Awwa Research Foundation
Advancing the Science of Water®

No-Dig and Low-Dig Service Connections Following Water Main Rehabilitation

Subject Area:
Infrastructure Reliability

No-Dig and Low-Dig Service Connections Following Water Main Rehabilitation

Awwa Research Foundation

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The Awwa Research Foundation (AwwaRF) is a member-supported, international, nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers.

The Foundation's mission is to advance the science of water to improve the quality of life. To achieve this mission, the Foundation sponsors studies on all aspects of drinking water, including supply and resources, treatment, monitoring and analysis, distribution, management, and health effects. Funding for research is provided primarily by subscription payments from approximately 1,000 utilities, consulting firms, and manufacturers in North America and abroad. Additional funding comes from collaborative partnerships with other national and international organizations, allowing for resources to be leveraged, expertise to be shared, and broad-based knowledge to be developed and disseminated. Government funding serves as a third source of research dollars.

From its headquarters in Denver, Colorado, the Foundation's staff directs and supports the efforts of more than 800 volunteers who serve on the board of trustees and various committees. These volunteers represent many facets of the water industry, and contribute their expertise to select and monitor research studies that benefit the entire drinking water community.

The results of research are disseminated through a number of channels, including reports, the Web site, conferences, and periodicals.

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More information about the Foundation and how to become a subscriber is available on the Web at **www.awwarf.org.**

No-Dig and Low-Dig Service Connections Following Water Main Rehabilitation

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FOREWORD

The Awwa Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of a Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The foundation also sponsors research projects through an unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering firms. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The foundation's trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

THE NEED FOR NO-DIG AND LOW-DIG SERVICE CONNECTIONS

Significant reductions in the cost of water main rehabilitation will be achieved, once methods are developed to reconnect services without excavating a large hole at each one. With this one problem solved, pipeline rehabilitation could very likely become the most common method of renewing water mains, just as it is now for sewer mains. Ultimately, utilities could complete many more miles of pipeline renewal each year, with the side benefit of causing fewer inconveniences to their customers. This report explores this subject, presenting various concepts for remaking service lateral connections following pipebursting, slip lining, tight-fit slip lining, cured-in-place lining, and horizontal direction drilling—without digging large holes in the streets.

This goal is achievable. Service laterals can certainly be connected without digging. We accomplish things every day using tools that our predecessors could never imagine. For example, heart surgery is routinely performed using miniature tools at the ends of long catheters. Yet lateral pipes are still connected to mains in basically the same way as a century ago. The technical challenges in reconnecting services are not as difficult as heart surgery. In fact, this report demonstrates that the technical issues are indeed quite solvable, given the array of tools currently at our disposal, many of which come from related fields, particularly the wastewater and natural gas industries.

WHY NO-DIG CONNECTION METHODS DO NOT EXIST

Many very good concepts for service reconnection have already been developed, and several have been tested. At least one of these concepts includes a sophisticated pipeline robot that has been patented and a prototype has been built. Unfortunately, this tool will not be at a trade show any time soon. Its inventor, a major company, has decided not to spend additional money on the robot's development, because it does not foresee a large enough return on investment. This is because the current market for water main rehabilitation is perceived by many to be relatively small. Of course, once laterals can be connected without digging large holes, the market will grow substantially, but estimating when this might occur, and how large the market might become is difficult.

This report does not focus on the financing of tool development, but rather looks at the technical issues, and what might be done to solve them. By discussing these technical issues and presenting various ideas here, it is hoped that others can expand upon them, and the industry will get closer to the goal. It is hoped this report will ultimately make the economic problem easier to solve. The author is confident that sufficient economic incentives will eventually exist, because billions of dollars of needed infrastructure work is deferred every year. As the pipelines grow older a point will come when deferral is no longer possible, and the backlog of work will be enormous. When this happens, the incentives to develop new techniques will be considerable.

THE RESEARCH

The ideas and concepts presented in this report came from the individuals listed in the *Acknowledgements* section, many of whom are among the foremost experts in the pipeline rehabilitation field. Most of these individuals attended a workshop organized for this project, and freely shared ideas that, in some cases, had been developed over a lifetime of working in the pipeline rehabilitation field. These ideas were then further researched and refined, and several were eventually tested in the laboratory or under actual field conditions. Several of these contributors participated in these field and laboratory tests. Many were also technical editors of the draft of this report. This team of experts came from a variety of backgrounds, including the water, wastewater, and natural gas industries, and represented utilities, contractors, inventors, academia, and consultants.

The concepts contributed by these individuals are discussed in Chapter 4. Six different cases are examined, reflecting the different conditions that occur at lateral connections when different trenchless construction techniques are used. Various facets of these concepts were later tested at the Trenchless Technology Center (TTC) and at the Los Angeles Department of Water and Power.

THE TECHNICAL CHALLENGES

For most of the pipeline rehabilitation techniques, there are three basic challenges to be overcome, in order to reconnect a service without excavating. These challenges are (1) finding the lateral, (2) re-establishing the opening (i.e., the "bore") at the lateral, and (3) connecting the lateral to the liner or carrier pipe. These issues are discussed throughout this report, and are briefly summarized here.

Finding the lateral. To accomplish reconnections in a no-dig manner, work from within the pipeline will likely be required. The insertion of a pipe or liner within the old main generally obscures the lateral. In the wastewater industry, where laterals are large, a "dimple" is often visible in the liner, indicating that a lateral is present. In water mains, the lateral locations are generally invisible. Among the techniques that have been proposed for finding the laterals are: (1) homing in on a radio frequency signal transmitted on the lateral, (2) homing in on a transmitter inserted within the lateral, (3) using remote-field eddy current technology to detect the corporation stop and tap, and (4) precisely mapping the lateral's location prior to lining.

Re-establishing the lateral opening. Most concepts for re-establishing the lateral opening involve a pipeline robot that drills a hole through the liner or carrier pipe. Similar devices are used routinely in the wastewater field for this exact function. Re-establishing the opening should not be difficult, if its location is known with precision, but precision is the key. Because the average water service lateral is small, a liner hole that is off the mark by a fraction of an inch may be useless, particularly as a poorly made hole might interfere with the next steps in the reconnection process.

The other way to re-establish the opening is, of course, to drill from the outside in. Testing performed at the TTC demonstrated some of the many difficulties that might be encountered in one such method, using a drill bit attached to a plumbing snake. This concept does not appear to be very promising. A more intriguing concept involves small boring devices that are deposited into the corporation stops prior to lining, which are later signaled to bore their way back into the main.

Connecting the lateral to the liner or carrier pipe. Achieving a positive connection between a service lateral and the liner pipe is the issue that most profoundly separates water system conditions from wastewater system conditions, in regards to this subject. In the case of water mains, pipelines are pressurized, and if the liner is intended to be "structural" or "semi-structural", leakage into the annulus between liner and host pipe must be prevented. In wastewater pipelines, this leakage into the annulus is generally only a concern if infiltration is a significant problem, and even then, the infiltration pressures are generally a small fraction of what is found in a typical water system.

Where a tight-fitting or a spray-on liner is used, the problem still may be relatively simple. Grouts, sealants, and adhesives of various types may be capable of preventing this leakage. The problem becomes more difficult if HDPE is used, which is resistant to most chemical and mechanical bonding methods. In the case of HDPE, a small connecting piece that is inserted into the corporation stop and fuses to the liner pipe may be needed.

The problem of sealing the annulus becomes at least a magnitude more difficult to solve if a loose-fitting slip lining is used. Not only is there a large gap between host and liner pipes that needs to be bridged, but also the host pipe and liner pipe are not concentric. As a result, the geometry of the connection becomes both complex and unpredictable. Several tests at the TTC demonstrated the difficulties involved with loose-fitting slip liners.

One of the difficulties in making the connection between liner and lateral is dealing with the numerous variations in conditions that will be encountered within existing water systems: differences in pipeline materials, corporation stop designs, and lateral materials; differences in existing linings, scales, and other surface conditions; uncertainties regarding the structural integrity of old mains and old laterals; and differences in diameters and other dimensions. These differences create complications in the design of anything that connects the lateral to the liner. As a result, a better solution may be to completely replace the old lateral, rather than connect it to the new liner. One method for doing so may be the "extraction" technique presented in Chapter 7. In Chapter 4, an alternative is also described for installing new laterals using trenchless construction methods.

All three of the technical challenges (finding the lateral, re-establishing the opening, and connecting to the lateral) likely cannot be met using a *no-dig* approach, if pipebursting is used. If absolutely no excavation is made at the lateral connection, and if this connection is not severed from the main prior to pipebursting, the location of the lateral and its condition after pipebursting is highly unpredictable. Chapter 5, however, demonstrates a low-dig method, using "keyhole" tools, wherein the work is performed within a small excavation using long-handled tools of various designs. The method demonstrated in this chapter (and shown in the enclosed CD) is one that can be applied today.

LOOKING AHEAD

More research is clearly needed in this area, but significant near-term progress should be possible without multi-million dollar investments. In many cases, incremental improvements may be sufficient to spur the industry forward. For instance, the general feasibility of keyhole techniques has been demonstrated, but a larger assortment of long-handled tools must be developed to make these techniques more practical. The development of such tools could be accomplished by many would-be inventors, including engineering students, contractors, and modern-day Edisons working in their garages. Industry organizations (e.g., AWWA, AwwaRF, the Gas Technology Institute, and their European counterparts) could help by communicating the need for such tools in their publications, by funding additional research projects, or by sponsoring contests with cash prizes. Water utilities could also help spur these inventions by bidding large tracts of water main renewal using performance-based specifications that allow pipebursting with keyhole technology among the options available for bidders. With this combination of efforts, it should not take long to double the number of long-handled tools that are available. Pipebursting using keyhole reconnection technology might then become the preferred method of water main replacement, offering substantial economic advantages over conventional open-trench replacement.

To develop no-dig connections for the various tight-fit linings may be easier, because fewer inventions are needed and many of the issues are already well defined. The primary problem is how to make a positive seal between the liners and the lateral pipes. If the liner is PVC, methods to seal the annulus or adhere the liner to the host pipe need to be investigated. If the liner is HDPE, a connecting piece must be developed that both fuses to the liner, and seals to the lateral pipe. If the liner is CIPP, the problem may be readily solved by accomplishing and demonstrating adherence of the liner to the host pipe. The concept of lateral extraction also merits additional testing. So far, research and development efforts in these areas have largely been left to the few companies that market these liners, and because the market has remained small, little funding has been available. There are therefore many opportunities for AwwaRF and similar organizations to advance the development of these concepts. Once the fundamental issues of keeping water out of the annulus are resolved, then the task of adapting various pipeline robots to perform the needed tasks can be tackled. Development is needed for both the positive seals and the robots needed to install them, so it may take several years to bring these methods to market. However, if true *no-dig* service lateral reconnections become available, the tight-fit lining techniques may have greater potential than the other rehabilitation methods for normal water main replacement.

It is hoped that this report proves to be a valuable resource for others who are interested in the subject of water main rehabilitation. By considering the concepts that are outlined here, the tools that are described, and the tests that have been performed, the next steps needed in the development of no-dig and low-dig reconnections should be clearer. Ultimately, more efficient, less disruptive methods of renewing water mains will result.

CHAPTER 1
INTRODUCTION AND OVERVIEW

The expense and disruptive nature of reconnecting lateral pipes has been a significant impediment to greater use of water main rehabilitation techniques. The emergence in recent decades of various pipeline rehabilitation and trenchless construction methods has raised the hope that more work could be accomplished with limited funds, but the cost of these methods when applied to water main construction has often disappointed. One of the reasons has been the added cost to reconnect service laterals. By the time that holes are excavated to tie each service lateral to a main installed or rehabilitated with trenchless technology, the project sometimes starts to resemble the open-trench projects that the water utility is trying to avoid—and so do the costs. Solving this problem is very important, as the funding for renewal has not kept pace with the growing need for infrastructure renewal.

This study is intended to help solve this problem by determining ways in which laterals can be reconnected in "no-dig" and "low-dig" manners. Various concepts are presented, spanning the range of rehabilitation techniques that are currently in use for water mains. The ideas presented in this report are a synthesis of thoughts from many of the leading experts in the field. These concepts range from the theoretical to the practical. One of the techniques presented in this report can be applied today, resulting in lower costs and fewer construction impacts on communities. Most other techniques will require some additional research and investment, but the potential for several technology breakthroughs is apparent.

This report examines existing tools, emerging technologies, and possible new inventions that could be used for the non-disruptive reconnection of service laterals after mainline rehabilitation. Some of the information is based on technologies in use in the sewer and gas pipe rehabilitation industry; but the project also addresses conditions that are unique to water distribution—such as concerns about maintaining sanitary conditions. The applications, descriptions of processes, and the capabilities and limitations of each method are described. It is hoped that this report will spur the further development of no-dig and low-dig reconnection techniques.

BACKGROUND

Water utilities in the United States currently replace about 0.5 percent of their pipeline assets each year, with individual programs typically ranging from 0 to 1.5 percent per year (Stratus, 1998). As a long-term rate, this appears inadequate—most experts do not expect the average water main to last 200 years. In the near-term, this replacement rate may be sufficient, but only because most pipes are relatively young. However, as systems grow older, replacement rates will increase—whether we want them to or not. Eventually the pipes themselves will demand to be replaced.

Challenges are coming for the water utility community, because replacement of these pipelines will be neither inexpensive nor easy. The U.S. Environmental Protection Agency estimates that $276.8 billion will be needed over the next 20 years for water infrastructure (US EPA, 2005). Two-thirds of this amount arises from upgrades needed for transmission and distribution systems—primarily the replacement and rehabilitation of pipelines. These needs are growing, because funding is not keeping pace.[1] In March, 2005, the American Society of Civil Engineers estimated that the current funding shortfall is $11 billion per year (ASCE, 2005). Other obstacles are contributing to a gap between what is needed and what is accomplished. Congestion both above and below the ground is making the replacement of water mains more difficult. Due to utility congestion, it is becoming increasingly difficult to find space within many public right-of-ways for new pipelines. Due to traffic congestion, it is equally difficult to find enough space in many public thoroughfares to perform the construction. Moreover, it is believed that public tolerance for the mess and disruption caused by construction work is diminishing.

