CHAPTER 3.

STATE OF THE ART LITERATURE AND PRACTICE REVIEW FOR WATER SYSTEM PIPELINES

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Over the last few years, several advancements have been made in water pipe renewal technologies that have allowed utilities to utilize innovative renewal techniques that decrease project costs, the impact of the project on the surrounding citizens and environment, and allow for expedited pipeline renewals compared to traditional open trench methods. The challenge now is in getting utilities to implement new innovative technologies within their system. This paper provides background information for the technologies available for the renewal of water system pipelines and then provides State of the Art Literature and State of the Art Practice Reviews based on technology use trends in literature and technology use trends practiced by utilities. The information from both reviews is then synthesized to provide a clear view of the state of the water pipeline renewal technology industry, including the trends by pipe material, technology type, and drivers for renewal projects.

Keywords: drinking water pipe; renewal; repair; rehabilitation; replacement; pipe renewal technologies

3.1. Introduction

There are over 156,000 public water systems in the United States (EPA, March 2008), each with needs that are unique to their size, geographic location, and system characteristics. Drinking water utilities face a unique set of challenges associated with buried pipeline renewal for a number of reasons such as increased consequences of failure compared to gravity pipelines, increased risks associated with new or un-proven technologies, limited access, level of service responsibilities to customers, etc. With the increased awareness of the severity of underground infrastructure deterioration, paired with the decreasing budgets available to utilities to renew their municipal infrastructure, strategies for pipeline renewal have become a major focus for utilities across the nation. This is especially true for water pipelines which have limited options for cost effective renewal.

3.2. Pipeline Renewal Technology Background Information

The United States Environmental Protection Agency (EPA) defines Pipeline Renewal to be "the application of infrastructure repair, rehabilitation, and replacement technologies to return functionality to a drinking-water distribution system or wastewater collection system." (EPA, 2010) The line between whether to repair, rehabilitate, or replace a pipeline is often a fine one, and each utility currently has its own protocol for making this decision. The EPA provides a few generalized guidelines and host pipe requirements describing appropriate situations for the application of each type of pipeline renewal as summarized in Table 3-1 below.

To further complicate the decision to renew a pipeline, there are a number of different technologies available to complete each type of pipeline renewal and several products available to represent each technology. The technologies discussed in this paper have been broken down by type of renewal and are then further broken down into more specific technology categories. It was necessary to define these technology categories to encompass the more specific products and technologies due to the number of technologies currently on the market. The technology descriptions that follow are meant to provide a general definition for each type of renewal and technology category in an effort to help the reader understand the technologies and their general applicability to drinking water pipelines

Table 3-1. Renewal Engineering Components and Descriptions of Use (EPA, 2010)

Pipe Repair Technologies	
Pipe Joint & Leak Seals	Pipe joint and leak seal technologies can typically be installed by in-house operation and maintenance crews and are designed to repair leaking, cracked, or defective joints. Joints are commonly the weakest part of a pipeline, and these technologies are designed to seal leaking joints and prevent inflow and infiltration. There are three primary types of pipeline joint and leak seal technologies: (1) internal sleeves, (2) grouting, and (3) excavated repairs.
Pipe Point Repairs	Pipe point repair technologies are those technologies used to fix short sections of pipeline with a range of structural solutions and are designed to repair sections of pipeline with semi- or fully- structural repair options. There are two primary forms of point repair technologies: (1) Internal Point Repair Technologies and (2) Excavate and Repair Technologies. Examples of internal point repair technologies include internal pipe wraps, internal sleeves, and grouting. Examples of Excavate and Repair Technologies include exteral repair clamps, sectional replacement methods, and external pipe wraps.
Pipe Coatings	Pipe coatings are applied by hand or robotically to span small defects in the pipe wall or provide protection from degradation mechanisms such as corrosion. These linings are not considered stand-alone repair technologies and provide very little to no added structural integrity to the pipeline. There are two types of coating available: (1) cementitious and (2) polymer-based.

3.2.1. Drinking Water Pipeline Repair Technologies

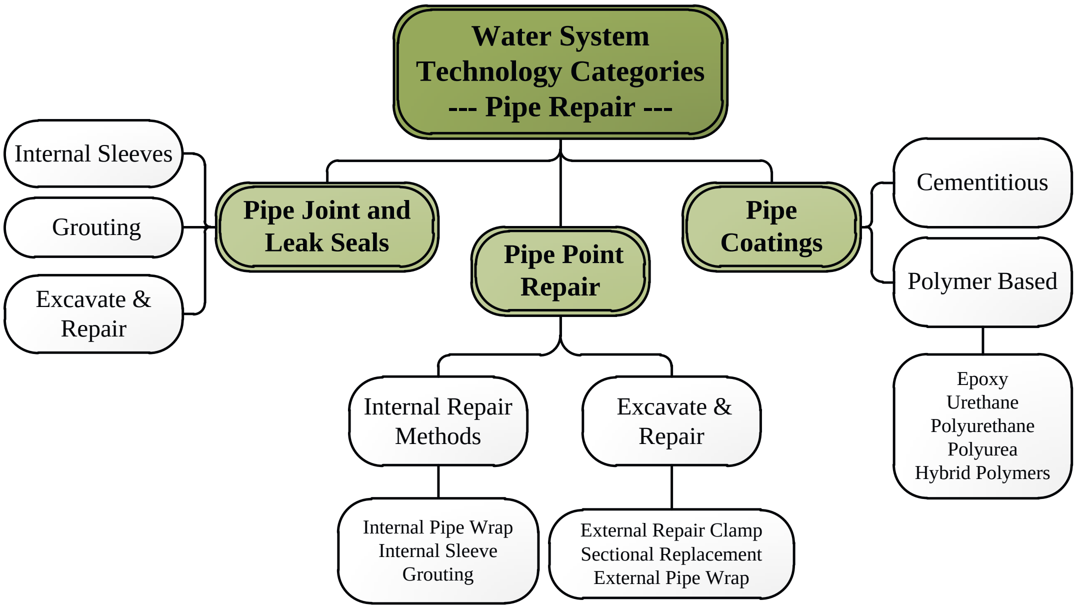

Figure 3-1. Water Pipe Repair Technologies

Pipeline repair technologies are used to restore normal pipeline operating conditions or repair small, localized leaks along the pipeline. The drinking water pipeline repair technology categories are shown in Figure 3-1 above. The technologies are typically used where the defect is not severe enough to require renewal of the entire pipe segment or where deterioration is contained to a small area. Repair technologies can be used to enhance structural stability of the host pipe, but the repair mechanism still relies on the host pipe for structural soundness (EPA, 2010). As shown in Figure 1 above, pipe repair technologies have been broken into three major technology categories: (1) pipe joint and leak seals, (2) pipe point repairs, and (3) pipe coatings. Table 3-2 below briefly describes each of the major pipe repair technology categories.

Table 3-2. Description of Water Pipe Repair Technology Categories

Pipe Repair Technologies	
Pipe Joint and Leak Seals	Pipe joint and leak seal technologies can typically be installed by in-house operation and maintenance crews and are designed to repair leaking, cracked, or defective joints. Joints are commonly the weakest part of a pipeline, and these technologies are designed to seal leaking joints and prevent inflow and infiltration. There are three primary types of pipeline joint and leak seal technologies: (1) internal sleeves, (2) grouting, and (3) excavated repairs.
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3.2.2. Water System Pipe Rehabilitation Technologies

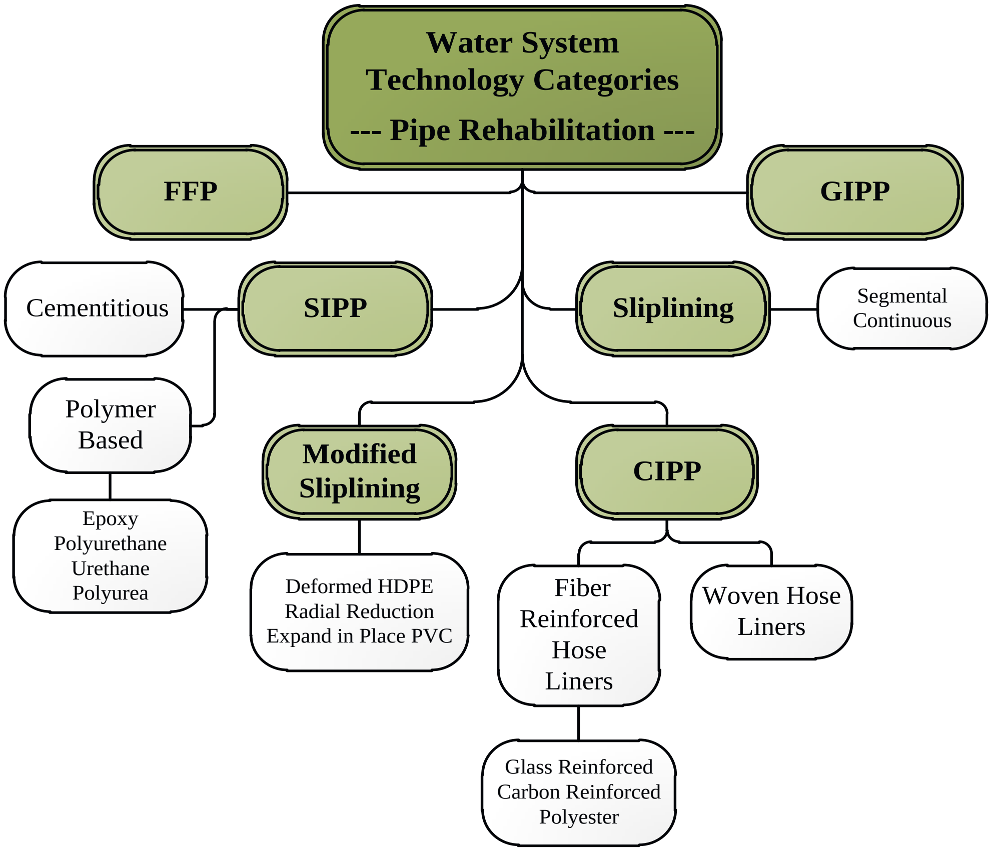


Figure 3-2. Water Pipe Rehabilitation Technologies

Drinking water pipeline rehabilitation technologies are used where the existing host pipe is structurally sound enough to at least partially support the use of the renewal technology. The drinking water pipeline rehabilitation technology categories are shown in Figure 3-2 above. These technologies are aimed at restoring the capacity of a defective pipeline, but slight increases in capacity are sometimes possible, primarily due to the reduction in surface friction that results from technology applications. Rehabilitation technologies also restore the structural integrity of the pipeline system, though still may rely on the host pipe for some support, and also extend the life expectancy of the pipeline, typically by at least 50 years. (EPA, 2010) The technologies are used where the defects are too numerous or severe for repair options to be feasible. As shown in Figures 2 above, rehabilitation technologies have been broken into six major technology categories: (1) Cured-in-Place Pipe (CIPP) Liners, (2) Fold and Form Pipe (FFP) Liners, (3) Grout-in-Place Pipe (GIPP) Liners, (4) Spray-in-Place Pipe (SIPP) Liners, (5) Sliplining, and (6) Modified Sliplining. These technologies are defined briefly in Table 3-3 below.

Table 3-3. Description of Pipe Replacement Technology Categories

Pipe Rehabilitation Technologies	
Cured in Place Pipe (CIPP) Liners	Cured in Place Pipe (CIPP) Liners are one of, if not the most widely used form of pipeline rehabilitation for wastewater systems but are seldomly used in drinking water applications. The CIPP Liner tube is impregnated with a liquid thermosetting resin and then pulled or inverted into place within the pipeline and cured with hot water, steam, or UV lights to form a "pipe within a pipe". There are two primary types of CIPP liners used in water systems including (1) Reinforced Hose Liners and (2) Woven Hose Liners.
Fold and Form Pipe (FFP) Liners	Fold and Form Pipe (FFP) Liners used in waterlines are made from variations of polyethlyene (PE) material that has been folded into a shape such as "U" or "W" to reduce the cross-sectional area and facilitate insertion into small access pits which have to be excavated for liner insertion. Once in position, the folded pipe liner is expanded with pressurized water or air to fit tightly against the host pipe. The primary form of FFP Liner for waterlines utilizes a fiber reinforced PE liner tube for pipelines up to 12-inches in diameter.
Grout in Place Pipe (GIPP) Liners	Grout in Place Pipe (GIPP) Liners are internal liners that do not fit tightly against the host pipe and thus require grouting of the annular space. These liners are typically installed by hand in the form of a flexible panel liner for watermain rehabilitation. Once in place, the liner is held steady with internal reinforcements while the annular space between the host pipe and liner is filled with expanisve grout to create a host pipe-grout-liner system that can withstand internal pressure and external loadings.
Spray in Place Pipe (SIPP) Linings	Spray in Place Pipe (SIPP) Linings are cementitous or polymer-based linings that are sprayed onto the pipe wall to provide a semi- or potentially fully- structural rehabilitation solution. Cementitous SIPP Linings are typically braced with steel reinforcing mesh to provide added structural capabilities to the cementitious material. The structural capabilities of polymer linings are increased through the addition of reinforcing fibers and/or through application of the material as a "high-build" lining.
Sliplining	Sliplining is accomplished by either pushing or pulling a new, smaller diameter pipe through the deteriorated host pipe. There are two different methods for sliplining: (1) continuous sliplining and (2) segmental sliplining. Where adequate space is available, the new pipe can be pulled into place continuously, or where space is restricted, it can be pulled in one segment at a time. Continuous pull-in sliplining requires the use of pipes with fused, welded, or restrained joints, whereas segmental pushed-into place sliplining can use traditional joint types. Because sliplined pipes do not fit tightly against the host pipe, grouting of the annular space is required for structural stability.
Modified Sliplining	Modified sliplining technologies are used to insert a thermoformed pipe within the deteriorated host pipe, making use of various technologies to reduce the diameter of the new pipe to facilitate insertion. Once inside the host pipe, the new pipe is allowed to expand to its original cross section either naturally or through the use of pressurized air/water or a specialized re-rounding plug. Modified sliplining creates a tight-fitting "pipe within a pipe" that, unlike sliplining, does not require grouting of the annular space. There are three primary methods for modified sliplining including: (1) Deformed HDPE, (2) Expand-in-Place PVC, and (3) Radial Reduction.

