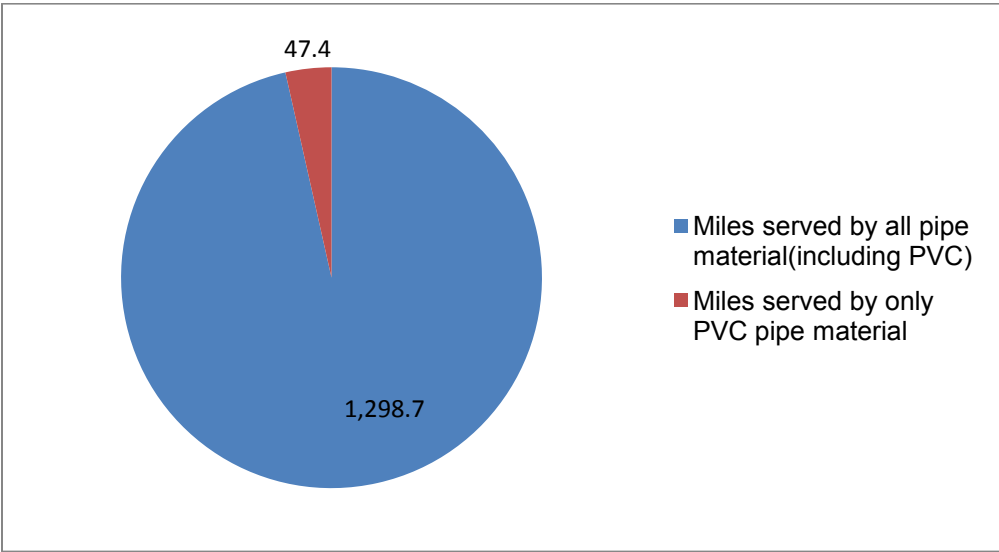


Figure 4.5 Footage (Miles) of Water System Served by All Pipe Materials vs. PVC Pipe Material for 24" and Larger Pipe Diameter (Based on 10 Respondents)

Figure 4.5 compares the footage (miles) of water system of the utility served by all pipelines and the water system of the utilities served by PVC pipelines only. PVC pipelines make up about 3.64 percent  $[(47.4/1,298.7) \times 100]$  of the total water pipelines in the utilities.