Pipeline rehabilitation has the potential to alleviate some of these problems. Twenty years ago, a water utility manager had two basic options when it came to the pipeline infrastructure: fix leaks or replace pipes. How many leaks one fixed depended largely on the age of the pipe inventory, the aggressiveness of the water, and the conditions of the soil. How much pipe one replaced was probably related to how bad the leaks were. Fixing leaks was reactive, replacing pipes was proactive—or so one hoped. The proper balance between repairs and replacement was something of a guessing game. There was no way to see underground and assess the condition of a pipe. There were also few options available for extending the life of a pipe. With technological advances, this is changing. It is now possible to assess pipelines and effect their rehabilitation, through excavations at both ends of a street. However, with more tools and more choices, the management decisions are not necessarily any easier.

Because most rehabilitation methods are relatively young, the advantages/disadvantages and capabilities/limitations of each system is seldom clearly understood, even by very knowledgeable managers. A pipeline renewal program thus should start with a review and analysis of the various pipeline rehabilitation techniques that are available. As part of this analysis, the utility should investigate the lateral reconnection requirements for each type of rehabilitation technology. These requirements vary considerably, as do the impacts on customer service, project risk, and final cost.

THE NEED FOR NO-DIG AND LOW-DIG METHODS

Pipeline rehabilitation has the potential of saving billions of dollars when used for water main renewal. Tremendous strides have been made over the past two decades, with the potential for much more. Rehabilitation is fast becoming the first approach that is considered when a pipeline requires renewal. However, the cost of rehabilitation has disappointed many water utility managers, and part of this disappointment arises from the number of excavations often needed to complete a rehabilitation project. After excavations are made for launching and receiving pits, to remove obstructions (valves, bends, and other fittings), and to reconnect service laterals and fire hydrants, many of the "trenchless" methods may look in practice like traditional open-trench replacement.

Of these excavations, the reconnections of the service laterals are generally the most costly, simply because they are the most numerous. Consider a typical residential street, with 50-ft wide lots. If houses front both sides of the street, then service connections occur, on average every 25 feet. If the cost of re-establishing each connection averages $1000, then this

[1] EPA estimates for 1995 and 1999 were $167.4 and $165.4 billion respectively, vs. the recent estimate of $276.8 billion.

adds ($1000/25 =) $40 per foot to the overall cost of the rehabilitation project—a very substantial sum.[2] This cost alone could increase the cost of the project by 50 percent.

Remaking the service connections is also disruptive. Typically it involves interrupting the water service to the customer (perhaps several times), the re-routing of traffic, the cutting of pavement, excavation, cutting off the old pipe, installing new connection hardware, backfilling, and repaving. The cost of paving alone is proving to be more and more costly, as the fees and conditions that the various cities and state departments of transportation are attaching to excavation permits have escalated by leaps and bounds in recent years. The cost in one major city ranges up to $14 per square foot to acquire a permit to cut the pavement, easily adding $200 to the cost of each service connection.[3] On top of these permit fees, cities and counties are often requiring more expensive pavement restoration methods, such as sand-cement slurry backfills and curb-to-curb pavement overlays.

In recognition of this problem, the Awwa Research Foundation has sponsored research to investigate existing, emerging, and potential methods for remaking these connections more efficiently. An overriding objective of this project is to help advance the field of water main rehabilitation, ultimately making pipeline renewal less expensive and less disruptive to the community. The project focus is entirely on small service laterals (1-inch in diameter or smaller). While it is recognized that lateral connections range to much larger sizes, the larger laterals constitute less than 5 percent of all laterals in a typical water system. If solutions to the residential-sized laterals can be developed, then most of the problem is solved.

DIFFICULTIES IN DEVELOPING NO-DIG AND LOW-DIG METHODS

This service lateral reconnection issue is not one problem to solve, but several—each with its own set of difficulties. There are a wide variety of rehabilitation methods currently available in North America and Europe. The method required to reconnect a service lateral following the application of one rehabilitation technique will, by nature, be different from the method needed for another rehabilitation technique. The techniques that are currently generally available for water main rehabilitation fall into one of the following categories:

- Spray-on linings
- Cured-in-place pipe linings
- Tight-fit slip lining
- Straight slip lining (loose-fit)
- Pipebursting or pipe splitting

The problems involved in reconnecting service laterals for each of these methods is briefly described below. A more detailed discussion of how these water main rehabilitation methods are accomplished is found in Chapter 2.

Spray-on linings (Figure 1.1). For the most common methods of the water main rehabilitation within the United States, the restoration of lateral connections is *not* an issue. Such work is already done routinely in non-disruptive ways. This is because the majority of water

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[2] The estimate of $1000/connection is based on the author's experience on large projects in the Los Angeles area that were bid to private contractors.
[3] The City of Los Angeles applies a sliding scale that is based on the age of the paving, and whether the street is "arterial" or residential. $14 per square foot was the rate charged in 2001 for new arterial streets.

main rehabilitation is currently performed using in-situ application of cement-mortar or epoxy lining. Since these methods are *non-structural*, service connections are easily restored by simply re-establishing the bore—i.e., making a hole in the lining at the lateral connection. In the case of cement mortar lining, the service tap is usually cleared using a blast of compressed air or water that is directed down the lateral from the meter connection, before the mortar has fully set. In the case of epoxy lining, the restoration of the lateral connection is even less of an issue, because the epoxy is not generally applied in sufficient thickness to plug the service taps at all. No effort is therefore needed to keep the lateral clear.

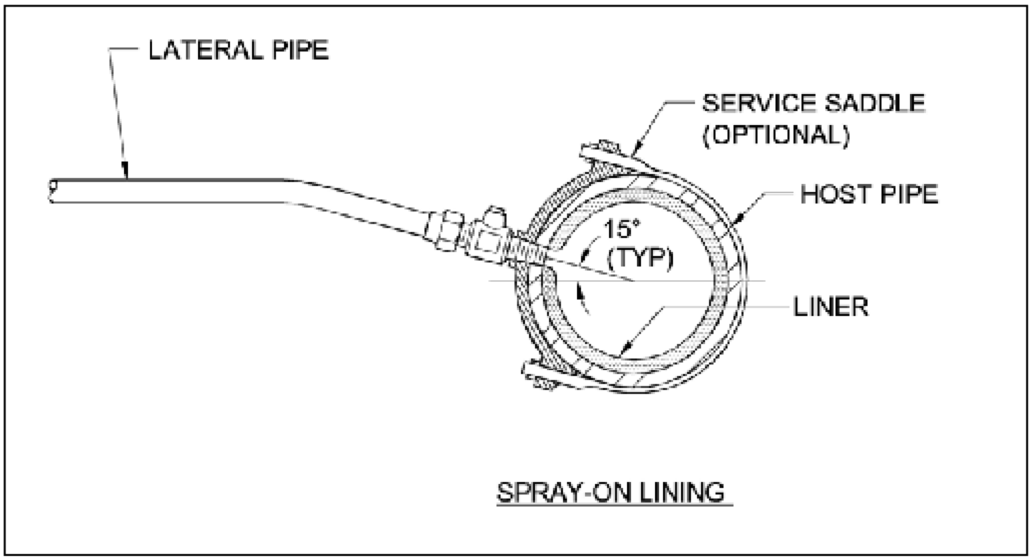

Figure 1.1. Illustrates typical conditions that exist following water main rehabilitation using spray-on linings.

However, not all cement-mortar, epoxy, and other spray-on linings are intended to be non-structural. Attempts are now underway to engineer variations of these systems to provide some structural reinforcement for the host pipe.[4] If that is the case, then restoration of the lateral opening, by itself, may not be sufficient; any gap between the lining and the host pipe at the connection will allow water pressure behind the lining, limiting (at least partially) the structural capacity of the system. In all cases, if a lining is intended to provide pressure resistance, a positive connection is needed between the corporation stop and the lining, or very good adhesion is required between the lining and the host pipe. Epoxy lining will generally provide such adhesion. Cement-mortar lining generally does not. Sections cut from water mains that have been lined in-situ with cement mortar will sometimes exhibit a small annular gap between the host pipe and the mortar.[5]

[4] This is being done by reinforcing the cement mortar with fibers, or by providing extraordinarily thick epoxy.
[5] In the sections cut from in-situ lined pipe, this gap will arise as the lining dries and shrinks; the mortar will pull away from the wall of the host pipe. Although this annulus may not exist between lining and pipe when the pipe is filled with water, there is a demonstrated lack of significant bond between the lining and the host pipe. In fact, the author has seen where an intact tube of lining could be slid out of a section of lined pipe.

Cured-in-Place Pipe Linings (Figure 1.2). Cured-in-place pipe (CIPP) linings are commonly used in the wastewater field, but are less common in water utilities. This difference in usage rates is partly due to the greater difficulty in re-establishing service connections. Two problems occur with re-connecting services in water main applications. The first is re-establishing the bore. The second is achieving pressure resistance.

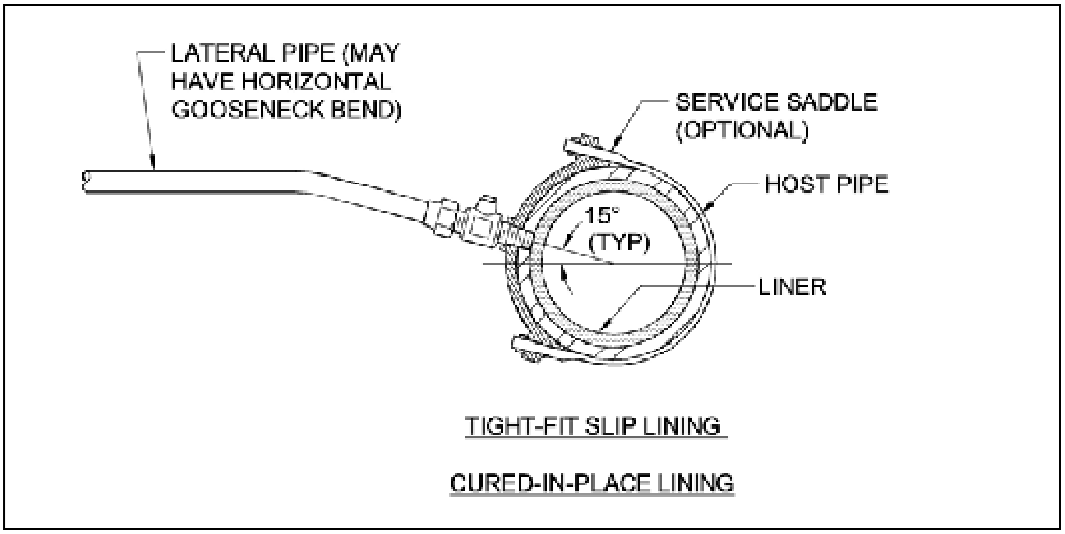

Figure 1.2. Illustrates typical conditions that exist following water main rehabilitation using tight-fit linings and cured-in-place lining.

Re-establishing the bore. When CIPP is applied in wastewater and stormwater pipes, "robots" are commonly used from within the pipes to cut holes in the CIPP linings at the service taps and other laterals. This is done by using closed-circuit television (CCTV) equipment to position a drilling or cutting device at a "dimple" in the lining. These dimples indicate where the laterals are present, and cutting or drilling at the dimple, re-establishes the bore. Alternatively, with an accurate pre-lining video, lateral locations can be documented with sufficient precision that bores can be located later, even in the absence of a significant dimple.

However, a typical service connection to a water main is so small (1-inch in diameter or less), that dimples can be nearly impossible to discern visually. Moreover, because the bore is small, there is an even greater need for precision. In a wastewater pipe, the cutting device can be off target by a significant margin, without serious consequence.

This problem of finding and re-establishing the bore is common to most of the methods that we will be discussing. In some water mains, visually locating the service location is possible, but this may be the exception more than the rule. This exception occurs where a ferrule from the service tap protrudes into the main. In such cases, laterals have been successfully located using CCTV and re-established using a pipeline robot.

Achieving Pressure Resistance. In most sewer applications, the pipe is not pressurized, so re-establishing the bore, by itself, is often considered adequate for re-establishing the service.

But this is not the case in most water main applications. Because water mains are pressurized, a positive connection between the CIPP lining and the lateral is needed. If a positive connection is not attained, the CIPP lining may have negligible structural value. This problem of making a connection between the lateral and lining, and thus achieving pressure resistance, is common to virtually all structural and semi-structural linings.

Contrary to some common notions and claims, various tests have shown that cured-in-place pipe (CIPP) linings generally do not fully adhere to the host pipe. Tests conducted for the City of Baton Rouge, Louisiana, have shown that CIPP linings, in fact, have an annulus between the host and liner pipes in virtually all applications (Bakeer and Guice, 1997). These tests were conducted for the purpose of testing the infiltration resistance of wastewater pipes lined with CIPP and other products, and the pressures applied were quite low (5 psi). Under these tests, the CIPP linings were found to be somewhat resistant to annular flow, but were definitely imperfect. Even under low pressure, water would enter and travel through the annulus. Extrapolating these test results to the case of water pipes, where much higher pressures are used, the water tightness of the lining would be called into question. Exfiltration (leakage) would be a significant risk, unless a positive connection or seal is made.

It should be noted that drawing inferences from these wastewater tests may be problematic. The walls of wastewater pipelines frequently have an accumulation of grease and other contaminants that prevent the CIPP lining from effectively bonding. Such contamination should not be present in water mains. On the other hand, tuberculation and other scales may well be present in the water mains that similarly inhibit bonding. The degree to which adhesion occurs between CIPP linings and water main pipelines is a question that warrants more testing of various lining materials installed within real water mains. [6]

Tight-fit Slip Linings (Figure 1.2). Several methods exist in which a plastic pipe can be installed to fit snugly within a host pipe. Most such methods involve deforming a high-density polyethylene (HDPE) pipe, inserting it within the host pipe, and allowing it to expand. An alternative method uses heat and pressure, to expand a loose-fitting polyvinyl chloride (PVC) slip-lined pipe until it fits snuggly in the host pipe. No matter which of these methods is used for tight-fit lining, there is a need to connect the service pipe directly to the lining, in order to prevent leakage into the annulus, loss of structural capacity and loss of fluid.