3.2.3. Water System Pipe Replacement Technologies

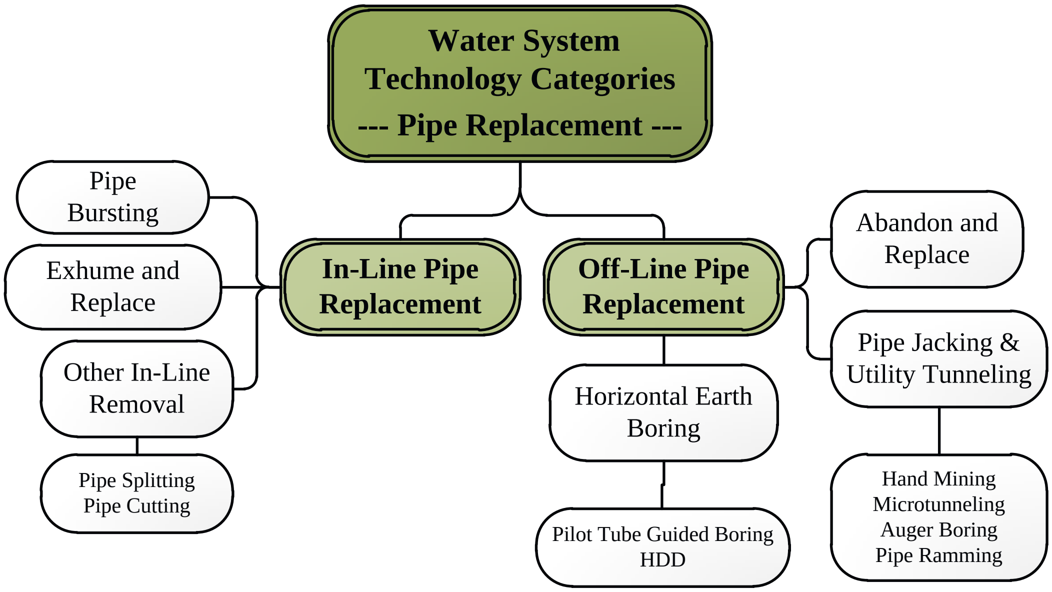


Figure 3-3. Drinking Water Pipe Replacement Technologies

Pipeline replacement technologies are used where the existing host pipe is no longer structurally sound enough to support repair or rehabilitation technologies or where the existing host pipe is severely deteriorated or collapsed. The drinking water pipeline replacement technology categories are shown in Figure 3-3 above. These technologies are designed to completely restore or increase capacity and structural integrity of a defective pipeline, and the old pipe is either abandoned in place or removed in some manner from its existing alignment (EPA, 2010). Replacement technologies re-start the life expectancy of the pipeline rather than just extending it with the new life expectancy is heavily dependent on the type of pipe chosen for installation. As shown in Figure 3 above, pipe replacement technologies have been broken into two major technology classes: (1) In-Line Replacement Methods and (2) Off-Line Replacement Methods. These are defined in Table 3-4 below.

Table 3-4. Description of Pipe Replacement Technology Categories

Pipe Replacement Technologies	
In-Line Pipe Replacement	In-Line Pipe Replacement Technologies are used to remove the existing host pipe and replace it with a new pipe of equal or slightly larger diameter on the same alignment. Methods for in-line pipe replacement of waterlines include pipe bursting or splitting, exhume and replace, and other forms of in-line pipe removal.
Off-Line Pipe Replacement	Off-Line Pipe Replacement Technologies are used to install a pipeline through a new soil tunnel, typically parallel to the existing pipe alignment where possible. Methods for off-line pipe replacement include open trench, pipe jacking & utility tunneling, and horizontal earth boring.

3.3. State of the Art Literature Review for Drinking Water Pipeline Renewal Technologies

3.3.1. Introduction and Scope of Review

Literature review is a critical first step in understanding the concepts involved in drinking water pipeline renewal engineering and in determining what knowledge already exists. It is important to understand what research has been completed or is underway so that the gaps in existing information can be identified and their significance evaluated. The literature review process began with the identification of sources from which to pull a comprehensive representation of literature types (major industry research reports, journal papers, conference proceedings, relevant theses, etc.). Table 3-5 below outlines the document source locations that were mined for all possible literature, including a description of common literature types found within that source.

Table 3-5. Locations Mined for Literature Sources

Name of Resource	Location (where applicable)	Description of Available Literature
EPA - National Service Center for Environmental Publications (NSCEP)	http://www.epa.gov/nscep/index.html	This allows the user to search for all research reports or white papers published by the EPA. The searches performed were for broad searches such as "pipe renewal" as well as for specific technologies such as "cured in place pipe liner".
Compendex, Inspec, NTIS		These bibliographic reference databases were searched for relevant sources, primarily for journal papers and conference proceedings, and where online sources were not available, a copy of the literature could usually be obtained through the Virginia Tech Library resources.
ASCE Civil Engineering Database (CEDB)	http://cedb.asce.org/	This database was searched for all relevant ASCE journal papers and conference proceedings.
EBSCO Host	http://search.ebscohost.com/	EBSCOHost was searched for all relevant academic journal articles, conference proceedings, magazine/newspaper articles, and books. Where direct links to articles were not available, a copy of the literature could usually be obtained through the Virginia Tech Library resources.
AWWA, NASTT, ISTT, and other prominent industry organization websites		The websites allowed the location of research reports or white papers published by the the industry association so that a copy of the literature could be requested through the Virginia Tech Library resources.

There were two basic types of literature that were reviewed: (1) major reports and (2) other literature. Major reports included research reports, workshop proceedings, etc. from key industry organizations and associations such as the EPA, Water Environment Research Foundation (WERF), American Water Works Association (AWWA), etc. Major industry documents/publications tended to focus on long-term research work that was completed or on capturing the main ideas from workshops that drive new research. These documents are important to understanding the gaps in knowledge that exist between literature and practice. Table 3-6 provides a list of the reports identified for use in developing the State of the Art Literature and Practice Reviews for drinking water pipeline renewal in North America.

Table 3-6. Water Pipeline Renewal Technology Use Research Reports

	Title	Publisher	Year	System Type
1	Buried No Longer: Confronting America's Water Infrastructure Challenge	AWWA	2012	Both
2	Decision Support for Renewal of Wastewater Collection and Water Distribution Systems	EPA	2011	Both
3	Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains	EPA	2011	Both
4	State of Technology Review Report for Rehabilitation of Wastewater Collection and Water Distribution Systems	EPA	2009	Both
5	Designing a Framework to Guide Renewal Engineering Decision-Making for Water and Wastewater Pipelines	Virginia Tech	2010	Both
6	Guidelines for Pipe Bursting	Army Corps of Eng.	2001	Both
7	AWWA M28	AWWA	2001	DW
8	Performance Evaluation of Innovative Water Main Rehabilitation Cured-in-Place Pipe Lining Product in Cleveland, Ohio	EPA	2012	DW
9	Performance Evaluation of Innovative Water Main Rehabilitation Spray-on Lining Product in Somerville, New Jersey	EPA	2012	DW
10	Global Review of Spray-On Structural Lining Technologies	EPA	2010	DW
11	Control and Mitigation of Drinking Water Losses in Distribution Systems	EPA	2009	DW
12	Costs for Water Supply Distribution System Rehabilitation	EPA	2002	DW
13	The Clean Water and Drinking Water Infrastructure Gap Analysis	EPA	2002	DW
14	Multi-Agency Response to a Major Water Pipe Break: A Massachusetts Case Study and Evaluation	AMWA, WRF, WaterISAC	2011	DW
15	Evaulation of Trenchless Renewal Methods for Potable Water Distribution Pipes	UT Arlington	2010	DW
16	Testing & Design Life Modeling of Polyurea Liner for Potable Water Pipes	UT Arlington	2010	DW
17	AC Pipe in North America: Rehabilitation/Replacement Methods and Current Practices	NRC	2009	DW
18	Water Leak Detection and Repair Program	EPD	2007	DW
19	Review of Test Data and Field Trials for the MainSaver Process	TTC	2007	DW
20	Demonstration of Innovative Water Main Renewal Techniques	AWWA	1999	DW

Essentially any type of literature reviewed that was not a major industry association/organization report or research report fell in the category of "other literature sources". The most common forms of other literature sources reviewed were journal papers and conference proceedings. The primary sources considered in this state of the art literature review for pipeline renewal technology use include those that were focused on providing actual technology use information or that covered examples of technology uses in case studies.

3.3.2. Intent and Scope of Review

This State of the Art Practice Review will seek to define the true state of the industry with regards to drinking water pipeline renewal technology use. The content is based on the experiences of utilities captured through a series of technology use case studies that were developed as well as through interviews with key utility personnel. The objective of the review is to determine the following:

(1) Which technologies are being implemented by utilities and how often;
(2) How the technologies are being used in utility systems;
(3) General benefits/limitations of the technologies; and
(4) Primary cost drivers for technology applications.

This Review will provide the above determinations for utilities in North America as a whole and defines each in terms of the major technology categories defined above in the "*Pipeline Renewal Engineering Technology Background Information Section*" of this paper. The broad technology categories and classifications have been carefully selected to encompass the more specific technologies and products available in an effort to provide information on as many different technologies as possible.

3.3.3. Drinking Water Pipe Repair Technologies

Pipe repair is common practice for every infrastructure owner, and several technologies are typically kept on-hand by utility maintenance and repair crews to handle pipe repairs. One of the major issues encountered in waterlines is corrosion, both internal and external, which can lead to defects such as circumferential cracking and joint leaks. If the leaks or cracks that develop in the pipe walls or at joints are not sealed, water will be forced out into the surrounding soil and eventually lead to bedding washout and subsequent failure. (Dr. Ray Sterling, State of Technology Review Report on Rehabilitation of Wastewater Collection and Water Distribution Systems, May 2009)

Where defects are localized, repair technologies can be installed to help the pipeline live out its design life at significantly reducing costs compared to replacement of the entire pipe segment. Corrosion and leakage are reported to cause 61% of failures in ferrous force mains and 30% of failures in non-ferrous force mains (Robert Morrison, March 2010), highlighting the importance of pipeline repair since these failures could be prevented with through pipe repairs if located early on. The major industry reports considered related to drinking water pipe repair technology usage are shown in Table 3-7 below which also note the individual technology types covered within each report. Examples of literature sources for each technology type are provided in the sections below which discuss the state of the technology for drinking water pipeline repairs.

Table 3-7. Technologies Covered in Drinking Water Pipe Repair Technology Reports

Title	Water Pipeline Repair Technologies						
	Pipe Joint & Leak Seals			Pipe Point Repair		Pipe Coatings	
	Internal Pipe Sleeves	Grouting	Excavate & Repair	Excavate & Repair	Internal Repair Methods	Cementitious	Polymer Based
Rehabilitation of Wastewater Collection and Water Distribution Systems: State of Technology Review Report	X		X	X	X	X	X
State of Technology Report for Force Main Rehabilitation	X		X	X	X		X
Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains						X	X
Costs for Water Supply Distribution System Rehabilitation						X	X
Rehabilitation of Water Mains - Manual of Water Supply Practices, M28	X					X	X
Global Review of Spray-On Structural Lining Technologies						X	X

Pipe Joint & Leak Seal Technologies

Joints are the weakest point of a pipeline, with their performance being dependent on several different factors such as the health of the pipeline itself, seal integrity, internal/external pressures and loadings, water chemistry, groundwater, and the characteristics of the surrounding soils (Claudio Dittel, 2008). Examples of pipe joint and leak seal technology usage from literature are shown in Figure 3-4 below. It is used in the installation of other repair methods such as an internal sleeve where it is covered by a material that with more ability to withstand pressure and that is NSF 61 approved if the waterline is carrying potable water.