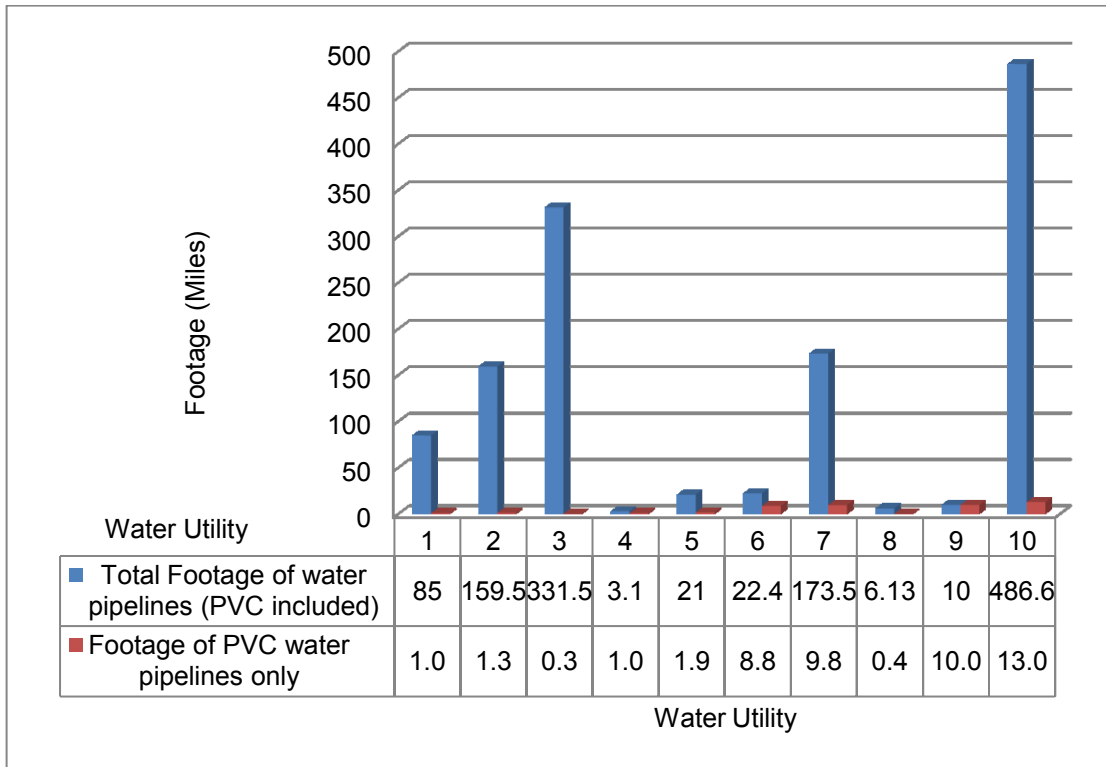


Figure 4.6 Footage (Miles) of Water System Served by All Pipe Materials vs. PVC Pipe of 24" and Larger Diameter by Water Utility (Based on 10 Respondents)

Figure 4.6 compares the footage (miles) of water system of the utility served by all pipelines and the water system of the utility served by PVC pipelines only.

Table 4.1 breaks down Figure 4.6 in percentages of the footage (miles) of water system of the utility served by PVC pipelines only. Utility 3 employs the lowest amount of PVC water main lines while utility 9 employs the highest amount of PVC water main lines.

Table 4.1 Percentage of Footage (Miles) Served by PVC Pipes Only For 24" and Larger Pipe Diameter (Based on 10 Respondents)

Water Utility	Percentage of Footage (Miles) Served by PVC Pipes Only
1	1.18%
2	0.82%
3	0.09%
4	32.3%
5	9.05%
6	39.3%
7	5.65%
8	5.70%
9	100%
10	2.67%

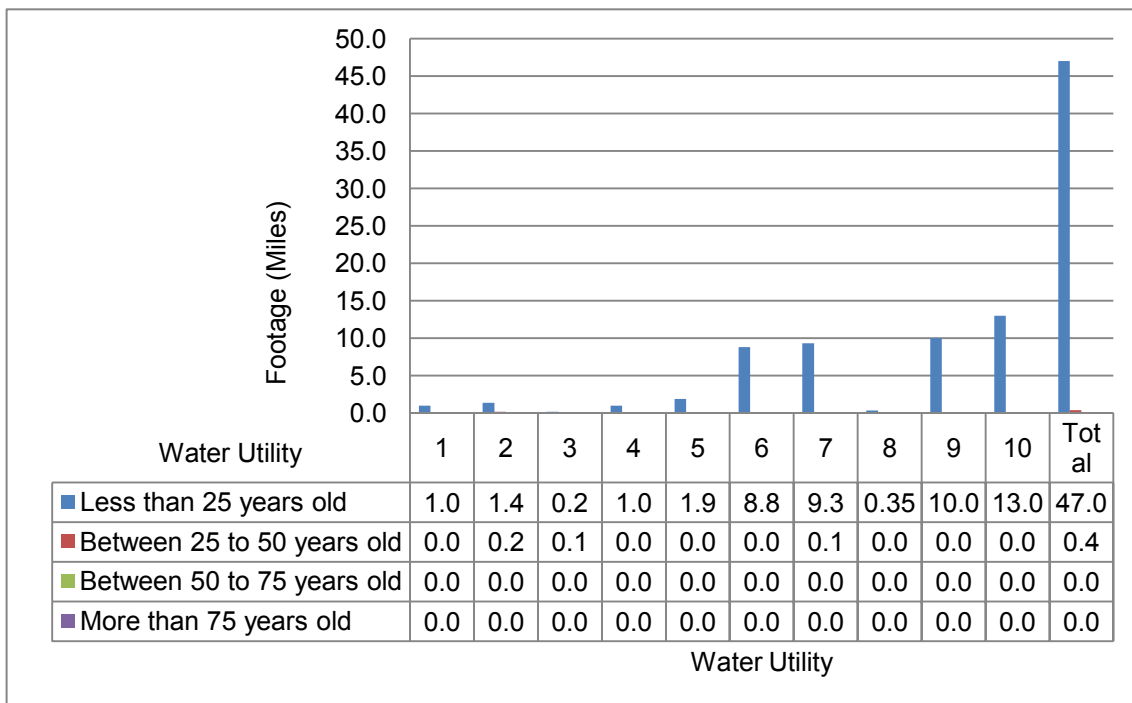


Figure 4.7 Relationship between Inventory and Age of PVC Pipes for 24" and Larger Pipe Diameter (Based on 10 Respondents)