Again, the first problem is re-establishing the lateral bore. For a tight-fit liner, the difficulties with accurately finding and precisely re-establishing the bore are as discussed with the CIPP lining. However, in this case, it is safe to assert that visible dimples will be virtually non-existent. However the bore-establishment problem likely pales when compared to the second problem, which is providing a reliable, positive connection between the lateral and the liner. Without such a connection, the liner will provide little, if any, structural benefit, and little, if any, corrosion-resistance. In the case of tight-fit slip linings, no argument can be made that the liner pipe adheres to the host pipe. It absolutely does not. So without a positive connection between the lining and the lateral, water will flow into and through the annulus. Pressure on both sides of the liner will eventually equalize (meaning the lining will provide no structural value), and exposure of the host pipe to internal corrosion will continue.

Straight (or Loose) Slip Lining (Figure 1.3). Straight slip lining poses even larger problems when it comes to re-establishing service connections in a no-dig, or low-dig manner. As the figure illustrates, a significant gap exists between the lining and host pipes. Bridging, or

[6] A newly introduced product on the market, designed for water mains, is purported to adhere tightly to the host pipe. This product is discussed further in Chapter 2.

filling and sealing this gap might be one approach to re-establishing the connection. Fusing a new lateral onto the side of the liner might be another approach. However, with this latter approach, the wall of the host pipe presents a significant impediment to making the connection without an excavation.

Note also the difficulties created by the geometry shown in the illustration. The carrier pipe and host pipes are not concentric. So while the lateral pipe is perpendicular to the host pipe, its projection will intersect the carrier pipe at an angle that is difficult to define. This angle between the lateral and carrier pipes will vary depending on the diameter of the host pipe, the diameter of the carrier pipe, and the angle the lateral pipe makes with the horizontal. (There can be considerable variation in this last parameter, even along a street where all the connections were supposedly done by the same crew on the same day.)

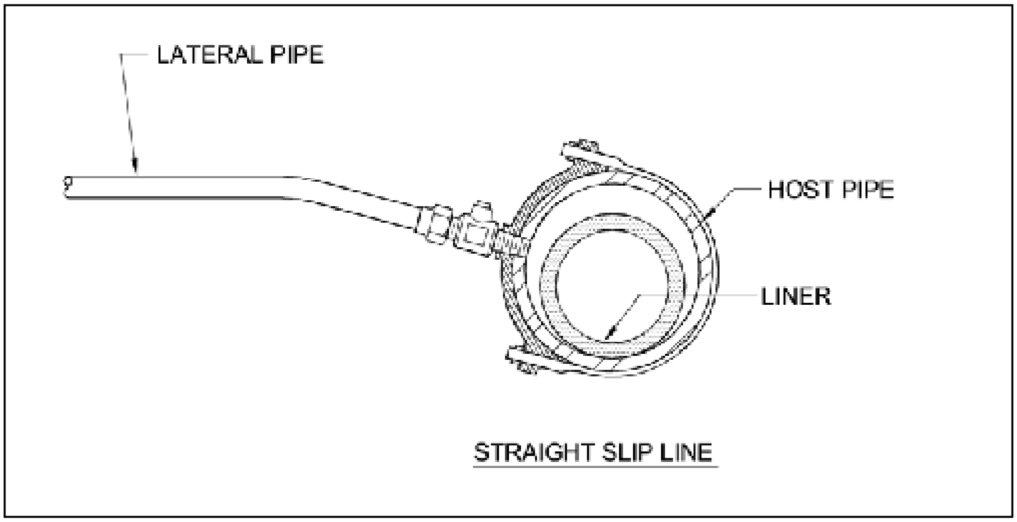

Figure 1.3. Illustrates typical conditions that exist following water main rehabilitation using straight (or loose fit) slip lining.

Note also that while we have shown the carrier pipe to be resting at the bottom of the host pipe, its position can also vary. If ground water is present, it may float to the top, and under some circumstances tension in the carrier pipe may also pull the pipe to the top (such tension may exist due to temperature changes). If grout is placed in the space between host and carrier, the carrier should also float, but depending on how the grout is introduced, the carrier may be displaced to one side or the other.

Pipebursting (Figure 1.4). Reconnection of services using a low-dig or no-dig approach when pipebursting is used will likely pose the greatest technical challenges. As the figure illustrates, the host pipe is typically broken into several pieces. When this happens, the condition of the existing lateral connection will be difficult to determine. Perhaps there is an advantage over straight slip lining, in that the host pipe is broken, and thus the walls of the old pipe may not pose as significant a hurdle to connecting a new lateral, but the broken pieces of pipe will present hurdles to overcome, nonetheless. A further complication may occur where a service saddle exists. This saddle may be dragged through the ground some distance by the bursting tool, with the lateral pipe still attached.

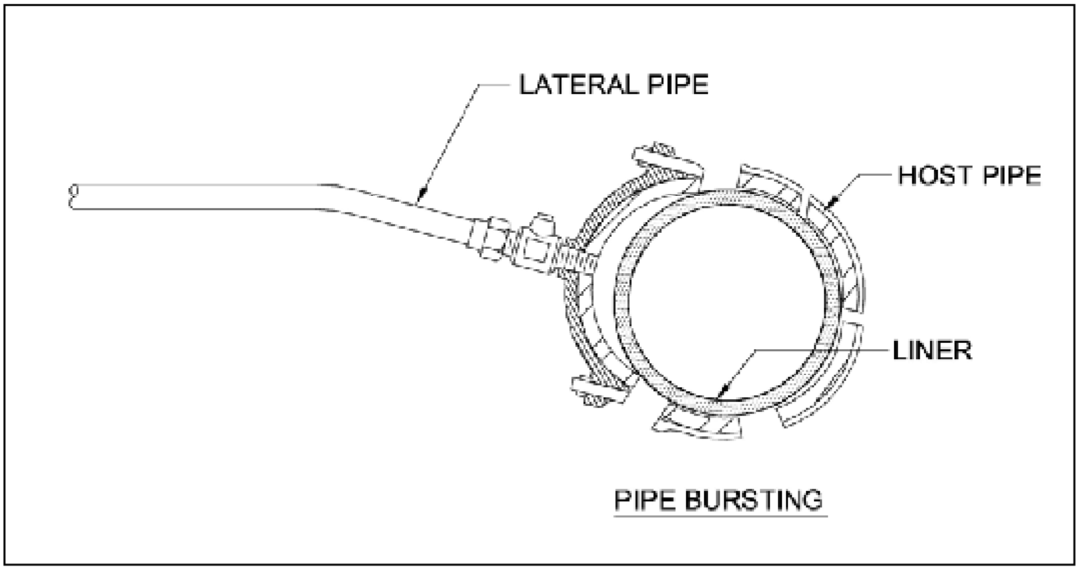

Figure 1.4. Illustrates typical conditions that exist following water main rehabilitation using pipe busting or splitting.

CONDITIONS CONSIDERED IN THIS STUDY

A host of difficulties would seem to face someone hoping to develop methods for non-disruptive reconnection of services. The number of conditions to be encountered varies considerably, with possibly thousands of potential combinations. Table 1.1 lists some of these conditions with brief comments regarding the focus of this study. Generally, this study was aimed at developing methods of service lateral restoration that would work for a large portion of conditions.

Table 1.1

General Assumptions Used in Developing No-Dig and Low-Dig Methods of Service Lateral Reconnection

Condition	**Assumptions**
Sizes of water mains	The focus of this study is on mains that are 6 inches (150 mm) in diameter and larger. Mains that are 4 inches (100 mm) or smaller, would be less likely to be rehabilitated; they are often considered substandard, and the economics for main renewal are less likely to favor rehabilitation.[7]
Sizes of lateral pipes	The focus of this study is on laterals that are 5/8-inch (15 mm) to 1-inch (25 mm), representing typical sizes for single-family residential services—the majority.
Lateral pipe material and condition	The focus of this study is on copper lateral pipes. Steel, lead and polybutylene service pipes, if present, should be considered for replacement. Polyethylene services are not commonly found in the United States, and are not likely to be present on a water main that is being rehabilitated.
Presence of corporation stops (before service reconnection)	This study generally assumes that a corporation stop is present, with or without a service saddle or protruding ferrule. It is assumed that the design of these corporation stops may be highly variable.
Presence of corporation stops (after service reconnection)	This study assumes that a functional corporation stop need not be present after the water main is rehabilitated. The corporation stop is believed to serve two functions: (1) it is used to "hot-tap" the main; (2) it can be used to stop leakage from an abandoned lateral. Neither of these functions is essential to the operation of a rehabilitated main.
Host pipe material	Common materials: ductile iron, cast-iron, steel, asbestos cement. Because of their age, mains that are constructed of PVC or HDPE are less likely to be rehabilitated in the next few decades.
Lining materials	Common lining materials are: PVC, HDPE, epoxy, and various cured-in-place resins with cloth tubes. While cement mortar is the most common lining material, for the reasons discussed earlier, it is not a focus of this study.

[7] Generally, the larger the pipe, the more advantageous is rehabilitation. For instance, the amount of work needed to rehabilitate a 4-inch and a 12-inch pipeline is similar—only the cost of the liner material will vary. Conversely, there is a significant difference in the open-trench construction cost for these two sizes of pipes.

PROBLEM SUMMARY

Table 1.2 summarizes the issues that complicate the restoration of services following the rehabilitation of water mains.

Table 1.2
Critical Issues to be Considered in Remaking Service Connections, Following Water Main Rehabilitation

Issue	Comments
Bore restoration	• Accurately determining the location of existing taps can be difficult after a water main pipe has been lined • If a structural or semi-structural pipeline rehabilitation is needed, the locations of existing service taps need to be determined with much greater precision than is typically done in wastewater or stormwater applications.
Sealing of annulus (between carrier and host pipe, or between lining and existing pipe)	• For structural rehabilitation, water entry into the annulus must be prevented • Sealing of the annulus can be difficult due to incompatibility of materials (see below) and the deteriorated condition of existing mains (see below)
Geometry difficulties	• Various sizes of laterals and mains will be encountered on any project • The angle the lateral pipe makes with the horizontal will generally vary from one connection to the next • Liner and host pipes are not always concentric
Variable materials	• By the time a main is rehabilitated, several different kinds of lateral pipes may be connected to it (lead, galvanized steel and copper are common) • Horizontal "goose necks" or other bends in the lateral pipes likely exist • Many variations in corporation stops and tapping methods have been used (continued)

Table 1.2 (continued)
Critical Issues to be Considered in Remaking Service Connections, Following Water Main Rehabilitation

Issue	Comments
Compatibility of materials	• The surface properties of HDPE generally preclude the use of adhesives for sealing the annulus • “Creep” (or “relaxation”) of plastic materials (HDPE or PVC) must be considered • The inside surface of existing mains may be rough: tuberculation, scale, or corrosion pitting may be present • Taste, odor, and heath issues must be considered. NSF61 approval is generally required for any materials in contact with potable water.
Condition of existing mains and laterals	• There is a significant probability that mains and laterals will be deteriorated due to their advanced age • While various condition assessment tools exist, the cost to employ them can be significant (often approaching the cost of rehabilitation by itself)

EXPERIENCE FROM OTHER UTILITY SECTORS

In several ways, other utility sectors are considerably ahead of the water industry when it comes to “trenchless” construction. In the wastewater field, pipes are usually much deeper, not pressurized, but easily accessed through manholes, making the economics of pipeline rehabilitation much more favorable. As a result, the mileage of sewer mains that are rehabilitated each year is believed to be several times that of water mains.

In the oil and gas industry, pipeline integrity is naturally a greater safety and environmental concern than in the water industry. The value of the commodity transported is also greater. As a result, the industry moved many years ago toward the use of non-destructive condition assessment techniques, and the use of non-corroding, fully fused pipeline materials, such as HDPE pipe. The techniques and products associated with HDPE piping lend themselves to many trenchless techniques. HDPE is particularly useful in trenchless construction due to its pliability and the ease of making remote connections (using electro-fusion techniques).

Additionally, simple advances in technology that we now take for granted provide tools that did not exist before. Closed-circuit televisions (CCTV), robotics, soft-dig (vacuum) excavation, and ground-penetrating radar are just some of the systems that may soon prove invaluable in developing no-dig and low-dig techniques for re-establishing connections where pipe rehabilitation has occurred. Even the telecommunications boom of the 1990s advanced the industry, with the introduction of various robotic cable installation techniques, and the rapid growth of horizontal directional drilling (HDD).

With innovation, trial, and error, it is hoped that a synthesis of tools and techniques taken from many sources can provide a path toward the goal of creating no-dig and low-dig methods for remaking connections, thereby significantly reducing the cost of pipeline rehabilitation.

RESEARCH APPROACH

The need to solve these various problems has been recognized for many years by many individuals, and if the problem were easily solved, there would be no need for AwwaRF to lend a hand. As the pipeline rehabilitation industry has grown in North America, Europe, and Australia, so has the incentive to find better methods of reconnecting service pipes. This has been true for natural gas distribution utilities, wastewater collection utilities, as well as the water industry.

The basic approach to this investigation focused on bringing together the best expertise the world has to offer, including:

- The company that invented pipebursting, pipe splitting, Swage® lining, and other processes
- The company that is recognized as the leader in development of bursting and splitting tools; a holder of more than 200 patents
- The company that invented the Subline® process and is a recognized leader in pipeline rehabilitation in the United Kingdom
- The company that developed the tight-fit PVC process for water main rehabilitation
- A leading company in pipeline robotics, pipeline locating, and vacuum excavation techniques
- Companies specializing in wastewater pipeline rehabilitation
- Academic experts in the testing and evaluation of trenchless technology
- Several major pipeline rehabilitation contractors
- Rehabilitation experts from several leading water utilities and water engineering consultants

This assembly of knowledge occurred in several ways: through a review of existing publications, contacts with leading organizations, interviews with leaders in the field, and—most importantly—at a technical workshop, where the top experts discussed various approaches to the problem of service lateral reconnection. The following provides a brief description of these activities.