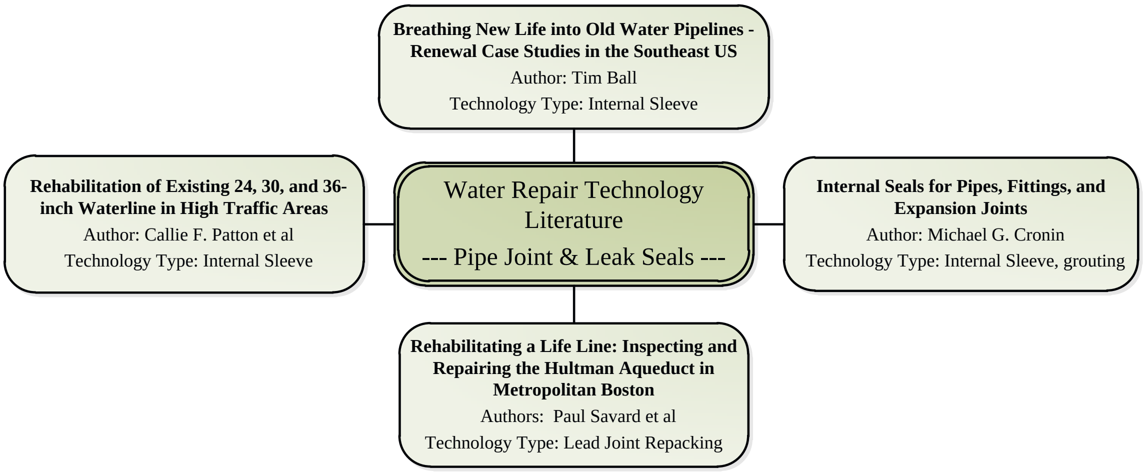


Figure 3-4. Pipe Joint & Leak Seal Technology Application Literature Sources

Based on literature, one of the most common methods for repair of joint defects that are not severely impacting the structural integrity of the pipeline are internal mechanical joint sleeves. The sleeves can be applied to pipelines with diameters greater than 16-inches and up to 216-inches, with larger sizes available on a case by case basis. Most examples of use in literature were for large diameter pipelines. Essentially, the technology consists of an elastomeric sleeve which is held in place by metal retaining bands, usually steel alloy. There are several issues to consider with regards to mechanical joint sleeves, the first of which is the requirement for man-entry. Also, since excavation is required more often than not because there are few existing access points on water main through which to gain entry into the pipeline. The sleeves have been used for leaking joints in potable pipelines as well as in other clean-water applications such as for the repair of a 120-inch carbon steel circulating water pipeline with expansion joints that carried raw water from a nearby river to a power plant (Croning, 2002).

Another application for the joint sleeves is the repair of bell and spigot joints which are very common in waterlines. The City of Houston used internal mechanical sleeves to repair cast iron water mains, while Cobb County Marietta Water Authority used them to repair PCCP water mains. Both pipe types had bell and spigot type joints. Additionally, the joint sleeves are used in situations where impacts to commercial and/or residential traffic as well as shut-down time are important considerations; internal sleeves can be installed quickly, reducing installation impacts for both issues. The City of Houston installations were on 24-, 30-, and 36-inch pipelines in areas where impacts to commercial and residential traffic were important factors (Callie F. Patton, 2006). Cobb County needed to minimize shut down time because the PCCP pipeline to be repaired was an 84-inch pipe at the treatment plant north of Atlanta with a circumferential that spanned the crown of the pipeline, extending down through both springlines (Ball, 2011).

A second internal option for repair of leaking bell and spigot joints is joint repacking. Traditional joints are packed with a water activated resin soaked fiber such as Oakum that is packed into the joint, activated so that it expands to completely seal the joint, made flush with the inside pipe surface, and covered with an appropriate mortar or grout which, if being used for a potable waterline, must be NSF 61 approved for such use (Prime Resins, 2010). Before making the repair, the mortar lining is removed from the pipe to expose the leaking gasket, and it was then repacked. The Massachusetts Water Resources Authority (MWRA) used this method in the repair of an 11.5-foot aqueduct after determining that it was more cost effective than other methods of repair such as point repairs using welded steel liner plates (Paul Sevard, 2011).

The oldest method for repairing joints requires local excavations at the site of the defect. If the joint condition is such that the structural integrity is compromised, the joint may be replaced completely. If the joint is sound enough for repair, the most common technology for excavated repairs is a full circumferential repair clamp installed to seal the leaking joint. There are specially designed repair clamps for waterlines that fit the traditional bell and spigot style joint. Prior to installation of the leak clamp, the joint of the pipe is often re-caulked to repair the seal as was typical practice in the City of Houston until the switch to internal methods was made (Callie F. Patton, 2006). Clamps are traditionally available in larger sizes for cast iron pipes than for PVC.

Pipe Point Repair Technologies

According to literature sources, it seems that most of the water pipeline point repairs are completed with either excavate and repair methods or with internal pipe wraps. Excavate and repair methods include replacement of short segments of the pipe, the installation of an external repair clamp, or the wrapping of the pipe exterior with a fiber-reinforced pipe wrap. Figure 3-5 provides examples of literature that discuss point repair technology applications.

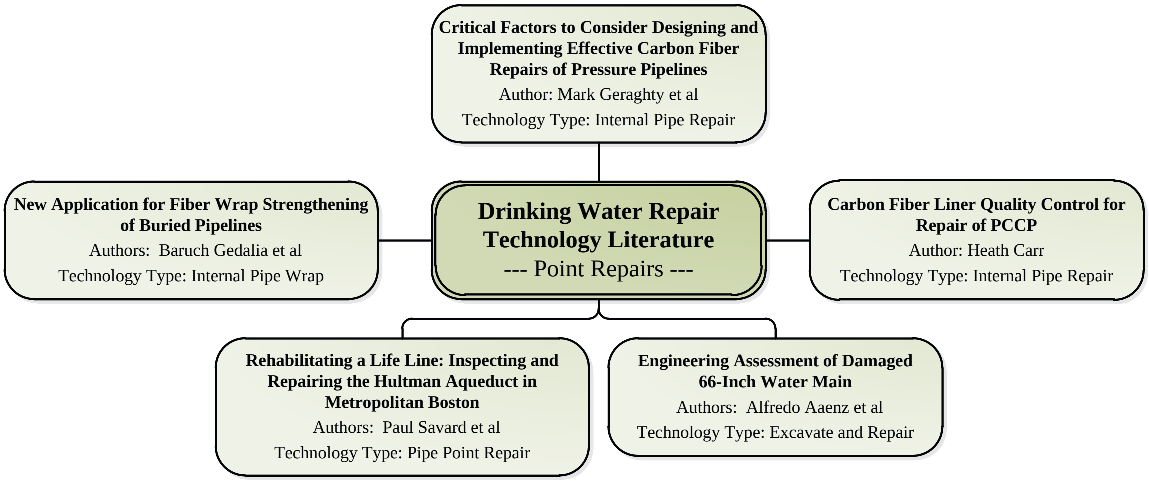


Figure 3-5. Pipe Point Repair Technology Use Literature Sources

Traditionally, excavate and repair techniques were most common for water main repair, and they are still standard protocol in the event of emergency failures where short segments of pipeline are often replaced. Where short segments of pipe need to be replaced, it is necessary to consider the potential need for special adapters or splicing mechanisms to join the new pipe segment to the original host pipe segments (Robert Morrison, March 2010). Full circumferential repair clamps can be used to seal leaks where the pipe wall is still structurally sound. Pipe repair clamps work by locking a flexible rubber gasket tightly against the location of the leak, thereby sealing it.

Another form of excavated point repair involves the application of a non-shrink cement grout that is allowed to harden on the exterior surface of the pipe so that it extends 1-foot past the defect in all directions. The grout is then covered with a Styrofoam material and the trench backfilled with approved cement-stabilized sand material. This method is discussed in a case study for the City of Houston for the repair of a 66-inch water main that required further rehabilitation but needed immediate attention (Alfredo Saenz, 2011).

A commonly implemented technology for point repair of waterlines is fiber-reinforced pipe wraps. These wraps can be applied to either the internal or exterior surface of the pipeline and are therefore both an internal and excavate and repair technology. Pipe wraps are particularly common for repair of PCCP water mains where the number of broken wires creates the need for structural repair. Howard County, MD used the fiber reinforced polymer (FRP) wrap to structurally repair a 66-inch PCCP transmission main where the construction of a railroad could not begin until the repairs were made (Mark Geraghty, 2010). Geraghty also provides an example for emergency repair in San Diego, CA for two large diameter pipelines, 84-inch and 96-inch, with high working pressures and strict limits on shut down time.

The Metropolitan Water District of Southern California (MWDSC) applied the FRP wrap to defects in a 201-inch feeder line that were 1,200 feet and 2,400 feet away from the closest access points. The feeder line carried water to surrounding districts, so shut down time needed to be minimized (Carr, 2007). Carr provides a great deal of information outlining the importance and steps involved in proper installation, highlighting the importance of quality control procedures and providing a number of reference documents for quality control of FRP wraps. Installation procedures are stressed in other literature sources as well, including the paper by Mark Geraghty that was discussed above.

The literature suggests that FRP wraps are particularly useful for PCCP pressure pipe applications with large diameter pipes that require structural reinforcement. When a 66-inch waterline beneath a major interstate ruptured in Denver, CO, FRP wrap was used to reinforce the newly installed pipe because the pipe alone did not have an adequate pressure rating. Layers of carbon fiber and glass fiber composites were used, with the glass fiber reinforced wrap required to prevent galvanic corrosion between the steel and carbon fiber material (Baruch Gedalia, 2010).

Pipe Coating Technologies

The primary coating for water mains in the United States is cement mortar lining which is the only coating technology with an available specification from AWWA (Dr. Ray Sterling, State of Technology Review Report on Rehabilitation of Wastewater Collection and Water Distribution Systems, May 2009). Besides cement mortar, epoxy is the only other coating material addressed by the AWWA Manual M28 for Rehabilitation of Water Mains. Examples of literature that provide examples of pipe coating applications are shown in Figure 3-6 below.

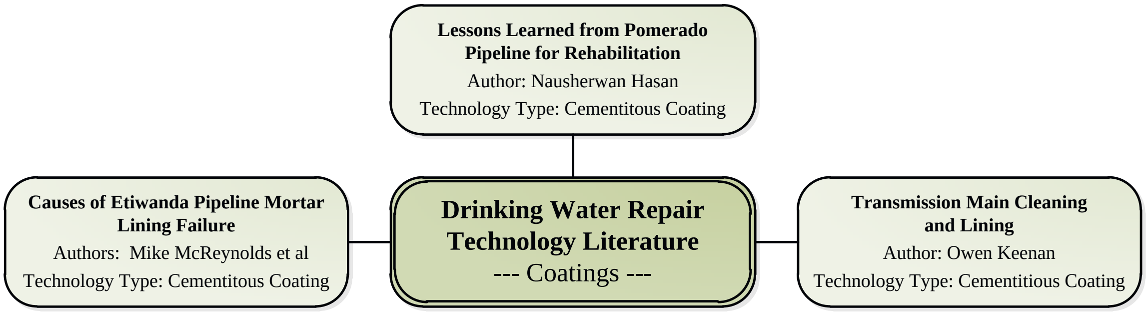


Figure 3-6. Pipe Point Repair Technology Use Literature Sources

Cement mortar coatings are used to maintain or slightly improve pipeline capacity by providing a smooth interior surface and preventing the development of tuberculation (Keenan, 2006). In his paper, Keenan provides examples of three different cases where cement mortar lining is applied to 30- and 36-inch cast iron water mains. The benefits were increased residual pressure, increased capacity, and smoother internal pipe surface, but the author also notes that excavations are required at all service connections and appurtenances, increasing shut down time but still significantly reducing costs compared to replacement. In much the same way, the City of San Diego (Hasan, 2008) used cement mortar to coat a new pipe after rehabilitation of a PCCP water main with steel liners and faced time constraints paired with restrictions to night work only due to the location of the pipeline.

Cement mortar coatings are prone to early failure if design and installation are not carried out correctly. The Metropolitan Water District (MWD) outside of Los Angeles experienced premature failure of a 144-inch, 5.3 mile long welded steel feeder pipe that was lined with a ¾-inch thick layer of cement mortar in the early 1990’s. Lining failure in that case was extreme, and long sections of the pipeline had delaminated mortar or was missing the mortar altogether. Constant pressure fluctuations and the size of the pipe were thought to be causes of the failure, and in hindsight, a flexible lining would have been more appropriate for a pipeline with such variations in stress levels. (Mike McReynolds, 2010) The author provides pictorial examples of the lining failures and as well as an example from LADWP and Saudi Arabia where linings failed prematurely due to temperature fluctuations and corrosion caused by high Chlorine-ion content in the salt water it carried, respectively. These examples were discovered by MWD during their research into other utility experiences with similar cement mortar failures.

The use of spray on polymer-based coatings is a common practice in other countries such as the United Kingdom but is just beginning to catch on in the United States. This could be a potential reason for the lack of available literature on polymer-based coating applications. Epoxy coatings are somewhat common for bridging small cracks and gaps as well as for corrosion control, but they are not ideal for high-build applications due to their long curing time.

3.3.4. Water Pipe Rehabilitation Technology Usage

The technologies available for waterline renewal continue to advance, and this paired with other benefits such as decreased social and environmental disruption and reduced project costs have led to steadily increasing sources for literature on rehabilitation technology uses. Table 3-8 below provides a list of the major research reports that provide information on rehabilitation technology usage, noting the technologies addressed within.

Table 3-8. Technologies Covered in Drinking Water Pipe Rehabilitation Technology Reports

Title	Drinking Water Pipeline Rehabilitation Technologies														
	CIPP Liners			FFP Liners		GIPP Liners			SIPP Liners		Sliplining		Modified Sliplining		
	Felt Hose Liners	Woven Hose Liners	Fiber-Reinforced Hose Liners	Thermoformed PVC Liners	Deform/Reform PE Liners	Spiral Wound Liners	Tube Liners	Panel Liners	Cementitious	Polymer Based	Continuous	Segmental	Deformed HDPE	Radial Reduction	Expand in Place PVC
Rehabilitation of Wastewater Collection and Water Distribution Systems: State of Technology Review Report	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
State of Technology Report for Force Main Rehabilitation	X	X	X	X	X	X			X	X	X	X	X		X
Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains								X	X	X					
Costs for Water Supply Distribution System Rehabilitation	X	X	X	X	X						X	X	X	X	
Demonstration of Innovative Water Main Renewal Techniques		X	X											X	
Rehabilitation of Water Mains - Manual of Water Supply Practices, M28	X	X	X	X	X				X	X	X	X	X	X	X
Global Review of Spray-On Structural Lining Technologies									X	X					
Evaluation of Trenchless Renewal Methods for Potable Water Distribution Pipes	X	X	X	X	X				X	X	X	X	X	X	
TTC Evaluation Report: Review of Test Data and Field Trials for the MainSaver Process							X								

Cured in Place Pipe (CIPP) Liner Technology Usage

CIPP Liners are not as common for drinking water applications as for wastewater applications. A traditional CIPP liner utilizes a felt tube impregnated with polyester or styrene resin but is not used for waterline rehabilitation because it does not have an adequate pressure rating, and styrene resins are not approved for use in potable water applications. The two common types of CIPP Liner for water pipe applications are woven hose liners and fiber-reinforced hose liners. It was surprisingly difficult to find publications documenting the use of these technologies within utilities in North America which is an indication of the innovative nature of the technologies. Examples for water pipe CIPP installations are shown in Figure 3-7 below.