Figure 4.7 breaks down the PVC pipe material footage based on its age. Utility 1 has 1 mile of PVC material that is less than 25 years old. Utility 2 has 2 miles of PVC material that is less than 25 years old and 0.2 miles of PVC material between 25 to 50 years old. Utility 3 has 0.2 miles of PVC pipe that is less than 25 years old and 0.1 miles of PVC pipe that is between 25 and 50 years old. Utility 5 has 1.9 miles of PVC pipe that is less than 25 years old. Utility 6 has 8.8 miles of PVC pipe that is less than 25 years old. Utility 7 has 9.3 miles of PVC pipe that is less than 25 years old and 0.1 miles of PVC pipe that is between 25 to 50 years old. Utility 8, 9 and 10 have 0.35 miles, 10 miles and 13 miles of PVC pipes respectively and all are less than 25 years old. A total of 47.0 miles of PVC pipe is less than 25 years old and 0.4 miles of PVC pipe is between 25 to 50 years old in all the utilities combined.

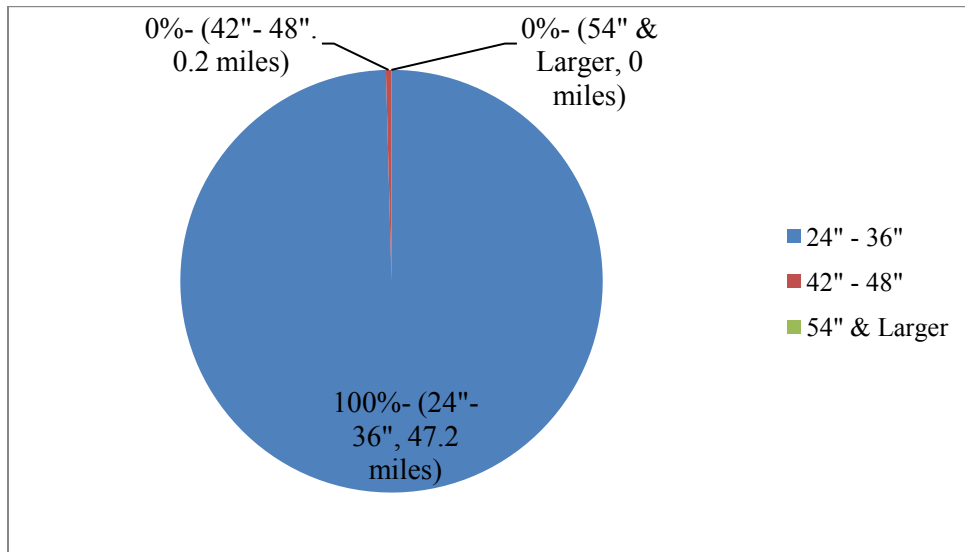


Figure 4.8 Percentage of PVC Pipe by Different Diameter Range for 24" and Larger Diameter Pipe (Based on 10 Respondents)

Figure 4.8 explains that 100 percent of PVC material is in the 24" to 36" diameter range, while a negligible percentage (0.2 miles out of 47.4 miles) is in the 42" to 48" diameter range. No pipes were reported as being in the 54" and larger diameter range.

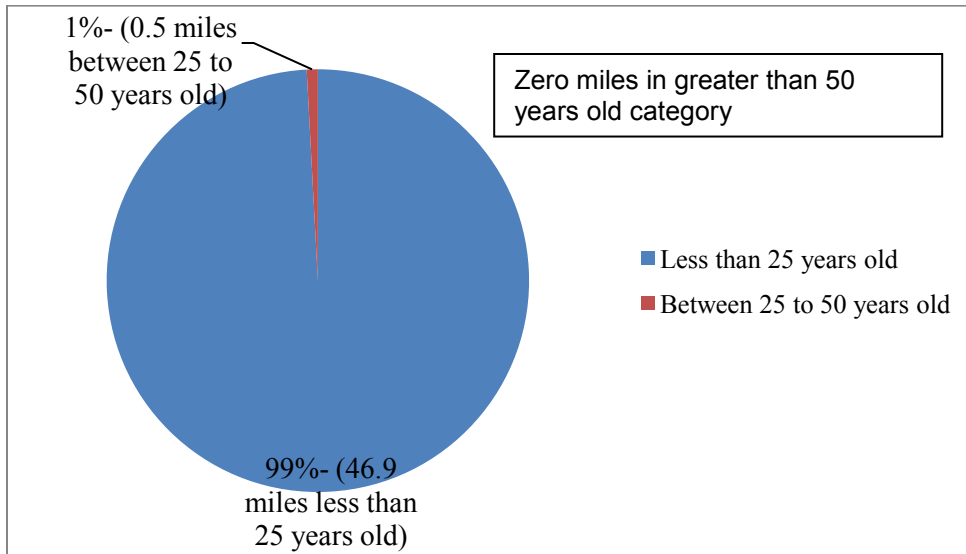


Figure 4.9 Percentage of PVC Pipe by Different Age Ranges for 24" and Larger Pipe Diameter (Based on 10 Respondents)