Literature search and reviews. The project team conducted internet and library searches, including the sites and archives of AWWA, AwwaRF, ASCE, UCT, NASTT, WRc, GTI,[8] and other organizations in the utility and trenchless construction fields. Lists of organizations, publications, authors and contacts were assembled.

The amount of published material on this subject, not surprisingly, was minimal. It is a highly specialized area, and information is often kept confidential until patents are secured and tools are ready for market.

Survey/Interview of Pipeline Rehabilitation Leaders. The project team interviewed utilities, companies, industry trade groups, professional organizations, and others considered

[8] See Abbreviations list at the back of the report for the full name of these organizations.

leaders in the field of pipeline rehabilitation and trenchless construction. Descriptions of concepts, tools, and techniques for re-establishing connections were documented. These interviews included those listed in the Acknowledgments section of this report, as well as others identified through the interview process and literature search. By tapping into the knowledge base of the technical advisory team, we documented the cutting edge of technology in this particular area.

Technical Workshop. The technical workshop was the cornerstone of the project. By bringing into one room many of the foremost experts in the field, the team was successful in identifying key concepts for tools and techniques required to re-make connections following water main rehabilitation.

The workshop was held in conjunction with the Underground Construction Technology Conference, January 16, 2003, in Houston. Prior to the workshop, "homework" was distributed to the participants. This consisted of documents that defined the problem, along with concepts and questions to stimulate thought processes beforehand. Specific workshop goals were:

1. Develop general concepts for remaking connections for each of the common conditions (i.e., tight-fit, slip lining, pipebursting, etc) that are expected to be encountered.
2. Document the steps and tools anticipated for successful implementation of each concept.
3. Document the hurdles—and possibly the fatal flaws—that exist for the development of each concept.
4. Resolve which ideas (if any) were worth pursuing through "proof-of-concept tests".
5. Acquaint project participants with each other, to facilitate future discussions and participation in the project. (Relationships developed during the workshop were important, because several participants acted as general consultants to the work and participated in the testing of the concepts.)
6. Generate interest and enthusiasm for subsequent project activities, including proof-of-concept tests.

During the workshop, participants were split into 4 groups, with each group assigned the task of developing a concept to address one of the following cases:

1. Tight-fit HDPE lining – lateral reconnection
2. Pipebursting – lateral reconnection
3. Slip lining – lateral reconnection
4. Low-dig installation and connection of a new lateral to an existing main

The concepts addressing these conditions are presented in Chapter 4 of this report. Additionally, a fifth concept that addresses the tight-fit PVC liner product is described, as conceived by the developer of the liner.

Overall, the workshop exceeded expectations. Not only were the foremost experts in various fields present, but each was generously forthcoming with information. Despite the danger that discussion might diminish the market value of individual ideas, the participants recognized the value of the group discussions. Many who attended brought healthy skepticism to these discussions, but, in the end, a consensus for which ideas merited further testing was achieved.

Proof-of-concept tests. Chapters 5, 6, and 7 present the results of field and laboratory testing of several ideas generated at the workshop. The CD that accompanies this report highlights key events in the testing program.

In general, the testing program demonstrated that with additional investment of time, money, and energy, most *technical* problems will eventually be solved. The major hindrance at this point appears to be simple economics. The US market for structural rehabilitation of water mains is still rather small. One reason is that not enough mains are being replaced each year. Another reason is the current lack of fully-effective rehabilitation techniques (i.e., methods that are truly "no-dig"). This often results in selection of open-trench rather than rehabilitation. Because the water main rehabilitation market has remained relatively small, the amount of money that investors are willing to devote to development and refinement of new tools and techniques has also been relatively small.

Some of the methods described later in this report can be applied today. "Keyhole" techniques, for example, have seen limited use in various areas, but the tools themselves need further perfection. If a greater number of large-size rehabilitation projects were bid, then the marketplace might take care of getting better tools developed. As soon as one bidder gains an advantage through using such tools, their use will quickly spread. Hopefully, it is just a matter of time before large rehabilitation projects are bid routinely, then competition should assure further innovation and development of these keyhole methods.

More sophisticated methods, requiring the use of exotic pipeline robots and custom-made materials, will require a more focused effort and greater capital investments to achieve practicality. One such method has been patented and "proto-typed", but the perceived size of the market has stalled further investments. Corporations find it difficult to justify significant investment in these areas, given the current size of the market. However, because of the infrastructure deterioration that is known to exist, there is no doubt that a larger water main rehabilitation market will eventually develop in the United States. Such a market has been emerging in Europe over the last 10 to 15 years.

CHAPTER 2
INTRODUCTION TO WATER MAIN REHABILITATION TECHNIQUES

This chapter provides an introduction to common methods of water main rehabilitation that are currently available in the United States, Canada, Europe and Australia. The intent is to introduce the options, outline their advantages and disadvantages, and glimpse where the industry seems to be headed. Conventional, open-trench pipeline construction is not discussed, since it really needs no explanation, however it remains a viable option in most cases where pipeline renewal is being considered. Only brief descriptions of the available methods are provided. Because the field is rapidly evolving, every available technique may not be described, and some descriptions may soon be out-of-date. For a more complete understanding of the subject, it is suggested that the reader contact the AWWA Water Main Rehabilitation Committee, or consult other publications of AwwaRF (Ellison, 2001; Grigg, 2005, among others).

Until recently, pipe renewal *generally* meant conventional pipe replacement. A new pipeline would be constructed in a new alignment, and then (after services were connected to the new pipe) the old pipe would be abandoned in place. However, pipeline rehabilitation or "trenchless" replacement methods are being employed with greater and greater frequency. Depending on the method used, rehabilitation is capable of improving hydraulic capacity, arresting water quality deterioration, restoring structural integrity, and extending the life of the old pipe, at a cost that may be substantially less than conventional replacement. The move toward pipe rehabilitation and "trenchless" methods, has been driven by several different factors:

- **Technology Development**. The development in recent years, of several new "trenchless" methods has greatly increased the options available. As a result, the rehabilitation industry has been gaining momentum, as more owners, contractors, and engineers become familiar with the processes, and are willing to try them.
- **Cost Effectiveness**. In many applications, the cost for trenchless construction can be substantially less than the cost of conventional construction. As the use of these alternatives spreads, competition will increase, and experience will develop. When this occurs, the costs for "trenchless" should be even less.
- **Community "Impacts**." Trenchless methods are perceived as more community friendly, with less mess and other construction effects. Rehabilitation work can often be performed substantially quicker than conventional replacement.
- **Street Cuts**. More and more cities are imposing fees, moratoriums, and other restrictions on utility pavement cuts. This favors rehabilitation techniques that require less digging.
- **Congestion**. The increasing congestion of utilities under the pavement has made it more difficult to find new alignments for replacement pipes. Moreover, the increasing congestion of vehicles above the pavement has made it more difficult to open up trenches up and down the streets.

Rehabilitation methods also fill specific niches. They work well in narrow easements, through backyards, under rivers or down steep hillsides. They can save money, by solving a specific problem, while taking advantage of the properties of an old pipe that still are valuable.

Every pipeline renewal plan should be different, depending on information obtained from an assessment of the system, the future plans for the system, and the owner's preferences. Typically, a pipeline rehabilitation project will include upgrades or replacements of valves. It may also be a good time to consider installing or replacing hydrants, meters, and substandard service laterals, particularly those with lead pipe or lead components.

IN-SITU CEMENT MORTAR LINING

The benefits of cement mortar lining are indisputable. The lining provides a highly alkaline environment next to the metal that virtually eliminates corrosion of the interior surface. This in turn eliminates the formation of iron mineral deposits (tuberculation) that choke off flow, waste energy, and lead to water quality complaints and concerns (Figure 2.1).

The ability to line pipe in place has existed since 1933, but only a handful of companies perform this specialty. The cost to clean and cement mortar line pipe in place ranges from one quarter to one half the cost to replace it, depending mostly on the size of the pipe, the complexity of the system, and the size of the project.

Since the lining virtually stops interior corrosion, the life of most pipes will be extended considerably—no one is sure how much. This is because in the absence of corrosive soils, very little in-situ lined pipe has ever failed, even after 50 years. We do know that cement lining can cause leak rates to drop dramatically. On a major pipeline in Los Angeles, for instance, 220 leaks were recorded in the pipeline's first 58 years, but only 2 in the 35 years since it was lined (Ellison, 2001).

Figure 2.1 - Cement Mortar Lining (before and after).
Photo courtesy L.A. Department of Water & Power

Cement mortar lining is generally considered "non-structural", and should not be used for small-diameter pipelines where there have been significant problems with leaks and breaks. However, the lining undoubtedly lends some strength, spanning over rust holes and other small weaknesses in the pipe. To increase the structural value of the lining, some companies have recently introduced polypropylene fiber reinforcement to the cement mortar. For large diameter pipelines, the lining has also been reinforced with welded wire fabric.

For small mains, the method is accomplished as follows:

1. After connecting customers to a bypass system (described later in this chapter), the inside of the main is accessed by cutting out sections of the pipe at bends, fittings, valves, and intermediate points.
2. Tuberculation and scales are removed using a mechanical cleaning method—drag scraping and rack-feed power boring are the most common methods (Ellison, 2003). Drag scraping, the method most common in the US, involves the repetitive scraping of the inside of the pipe using spring-steel scrapers. Following the initial cleaning, squeegees are pulled through the pipe to remove water and remaining sediment.
3. A machine is then pulled through the pipe that sprays a uniform thickness of mortar onto the pipe wall. The pumping of mortar to the machine and the pulling of the machine through the pipe are carefully controlled, to provide the thickness of material that is desired.
4. A conical steel "trowel" attached to the lining machine smoothes the mortar as the machine is advanced.

As described in Chapter 1, the reconnection of service laterals following in-situ cement mortar lining is not an issue. While the laterals are temporarily plugged with mortar, a blast of compressed air or water into the lateral pipe, while the mortar is still plastic, is sufficient to clear the lateral. Occasionally, if a service line is not cleared in time, an excavation at the service tap will be needed.

EPOXY AND OTHER SPRAY-ON PLASTIC LININGS

In areas where water is very soft, deterioration of cement mortar lining can occur.[1] For this reason, in Britain, epoxy lining is commonly used instead. British systems also tend to have smaller diameter mains, where the economics of epoxy lining are more favorable. However, epoxy lining is much less tolerant of small defects and is thus less effective in stopping internal corrosion. Pinholes or other imperfections in the lining will enable corrosion to get started again in an epoxy-lined pipe.

In addition to epoxy lining, several other spray-on plastic lining materials are being developed, including polyurethane, polyethylene, and polyurea. Some of these linings promise a very fast cure, allowing the pipe to be repressurized in just a few hours. Conceivably, these linings may eventually enable the rehabilitation of distribution pipes without the need for bypass piping systems, provided that concerns about disinfection and bacteria testing can be resolved to the satisfaction of utilities and regulators. Because of the nature of these materials, it is sometime argued that the product is inherently sanitary.

Epoxy and other spray-on plastic linings are generally thin (less than 1/8 inch or 3 mm), and thus provide no significant structural value. However, various companies have developed methods of providing liners of greater thicknesses, with greater structural worth. Although the hoop strength of a pipe is seldom increased appreciably by using an unreinforced plastic liner (the elastic modulus of the plastic is too low compared to that of an iron or steel pipe), a thick liner is capable of spanning over weaknesses in the host pipe, caused by corrosion or other defects.

[1] Generally, if alkalinity is less than 55 mg/l (as $CaCO_3$), then in-situ cement mortar lining should not be used. For more information, see Douglas and Merrill 1991.

The process of cleaning and lining a pipe with epoxy is very similar to the one described earlier for cement mortar. The restoration of service connections following epoxy lining is even less of an issue with epoxy lining than it was with cement mortar lining. Generally the service bores are not plugged. No blast of air is needed. Moreover, if the liner is intended to be structural, good adhesion should be present between the liner and the pipe.

STRAIGHT (OR LOOSE-FIT) SLIP LINING

Where a reduction in pipe size can be tolerated, slip lining with high-density polyethylene pipe (HDPE) is an economical method, particularly for transmission mains with few lateral connections. The method is really a replacement technique rather than rehabilitation. The end product is a new pipe that is structurally independent of the host pipe.

Segments of HDPE pipe are fused together, above ground, into a single pipe string. Then the HDPE pipe is pulled inside the host pipe between access pits (Figure 2.2). While steel, ductile iron, PVC and fiberglass pipe have also been used for slip lining, HDPE is particularly suitable because of its tremendous flexibility, fully fused joints, and general tolerance for scrapes and gouges.[2] There are differences of opinion regarding whether the annulus area between pipes should be grouted. Grouting adds substantially to the cost of the installation and is difficult to inspect.

The major limitation of this method is capacity reduction. Generally, the outside diameter of the new pipe should be approximately 10 percent smaller than the inside diameter of the existing pipe to facilitate insertion. In addition, if HDPE is used, the pipe walls may need to be rather thick, in order resist common water system pressures and external loads, further reducing the hydraulic capacity.

Figure 2.2 - HDPE Slip lining. Photo courtesy of J. Fletcher Creamer & Sons, Inc.

[2] The molecular structure of HDPE is heavily cross-linked. Scratches and gouges do not normally lead to fatigue cracking.

TIGHT-FIT SLIP LINING

The capacity reduction associated with straight slip lining can be largely solved by using a tight-fit lining. This can be done with various materials, HDPE, PVC, and steel being the most common. The chief disadvantage of tight-fit lining using either HDPE or PVC lining is its relative novelty, particularly in the United States. The techniques and hardware (fittings and couplings) are not widely used, and only a few contractors are experienced in this method and have the requisite equipment.

Tight-Fit HDPE Lining. The tight-fit HDPE process is similar to straight slip lining, except that a larger-diameter, thinner-walled HDPE pipe material is used. (The OD of the liner is approximately equal to the ID of the host.). A couple of techniques have been developed that involve the concentric reduction of the pipe just prior to insertion. After the pipe is fused, it is pulled (or pushed) through either a die or a series of rollers, which temporarily reduces its diameter just before it is inserted into the host pipe. Then, once in place, the liner pipe either slowly expands or is pressurized, thus returning to its original size and fitting snugly within the host pipe. An alternate method uses a device to deform the liner pipe into a "U" shape just prior to insertion (Figure 2.3). This shape is secured with plastic bands. Once the liner pipe is in place within the host, the bands break as the pipe is inflated using air pressure, fitting snugly within the host pipe.