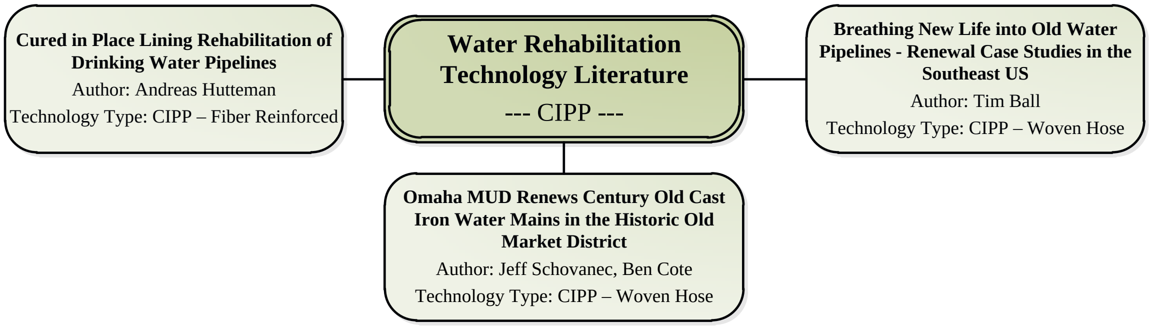


Figure 3-7. Pipe Rehabilitation Technology Use Literature Sources

CIPP liners for waterlines are limited to use in pipes up to 60-inches in diameter, and whereas it is a completely trenchless technology for sewer applications, it requires at least two excavations to provide access to a waterline (Behnam Hashemi, 2011). The technologies must also obtain the NSF 61 certification for materials such as the resin that would potentially come in contact with the water. All of these factors make CIPP Liners less common for waterline than for sewerline applications.

Charleston Water System (CWS) utilized a woven hose liner to structurally rehabilitate an 8-inch cast iron and ductile iron water main, with a portion of the cast iron pipe having been previously lined with cement mortar. The location of the project was in a somewhat remote location where the installation would have little to no impact on the public, and there were no active service connections on the portion of the main to be lined. (Ball, 2011) These two factors make the location great for a pilot project, but realistically, these are two very important factors to consider when choosing a technology.

A more accurate reflection of technology application was documented by the City of Omaha who utilized a woven hose CIPP Liner to rehabilitate portions of a 10-inch and a 12-inch pipeline, both of which were located in an old historic part of the City. The project dealt with a number of individual lining segments, multiple excavations, active and inactive service connections, appurtenance replacement, and setup of a temporary bypass system. (Jeff Schovanec, 2011) This paper presents considerations for installation costs as well as comparisons to traditional open trench replacement.

Fiber-reinforced CIPP Lining technology was used in the Czech Republic to rehabilitate various lengths of pipeline in rough terrain and with bends ranging from 11° to 30° (Huttermann, February 2008). All examples of use for use of this type of liner were from other Countries, suggesting that it has not yet caught on in the United States.

Fold and Form Pipe (FFP) Liner Technology Usage

It was difficult to locate literature that documented the use of FFP Liners in the United States, though there are examples of use in foreign countries such as the United Kingdom. One example of a FFP Liner installation in the U.S. provided in the document listed in Figure 3-8 below.

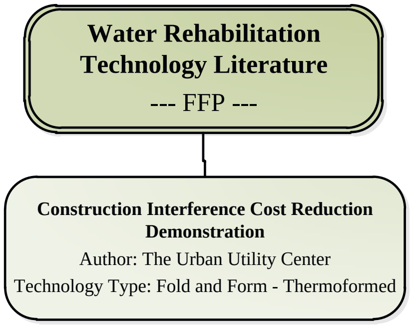


Figure 3-8. Pipe Rehabilitation Technology Use – FFP Liner Literature Sources

In the United Kingdom, the use of fold and form thermoformed liners is common for water main and other pressurized pipe system rehabilitation, but not in the U.S. The St. Louis County Water Company (SLCWC) used a FFP Liner to rehabilitate three 6-inch distribution mains beneath high-traffic railroad tracks (Urban Utility Center, 2005). This was, however, only a pilot of the technology for the water company, highlighting the infant state of this rehabilitation method in the U.S.

Grout-in-Place Pipe (GIPP) Liner Technology Usage

Most GIPP Liner technologies available, like other rehabilitation technologies, are more frequently used in wastewater system applications, but there were multiple examples of steel GIPP liners, especially for large diameter PCCP transmission mains. The literatures sources shown in Figure 3-9 provide good examples of the liner installations and design/construction considerations.

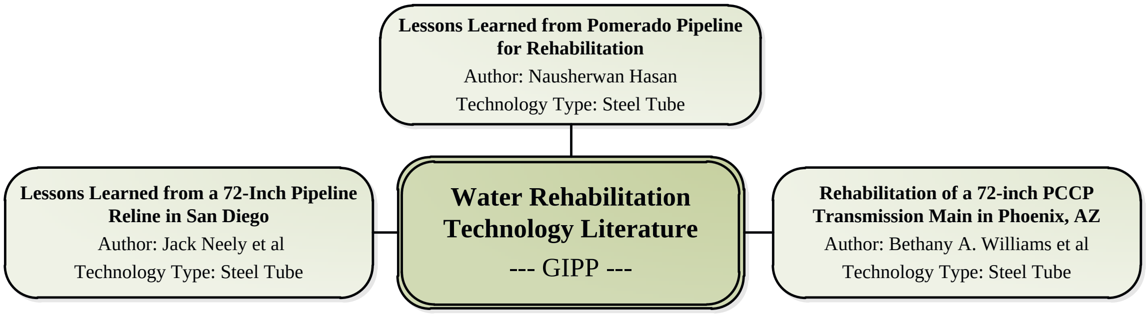


Figure 3-9. Pipe Rehabilitation Technology Use – GIPP Liner Literature Sources

The City of Phoenix used a "solid can" type steel liner to rehabilitate a 72-inch diameter PCCP transmission main which involved the insertion of a steel liner that was banded to prevent the liner plates from expanding until they were in within the host pipe (Bethany Williams, 2006). Grout was injected around the steel liner once it was expanded to fill the annular space and anchor the liner to the host pipe. A thin coating of mortar was then applied to protect the steel material from corrosion. The San Diego County Water Authority used the same method to rehabilitate two segments of a pipeline, one 69-inches and the other 84-inches in diameter; the resulting loss in internal diameter totaled 3-inches for each segment. (Hasan, 2008). The utility also used it to rehabilitate a 72-inch PCCP transmission main, though the focus of this paper was on the design issues of project related to the site location environmental sensitivities and close proximity to residential neighborhoods rather than the construction phase of the project (Jack Neely, 2009).

Sprayed-in-Place Pipe (SIPP) Liner Technology Usage

Though cementitious and polymer based materials have been used for years as non-structural coating technologies, SIPP Liners are a relatively new technology that uses the same materials to achieve semi- or fully-structural rehabilitation solutions. The technology is still innovative, but two examples of use are provided in the literature sources in Figure 3-10.

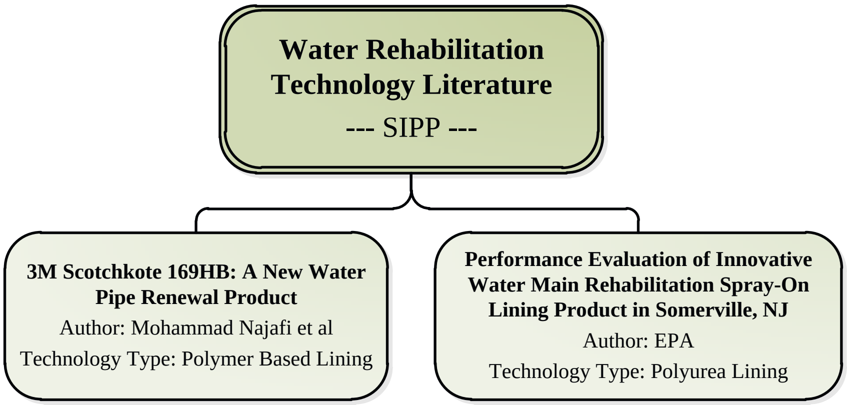


Figure 3-10. Pipe Rehabilitation Technology Use – SIPP Liner Literature Sources

There are several literature sources available that provide lab testing results for SIPP Liners such as Pipeline Rehabilitation with Fiber-Reinforced Mortar Lining by G.K. Luk for cementitious linings and Testing and Evaluation of a New Potable Water Pipe Renewal Product by Trupti Kulkarni et al. and the Water Research Foundation report titled Global Review of Spray-On Structural Lining Technologies for polymer based linings. The EPA performed a pilot project in Somerville, NJ to test the installation of a high-build polymer based lining as a semi-structural solution since the host pipe still needs to have some degree of structural soundness. This application failed, however, leading to the conclusion that high-build lining materials still require some research before they will be ready for a full integration into the market.

Modified Sliplining Technology Usage

Modified sliplining can be used in water pipe rehabilitation, with examples of use demonstrated by the literature shown in Figure 3-11. As with so many other rehabilitation technologies for waterlines, other countries such as Australia and the UK much more experience with this technology.

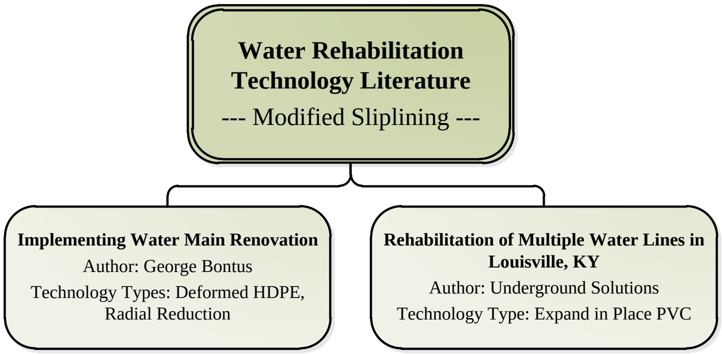


Figure 3-11. Pipe Rehabilitation Technology Use – Modified Sliplining Literature Sources

Louisville Water used an expand-in-place PVC technology to rehabilitate approximately 2,000 LF of water mains with diameters ranging from 6- to 12-inches at several locations throughout their system (Underground Solutions, 2012). The City of Amarillo, TX used a radial reduction technology to provide a class IV, fully structural rehabilitation solution (Matt Wassam, 2011). Perhaps the best example of radial reduction found in literature was by the City of Calgary who used modified sliplining to rehabilitate a 12-inch water main that ran through residential areas and where open cut would have had too great an impact on matured spruce trees (Bontus, 2008).

Sliplining Technology Usage

Sliplining is a well-known method for rehabilitation, but it is not ideal in many cases because of the associated loss in diameter. Most of the major technology reports address sliplining in a general sense, though nearly all of the examples in literature were for large diameter rehabilitation. Figure 3-12 lists three case studies found in literature that document the use of sliplining.

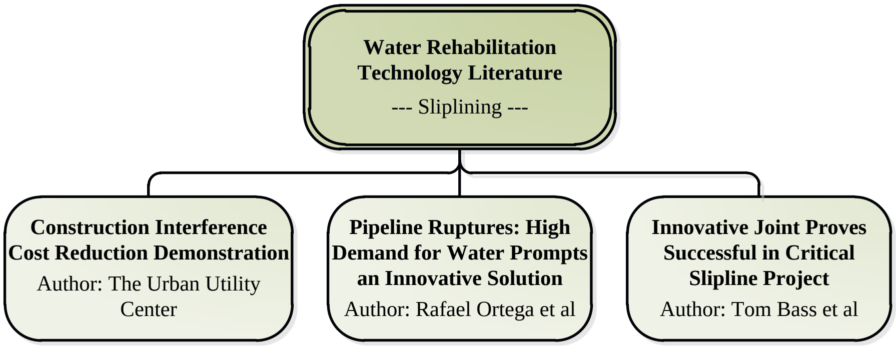


Figure 3-12. Pipe Rehabilitation Technology Use – Modified Sliplining Literature Sources

Halifax Water in Nova Scotia used sliplining to rehabilitate a 48-inch PCCP transmission main with a spirally welded steel pipe that utilized a unique O-ring rubber-gasket joint (Tom Bass, 2011), and in Ottawa, a 914-mm cast iron water main was sliplined with an 840-mm HDPE pipe (Urban Utility Center, 2005). This paper focused on the benefits of sliplining in an urban area where the utility could not afford to lose capacity.

3.3.5. Water Pipe Replacement Technology Usage

Pipe replacement is the most common form of renewal, with dig and replace methods being the preferred alternative for water utilities across the United States. Innovative replacement technologies have allowed the installation of waterlines in otherwise challenging locations such as beneath wetlands or surface structures. Table 3-9 below provides a list of the major research reports that provide information on replacement technology usage.