Figure 4.9 explains that 99 percent of PVC material in the utilities surveyed is less than 25 years old category, 1 percent of the PVC pipe material is in the 25 to 50 years old category and 0 percent in the greater than 50 years of age category.

Table 4.2 Reasons for Considerations of PVC Pipes for 24" and Larger Pipe Diameter  
(Based on 10 Respondents)

Reasons for Considerations – PVC Pipes
Large diameter pipelines do not meet pressure requirements
Availability
Concern over life of product vs. Concrete/metal pipe
Prone to dig-in damage
Lower safety factor
Failure of a PVC transmission main would be catastrophic

Table 4.2 summarized the reasons for PVC material consideration. This list is compiled not only from the 10 utilities that responded specifically with PVC data but also from the other utilities that do not employ PVC material at their water utility. These other utilities provided reasoning for not considering of PVC pipe installation at their facilities.

Table 4.3 Information on Past Failures of PVC Pipes for 24" and Larger Pipe Diameter  
(Based on 10 Respondents)

Water Utility	Pipe ID	Pipe Dia.	Date of Installation	Date of Failure	Causes of Failures	Age of Pipe
1	003	24"	NA	08/14/2010	NA	< 25 yrs
2	1880202	24"	NA	NA	NA	< 25 yrs
3	Not Reported					
4	Not Reported					
5	Not Reported					
6	Not Reported					
7	Not Reported					
8	Not Reported					
9	Not Reported					
10	Not Reported					

Table 4.3 summarizes failures for PVC pipes with a diameter of greater than 24". It also provides information on the date of failure, failure causes and the age of the pipe as per utility survey response. Utility 1 does not have a date of PVC pipe installation on file but claims that the pipe (which was less than 25 years old) failed on August 14, 2010, due to unknown causes. Utility 2 has no detailed record of PVC pipe failures but claims that the installed pipe is less than 25 years old. Utility 1 and utility 2 are the only two utilities that have provided some type of failure data out of the 10 utilities' responses. Utility 3 and utility 5 have not provided any failure data. Utility 4, 6, 7, 8, 9 and 10 have reported no failure in PVC pipe to date.

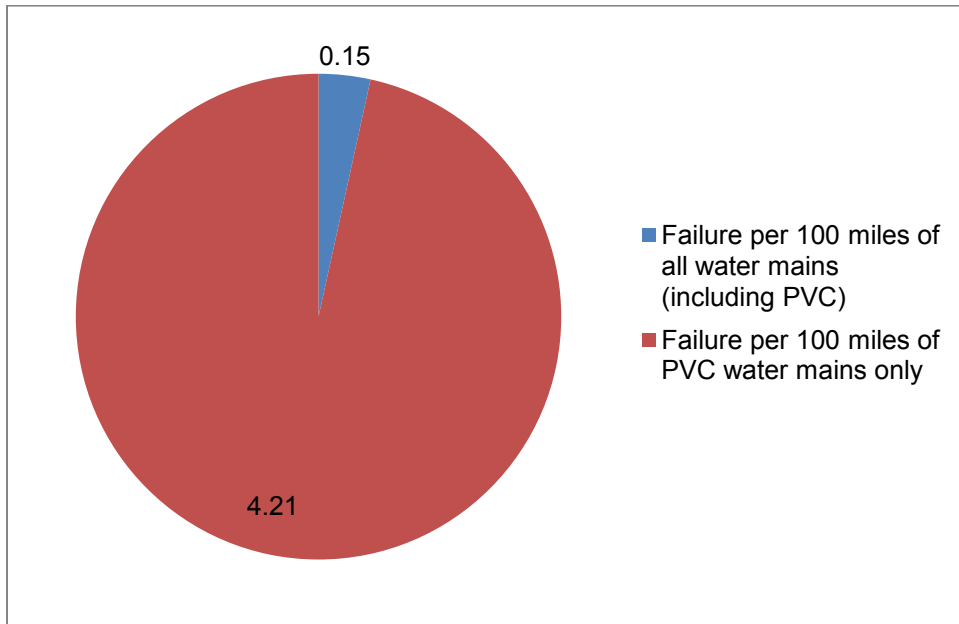


Figure 4.10 Failure Rates per Hundred Miles of All Pipes Compared to PVC Pipes of 24" and Larger Pipe Diameter (Based on 10 Respondents)

Figure 4.10 compares the failure rate per 100 miles of all water mains and that of PVC water mains only.