Figure 2.3 Large-diameter HDPE pipe deformed and banded for tight-fit lining. Photo courtesy of Boyle Engineering Corporation

Whichever method is used, the liner pipe must be relatively thin in order to accommodate the large deformations. Because the liner is in contact with the existing pipe, the liner/host product behaves somewhat like a composite. While the plastic liner adds very little hoop strength to the existing pipe, it does span holes and weak spots in the host. It also eliminates internal corrosion. These methods are therefore "semi-structural" in most applications, meaning that the host pipe is still needed for pressure resistance.

Tight-fit PVC Lining. This method involves the use of a butt-fused PVC pipe that is slipped into the host, then softened and expanded using steam, until it fits snugly within the host. A special "fusible" PVC pipe is used, with an outside diameter that is smaller than the inside diameter of the host pipe. Ultimately a liner pipe with a stand-alone pressure resistance of 100 to 150 psi can be achieved, often without significant reduction in hydraulic capacity. While the method is only a few years old, it has gained considerable interest.

The thickness of the PVC material is selected such that when it is fully expanded, it will provide the required pressure resistance. In general, the pipe liner is designed to provide "stand-alone" strength—meaning the strength of the host pipe is not included in the pressure rating calculation. In other words, this method is considered "fully structural."

Polyester Reinforced Polyethylene (PRP). This rehabilitation method is similar to both tight-fit slip lining and RCIPP (discussed later). When delivered to the job, the product looks much like a fire hose. It arrives flattened, on reels, and is simply pulled into the host pipe. Unlike a fire hose, however, the product is stiff, with a polyethylene lining and coating. A polyester fabric within a composite material provides the strength to resist pressures up to 225 psi (16 bars). Once in place, the liner is temporarily softened and inflated using steam.

PRP does not bond with the host pipe; it is designed to resist 100 percent of the internal pressure by itself. But because the PRP pipe is thin and flexible, the host pipe is still needed as a casing to resist the compression loads from the soil, particularly for those times when the line is out of service. An annular space most definitely exists between the host and liner in the finished condition, thus a positive connection to each lateral pipe is needed, for the liner to provide any value.

Tight-fit Steel Lining. Steel plate liners have often been used to reinforce large-diameter pipes. Rolled steel plates are maneuvered and jacked into position inside the pipe, then following welding of the longitudinal and circumferential seams, the annulus is grouted. The last step in the process is in-situ cement mortar lining of the newly constructed steel liner.

This method is as expensive as it sounds, but is often less expensive than replacing a large-diameter pipe that is deep underground. Tight-fit steel liners are nearly always "fully structural."

Reconnection of Services Following Tight-fit Lining. In all tight-fit slip lining cases, the value of the liner will be seriously compromised if a positive connection to the lateral is not made. Generally this is currently done by excavating at each connection. The restoration of the service bore, by itself will generally not suffice, for no matter how tightly the liner fits within the host, it does not bond to it, leaving an annular space where water can migrate under pressure.

PIPEBURSTING

Like slip lining, this technique is really a replacement method. The advantage of pipe busting is that no reduction in capacity is required—in fact the pipe size often can be increased to some extent. Again, the technique resembles slip lining; however, a "bursting tool" is inserted in advance of the new pipe (Figure 2.4). The "bursting tool" breaks the existing pipe and expands the opening, enabling a larger pipe to be simultaneously pulled into place. Tools have been developed that split clay and cast-iron pipes with ease. Some types of concrete pipe have also been "burst," but the steel reinforcement can be a concern. Tools capable of splitting steel and ductile-iron pipes have also been introduced in the last few years.

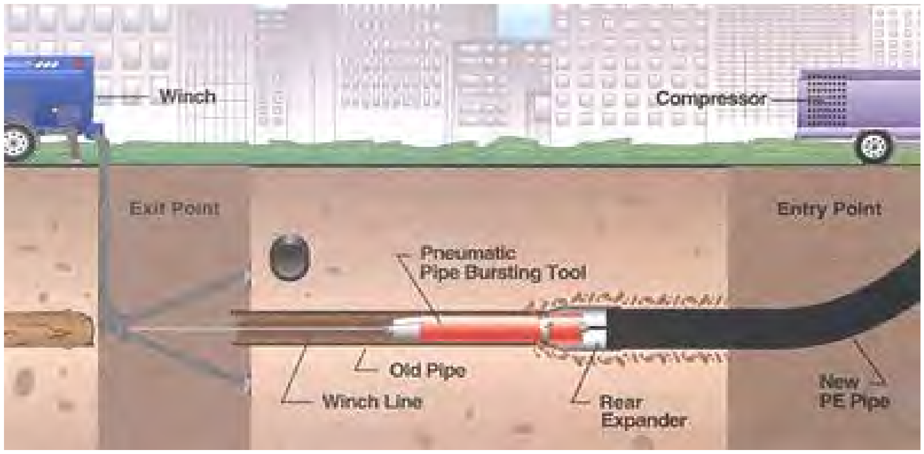

Figure 2.4 - Pipebursting. Illustration courtesy of TT Technologies

The amount of "upsizing" that can be achieved through pipebursting is a matter of site conditions—the compressibility of the soil, the depth of the pipe, and the proximity to other utilities. A significant associated risk with pipebursting is heaving of the soil, and consequent damage to pavement and other utilities. Pot holing is recommended prior to bursting to expose any utilities of concern. Also, the greater the upsizing, the slower the process, and the more the new pipe might be gouged as it is pulled through the ground. HDPE is the generally preferred insertion material, although PVC, ductile iron, and steel pipes have been used as well.

The gouging of the soft HDPE pipe is generally not a concern. When pipebursting was initially used, some specifications required that casing pipes be installed to protect the carrier pipes. The casing pipes would be pulled into place using the bursting tool, and then the carrier pipes would be slipped into the casing. This more expensive two-pipe approach is seldom used today. Typical specifications allow gouges up to 10 percent of the wall thickness, and an examination of the leading portion of the pipe generally indicates that the gouges meet this standard.[3]

Pipebursting has tremendous potential. When it works well, construction can be remarkably easy. The method is especially cost effective where physical constraints to conventional open-trench installation exist. However, there are risks involved, limiting its current acceptance and elevating prices. As more contractors gain experience in the method, prices should fall.

Reconnection of Services Following Pipebursting. It may be impossible to develop a practical way to reconnect services using a no-dig approach following pipebursting. The host pipe is typically broken into many pieces, and the condition and location of the existing lateral connection would be difficult to determine. However, a low-dig approach is certainly possible using "keyhole" tools, as described in Chapter 5.

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[3] A new product being used in Europe provides additional insurance against gouges, using a tough polypropylene "skin" to protect the HDPE. (The skin and pipe are extruded simultaneously.)

CURED-IN-PLACE PIPE (CIPP)

Cured-in-place pipe lining is a very common technique, used primarily in the wastewater industry to rehabilitate pipe. In this method, a resin-impregnated fabric tube is inverted within the host pipe using air or water pressure. The resin is then cured using steam or hot water. The product forms a tight-fitting liner within the existing pipe, and is primarily used to resist soil, traffic, and other external pipeline loads. The pipe lining can be designed for a host pipe that is either fully deteriorated or partially deteriorated. Epoxy resins and CIPP liner materials for potable water application have been available since the early 1990s.

Because CIPP was developed for gravity-flow pipelines, it generally is not that useful in water pipeline applications. As corrosion protection for the host pipe, it is probably comparable to CML or epoxy. Like other plastic liners, it provides little hoop strength and thus does little to restore or increase the pressure resistance of the host pipe, but it can serve as a semi-structural liner, spanning over weak areas in pressurized pipes.[4]

Reconnection of Services Following CIPP Lining. Because CIPP lining is so widely used in the wastewater field, lessons can be learned regarding no-dig methods of reconnecting services. Typically, in CIPP projects, a robotic cutter, guided by CCTV, is used to restore the bore at the service lateral. (Chapter 3 provides a more detailed description of these robots.) The bore location is discerned by a "dimple" created in the liner when it is cured under pressure. After the bore is cut out, flow from the lateral can find its way into the liner. However, in some cases, additional efforts are made to seal the space between the liner and the lateral. Sealing between the liner and lateral is often necessary, if the purpose of the lining is to stem infiltration. While many products are available for sealing these connections, few have shown their efficacy in large-scale field applications. Two methods that are known to work are: (1) the use of epoxy grouting methods, or (2) using CIPP-type "top hat" or "T" Liner service lateral connections. Both of these techniques are described in Chapter 3. It is not known whether these wastewater methods would be effective in water main applications, where pressures are many times higher, and the laterals are many times smaller.

In pressure pipe applications, proper attention must be paid to the connections at each end of liner pipe, to prevent leakage into the annulus between host and liner. Over the years, several methods have been tried. One method employs expanded internal mechanical seals, with either rubber gaskets or chemical grout to accomplish the seal. Another method employs a short internal cured-in-place seal with or without "O" rings.

REINFORCED CURED-IN-PLACE PIPE (RCIPP)

The major difference between reinforced and traditional CIPP is the fabric tube that is used. RCIPP uses a woven jacket made from polyester, fiberglass, or carbon fibers instead of a more simple (unwoven) felt. The woven fabric reinforcement can add considerable strength, and has been used for pressures over 400 psi, and in pipes up to 40 inches in diameter.

One RCIPP product, introduced to the market within the last 3 years, was designed specifically for water main rehabilitation, and uses two concentric, tubular, woven polyester jackets. The inner jacket is bonded onto a polyurethane sleeve that is potable water compatible and intended to maintain the water tightness of the liner. Both jackets are impregnated with a curable polymeric resin that plays two important roles. First the resin allows the tubular liner to

[4] In non-pressure pipe applications, CIPP is generally designed for external loads and is considered fully structural.

adhere to the host pipe.[5] The resin also cures and completes the formation of the composite structural liner. The resulting composite material liner has sufficient strength to resist normal water system pressures, without aid from the host pipe.

Reconnection of Services Following RCIPP Lining. The rehabilitation technique just described employs a mechanical robot equipped with a camera to reinstate the service laterals. The robot is operated using a remote control and television unit. The robot is equipped with a drilling tool that allows the operator to drill a hole in the liner at the precise location of the connection, the approximate location of each lateral having been recorded and mapped prior to the rehabilitation and insertion of the liner. This technique is reportedly very successful where a ferrule or other protrusion is present at the lateral tap, otherwise the tap is generally not discernable. If the liner adheres tightly to the host pipe, as claimed, no additional effort may be needed to provide a fully structural connection between liner and lateral.

HORIZONTAL DIRECTIONAL DRILLING (HDD)

Horizontal Directional Drilling (HDD) is a pipeline installation technique involving drilling in a shallow arc using a steerable drilling head. This technique is often considered together with pipeline rehabilitation, because it also promises trenchless construction. The HDD process was initially developed to minimize the surface disturbance when installation of pipelines across rivers was required, as well as for installing pipelines under obstacles. However, it is becoming a preferred method of construction for many applications.

Current HDD technology reflects a rapid advancement of drill rig and guidance technologies. With HDD, surface disturbances are limited to small areas on either end of the pipe reach. The HDD process involves three main components: pilot hole, pre-ream, and pullbacks. Initially, a pilot hole is drilled from entry to exit points. Once the pilot-string is completed, the bore is enlarged (pre-reamed) with a succession of reaming tools. At the final reaming, the new carrier or casing pipe is pulled back through the HDD cavity. Drilling mud is used to help sustain the hole, and lubricate the pull-back process, in addition to removing the cuttings during the boring and reaming processes.

HDD can be accomplished for small diameters over short distances with either small surface drill rigs or pit-launched HDD units. For long distances, particularly with large diameter bores, large equipment will be needed, requiring a large site footprint. Also, HDD is sometimes limited in that certain paths are virtually impossible to drill due to the inherent limitations of the current available technology. A successful HDD project requires a thorough understanding of the existing subsurface conditions. Frequently, potholing of each crossing utility is required.

To date, HDD has not been commonly used for water main installation or replacement. One problem has been that HDD often places the pipeline at a greater depth than normal, making the connection of service laterals relatively difficult. The greater depth of installation is partly due to the need to stay well clear of other utilities. One strategy for solving this problem is to insert detection devices in the ground that allow for better control of the pipeline profile.[6]

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[5] The degree to which adherence can be achieved within real water mains is a subject that merits further investigation.

[6] One company claims that its technology allows construction of pipelines to grade. It is said that sewer mains can be constructed without sags.

COMPARISON OF REHABILITATION METHODS

Table 2.1 (following page) summarizes the commonly available rehabilitation methods. A choice of method will be largely dictated by the condition of the pipes, project objectives, and estimated costs. Determining which method is the most economical for any given situation is difficult, since it really depends upon the perceptions of the contractors who bid the work, and, if a method is highly specialized or proprietary, the number of bidders will be limited. It's a good idea to permit alternative methods to be bid, letting the marketplace decide which is most economical for a particular situation. Where the alternatives don't provide equally desirable products, then the bid documents need to clearly indicate how the alternative bids will be compared.