Table 3-9. Technologies Covered in Drinking Water Pipe Replacement Technology Reports

Title	Water Pipeline Replacement						
	In-Line Pipe Replacement				Off-Line Pipe Replacement		
	Pipe Bursting	Pipe Reaming	Exhume & Replace	Other In-Line Pipe Removal	Pipe Jacking & Utility Tunneling	Horizontal Earth Boring	Abandon & Replace
Rehabilitation of Wastewater Collection and Water Distribution Systems: State of Technology Review Report	X	X	X	X	X	X	
State of Technology Report for Force Main Rehabilitation	X	X	X		X	X	X
Quality Assurance and Quality Control Practices for Rehabilitation of Sewer and Water Mains	X						
Costs for Water Supply Distribution System Rehabilitation	X				X	X	X
Demonstration of Innovative Water Main Renewal Techniques	X						

In-Line Pipe Replacement Technology Usage

In-line pipe replacement is an effective means of replacement when the density of underground infrastructure makes using the existing soil tunnel most desirable, but there are other factors to consider as well such as the number of service connections and temporary bypass requirements. Figure 3-13 below lists three papers that provide examples of use for multiple in-line replacement technologies.

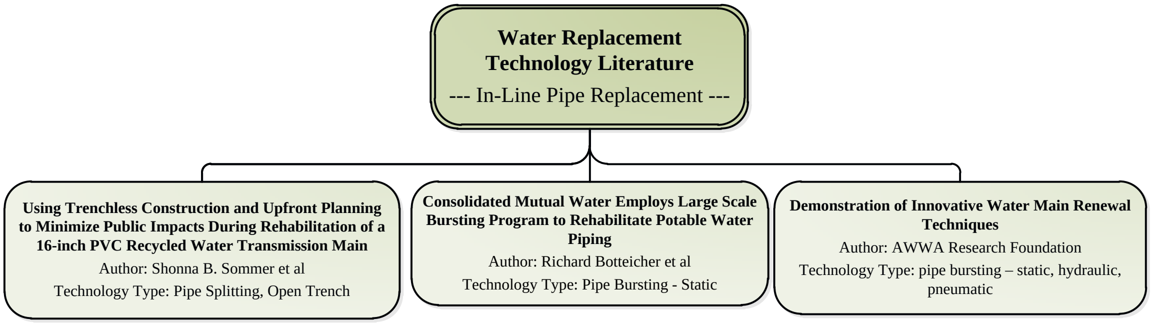


Figure 3-13. Pipe Replacement Technology Use – In-Line Replacement Examples

There are two heavily cited forms of waterline replacement, open trench and pipe bursting. Open trench methods are so common-place now that the methodology is not often included in case study papers. Instead, trenchless technologies such as pipe bursting are used and then compared to the costs or impacts of open trench. (Behnam Hashemi, 2011) (Richard (Bo) Botteicher, 2011)

In other cases, open trench is used to supplement trenchless methods. The Calleguas Municipal Water District in California used pipe splitting to replace a 16-inch PVC recycled water transmission main that had failed seven times in the same area within 12 years (Shonna B. Sommer, 2009). One of the limitations of trenchless methods is that open-cutting is still required at every connection, valve, etc. In this case, pipe splitting was the primary technology used in the project, but open trench was used on segments of the pipeline where the number of connections or type of connection (tee connection in a busy intersection for example) made pipe splitting uneconomical.

Because of the popularity that pipe bursting in particular has gained, utilities are in some cases beginning to start their own “in-house” replacement crews that are certified for pipe bursting installation procedures such as joint fusion for thermoplastic pipes. Consolidated Mutual Water Company outside of Denver did just this, getting their technicians certified for fusion of fusible PVC joints and proper installation techniques so that all pipe bursting could be done through an in-house program (Richard (Bo) Botteicher, 2011) . This reduced costs by eliminating the bid process for all bursting projects as well as costs associated with third parties such as contractors or consultants.

Two, more specific pipe bursting projects were completed by the cities of Chicago and Houston. In Chicago, static pipe bursting was used to replace a 6-inch cast iron water main with an 8-inch ductile iron, bell-less joint pipe. Houston used hydraulic pipe bursting to replace a 6-inch cast iron pipe with a 6-

inch HDPE pipe. The City also used an 8-inch HDPE sleeve to protect the 6-inch HDPE pipe because of the fear that settled pieces of cast iron left over from the burst would damage the new HDPE material in the future. Houston also completed a pneumatic pipe bursting project to replace a 6-inch asbestos cement pipe with a 6-inch HDPE pipe. (Arun K. Deb, 1999)

Off-Line Pipe Replacement Technology Usage

Off-line pipe replacement technologies include those used for open trench projects, pipe jacking & utility tunneling, and horizontal earth boring. All of these are common practices for pipe installation, and there is a significant quantity of information available for these technologies. Figure 3-14 lists examples of literature that provide details for off-line replacement technology usage.

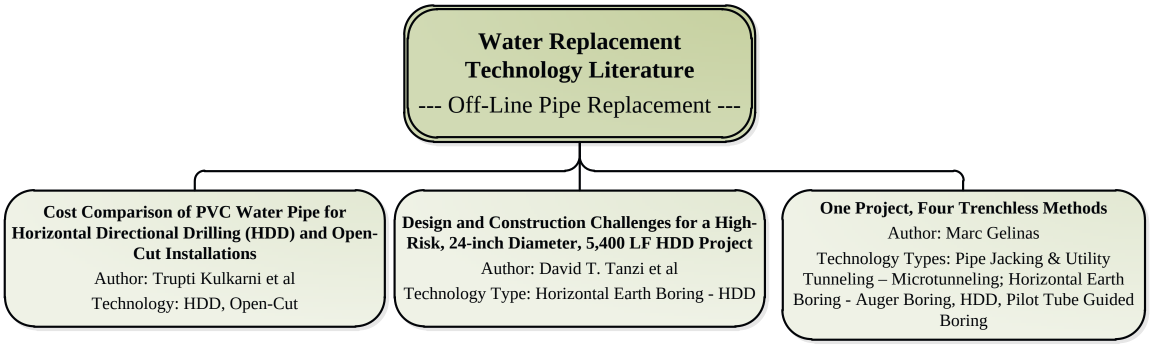


Figure 3-14. Pipe Replacement Technology Use – Off-Line Replacement Examples

Many replacement projects are completed in conjunction with other forms of renewal. In the Alameda County Water District service area in California, a pipe replacement project had a number of difficult crossings. The District used Microtunneling beneath the interstate; Auger Bore and Jack Tunneling beneath the aqueduct; Horizontal Directional Drilling (HDD) beneath the major arterial roadway; and Pilot Tube Guided Boring beneath a second major arterial roadway. (Marc Gelinas, 2010) This case study is useful in explaining why technologies were chosen as well as how they were used.

The City of Athens, Texas used HDD to replace a cast iron pipe with a new 6-inch restrained joint PVC pipe on a parallel alignment, while the City of Eastland, TX used HDD to replace an undersized 2-inch cast iron waterline with a 6-inch PVC pipe. Clay County, FL did essentially the same thing, replacing a 2-inch cast iron pipe with a 4-inch PVC pipe. (Trupti Kulkarni, 2011) This paper also discusses the cost per linear foot of open-trench versus HDD which is an important determinant in technology selection. All of these case studies document the transition from more traditional cast iron pipe to the more recent favorite, plastic. Middlesex Water Company also made the switch, using HDD to replace a 24-inch cast iron pipe with a 24-inch Fusible PVC (David J. Tanzi, 2011)

3.4. State of the Art Practice Review for Drinking Water Pipeline System Renewal Technologies

3.4.1. Introduction

There is often an apparent disconnect between the state of the industry as portrayed by academia through research reports and conference/journal publications and the true state of the industry in the eyes of the actual infrastructure owners. Industry conferences and journals are excellent methods for academics and technology providers to showcase innovative technologies and advanced technology applications, and while these outlets are useful for raising awareness of solutions available to solve pipeline system problems, they capture only snapshots of the complete picture.

In the past, academics, industry professionals, and infrastructure owners alike have been able to easily collect information from existing literature sources on the vast array of products available in the market today, but the literature is not necessarily an accurate representation of the technologies most commonly used in practice. Technology providers are also more than willing to supply information on their technologies, but this information only provides a picture of what is available to infrastructure owners. In reality, most of the water and wastewater utilities in the United States only utilize a handful of the technologies available to them.

3.4.2. Intent and Scope of Review

This State of the Art Practice Review will seek to define the true state of the industry with regards to drinking water pipeline renewal technology use. The content is based on the experiences of utilities captured through a series of technology use case studies that were developed as well as through interviews with key utility personnel. The objective of the review is to determine the following:

1. Which technologies are being implemented by utilities and how often;
2. How the technologies are being used by utilities in their systems;
3. General benefits and limitations of the technologies; and
4. Primary cost drivers for technology applications.

This Review will provide the above determinations for utilities in the United States as a whole and defines each in terms of the drinking water pipeline renewal technologies listed above in the “Background Information Section” of this thesis. There are an incalculable number of technologies available for drinking water pipeline renewal and even more products that make use of different combinations of technologies, making it impossible to address every technology available in the industry today. The broad technology classifications and types have been carefully selected to encompass the more specific technologies and products available in an effort to provide useful information on as many different technologies as possible.

3.4.3. Approach

Drinking water utility participation was essential to a thorough investigation of the true state of the industry. Utilities all across the nation and even were contacted to participate in the initiative to document overall utility experiences with drinking water pipeline renewal technologies, and 17 full and 5 abbreviated case studies were developed to capture as complete a picture as possible. At the end of the development period for full case studies which require a great deal of data and time to develop, abbreviated case studies were developed that captured only the basic information of technology use including, but not limited to, information such as technology type, product name, project location and conditions, project length, pipe types and materials involved, and benefits/limitations for use.

The objective of case study development was to provide a clear view of the state of the drinking water industry related to pipeline renewal technology use, so it was desirable to cover an even distribution of technology types as well as an even geographic distribution of utilities. Table 3-10 shows the distribution of renewal types covered by the case studies. Figure 3-15 below shows the name and geographic location of utilities for which case studies were developed, with blue dots denoting locations for which full case studies were developed and red pins denoting locations where abbreviated case studies were developed. Upon review of the case study by the utility involved and an expert on the topic, case studies will be published in the new Water Infrastructure Database, WATER*i*D (www.waterid.org). Case studies for technology uses across the nation were able to be captured, with the exception of EPA Region 7 which includes Kansas, Missouri, Iowa and Nebraska. While initial meetings were held with people in that region, either timing was not appropriate for them to participate or there were critical issues with the transfer of private data.

Table 3-10. Water Technology Case Study List and Distribution

Full Case Studies	
Repair	3
Rehabilitation	5
Replacement	9
Total	**17**

Abbrev. Case Studies	
Repair	1
Rehabilitation	4
Replacement	0
Total	**5**

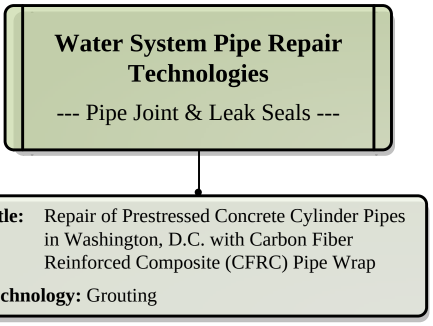
Figure 3-15. Geographic Distribution of Case Studies

3.4.4. Water System Pipe Repair Technology Use in Practice

Three full case studies and one abbreviated case study were developed for pipe repair technologies. However, most of the project included the use of multiple technology types and will appear below more than once as the case studies are discussed below by technology type.

Pipe Joint and Leak Seal Technologies

There was one case study that dealt with pipe joint and leak seal technologies as shown in Figure 3-16 below, but it is worth noting that the joint sealing method was not the primary focus of the case study.



Water System Pipe Repair Technologies

--- Pipe Joint & Leak Seals ---

Title: Repair of Prestressed Concrete Cylinder Pipes in Washington, D.C. with Carbon Fiber Reinforced Composite (CFRC) Pipe Wrap

Technology: Grouting

Figure 3-16. Water System Repair Technology Case Studies – Pipe Joint and Leak Seals

In order to prepare the interior of the pipeline for the application of the internal pipe wrap, there were several defects that had to be addressed. If the surface was not properly repaired, the pipe wrap would be unable to properly adhere to the pipe wall. Internal joint parging, patching of the outer coating, or patching of the internal lining were performed with a high-strength, polymer modified cementitious mortar.

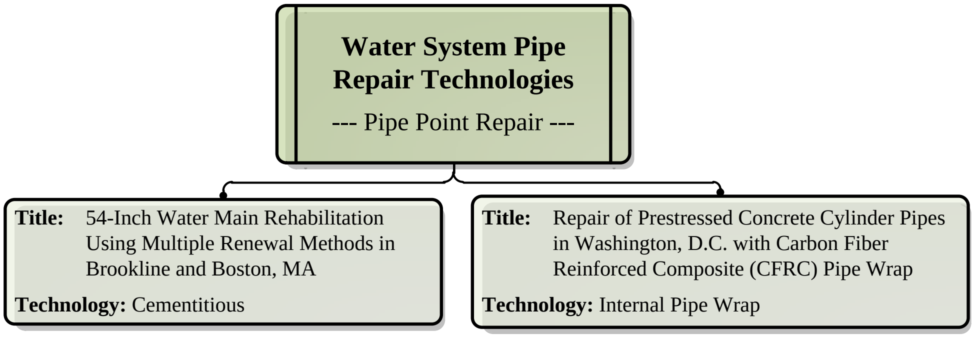


Figure 3-17. Water System Repair Technology Case Studies – Pipe Point Repairs

Pipe Point Repair Technologies

One case study dealing with pipe point repair technologies was developed, as shown in Figure 3-17 above.