Calculation:

- Failure per mile of all pipelines = (Number of Failures reported) / (Total miles of all water mains) =  $2 / 1,298.7 = 0.0015$  per mile. Hence,  $(0.0015 \times 100) = 0.15$  almost 0 to 1/2 failure per 100 miles of all mains reported for 10 utilities.
- Failure per mile of PVC pipelines only = (Number of Failures reported) / (Total no. miles of PVC water mains) =  $2 / 47.4 = 0.0421$  per mile. Hence,  $(0.0421 \times 100) = 4.21$  which is approximately 4 failures per 100 miles of PVC water mains reported for 10 utilities.

To summarize, 0.15 failures occur per 100 miles for all the water mains combined while 4.21 failures occur per 100 miles for PVC water mains only.

Table 4.4 Most Frequently Occurring Causes of Failures of PVC Pipes as Stated by Utilities for 24" and Larger Pipe Diameter (Based on 10 Respondents)

Rank	Causes of Failures
1	Third Party Damage
2	Installation Practices
3	Improper Bedding
4	Joint Failure
5	Longitudinal Failure

Table 4.4 summarizes the causes of failures as reported by each utility. It is important to note that in Table 4.3, most of the utilities do not give direct causes of failures, but they do mention them in this table. As mentioned in the methodology chapter, one of the 8 questions on the survey asked to list the most frequently observed causes of failures for the pipe material and to rank these causes from the most common to the least common. Listed above are some of the common causes of failures that utilities ranked in the order listed (with #1 being the most common and #5 being the least common) in Table 4.4.

## CHAPTER 5

### DISCUSSION OF RESULTS

This chapter will discuss the results compiled from the 10 survey responses received and tie these back to the overall focus of this thesis: performance of PVC pipes with 24" and larger diameter in water applications. Hypothesis testing was used to infer relationship between pipe length and maintenance. Furthermore, other similar studies done on PVC as a pipe material will be summarized and reviewed. This will allow for a better understanding of the differences in results seen in the current study versus past studies.

#### 5.1 Comparison to Other Studies

The studies discussed in chapter 2.6 are described in detail and are compared to the current CUIRE study. Tables 5.1, 5.2 and 5.3 compare the CUIRE study with other studies discussed in this thesis' literature search. This highlights the similarities and differences between the past studies and current study. Understanding the differences between the studies allows for a better understanding of the performance of PVC pipes with diameters larger than 24" in water utilities.

Table 5.1 Comparison of Rajani & McDonald (1992-1993)  
Study and Current Study

Study Name	Rajani & McDonald (1992-1993)	Current Study (2012)
Study Results	<ul style="list-style-type: none"> <li>• Based on 21 survey responses</li> <li>• Did not consider PVC pipe diameters</li> </ul>	<ul style="list-style-type: none"> <li>• Based on 10 survey responses</li> <li>• Consider PVC pipe diameters greater than 24"</li> </ul>
Study Exclusion Parameters	<ul style="list-style-type: none"> <li>• Total Footage of PVC pipes: 1130 miles- 10% of all piping material</li> <li>• Average failure rate: 1.12/100 miles</li> <li>• Predominant causes of failures were longitudinal split and joint failure.</li> </ul>	<ul style="list-style-type: none"> <li>• Total Footage of PVC pipes: 24" to 36" is 47.25 miles 42" to 48" is 0.2 miles</li> <li>• Failure rate (for PVC pipes greater than 24") = 4.2/100 miles</li> <li>• Most common causes of PVC pipe failures: third party damage, improper installation practices, joint failures and longitudinal failures</li> </ul>
	<ul style="list-style-type: none"> <li>• Diameters of PVC pipe</li> <li>• Age of pipe</li> <li>• Focused only on major urban centers.</li> </ul>	<ul style="list-style-type: none"> <li>• Did not consider PVC pipes with diameters less than 24"</li> <li>• Did not investigate use of PVC in countries other than U.S.</li> </ul>