Table 2.1
Comparison of Pipeline Renewal Methods

Method	**Advantages**	**Disadvantages**
Open Trench	• Time tested • No bypass system usually needed • No special equipment or expertise needed • No limit on upgrade of size or material	• Extensive pavement cutting and restoration • Traffic impacts • Other construction impacts • Difficulty finding spaces within congested areas for new pipes
Cement Mortar Lining (CML)	• Time tested • 25 to 50% of replacement cost • Several contractors available	• Non-structural • pH problems where water is very soft • Requires bypass system • Uncertain pipe life extension
Spray-on Epoxy Lining	• Works with soft water • Cost competitive with CML on small diameter piping	• Non-structural • Small defects lead to continued corrosion • Few US contractors • Cost for large pipes higher than CML • Requires bypass system • Uncertain pipe life extension
Other Spray-on Plastic Linings	• Short cure times may mean shorter service outages. Bypass system may not be needed, if done sanitarily.	• Uncertain long-term performance • Limited experience • Uncertain pipe life extension
Polyester Reinforced Polyethylene	• Provides full-pressure restraint	• Proprietary • Special fittings required • Uncertain long-term performance
Cured-in-place Pipe Lining (CIPP)	• Provides some structural improvement • Several contractors available • Can handle pipe bends	• More costly than CML or Epoxy lining • Requires bypass system • Uncertain pipe life extension • NSF approval depends on materials used

(continued)

Table 2.1 (continued)
Comparison of Pipeline Renewal Methods

Method	Advantages	Disadvantages
Reinforced CIPP	• Can provide full structural rehab • Can handle pipe bends	• Proprietary • Requires bypass system • Uncertain pipe life extension
Straight (Loose-Fit) Slip lining	• Provides full structural renewal • No special equipment or expertise needed • Various materials can be used • Can be very cost effective	• Reduced hydraulic capacity • Requires bypass system • Requires area to layout pipe string
Tight-fit HDPE Slip lining	• Generally provides partial structural improvement • Can be cost effective	• Requires special equipment/license • Requires bypass system • Requires area to layout pipe string
Tight-fit PVC Slip lining	• Full pressure rating • Can be cost effective	• Proprietary • Uncertain long-term performance • Requires bypass system • Requires area to layout pipe string
Tight-fit Steel Slip lining	• Cost effective for large-diameter pressure pipes	• Reduced hydraulic capacity • Welding problems have led to failures
Pipebursting	• Provides full structural renewal • Size upgrades available (within limits) • May be less expensive than conventional replacement	• Can damage other utilities and pavement • Requires special equipment • Requires bypass system • Requires area to layout pipe string
Horizontal Directional Drilling	• Can be used to install new pipelines with minimal excavation • Effective for crossing rivers and highways, where trenching is impractical • Bypass piping is not needed	• Can damage other utilities • Difficulties in maintaining profile • Generally results in a deep, arching pipeline • Requires area to layout pipe string

BYPASS PIPING SYSTEMS

For most rehabilitation techniques, keeping customers supplied is a major consideration. This is typically done using temporary pipe laid in gutters on each side of the street (Figure 2.5). The temporary pipes are generally 2 to 4 inches in diameter and are supplied from a fire hydrant, but can range up to 12-inches. Sometimes a tap or connection to an adjacent main is required.

Figure 2.5 – Bypass Piping System. Photo courtesy of J. Fletcher Creamer & Sons, Inc.

Short pieces of hose are used to connect this "bypass or "sideline" pipe to the service pipes at the meter. To make the connection at the meter, the meter must be removed, and is either reinstalled laying on the ground, or is simply removed completely, and the customer's water use is estimated for the duration of the project.[7] Where the bypass pipe crosses driveways, special rubber ramps or cold asphalt mix mounded over the pipe permit the passage of vehicles.

Rehabilitation contractors often have crews that specialize in installation and removal of such systems, and the work can be quite a project in itself. Among the complications:

- Assuring adequate disinfection, bacterial testing, and flushing, before the bypass system is placed in service.
- Sizing of pipe to serve large customers or to replace large mains. (Where bypass piping exceeds 4 inches in diameter, shallow trenches are required where the pipe crosses driveways and alleys. These trenches are typically covered with plates or temporary pavement.)
- Assuring customers are supplied from the correct pressure zone, where two mains exist in the street.
- Assuring that an adequate number of hydrants remain in service, and that they are adequately supplied. (Hydrants that are inoperable must also be properly identified.)
- Avoiding undue hazards to vehicles and pedestrians from the pipes and hoses laid on the ground.
- Keeping the water from getting too hot in the summer (customers complain), or too cold in the winter (pipes freeze).

[7] Where meters are deeply buried or installed within basements, other connection details are needed.

CHAPTER 3
AVAILABLE TOOLS AND TECHNIQUES

This chapter describes currently available tools and techniques that may be useful in developing no-dig and low-dig lateral restoration methods for water mains. Most of the tools and techniques have been developed for other industries (principally wastewater), but many are adaptable for use in water systems. They are presented here to illustrate what technologies are currently available, and as an introduction for readers who may not be knowledgeable regarding certain tools. The possible use of some of these tools is described elsewhere in this report

In using or adapting these tools for water system use, there are several issues that must be considered:

- **Main sizes**. Water mains are generally smaller than wastewater mains. In the United States, the minimum size of most new water distribution mains is 6 inches (150 mm), although 4 inch (100 mm) pipe is also sometimes used. For wastewater pipelines, the minimum pipe size is generally 8 inches (200 mm), although 6 inches (150 mm) is also sometimes used.
- **Lateral sizes**. Water service laterals are generally much smaller than wastewater laterals. Typical residential water laterals are 1 inch (25 mm) or smaller, vs. 4 inches (100 mm) for wastewater. For very large homes, or where fire sprinklers systems are used, laterals can range up to 2 inches (50 mm), but these tend to be related to newer construction, and are not commonly found on water main rehabilitation projects.
- **Contamination**. Processes and equipment used in water systems must provide assurance that the system is kept free of any contamination, or the system must be disinfected and tested for bacteria before being returned to service.
- **Service interruptions**. Because invasive work on water systems will often involve time-consuming bacterial testing, bypass supply systems may be needed. This is true even if the in-pipe work takes only a few minutes. In wastewater applications, short-duration tasks on low-flow pipes can often be accomplished with the pipe in service, or by temporarily stopping flow with pipe plugs, and allowing the water to backup.
- **Manholes**. Robots and other tools are easily inserted in most wastewater pipelines, through existing manholes. Rarely do similar appurtenances exist on water mains.
- **Obstructions.** While wastewater pipes run generally in a straight line between manholes, with a constant slope, water mains are more likely to have horizontal and vertical bends, and valves that will impede the passage of robots or other tools through the pipe.
- **Pressure.** If a robot or other tool is to be used in an operating water system, it will need to withstand pressures that often range up to 200 psi. While some of the wastewater equipment can function underwater, pressures are seldom greater than 5 psi. (Working on an operating system, however, should not be a common condition expected in water main rehabilitation.)

PIPELINE ROBOTS

Pipeline robots generally consist of remote control systems designed to carry out a variety of specialized maintenance and rehabilitation tasks. At present, these devices are primarily used in gravity pipelines such as sewer mains; however, a hybrid version of this technology (designed for operation in pressurized gas pipelines) is currently in use by British

Gas. These remotely operated systems generally consist of a self-propelled transport unit upon which a variety of custom tools are fitted: grinding, cutting, grouting, machining, injecting, and smoothing working units. Work is generally guided by closed circuit television equipment that is either mounted on the robot, or mounted on a separate robot that works in tandem. Figure 3.1 illustrates a variety of such devices.

Sewer Repairs/Rehabilitation. The following operations and tasks are routinely performed by pipeline robots on gravity-flow pipelines:

1. Removal of obstructions by milling or grinding of protruding laterals, exposed steel reinforcement, and tree roots.
2. The grinding or routing of cracks in preparation for grouting and other repairs.
3. Re-opening of laterals following mainline rehabilitation using tight-fit slip lining and cured-in-place lining.
4. The insertion of lateral liners of limited lengths.
5. Pressure testing of joints.
6. Resin and chemical grout injection into cracks and joints.
7. Sealing between main liner and lateral, using resin or chemical grouting.
8. Insertion of cured-in-place service lateral connections for joining laterals to main liners.
9. Core sampling and retrieval.
10. Performance of various spot repairs, including the installation and grouting of sleeves, and the placement, inflation, and curing of cured-in-place pipe.

Figure 3.1. Sewer Repair Robots with Attachments.
Photo courtesy of KA-TE Robotics.

Complete sewer repair robotic systems are currently available from various manufacturers. A typical self-contained system may include various attachments required to repair a broken, leaking, recessed, or protruding lateral to mainline connection.

LATERAL PREPARATION AND REINSTATEMENT

Among the most common applications of pipeline robotic tools is preparing lateral connections in advance of main lining, and reinstating the laterals after the lining. This is often done with a single remote-controlled grinding tool, guided by CCTV equipment. After the liner is inserted, the location of the lateral is discerned by a visible dimple in the liner. A very typical tool is shown in Figure 3.2.

For the rehabilitation of water mains, similar tasks must be performed. If a lateral tap extends into the main, the protrusion must often be removed prior to insertion of the liner. Then after the liner is in place, the lateral bore must be reinstated. However, in the case of water laterals, seldom will a visible dimple be present, because the lateral is simply too small. The small lateral also means that there is a greater need for precision in the reinstatement process. If a drill is off-target by just 1/2-inch (12 mm), chances are that it will completely miss the mark.

CHEMICAL GROUTING AND RESIN INJECTION

Another very common sewer rehabilitation process is the sealing of joints, cracks, and other points of leakage using chemical grouts and other sealants. This pipeline rehabilitation method has been in use since the 1970s. Chemical grout is typically a two-component polymer that solidifies into a substance resembling Styrofoam. The process of chemical grouting is actually more of a soil-sealing process than a pipeline rehabilitation method. The grout penetrates the leak and then permeates the soil. The permeability of the soil is thus reduced when the grout sets.

Figure 3.2. Lateral Cutting Tool.
Photo courtesy of Amerik Supplies.

Chemical grouting is performed using a grout "packer". The simplest packers are cylindrical tools with seals on each end. These devices are either winched through the mainline or positioned by a robot crawler. After it is positioned in a location straddling a leak, the seals are inflated and grout is injected through ports. Other grouting equipment includes CCTV, pumps, regulators, valves, and hoses.

Packers have also been developed for deployment in laterals and at lateral joints, as shown in Figure 3.3. Once in position, these packers are rotated to align with the lateral opening, and are extended into it. After the grout has cured, a vacuum retracts the deflated packer and the device can be transported to the next lateral. These lateral packers cover laterals 4 to 6 inches

(100 to 150 mm) and can extend up to 30 feet inside the lateral. They operate inside of mains that are 6 inches to 30 inches (150 mm to 750 mm) in diameter.

For a more "structural" repair of joints and cracks, epoxy is frequently applied using other robotic devices. The technique of sealing the pipes and injecting the sealant is similar, but the objective is not permeation of the soil, but sealing of the joints. Among the spaces frequently sealed with epoxy is the annulus between a main liner and host pipe. Such sealing is required at manholes and laterals for effective control of infiltration and inflow. If sealing is not performed at these locations, water that leaks through the cracks and joints into the host pipe, will then migrate along the annulus, and enter the liner at these locations.

Figure 3.4 shows a device used for sealing laterals. A similar tool could be useful in sealing water main laterals, where CIPP lining or tight-fit PVC lining is installed (see discussion in Chapter 4, Case 6). In general, the lateral connection repair process begins first with the preparation of the application site; this often involves grinding of some sort. Next, a collar and/or balloon assembly is inserted to form a closed space around the joint to be sealed. Lastly, a compound (grout or epoxy) is used to seal the joint.

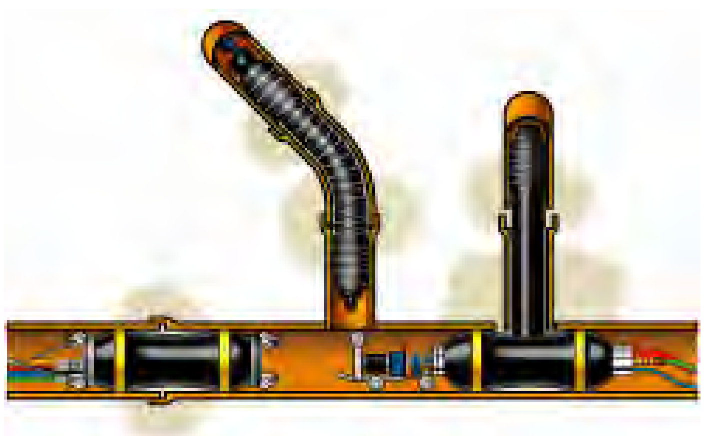

Figure 3.3. Chemical Grout Packers.
Illustration courtesy of Logiball, Inc.

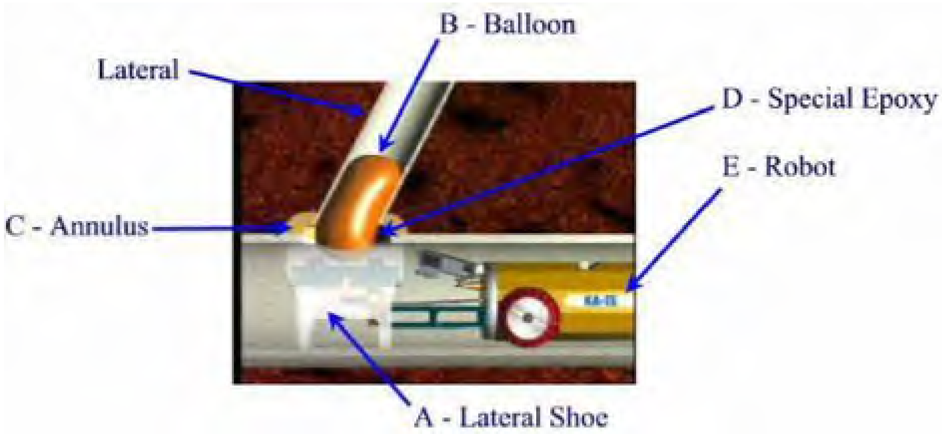

Figure 3.4. Lateral Sealing Tool
Illustration courtesy of KA-TE Robotics.

OTHER PIPELINE ROBOTS

The advent of the Internet and the Telecommunications Act of 1996 generated a huge wave of telecommunications investment and construction in the United States in the late 1990s. As entrepreneurs of all types attempted to ride this wave, the goal for many was to develop an inexpensive method of connecting individual homes and small businesses to high-speed data networks. This boom brought about the novel idea of using existing sewers, as well as other utilities, for the installation of optical fiber networks. The drive towards this goal led to the development of various robots capable of installing optical cables within existing wastewater pipes, using drilled-in anchors or circumferential clamping devices that place the cables at the crown of the pipe, away from the normal flow stream. Alternatively, other robots and tools were developed for installing cables inside natural gas pipelines, often without depressurizing the systems. With the subsequent bursting of the telecommunications bubble, interest and investment in these technologies has naturally plummeted. However, the rapid development of these tools aptly illustrates that pipeline robots can be invented for a myriad of functions, when sufficient incentives exist.