The Washington Suburban Sanitary Commission (WSSC) used an internal pipe wrap that was adhered to the internal pipe surface and did not, therefore, require grouting. Two different types of pipe wrap were used: a glass-fiber reinforced polymer (GFRP) wrap and a carbon-fiber reinforced polymer (CFRP) wrap. One layer of the GFRP wrap was applied in a longitudinal direction, followed by 2-6 layers of hoop CFRP wrap depending on the amount of structural support the defect required for repair.

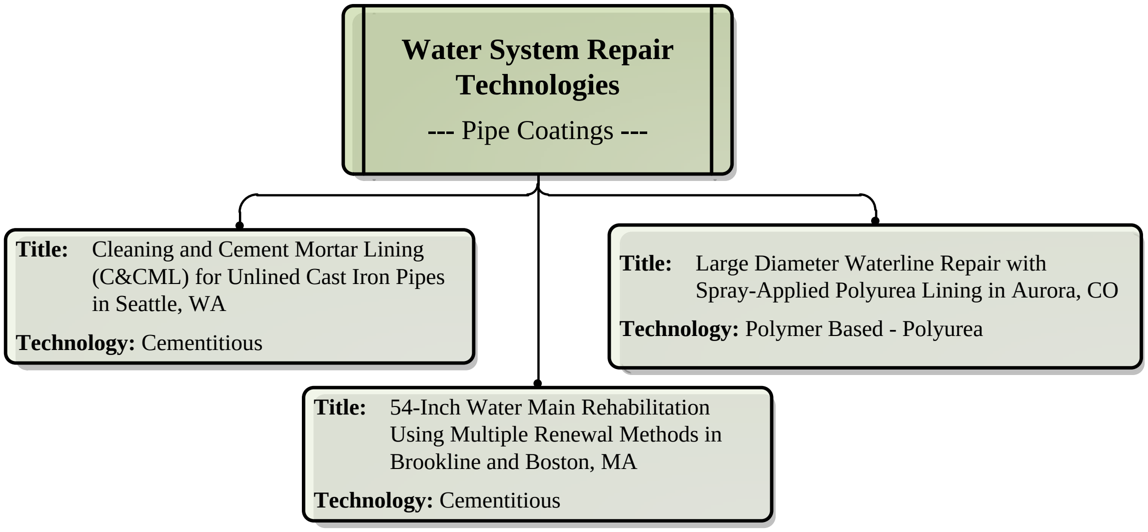


Figure 3-18. Water System Repair Technology Case Studies – Pipe Coatings

Pipe Coating Technologies

There were three case studies developed that dealt with non-structural pipe coating technologies, and these are shown in Figure 3-18 above.

As a general rule, there were many more utilities that used cementitious linings because of the transmission main cleaning and cement mortar lining (C&CML) programs that were in place. Seattle Public Utilities began this program in June of 2003 with a neighborhood in northwestern Seattle which included the lining of approximately 19,000 linear feet of 8, 10, and 24-inch diameter unlined cast iron water mains. MWRA also used C&CML as part of the rehabilitation of the 54-inch Water Main in Brookline and Boston, MA. Both utilities used it as a class I, non-structural coating to prevent corrosion, inhibit the growth of tubercles on the interior pipe walls, and improve water quality. For Seattle, it was a significant undertaking because approximately 37% (~ 700 miles) of their system, as of 2007, was unlined cast iron pipe.

The other type of pipe coating is polymer based which was used in Aurora, CO to prevent further degradation due to corrosion in a 66-inch welded steel pipeline suspended along the spillway channel of a dam. It was previously lines with a tar coal epoxy interior coating, but it had deteriorated over time and now had areas of blistering, disbondment, and minor pitting as well as complete failure. A number of different repair technologies were evaluated for use before a polyuria coating was chosen, and the primary cited benefit of polyuria above all other lining options was its short cure time.

3.4.5. Water System Pipe Rehabilitation Technology Use in Practice

Five full case studies and four abbreviated case studies were developed for pipe rehabilitation technologies. Each of the rehabilitation technology categories is discussed separately below with details about the technologies covered in utility case studies.

Cured-in-Place Pipe (CIPP) Liner Technologies

There were two case studies developed for CIPP Liners as shown in Figure 3-19 below, both of which dealt with woven hose liners. CIPP lining of water mains is not a common practice but is becoming more common as technologies improve and become more cost effective for utilities to use.

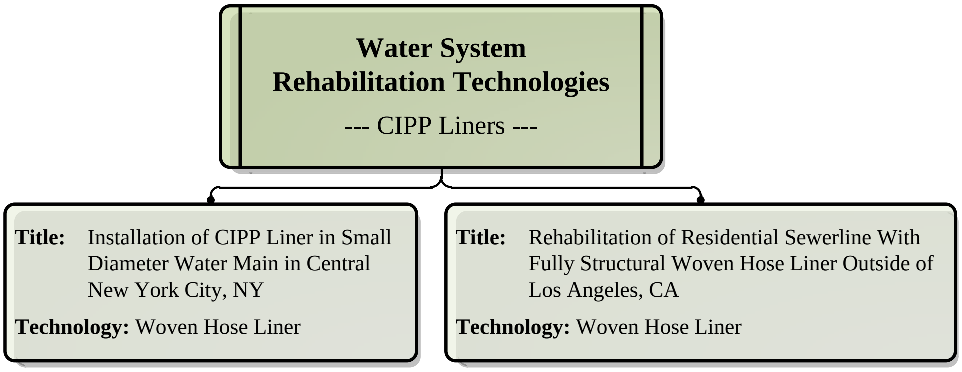


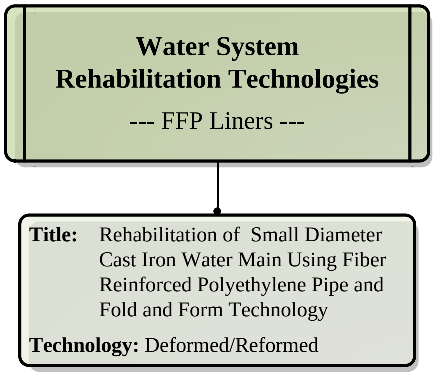
Figure 3-19. Water System Rehabilitation Technology Case Studies – CIPP Liners

The Los Angeles Department of Water and Power (LADWP) used a woven hose CIPP Liner to rehabilitate 8-inch steel and 8-inch cast iron water mains in residential areas in early 2000. The utility needed an NSF 61 liner approved for use in potable water mains and also needed a Class IV fully structural solution. The installation was successful, but it is not a commonly used method for water main rehabilitation in their system.

The New York Department of Design and Construction (DDC) also installed a woven hose liner, but this was in 2010, a decade after the LADWP installation. DDC chose to use the proprietary product because a current water main replacement segment in Manhattan had a short segment of pipeline that was ideal for a pilot test of the new product. The 12-inch cast iron water main would only require 230 LF of lining, but most importantly, the segment was straight and had only one active service connection. The project only took 1 week to complete.

Fold and Form Pipe (FPP) Liner Technologies

There were no full case studies developed for FFP Liners, but one abbreviated case study was found as shown in Figure 3-20 below.


Water System Rehabilitation Technologies

--- FFP Liners ---

Title: Rehabilitation of Small Diameter Cast Iron Water Main Using Fiber Reinforced Polyethylene Pipe and Fold and Form Technology

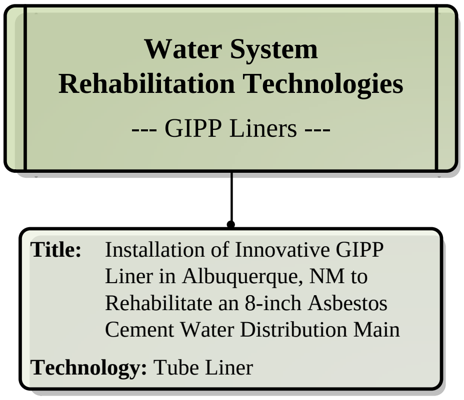
Technology: Deformed/Reformed

Figure 3-20. Water System Rehabilitation Technology Case Studies – FFP Liners

The Town of Highland, IN had a problematic 8-inch cast iron water main that had an extensive history of circumferential breaks along one portion of the pipeline buried under 10-inch thick concrete pavement with heavy traffic. When the main finally failed, the water pressure damaged the wall of a residential basement, and the Town began investigating alternatives for renewal. The main issues were associated with gaining access to the pipeline and with adjacent utilities/obstructions. A number of exhume or abandon in place alternatives were evaluated, as well as a three trenchless technologies (pipe bursting, a CIPP Liner and a FFP Liner). The FFP Liner was chosen based on its installation cost, its burst strength, its ability to maintain flexibility after installation and reduce the likelihood of shear failure, and its ability to provide a fully structural solution independent of the host pipe. The installation of this technology was significant because of the challenging site conditions, but it was also significant because there were only two other agencies in the United States that had installed the technology. Over 250,000 LF of the product have been installed in Britain, once again highlighting a lag between technology availability and implementation in the United States versus other countries such as Britain or the UK.

Grout-in-Place Pipe (GIPP) Liner Technologies

There were no full case studies developed for GIPP Liners, but one abbreviated case study was created as shown in Figure 3-21 below. This is not a technology commonly used to rehabilitate water pipelines.


Water System Rehabilitation Technologies

--- GIPP Liners ---

Title: Installation of Innovative GIPP Liner in Albuquerque, NM to Rehabilitate an 8-inch Asbestos Cement Water Distribution Main

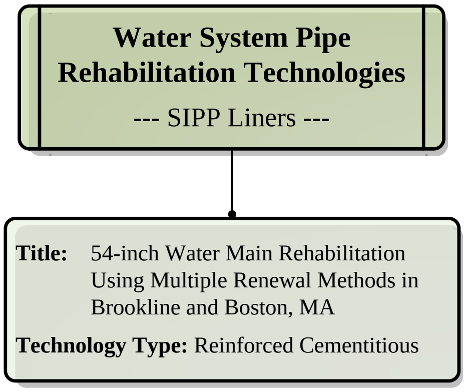
Technology: Tube Liner

Figure 3-21. Water System Rehabilitation Technology Case Studies – GIPP Liners

The City of Albuquerque, NM chose an innovative GIPP Liner to rehabilitate an 8-inch asbestos cement water distribution main and was the first to try the product commercially in North America. There were a couple of significant challenges during installation, the first of which was maintaining tension during pull-in. A vacuum is pulled to deflate the liner before the liner is installed, but in the first two installation segments, the tension was not maintained. When the tension was released, the liner tended to fold, increasing resistance to the swabbing pig which is sent through the pipeline after insertion to re-round the liner and allow grout to be injected into the annular space between the liner and host pipe. At one point, the pig got stuck, and the pressure had to be increased significantly to keep pushing it down the line. This resulted in the liner ends splitting, but because the splits were so close to the pipe end, the pig was pushed past the split to pressurize the pipeline and keep the liner tight against the host pipe until the grout cured. Grout dispersal was determined to be the biggest problem with the installation, but this was solved if the liner did not lose tension during deflation.

Sprayed-in-Place (SIPP) Liner Technologies

There was not a full case study developed for SIPP Liner technologies, but an abbreviated case study was created as listed below in Figure 3-22.



Water System Pipe Rehabilitation Technologies

--- SIPP Liners ---

Title: 54-inch Water Main Rehabilitation Using Multiple Renewal Methods in Brookline and Boston, MA

Technology Type: Reinforced Cementitious

Figure 3-22. Water System Rehabilitation Technology Case Studies – SIPP Lining

The Massachusetts Water Resources Authority (MWRA) used reinforced concrete lining as a Semi-Structural rehabilitation method for rehabilitation of a segment of 54-inch water main as part of a much larger rehabilitation project. A layer of cement lining was first applied over the rivets, and a web of metal reinforcements was then welded into place as shown in Figure 3-23. Another layer of cement lining was then installed over the reinforcing layer to create a self-supporting liner. Man entry was required for welding and lining applications, so confined space entry permits, safety plans, rescue teams, etc had to be in place before the rehabilitation could begin.

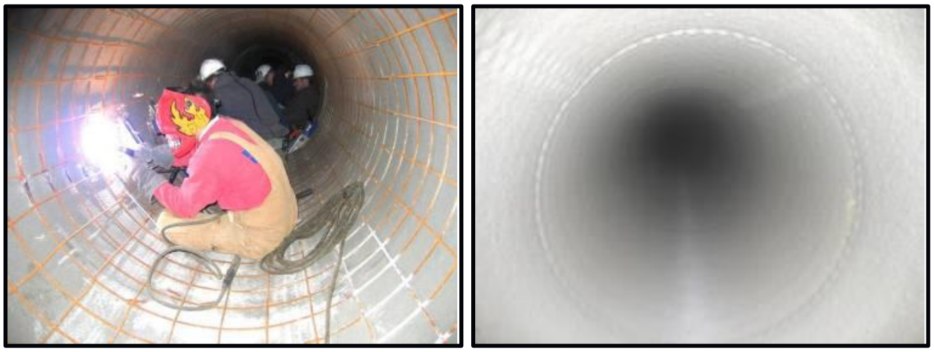


Figure 3-23. SIPP Lining Welding of Reinforcements (left) and Finished Pipeline (right) (Authority, 2009)

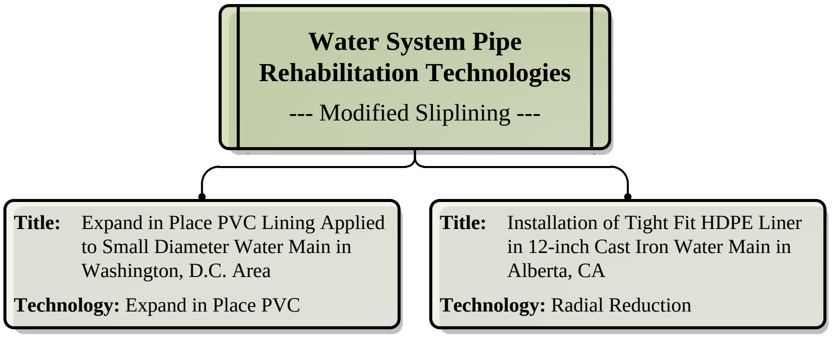


Figure 3-24. Water System Rehabilitation Technology Case Studies – Modified Sliplining

Modified Sliplining Technologies

Two full case studies were developed for modified sliplining technologies as shown in Figure 3-24 above.