Table 5.2 Comparison of Burn et al. (2005)  
Study and Current Study

Study Name	Burn et al. (2005)	Current Study (2012)
Study Results	<ul style="list-style-type: none"> <li>• Based on 17 survey responses</li> <li>• Did not consider PVC pipe diameters</li> </ul>	<ul style="list-style-type: none"> <li>• Based on 10 survey responses</li> <li>• Consider PVC pipe diameters greater than 24"</li> </ul>
Study Exclusion Parameters	<ul style="list-style-type: none"> <li>• Average PVC pipe failure rate 3.65 /100 miles</li> <li>• PVC experienced the least amount of failures</li> <li>• The average age of PVC pipes - 9 years, oldest 20 years.</li> <li>• Most common causes of PVC pipe failures: Joint leakages, longitudinal and circumferential cracks - most common causes of pipe failures.</li> </ul>	<ul style="list-style-type: none"> <li>• Failure rate (for PVC pipes greater than 24") = 4.2/100 miles</li> <li>• 99% of PVC pipelines are &lt; 25 years, 1% are 25-50 years old</li> <li>• Most common causes of PVC pipe failures: third party damage, improper installation practices, joint failures and longitudinal failures</li> </ul>

Table 5.3 Comparison of Folkman (2012) Study and Current Study

Study Name	Folkman (2012)	Current Study (2012)
Study Results	<ul style="list-style-type: none"> <li>• Based on 188 survey responses</li> <li>• Consider PVC pipe diameters lesser than 24 in</li> </ul>	<ul style="list-style-type: none"> <li>• Based on 10 survey responses</li> <li>• Consider PVC pipe diameters greater than 24"</li> </ul>
Study Exclusion Parameters	<ul style="list-style-type: none"> <li>• 9,000 miles of PVC pipelines- but less than 24"</li> <li>• 23% of facilities used PVC material for water mains</li> <li>• Failure rate (for PVC pipes less than 24") = 2.6/100 miles</li> <li>• Common causes of PVC pipe failures: longitudinal cracks, circumferential cracks, the lack of strength of the material, tapping difficulties, and bedding concerns</li> <li>• 51.5% of PVC pipelines are &lt; 20 years old, 46.4% are 21-40 years old, 2.1% are 41-60 years old</li> </ul>	<ul style="list-style-type: none"> <li>• Total Footage of PVC pipes: 24" to 36" is 47.25 miles 42" to 48" is 0.2 miles</li> <li>• 33% of facilities used PVC material for water mains</li> <li>• Failure rate (for PVC pipes greater than 24") = 4.2/100 miles</li> <li>• Common causes of PVC pipe failures: third party damage, improper installation practices, joint failures and longitudinal failures</li> <li>• 99% of PVC pipelines are &lt; 25 years, 1% are 25-50 years old</li> </ul>

### 5.2 Hypothesis Testing

The following hypothesis testing was done as an exercise only to show how statistical concepts can be used for pipeline performance. This exercise infers the relationship between pipe length and maintenance required. Maintaining pipelines will reduce pipe failures and ensure efficient pipeline function. This hypothesis testing will assume the length at which pipeline maintenance is needed the most. There are some limitations to this hypothesis testing:

the data sample of 10 utilities is very small to form a definitive conclusion. The following equations and tables used for hypothesis testing are from *Probability, Statistics, and Reliability for Engineers and Scientists* (Ayyub & McCuen, 2003).

$H_0$  (null hypothesis):  $\mu \leq 1.5$  - Pipe length less than or equal to 1.5 miles will not influence pipe maintenance

$H_A$  (alternate hypothesis):  $\mu > 1.5$  - Pipe length greater than 1.5 miles will influence pipe maintenance

Calculation of Test Statistic:

$$T_{\text{statistic}} = (\bar{X} - \mu) / (S / \sqrt{N}) \text{-----Equation 5.1}$$

Where,

$$\begin{aligned} \bar{X} &= \text{Sample mean (length of PVC pipes in 10 water utilities)} \\ &= (X_1 + X_2 + \dots + X_N) / 10 \\ &= (1.0 + 1.3 + 0.3 + 1.0 + 1.9 + 8.8 + 9.8 + 0.4 + 10.0 + 13.0) / 10 = 4.75 \end{aligned}$$

$\mu$  = assumed value of 1.5

N= sample size = 10 (water utilities)