One robot of particular interest is shown in Figure 3.5. This was developed for use within natural gas systems for the insertion of fiber optic cable and for pipeline inspection. Gas systems are like water systems in that horizontal and vertical bends are common, and relatively small pipe diameters are used. As a result, this pipeline robot is designed to make 90-degree turns, and crawl vertically as well as horizontally. By contracting and expanding, the device is able to accommodate changes in pipeline diameter as it travels. This particular robot works in pipelines 3.5 inches (90 mm) to 6.5 inches (160 mm).

One feature of interest is how this robot can navigate through a network. When the robot encounters a tee connection, for instance, it can go forward or turn into the branch line, depending on instructions from the operator. The steering is accomplished by rotating the whole assembly until properly aligned for the intended direction. The device is first stopped, and then the wheels are rotated in place. When the device is restarted, it rotates around the pipe's axis as needed. This alignment process then allows the robot to enter any bend or tee, regardless of its angle.

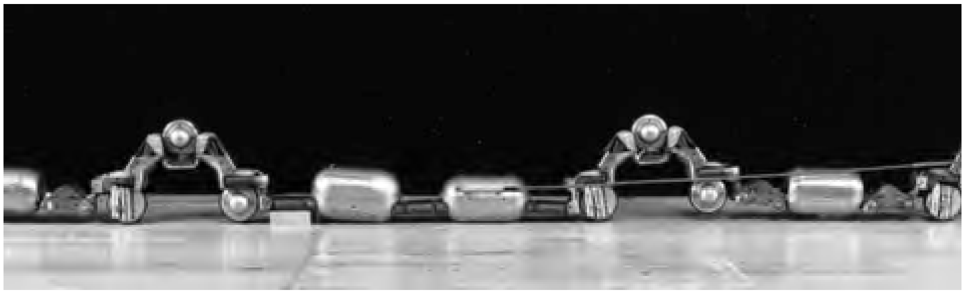

Figure 3.5. Gas System Robotic System.
Photo courtesy of Foster-Miller, Inc.

The robot is self-powered and includes on-board control. Thus it can travel untethered through a system, if needed, performing inspection and other tasks where an operator interface is not needed. Like a train, additional "cars" can be added for varying purposes.

Another feature of interest is the method of insertion. Using a hot-tap onto the main, the robot can be inserted in a pressurized pipe through a valve isolated lateral launching pipe. Because the robot adjusts to varying pipe diameters, the lateral launching pipe can be as small as one-half the main diameter.

A short video depicting a similar gas industry robot is found on the CD enclosed with this report. That latter robot is discussed in additional detail in Chapter 4, Case 1.

CLOSED-CIRCUIT TELEVISION

Closed Circuit Television (CCTV) is the primary means used for guiding remote sewer and storm-drain pipeline inspection and repairs. CCTV technology has gradually become commonplace over the last 30 years, and the equipment capabilities have matured significantly. The current technology includes cameras that can zoom, pan, and tilt, as well as special insertion models designed for the live inspection of potable water lines (Hayward, 2003). Most CCTV inspection systems consist of either the crawler or push types.

Crawler-type CCTV equipment generally consist of a self-propelled platform (either on tractor or wheels) upon which a lighting system and one or more multi-directional cameras can be mounted. Figure 3.6 illustrates one such unit. Equipment comes in many sizes, shapes, and configurations, designed for various pipe sizes and conditions. Crawlers are capable of inspecting up to 3000 linear feet of pipe, ranging in size from 2 inches (50 mm) to 60 inches (1.5 m). Some multi-functional units are capable of both cleaning and inspecting the mainline, as well as inspecting the lateral while within the main. This is accomplished by the insertion of a push-type camera from within the mainline. Current-generation equipment is typically equipped with lens that can pan and tilt, so that the camera can focus in on cracks or other items of interest at any position. However, even with these advances, it takes a skilled, experienced observer to interpret the images; the views are often distorted.

Figure 3.6. CCTV crawler.
Illustration courtesy of Envirosight, LLC.

While camera observation is widespread in gravity flow pipeline observation, its use in potable water line inspection is currently limited. The visual inspection of a water pipe interior will generally reveal little or nothing about pipe integrity; however, it can be useful in judging the condition of the lining as well as the conditions at the lateral-to-mainline connection. A complication is that to inspect a water pipe, the pipe must usually be removed from service, requiring customers to be placed on a bypass system. Very frequently, launching ports must be constructed so the camera can be inserted. After extraction of the camera, the pipeline must then be disinfected and tested for bacteria, before being placed back in service.

One manufacturer markets a laser device that operates in conjunction with a CCTV system. The device projects a light circle in front of the camera. By detecting variations in how the light circle is observed, geometry variations in the pipe can be detected, including dents, ovality, lining thickness variations, and protrusions of lateral taps.

PUSH CAMERAS

Push cameras (Figure 3.7) are manually-deployed units that take the CCTV technology a step further, providing for the remote viewing of small diameter pipelines—particularly laterals. A push camera generally consists of a portable frame and reel, a rigid push-rod, a push-rod mounted camera, a flexible cord, and a monitor. Push cameras are generally capable of inspecting up to 250 linear feet,[1] ranging in size from 1 inch (25 mm) to 8 inches (200 mm). A variety of cameras are available for use with these systems, ranging from a low-cost plumber's helper tool to more advanced models with VCR capabilities. Inspection applications for this technology are found in small diameter sewer and water lines as well as mainline inspection. Compared to robotic crawlers, this equipment is relatively inexpensive.

[1] Inspection capabilities may vary from manufacturer to manufacturer.

Figure 3.7. Push camera equipment.
Photo courtesy of RapidView IBAK USA.

FIBEROPTIC TECHNOLOGY

Fiberoptic technology allows for the observation of very small pipelines, smaller than those accessible by push cameras. Both rigid borescope technology and flexible articulating fiberoptic fiber borescope technology, with sizes ranging from 3.5 mm (0.14 inch) to 11 mm (0.43inch) in diameter are available. This fiberoptic inspection technology is based on the use of glass fibers to transmit the image of concern to the eyepiece and/or a video or image processor. The glass fibers are also used to transmit illumination down to the borescope's distal end.

Fiberoptic borescope technology has seen applications in aircraft turbine inspection, military and domestic engine inspection, as well as pipe corrosion inspection. A complete visual testing system generally consists of the scope, the camera control unit, the digital image processor or computer, the light source, and the system video display (Figures 3.8 and 3.9).

Figure 3.8 and 3.9. Flexible Borescope and Monitor
Photo courtesy of Lenox Instrument Company.

PIPE LOCATORS

The first step in locating underground utilities is to obtain as-built drawings from the utilities known to have facilities in the area. However, often times, these are not updated, are inaccurate, and may lack information about the size or type of conduit. Additionally, pipelines may be present that belong to unregistered utilities or that were long ago abandoned in-place. It's not unusual for a utility to have an incomplete record of their asset inventory. Field investigation methods are available to help locate pipes and other underground objects, before any potholing or digging occurs.

The most common method is to use a pipe locator. Currently, the three types of locating devices most commonly used are metal detectors, ferromagnetic locators, and radio frequency locators. Although their use is relatively simple, the application must match the equipment selection.

Metal Detectors. Metal detectors function on the basis of electromagnetic induction. Metal detectors work well for finding valve boxes, manhole covers, and other metal objects located relatively close to the surface. A metal detector uses a flat detection coil on the end of a pole. The device will signal the location of any metallic object near the surface, such as scrap metal, coins, or even gum wrappers. Larger objects will produce stronger signals.

Metal detectors have a relatively short depth/detection range—typically much less than 20 feet (6 meters) for even very large surface area targets). High concentrations of natural iron-bearing minerals, salt water, acids and other highly conductive fluids will limit the performance of metal detectors (EPA, 1993). Hence, most metal detectors have limited value for detecting deep objects.

Ferromagnetic Locators. Ferromagnetic locators are simple one-piece wand-type devices that can be used for any objects containing iron, such as steel, cast-iron, or ductile iron pipe. To detect the pipe, the device is swept from side to side, holding it at an angle to the ground (Figure 3.10). These tools work by detecting disturbances in the earth's magnetic field caused by pipes or other metal objects. Because the fields are weak, and these changes are very slight, small metal objects close to the device can cause problems, including steel-toed boots, or even wrist-watches. The devices can be greatly disturbed by large metal objects, such as cars, fences, or metal buildings. Without such interferences, they can detect iron pipe and other ferrous objects up to a depth of approximately 20 feet (6 meters). Depth of detection depends on size, type, and orientation of the object.

Radio Frequency (RF) Locators. Radio frequency locators are slightly more complicated tools that produce very reliable results. In most applications they can specifically target the object being sought rather than finding anything that happens to be in the ground. Two units are required, a transmitter and a receiver, and these units are configured in various ways for different applications. For example, the transmitter may be coupled to a hydrant or other appurtenance. Then the receiver can be used to trace the pipe. When a direct connection to the pipe is not possible, or when the distance from the available connection is large, the transmitter can be placed over a known location of the pipe, inducing a signal within the pipe that is then detected by the receiver. When the location of the pipe is unknown and a direct connection is not possible, the transmitter and receiver can be connected together with a handle and the general area scanned.

Figure 3.10. Using a ferromagnetic pipe locator.
Photo courtesy of Subsurface Instruments, Inc.

Because radio frequency locators utilize the pipe as an antenna, to be detectable the pipe must be metallic. Non-metallic pipe can be detected if a copper wire or aluminum tape has been buried alongside the pipe, particularly if a direct connection to the conductor can be made. If no tracer wire exists, the pipe can still be located if it is removed from service, an electrician's fish tape or a rod is inserted within the pipe, and a signal is induced. (Using a plumber's snake is not recommended, unless there is assurance that it has not been previously used within a sewer.) All such items should be cleaned and disinfected prior to insertion within the pipe.

Radio frequency locating can also be used to estimate the depth of the pipe, after its horizontal centerline location has been determined. This technique is performed by holding the receiver at a 45-degree angle, just above the ground. The minimum signal will occur at a horizontal distance from the center of the pipeline that is equal to the depth of the pipe. This method works best if the transmitter and receiver are relatively close together, so that a strong signal is available.

Locatable Magnetic Polyethylene Pipe. The Gas Technology Institute recently demonstrated the feasibility of magnetic polyethylene pipe. Magnetic particles embedded in the polyethylene before it is extruded are later magnetized in a spiral pattern intended to indicate a natural gas pipeline. An above-ground, hand-held magnetometer is used to detect the pipeline.

Transmitter Pigs and Robots. As described at the end of this chapter, pipeline pigs with transmitters are often used to trace the location of a pipeline. Transmitters are also used on pipeline robots that transport CCTV equipment.

OTHER UTILITY DETECTION DEVICES LOCATORS

Ground Penetrating Radar (GPR). Ground penetrating radar (GPR) is a geophysical technique not yet used frequently for locating utilities, but its popularity is growing. A key advantage of this tool is that an estimate of the utility depth is obtained.

The maximum effective range of GPR varies considerably, from 3 to 100 feet (1 to 30 meters), depending on the type of soil, and the resolution (wave length) that is used. The *visibility* of objects depends on their size, shape, and the contrast between the object and the surrounding soil. A key advantage of the tool is that an estimate of the utility depth as well as location of voids can be detected.

The result of a GPR investigation is a fairly abstract image like the one shown in Figure 3.11, requiring interpretation by a skilled technician. As advances occur in tool and software technology, this method is expected to see greater use. GPR is particularly useful for locating non-metallic objects, such as plastic and concrete pipes. Metal pipes and cables are more difficult to locate, because they can disturb the radar signal. However, in conjunction with conventional pipeline-locating devices, GPR can be used to survey an area of interest adding further dimensions to the picture that emerges.

Non-metallic Pipe Locators. Several tools have been developed specifically to locate plastic and other nonmetallic pipes. One method induces an electronic signal within the water that is then detected by a receiver on the surface. Another method uses a special valve to interrupt the flow from a hydrant or service lateral, thereby producing shock waves within the water. The resulting vibrations are detected and amplified by seismic sensors at the ground service. This method works well in close proximity to the exciter. It is particularly useful in tracing service lines.

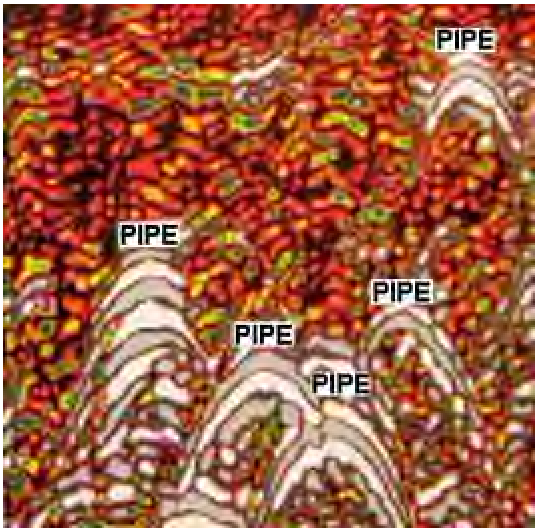

Figure 3.11. Ground-penetrating radar image.
Image courtesy of GeoModel, Inc.

POTHOLING AND VACUUM EXCAVATION

In spite of all the high-tech tools available for utility location, the need is likely to arise for the tried and tested method of pipeline locating by pot holing (exploratory digging). Pot holing is often done in advance of detailed design, to precisely locate alignment conflicts and determine where connections can be made. It's also frequently performed in advance of drilling, boring, or large excavation efforts, to better plan the construction and minimize risks. Pot holing may also be necessary to accurately determine information such as type, size, or condition of a utility, soil conditions, and bedding materials.

For decades, pot holing was performed using combinations of backhoes and hand tools, but with the increased presence of plastic utility lines and direct–buried communication cables, even the use of hand tools has become a fairly risky endeavor. Many utilities are turning instead to vacuum excavation as a safer, and often more efficient method of pot holing. A vacuum excavator is a machine that uses compressed air or high-pressure water to loosen soil, and a vacuum hose to lift and deposit it in a truck (Figure 3.12). The vacuum excavation concept is not new, having been tried since the 1920s, but advances in equipment design have reduced the clogging problems that plagued early equipment. In contrast with traditional methods of pot holing, vacuum excavation provides a quicker, less disruptive (smaller footprint), and safer way to pothole.