WSSC used expand in place PVC pipe to rehabilitate a 12-inch cast iron water main from 1918 in one of the oldest neighborhoods in the city. Whereas several utilities now are making the switch from metal to plastic, WSSC had only 10 miles of PVC pipe and no HDPE pipe in their system at the time this case study was written in 2011. This installation of PVC pipe was a pilot project to explore the possibilities of more cost effective water main rehabilitation than dig and replace. Interestingly enough, however, the installation of the technology ultimately failed to be successfully installed within the system. There were mis-communications between WSSC and the contractor almost immediately with regards to the detail for the water house connections, resulting in a delayed project start date. There were three attempts at installation, only two of which attempted expansion. The first expansion failed due to a failed joint fusion, while the second expansion failed when pressurization created a hole in the liner wall. After the second failure, the decision was made not to attempt expansion of the third installation and pulled the technology out so that open trench excavation could be used instead. One of the primary considerations that pushed WSSC to forego another shot at expansion was the approaching winter weather and the challenges associated with maintaining the temporary bypass supply for all customers; temporary bypass is undesirable in winter where there is a high likelihood of the pipeline freezing, and it is also undesirable during the holiday seasons due to increased flow demands. It is worth noting that this installation took place in 2003, and the product has made significant advances since that point; this was a pilot installation for an innovative version of the product.

In Alberta, Canada, a 12-inch cast iron water main was rehabilitated with a 12-inch HDPE pipe using radial reduction technology to insert the new liner pipe into the host pipe. The liner pipe was about 10-inches in diameter when it was first pulled into place, and after stabilization from natural reversion, it had a diameter of about 11-inches. The ends of the liner were then plugged so that a stepped water pressure induced inversion process could force the liner back out to fit as tightly as possible against the host pipe. The installation process was fairly smooth, with one delay resulting from a failed hydraulic power pack during the reduction of the first liner segment. There was also a need to slightly modify the retraction process when diameters after final reversion were smaller than expected, and a switch from variable diameter steel insert wedges with traditional adapters to solid wall stainless steel inserts and electro-fusion restraints was made to resolve issues with leaking at the liner termination during pressure testing. Before construction even began, one of the challenges faced by the City was finding a solution that would not impact the matured spruce trees planted almost directly above the pipe alignment along an arterial street.

Sliplining Technologies

One technology case study for sliplining was created, and two were created as ‘abbreviated case studies.’ Figure 3-25 lists all three of the case studies available.

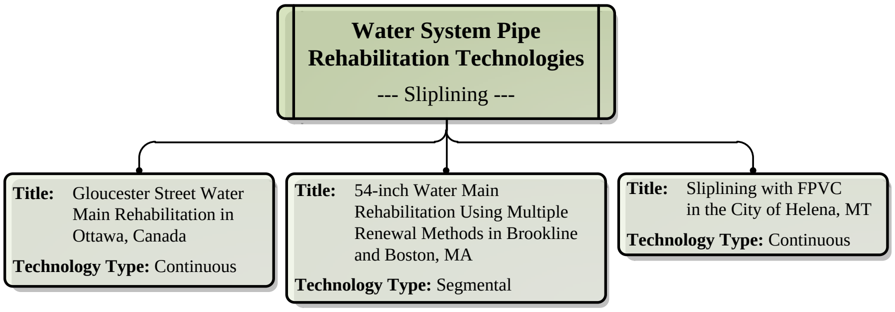


Figure 3-25. Water System Rehabilitation Technology Case Studies – Sliplining

The Massachusetts Water Resources Authority (MWRA) used segmental sliplining to rehabilitate one segment of a 54-inch water main as part of a much larger rehabilitation project. The new pipe had a smaller diameter than the host pipe and was installed in segments that were hand-welded together from within the pipeline. Man entry was required for welding of the liner pipe ends, and once inside the host pipe, the new liner pipe was held in position with spacers, securing it for grouting of the annular space. The grout provided additional strength for the new liner pipe and also had a corrosion inhibitor that acted as part of an integrated corrosion protection system. This particular segment needed structural renewal due to its location beneath Route 9. Figure 3-26 below shows a picture of the liner pipe insertion and man-entry for welding and grouting.

Figure 3-26. Segmental Sliplining Operations (Authority, 2009)

In Ottawa, Canada a cast iron water main had already failed twice and needed to be structurally renewed, as approximately 37% of its wall thickness had deteriorated over time due to corrosion. The location of the water main was the primary challenge because it crossed under every major north-south arterial road into center-city. Sliplining with an 840 mm HDPE pipe with fused joints was chosen as the preferred method for rehabilitation. One challenge was that two bends in the pipeline could not be negotiated by the HDPE pipe, so the pipe was replaced via open trench at these bends. Special fused ends allowed the connection of the HDPE pipe to the concrete pipe that would be used around bends. One note provided was that even with the density of underground infrastructure, the project was completed without the need for no utility relocations were required. This highlighted the importance and cost savings associated with an accurate base map.

In Helena, MT, the City used a continuous pull method to slipline just over 5,000 LF of 20-inch steel water main with 16-inch fusible PVC pipe. The project was initiated due to leaks in the pipeline, and one of the major challenges was space because the project was located near the airport right along a roadway with little to no open space. Excavations and pits were carefully planned based on the location of valves and an angled portion of pipe that had to be excavated anyway. The pipe was installed via only two pulls due, in part, to strategic pit locations.

3.4.6. Water Pipe Replacement Technology Usage

Nine full case studies and no abbreviated case studies were developed for pipe replacement technologies. Each of the technology categories is discussed separately below with details about the technologies covered in within the case study.

In-Line Pipe Replacement Technologies

Four full case studies were developed for in-line water pipe replacement technologies as shown in Figure 3-27 below.

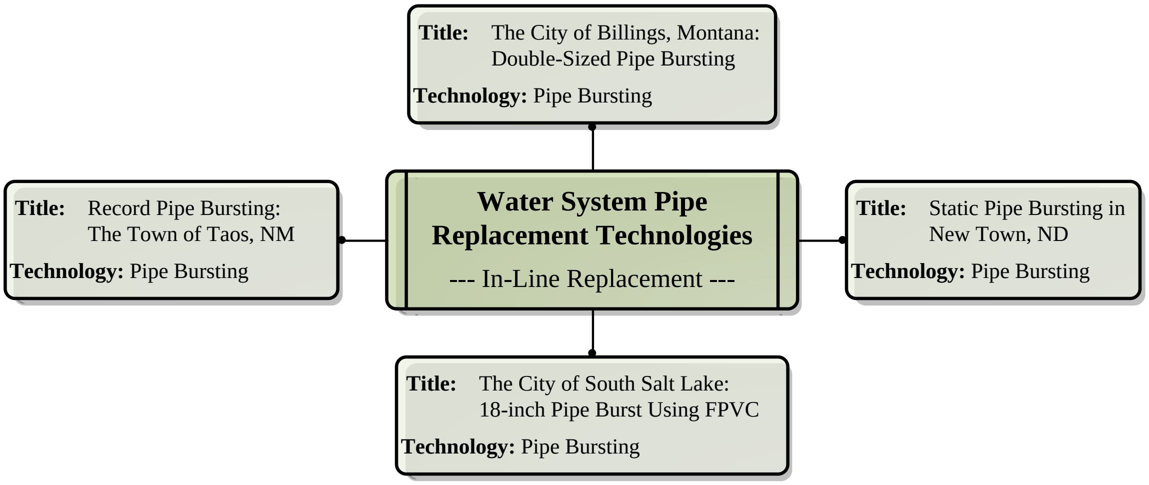


Figure 3-27. Water System Replacement Technology Case Studies – In-Line Pipe Replacement

All four of the case studies developed for in-line replacement technologies used pipe bursting. The Town of Taos, NM used static pipe bursting to replace about 16,500 LF of 8-inch fiberglass-wrapped PVC pipe with 10-inch HDPE pipe. The project ran through residential areas as well as beneath major thoroughfares. The two major concerns were surface disruption and out-of-service time for customers. Budgeting for the project did not have room for landscaping, sidewalk, curb/gutter, or asphalt replacement, so trenchless technologies were investigated.

The City of Billings, MT implemented a long-term, successful in-house pipe bursting program to handle as many of their own system replacements as possible. The City purchased their own equipment, and several of their staff members have been certified by the pipe supplier (Underground Solutions) for PVC pipe joint fusion. The City has replaced about 3,000 LF of pipeline to date and plans to replace nearly 27,000 LF before the project is complete.

The cast iron water mains in New Town, ND were only just over 50 years old, but they were already in need of renewal due to the high mineral content of the soil weakening the pipe from the outside and the high pH source water causing issues with built up mineral precipitation within. There were increasing leaks and breaks, so the Town decided to renew nearly 13,000 LF of pipe. Before choosing pipe bursting as the ultimate solution, a 1,100 LF section of 6-inch cast iron main was burst as a trial run. Pit placement was critical in reduce the number of excavations, and therefore reducing project costs, and flexible connecting rods made it possible to burst around large radius bends.

The City of South Salt Lake City, UT installed an 18-inch fusible PVC water line via static pipe bursting in 2009. The project was initiated after a redesign of the major interstate led designers to find that the existing waterlines beneath the roadway could not handle the new pressures. Open trench was not a viable option primarily because of the difficulty in shutting an entire interstate down for waterline replacement.

Off-Line Pipe Replacement Technologies

Four full case studies were developed for off-line water pipe replacement technologies as shown in Figure 3-28 below.

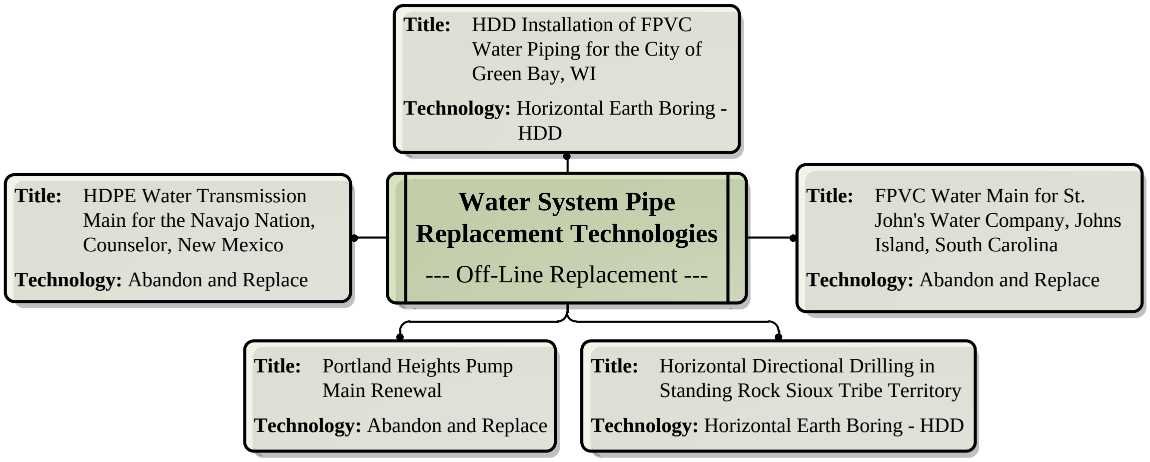


Figure 3-28. Water System Replacement Technology Case Studies – Off-Line Pipe Replacement

The City of Green Bay, WI replaced an existing water main with an 8-inch fusible PVC water main via HDD technology. Bentonite and No-Sag Gel were used to maintain smooth drilling operation and help the pilot hole retain its shape, and as drilling moved forward, the drill head location was tracked by on-site crew with an above ground technology to detect sonde in drill head.

The City of Jenks, OK used HDD to install 10-inch DR 11 HDPE pipe 10-feet below the Polecat Creek bed. During significant rain events, heavy runoff and sandy soils combined to create unfavorable conditions at the location where the water main crossed the creek in the City, causing 4 failures within 18 years. The City decided a permanent solution was needed and decided to move the pipeline completely out of the stream channel. The existing pipeline ran along the bank of one of the widest sections of the Polecat Creek where bank failures during runoff events caused the pipe to fracture.

The Standing Rock Sioux Tribe needed to transport water 80 miles from a different town, Nageezi, to their own location in Counselor, NM so that running water could be provided to the remaining portions of their territory without it. The installation included 13 miles of 24-inch DR 7.3 and DR 9 pipe, primarily with open trench methods, but a small amount of HDD was also used where the terrain, the crossing of the Grand River for example, prevented the use of traditional open trench methods. The Grand River crossing proved even more difficult because heavy rains added additional, unexpected depth to the River.