Using above values, standard deviation can be calculated as shown below:

$$\text{Standard Deviation (S)} = \sqrt{1/N \sum_{i=1}^N (X_i - \bar{X})^2} \text{-----Equation 5.2}$$

$$S = 4.99$$

Using value of S in Equation 5.1,  $T_{\text{statistic}}$  can be calculated as below:

$$T_{\text{statistic}} = (\bar{X} - \mu) / (S / \sqrt{N})$$

$$T_{\text{statistic}} = (4.75 - 1.5) / (4.99/3.2)$$

$$T_{\text{statistic}} = 2.1$$

Using one-tailed T distribution table (Ayyub & McCuen, 2003), with a 95% confidence level and 9 as degrees of freedom (N-1) = 10-1 = 9

$$T_{(0.05, 9)} = 1.833$$

Rejection Criteria:

If  $T_{\text{statistic}} > T_{\text{alpha}}$ , then reject null hypothesis

Since  $T_{\text{statistic}} (2.05) > T_{\text{alpha}} (1.833)$ , null hypothesis rejected, alternate hypothesis accepted. Therefore, pipe length greater than 1.5 miles will influence pipe maintenance. Installed PVC pipes with lengths greater than 1.5 miles should be maintained more often than those less than 1.5 miles. This is because, as the pipe length increases, probability of pipe failure and damage also increase. Again, it should be noted that the sample size of 10 is not enough to infer a definite conclusion.

### 5.3 Summary

This chapter discussed the results compiled from the 10 survey responses received by first comparing current study to other similar studies done on PVC as a pipe material in the past. Then, failure rates of PVC pipes were compared to CI and DI pipes. Finally, a hypothesis test exercise was performed to determine the relationship between pipe length and maintenance required.

## CHAPTER 6

### CONCLUSIONS, LIMITATIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

This chapter summarizes the thesis report by first drawing from the literature review to explain their advantages and causes for failures, then briefly going over the research methodology and finally discussing the results based on 10 respondent utilities. This chapter will also state possible study errors and will make future recommendations for researchers attempting to understand PVC material as piping material for 24" and larger diameters.

#### 6.1 Conclusions

Conclusions of this thesis can be summarized for large diameter PVC pipes (24" and larger) as follows:

- This study was focused on PVC pipes with diameters due to limited previous research on this topic.
- PVC pipes with diameters are not common in water utilities in the U.S. compared to diameters less than 24".
- As per literature study, most common causes of PVC pipe failures are structural failure (longitudinal, circumferential, joint failure, and so on). However, as per current study, most common causes of PVC pipe failure is operational/ environmental failures (third party damage, improper installation practices, bedding concerns, and so on).
- Failure rate of PVC pipes in the U.S. was found to be 4.2 failures/100 miles.
- Almost all PVC pipes with diameters are less than 25 years old.
- For some of survey respondents, PVC pipes is not considered because PVC pipe in larger diameters (24" and larger) is not easily available, and these water utilities may not be comfortable with PVC as piping material as compared to other pipe materials.

## 6.2 Limitations

This study had several limitations. The sample size was very limited, as 10 responses were received from 300 survey sent to different water utilities. It can be assumed that water utilities did not respond to the survey because they did have PVC pipe failures and/or decided not to report. Furthermore, some of the 10 survey responses had incomplete data and could not provide answers to questions such as the most common causes of PVC pipe failures. Additionally, only U.S. water utilities were surveyed. Finally, PVC pipes with diameters greater than 24" are still relatively new to water utilities, compared to other pipe materials; hence more time must elapse for better performance evaluation.

## 6.3 Recommendations for Future Research

Recommendations for future research can be summarized as follows:

- Similar type of research can be conducted in other applications to better understand performance of large diameter PVC pipes.
- When comparing failure rates of PVC pipes to other pipe materials, age and length of that material should be included to be accurate. For instance, since ductile iron pipes have been in the water utilities for a longer time period and have more footage installed, it is only normal that they will experience more failures than the newer and smaller ranged PVC pipes.
- Utilities and all water management facilities should keep better track of their pipe inventory and create a database for water main systems. Such data should be provided to research centers when requested. This will allow for an improved understanding of the influence of different materials of various diameters and various conditions.