There was a significant difficulty in this project with the variations in rock hardness. A specific tool had to be brought in to deal with the softer rock areas because softer rock kept sticking to the initial back-reaming tool. However, the softer rock tool had a hard time with harder sections of rock, leading to a 3 week delay in completion of the bore hole for pull-in. Stringing the pipe together for one pull also proved challenging because of the variations in elevation and the bending roadways by which the pipe had to be laid. In some cases, culverts had to be installed to allow the lay-down pipe to pass beneath roadways while still providing residents access to their homes. The entire pull took 14 hours.

A new transmission main was put into place on John’s Island because of increased demand, primarily due to tourism. Conventional open trench methods were not acceptable because of environmental concerns associated with nearby wetlands, and the high public profile that the project would have. FPVC was found to be the most cost effective in conjunction with HDD installation technology. While HDPE was originally specified, but a 10% cost savings was realized once FPVC was compared to the HDPE option. A total of 109 pipe joints were fused for the project starting from December 2007. The Project had to maneuver multiple river and wetland crossings, as well as a run under a row of protected trees. There were also difficulties with an active airfield and archaeological concerns, and as a result, over 50 private easements were required before construction could begin.

Open trench installation was chosen as the best solution by the Portland Water Bureau (PWB) to replace one of their pump mains primarily because PWB had no experience with HDPE lining but had extensive, successful experiences with open trench installation. The high confidence in installation quality and significantly larger number of certified contractors for open trench paired with the more than 150 year design life that could be achieved made it a more viable option in the eyes of the Bureau. CIPP Liners were also considered, but it had only a 50 year life expectancy and increased maintenance expectations due to its shorter service life.

3.5. Water System Pipeline Renewal Technology Usage – Synthesis of Current Practices from State of the Art Literature and State of the Art Practice Reviews

3.5.1. Purpose and Scope of Synthesis

In the above sections, the state of the industry was defined in terms of the technology practices commonly cited in literature and the technology practices based on case studies written to capture actual utility experience rather than vendor-driven claims. The experiences described in the previous sections are synthesized below to provide an overall view of the State of the Industry for Water Pipe Renewal Technology availability and use. It is important to understand that these snapshots only capture the current time period, and thus the state of the literature and practice reviews will need to be updated to stay current with existing trends.

3.5.2. Pipe Materials

Traditionally, the materials used in water systems include AC, CI, DI, PCCP, Steel, PE, and PVC, and though there are other pipe types, the types listed above account for just over 97% of distribution pipelines (Dr. Ray Sterling, State of Technology Review Report on Rehabilitation of Wastewater Collection and Water Distribution Systems, May 2009). In general, the trend for pipe materials seems to be shifting from traditional metal pipes to plastic pipes such as PVC and HDPE. This shift is predominantly in small diameter distribution pipelines since there are size limitations for thermoplastic materials. Large diameter transmission mains continue use predominantly PCCP, steel, or lined iron.

3.5.3. Trends by Renewal Type

A general trend in technology usage was seen through literature and in practice.

These observations are discussed below by type of renewal.

Repair Technologies

For sealing joints, mechanical sleeves seemed to be the most common technology cited in literature. The mechanical sleeves have the ability to withstand high internal pressures which would explain their frequent use in other applications such as repair of power plant circulating lines (Croning, 2002). One of the major benefits cited was the ability of the sleeves to structurally reinforce bell and spigot joints which are common in waterlines and are often the source for leaks. Literature is available as well that speaks more on the application for sleeves such as *Rehabilitation Scenarios for Sustainable Water mains* by Khaled Shahata et al.

For small holes and cracks, the use of internal carbon and glass reinforced-fiber reinforced pipe wrap was very common, and there are many sources available to provide details on the concepts and applicable situations for use (Baruch Gedalia, 2010) as well as the quality control recommendations and proper installation procedures (Carr, 2007). While external repair clamps are an old and proven technology that have likely been used by most utilities at some point, the most significant factors for the time and cost of repairs to waterlines is excavating the leak and dewatering the pipeline (EPA, November 2009). This could be a possible reason for the shift in focus to repair technologies such as internal wraps that do not require excavation. One of the benefits cited by WSSC in their use of internal CFRP wrap is the quick installation and effectiveness of the technology. It has been used extensively by the utility to make repairs to the large diameter PCCP transmission mains in their system.

Capturing repair technology use within utilities was difficult because repairs are typically made by in-house operation and maintenance crews, and detailed procedures for actual repair technology installations are not well documented. Repair clamps, for example, are often used as quick and easy repair options, but specific applications are not common in literature. The technology is, however, listed in all major industry reports that provide descriptions of water system pipe repair technologies such as the EPA State of the Technology Report and the EPA Report for Control and Mitigation of Drinking Water Losses in Distribution Systems.

Another common repair technology is pipe coatings. The use of cementitious coatings was commonly cited in literature and heavily used in practice as well. Cement Mortar Lining is a particularly common practice in water utilities today, with several utilities such as Seattle Public Utilities, Louisville Water, and Los Angeles Department of Water and Power all using it as a regular pipeline renewal practice. Polymer-based linings were not as commonly cited in literature as far as examples of use, but there is a plethora of information available explaining the technical background and applicability of the technology such as *Evaluation of Trenchless Renewal Methods for Potable Water Distribution Pipes* by Abhay Jain or *Global Review of Spray-On Structural Lining Technologies* by Dan Ellison which discusses the applicability of epoxies and polymer based materials as both coatings and semi-structural linings. Aurora Water used the coating to make repairs of their suspended water main, and cited one of the main benefits of the polyuria lining to be its ability to cure quickly so that the pipeline can be reinstated quickly.

Rehabilitation Technologies

One of the main challenges in rehabilitation of waterlines is the need for at least two excavations for installation and then additional excavations at service connections, valves, and other appurtenances (Behnam Hashemi, 2011). Where there are multiple connections or excavation points required, it is more cost effective at some point for the utility to just excavate the entire pipeline for full replacement rather than rehabilitation.

CIPP liners are a promising technology for water system application but examples of use are very limited in literature and very difficult to find in practice. No utilities that were interviewed used CIPP Liners regularly. The need for the liner and all materials to be NSF 61 approved for use in potable water and have the ability to withstand internal working pressures make them less commonly used in water applications than sewer. The commonly used resins for sewer applications such as styrene are difficult to get approved for use in potable water, and materials such as needled felt do not have the capability to withstand pressure without some type of reinforcement. Most of the examples of use from literature in the United States including the installations in the Charleston Water System (Ball, 2011) and the City of Omaha (Jeff Schovanec, 2011) were pilot projects. The case study developed for New York City was also a pilot project, suggesting that there is considerable interest in this technology within the United States. UV Curing of the woven hose and reinforced hose liners is also an advancement that is not commonly used in the United States at present but that has the potential to reduce curing times considerably.

The other commonly cited rehabilitation technology is SIPP Linings, but there were few examples of their use in practice, most likely because until now cement mortar and polymer based materials have been thought of as non-structural solutions. There are a number of advantages associated with spray-on polymer linings, most notably the reduces curing time and therefore the total time the water main has to remain out of service (Dan Ellison, 2010). There is extensive literature available evaluating their applicability and their effectiveness for semi-structural applications such as *Pipeline Rehabilitation with Fiber-Reinforced Mortar Lining* by G.K. Luk; *Global Review of Spray-On Structural Lining Technologies* by Dan Ellison et al; and *Testing & Design Life Modeling of Polyurea Liners for Potable Water Pipes* by Mustafa Kanchwala. The EPA also did a pilot evaluating the performance of a semi-structural SIPP Lining, but the ultimate determination was that the technology was still in need of improvement (John Matthews, February 2012). In practice, the utilities that had used SIPP Linings had used cementitious material that was reinforced with steel mesh. The one case study provided for SIPP Lining in Boston used steel reinforcing that was welded together to form a “cage” within the pipeline to provide structural support for the cementitious lining that was applied.

There is a lot of literature available documenting the exploration of new ways to rehabilitate water lines. However, there are very few alternatives available that are actually used extensively by utilities in practice. Other countries such as the UK use technologies such as CIPP and SIPP Liners extensively in their systems as well as modified sliplining technologies. The examples from utilities that use modified sliplining for water main rehabilitation had issues with expansion and joint integrity, and when searching for literature documenting the use of these products in the United States, there were only examples of pilot projects. While there is certainly promise in the innovative solutions coming available.

Replacement Technologies

In-Line Pipe Replacement for water system pipelines is fairly limited to pipe bursting. This was exemplified by the fact that all literature sources and case studies for in-line pipe replacement were different forms of pipe bursting. The primary limitation cited for pipe bursting, and in many cases the reason it was eliminated as a solution in renewal projects, are the ground vibrations which can be harmful to surrounding utilities or above ground obstructions. Explanations, background, limitations, and cost information for pipe bursting are available through many sources such as *Water Pipeline Renewal Evaluation Using AWWA Class IV CIPP, Pipe Bursting, and Open Cut* by Behnam et al which compares the benefits, limitations, and costs of each of these methods for use in water. One of the benefits of pipe bursting is that it allows the installation of a new pipeline in the same location as the old pipeline, preserving valuable underground infrastructure. It also allows for a small degree of upsizing which is great for situations where an increase in capacity is the driver for rehabilitation. In situations such as The City of Billings, MT, in-house pipe bursting programs have been developed to reduce costs associated with replacement.

In some cases, trenchless technology is not an applicable or cost effective method for installation such as where there would be numerous services to reconnect, and exhume and replace methods have to be used. These methods also may be required where an upsizing beyond the limitations of pipe bursting are needed. Detailed information on pipe bursting including installation procedures, design considerations, and costs can be found in the TTC Technical Report #2001.02, *Guidelines for Pipe Bursting*.

In regard to off-line pipe replacement, the most common methods are abandon and replace and HDD. Open trench construction is often chosen because of difficult soil conditions such as rock where trenchless installations have limited capability. Abandon and replace techniques are often used where the existing pipe alignment has access issues or obstructions that make a parallel alignment more attractive, or where there are too many issues with taking the pipeline out of service for replacement. In this case, the new pipeline is typically installed on the parallel alignment and the old pipe left in place to act as an overflow. In the case study for Replacement of a Pump Main in Portland, OR, a parallel pipe was installed and the old main used as an alternate pipe should the new main need to be shut down for maintenance or repair.

HDD has found success in the water pipe replacement industry primarily due to its usefulness in installing pipelines beneath obstructions and through environmentally sensitive areas. Most every example in literature and in the case studies used HDD because there was some type of water body, roadway, or other obstruction. Jenks, OK used it to install a pipe beneath a creek bed, the Sioux Tribe used it beneath a river, and John’s Island used it to cross several rivers and wetlands. The most notable limiting condition for HDD installations is the soil characteristics, though factors such as weather and depth of the alignment also play an important role. Technical information on HDD

3.5.4. Drivers for Renewal

The Government Accounting Standards Board (GASB) Statement Number 34 was released in June 1999 and required all utilities to report the value of all assets on a balance sheet. The value could be calculated using a standard calculation for infrastructure depreciation expenses based on historical acquisition costs or through implementation of an effective asset management system which required proof that the utility was maintaining assets at least well enough to meet minimum standards or spending enough on maintenance to prevent deterioration. Even so, in 2002 the Government Accounting Office released a report estimating that 33% of water utilities were not maintaining their assets at an appropriate level and that 29% were not able to maintain their current target service levels of service with their existing sources of income. Regulations and mandatory accounting for assets has become one of the drivers for water pipe renewal, and many utilities set a minimum percent of their pipelines that need to be renewed each year to stay on track.

Other drivers for renewal of waterlines are customer complaints. Some utilities have set up GIS systems that track the location of customer complaints such as those related to water quality, water discoloration, or pressure issues. When frequent complaints begin to appear in one location within the system, the utility can plan for inspection and possible renewal of those areas of the system in their budget. Water utilities strive to provide a certain level of service to their customers, so customer complaints are often a good way to identify problem areas.

External corrosion is a major issue driving water pipe renewal. Many pipes have been installed with cathodic protection systems either external to the pipeline or integrated into the pipe system in grouts as was demonstrated in the case study for sliplining of the 54-inch Water Main in Boston. Internal corrosion is an issue as well and can take a couple of different forms. Internal corrosion can degrade the pipe walls causing the thickness of the pipe wall to decrease over time until eventually failure occurs; it can cause the ‘growth’ of tubercles which lead to water quality, capacity, and pressure issues; and it can cause graphitization which is the most difficult to detect because it weakens the pipe without changing its appearance. Corrosion was cited in many literature sources as the primary reason for initiation of renewal. External corrosion, for example, was one of the issues in the 66-inch Water Main assessment which injected a “sleeve” of grout around the pipe exterior to seal the resulting leak off from the surrounding soil medium (Alfredo Saenz, 2011).

3.6. Conclusion

While the technologies available for renewal of water system pipelines have come a long way, there are still advancements needed before the technologies available for water system pipe renewal will offer anywhere close to the spread of options offered for wastewater system pipe renewal. The State of the Art Literature and State of the Art Practice Reviews above were based on examples of technology applications from literature and on examples of technology use identified through contact with utilities, respectfully. In general, the primary difference in what was found in literature versus practice was the literature sources focused on providing examples of innovative technology uses, pilot projects, for example, while in actuality utilities were only using a handful of technologies actually available to them. Most utilities were open about their tendencies to stick to practices with which they are comfortable and confident in. Until new technologies have been proven, the risk, especially in large diameter water mains, associated with failure is too high to warrant their application.

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