APPENDIX A  
SURVEY QUESTIONNAIRE



The University of Texas at Arlington  
**Center for Underground Infrastructure Research and Education (CUIRE)**

Phone: 817- 272- 0507 Fax: 817- 272- 2630  
 E-mail: [najafi@uta.edu](mailto:najafi@uta.edu)  
[www.cuire.org](http://www.cuire.org)

**Large Diameter\* (24" and Larger) 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 24" and larger 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 24" and larger water pipes.</p> <p style="text-align: center;"><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></p> <p style="text-align: center;"><b>**The average time to complete this survey is estimated to be 45 minutes**</b></p>							
<p>If you have any questions or concerns, please feel free to contact CUIRE at 817-272-9177 or Pradip Deshmukh, CUIRE Graduate Research Student, at 817-313-0716 or <a href="mailto:pradip.deshmukh@mavs.uta.edu">pradip.deshmukh@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. (24" and larger).

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 large diameter\* water pipe (24" and larger) inventory, what percentage is:

Type of Pipe	% Total Inventory			
	Less than 25 years old	Between 25 to 50 years old	Between 50 to 75 years old	More than 75 years old
PCCP*				
Steel*				
PVC*				
HDPE*				
DIP*				
CIP*				
Bar-wrapped*				
Asbestos Cement*				
Other (Please Specify):				

5. In your large diameter\* water pipe (24" and larger) inventory, what percentage is:

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

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

6. Not considering *environmental, operational, design, construction, material and other conditions*, please provide your ranking (high, medium or low) of failure rates for the following pipe materials.

High (H) = 25% or more of your total pipe inventory.

Medium (M) = between 10% to 25% of your total pipe inventory.

Low (L) = less than 10% of your total pipe inventory.

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):			

7. Check (✓) the following pipe materials which are limited or not considered for use in your large diameter\* (24" and larger) 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"/>

8. Why is the type of pipe material (24" and larger) mentioned in the Question #7 not considered?

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

9. Please provide information for past water pipe failures (24" and larger).

Pipe ID*	Pipe Type	Pipe Diameter*	Location	Date of Installation	Date of Failure	Cathodic Protection* (Y/N)	Soil Conditions*

10. For the pipe ID's\* mentioned in Question 9, please provide causes of failures, modes of failures, type of joint, type of coating and type of water for pipe failure.

Pipe ID*	Causes of Failures	Modes of Failures	Type of Joint*	Type of Coating*	Type of Water (treated or untreated)

11. In Question #9, is there any causes for pipe failures other than Age of the Pipe?

Yes  No

If yes, please proceed to Question #12. If No, please proceed to Question #13.

12. Rank the following causes of failures for each of the pipe materials according to their frequency of occurrence.

*Please rank with #1 being the highest frequency of occurrence*

**PCCP\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Soil Conditions*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Operation Related			
Other			

**Steel\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Over Deflection*			
Other			

**PVC\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
Manufacturing Defects*			
Third party Damage*			
Excessive Internal Pressure*			
Joint* Failure			
Longitudinal Failure			
Ultraviolet Radiation			
Oxidation*			
Permeation*			
Buckling*			
Other			

**HDPE\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
Manufacturing Defects*			
Third party Damage*			
Excessive Internal Pressure*			
Joint* Failure			
Longitudinal Failure			
Ultraviolet Radiation			
Oxidation*			
Permeation*			
Buckling*			
Other			

**DIP\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Soil Conditions*			
Other			

**CIP\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion*			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Soil Conditions*			
Other			

**Bar-wrapped\***

Causes of Failures	Range of Diameter*		
	24" – 36"	42" – 48"	54" and larger
Water Temperature			
External Corrosion*			
Internal Corrosion *			
Manufacturing Defects*			
Installation Problems*			
Third Party Damage*			
Soil Conditions*			
Excessive Dead Loads*			
Excessive Live Loads*			
Excessive Internal Pressure*			
Joint* Failure			
Coating Problems*			
Other			

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

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Thank you very much for your time. We will get back with you with the survey results in Fall 2012.

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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.
- **Cathodic Protection:** Preventing corrosion of pipeline by using special cathodes (and anodes) to circumvent corrosive damage by electric current.
- **Coating:** Coating is applied to the surface of the pipe to protect it from corrosion. For e.g. Three layer PE (3LPE), three layer PP (3LPP), fusion bonded epoxy (FBE or Dual FBE), coal tar enamel (CTE), asphalt enamel and polyurethane (PUR).
- **Corrosion:** The destruction of materials or its properties because of reaction with its (environment) surroundings.
- **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.



- **Internal Corrosion:** Corrosion observed in pipe due to the materials it carries.
- **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.
- **Over Deflection:** Deflection is the vertical or horizontal curvature or combination of both observed in pipe. Over deflection is defined as the deflection at which the pipe fails.
- **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. The problem of permeation is generally limited to plastic, non-metallic materials.
- **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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