Because the ground is not jabbed with sharp metal, there is much less danger that utilities will be damaged with vacuum excavation, as compared with other methods. In fact, the method is even used by archeologists as a way of quickly removing soil, without damaging artifacts. Also, vacuum excavation is different than tradition pot holing in that the product is a small hole, usually about 12-inches square. Because the hole is small, there is less chance of soil caving or unraveling, and damage to the pavement is minimized.

CURED-IN-PLACE SERVICE LATERAL CONNECTORS

"Top Hat" is the trademark name for a product developed in Austria used for connecting CIPP sewer main liners to laterals. "T Liner" is a similar product developed in the U.S. Both products consist of resin-impregnated fiberglass or polyester inserts that connect a main liner to a lateral pipeline.

Figure 3.12. Potholing with a vacuum excavator.
Photo courtesy of Vector Technologies, Ltd.

As the name implies, one product is shaped generally in the form of a top hat. The brim of the "hat" is intended to adhere to the inside wall of the pipe liner, while the top of the hat is inserted into the lateral. The "T" liner is different in that the portion of the connector within the main is a full, 360-degree tube, with "O" ring seals. The "T" liner can extend up the lateral as much as 60 feet. In both cases, a balloon-like applicator is used to insert the connector and hold it firmly against the pipe walls. Once in place, the resin is cured using ultraviolet light or steam. In this manner, a CIPP-type connection is made between the liner and the lateral. Figure 3.13a shows the application devices used to maneuver, insert, and then cure the connectors. Figure 3.13b shows a cross section of a completed "T" liner connection. The inserts and applicators are currently available in sizes covering 6 inch (150 mm) to 20 inch (500 mm) mains, and 4 inch (100 mm) to 6 inch (150 mm) laterals.

A similar connection device is shown in Figure 3.14, but with an important difference. This one has a polyethylene "brim" with embedded wires. As noted earlier, chemical adhesives do not work well on a polyethylene. Thus, the standard "Top Hat" insert will not work on a pipeline with polyethylene liner. The figure also shows the applicator tool that is used to transport and raise the connector into position at the lateral connection. The brim is then joined to the HDPE liner via electrofusion (see below), while the more conventional CIPP liner extends into the lateral.

A similar hybrid system may be applicable to various water main applications where HDPE is found, particularly if the lateral tube were reinforced with woven polyester or carbon fibers, making the finished product more pressure resistant. Obviously, for a water system application, the size of the lateral inserts will need to be scaled down significantly. Another issue in a water system would be achieving a seal between the CIPP insert and the lateral pipe capable of resisting high pressures. This might be accomplished using "O" ring seals, similar to the "T" liner.

Figure 3.13a. Applicators for Top-Hat Style Connectors.
Photo courtesy of Americk Supplies.

Figure 3.13b. Lateral connection lined with "T-Liner."
Photo courtesy of Sancon Engineering-Dave Badgely.

Figure 3.14 Lateral Connector for HDPE pipe.
Photo courtesy of D.T.I.-KASRO-Sewer Repair Robotics

ELECTROFUSION

Electrofusion is a method of joining two pieces of HDPE together. A wire embedded within a coupling or other fitting is heated by passing electric current through the wire. The heating process melts the outer surfaces of the two items, which are then welded together as they cool. The practice is very common and easily performed. A computer controls the amount of current that is used and its duration. The computer also records various data and sends an error message if the process does not meet specifications. A bar-coded sticker on the coupling is scanned, providing the information needed for the computer to select the run time, amperage, and other specifications for the process.

Electrofusion is primarily used to join polyethylene (PE) pipe systems used for conveying pressurized fluids, but could probably be used for other thermoplastic pipes such as PVC. Electrofusion has several advantages when compared to the conventional butt-fusion method. The weld surface is 2 to 9 times larger (depending on the pipe outer diameter) and, once installed, the fitting acts as a "shell" enclosing the joined elements and enhancing their mechanical properties. Unlike butt fusion, which is used to join pipes of the same pressure class (i.e. same thickness), electrofusion can be used to join pipes of different thicknesses and even different material classes.

One particular advantage as far as this project is concerned, is that electrofusion can be accomplished remotely. Electrofusion couplings (Figure 3.15) are frequently used in areas where the use of a butt-fusion machine is difficult or impossible, and the fusion can even be accomplished inside a pipe, using pipeline robots. This latter capability has been demonstrated in the use of the hybrid top hat connectors, as discussed earlier.

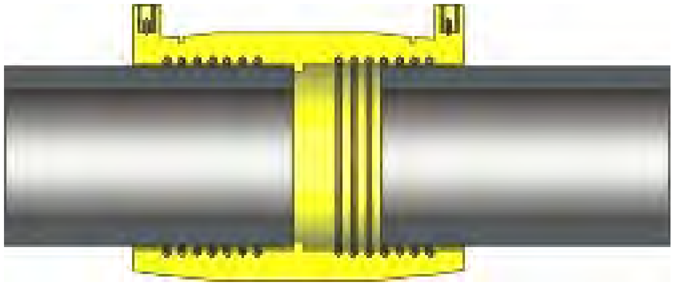

Figure 3.15. Electrofusion coupling HDPE Pipe.
Illustration courtesy of Unidelta S.p.A.

TRENCHLESS PIPELINE INSTALLATION

Moles and piercing tools. Impact moling (or piercing) is a trenchless method for installation of pipes up to 10-inches in diameter over distances up to 200 ft. It is the most widely used trenchless installation method and has applications in installation of gas and water lines, electrical conduits, communication cables, and sewer laterals. It is most often used under sidewalks, driveways and similar short undercrossings. When properly designed, impact moling is one of the simplest and the least expensive trenchless technology installation methods. The method uses compaction to create a bore and works best with compressible soils. Difficulties can arise in densely packed soils. Other problems can occur with loose sands and gravels, due to collapse of the borehole. In order to ensure successful completion of an impact moling job, it is essential to know the ground conditions and to identify the depth and location of all existing utilities and other underground objects nearby.

Most impact moles are non-steerable and most bores are planned as straight trajectories. In recent years, however, steerable systems have reached the market, allowing bores with curved paths and multiple direction changes. Steerable units can also make alignment corrections during the moling process. These moles are currently commercially available in only one size and, being still fairly new to the marketplace, are still waiting for wide acceptance.

Impact moling should be carried out at a depth of at least 10 times the diameter of the product pipe or 3-4 ft, whichever is greater, to avoid surface damage. The speed of moling can affect accuracy of the bore, and the advance rate is on average about 1-5 ft/min for non-steerable moling, and about 1 ft/min for steerable moling. (Simicevic and Sterling, March 2001)

Service Pulling or Splitting. Figure 3.16 shows a method frequently used for replacement of water service laterals. This is a essentially small-scale application of the pipebursting method that was discussed in the Chapter 2. Service line splitting works well for plastic laterals such as polybutylene, PVC, or PE, but also is used for steel and copper. Alternatively, lateral pipes are frequently pulled from the ground without splitting, while simultaneously pulling a new line into place.

Figure 3.16. Service Line Splitting.
Illustration courtesy of T. T. Technologies.

Pipe Ramming. Pipe ramming is a trenchless method for installation of steel pipes or casings over distances up to about 150 feet in length, and up to about 60 inches in diameter. In pipe ramming, a pneumatic tool is used to hammer a pipe into the ground. Once the pipe is in place, drilling or augering equipment removes the soil from within the pipe. The method is frequently used for shallow installations under railway and road embankments. While many of the installations are horizontal, the method can be used vertically or inclined. Foundation piles are frequently installed in this manner.

Because most pipes that are hammered into the ground will be damaged, ramming is used more frequently for installing casing pipes than carrier pipes. Even with very heavy walls, damage to the pipe is common, and few coatings will survive the abrasion. Remarkably, with the right equipment and enough persistence, pipes can rammed through boulders. Once the casings are installed, carrier pipes/conduits for sewerage, water, gas, electrical and/or telecommunication cables are subsequently inserted. One casing pipe may be used for several carrier pipes.

Compared to other trenchless methods such as bore-and-jack construction and directional drilling, pipe ramming can save both total installation time and costs under favorable conditions. Installation time can often be nearly 40 percent shorter than conventional bore-and-jack installations, because full-length casings can be inserted, rather than sectional pieces; however a longer launching pit will be required. The relative cost of steel is often a major determinant of whether this method is cost effective, because the rammed pipe generally has thick walls.

The method is most valuable for installing large pipes over shorter distances and for installations at shallower depths. It is suitable for all ground conditions except solid rock, and is often safe where some other trenchless methods can lead to unacceptable surface settling.

Pipe ramming is sometimes combined with directional drilling. Ramming is often used to install "surface casing" where unstable alluvium would make drilling difficult, and it is sometimes used to free the product pipe during pullback (or the drill pipe during pilot hole boring or reaming) if either gets stuck. The ramming tool will be attached to the end of the product pipe when pullback slows down or stops, and the percussive action of the tool helps to keep the pipe moving through a difficult section. (Simicevic and Sterling, December 2001).

Horizontal Directional Drilling (HDD). The use of HDD expanded rapidly during the telecommunications boom of the late 1990s. Once considered exotic and high-risk, HDD is now used routinely in applications that were once the domain of open-trench constructors. HDD is particularly suitable when crossing areas that are difficult or impossible to trench. Examples are rivers and channels, freeways, and large diameter pipelines or culverts.

The method evolved from the oil and gas industry, and typically involves drilling and reaming a shallow arc between entrance and exit points. Once a suitably-sized hole is achieved, the pull-back occurs—meaning a casing or a carrier pipe is pulled into the hole during a final reaming process. The final ream is generally about 1.5 times the diameter of the pull-back pipe. During drilling and reaming, bentonite slurry (or other drilling media) is used to flush cuttings from the hole, and to help stabilize the excavation. This mud also helps to lubricate the hole during the insertion process.

Unlike many other trenchless methods, this one is "steerable". Detectors on the ground surface are used to track the location of the drilling head below, and the angle of drilling head is adjusted as needed by remote control. With current technology, a target on the ground that is thousands of feet away can be hit within a couple of feet.

SMART PIGS / NON-DESTRUCTIVE TESTING DEVICES

Remote Field Eddy Current (RFEC) A relative recent development in the water industry is the adaptation of remote field eddy current analysis for the detection of defects in cast iron or ductile iron water mains. This development was partially spearheaded by a 1992 AwwaRF project that looked at this and other techniques for non-destructive testing of mains (Jackson, Pitt, and Skabo 1992). (The RFEC method had previously been used to inspect oil well casings and boiler tubes.)

The tool—a "smart pig"—calculates the wall thickness of cast-iron or ductile iron water mains from within. Unlike the smart pigs used in the oil and gas industries, it does not require intimate contact with the metal—the tool works despite the presence of cement-mortar lining or mineral scale deposits (i.e., tuberculation). The technique uses an electromagnetic coil to generate a magnetic field that penetrates the pipe wall. A "remote" detection coil picks up the field and relays it to a computer (Figure 3.17). By comparing differences in the speed and amplitude of the signal, the computer is able to calculate and pinpoint corrosion thinning, pitting, graphitization and casting defects—some as small as a dime. A similar technology is used to detect broken wires in prestressed concrete pressure pipe.

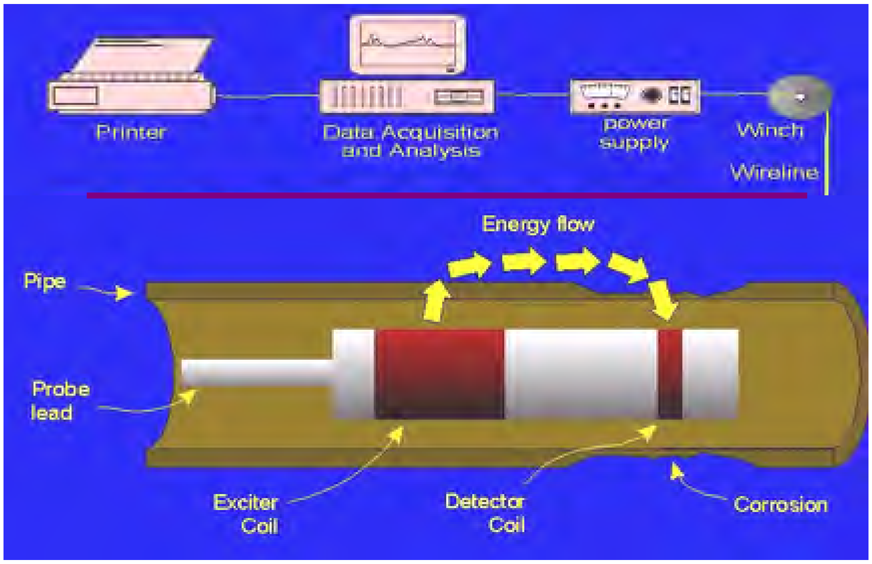

**Figure 3.17. Remote field eddy current testing.
Illustration courtesy of Hydroscope, USA**

Other smart pigs. Non-destructive testing devices developed for the oil and gas industry, using magnetic flux leakage and ultrasonic methods, have not been successfully adapted to most water pipe systems. The 1992 AwwaRF study (Jackson, Pitt, and Skabo 1992) concluded that tuberculation and cement mortar lining interfered with these methods, making the accurate measurement of pipe wall thickness difficult to impossible. The study also found that a magnetic flux leakage tool would seriously damage most other types of pipe lining, so these techniques may only be appropriate for clean, unlined pipe—something that rarely exists in a water utility. To achieve a pipe that is clean enough to test, a fairly aggressive cleaning method would need to be employed.

Other pipeline pigs. Most pipeline pigs are used to clean pressure pipelines, and are forced through the pipes under pressure. However, in addition to the "smart" pigs that were briefly discussed above, there are two other types of pigs that could be helpful in accomplishing no-dig and low-dig construction:

(1) **Gauging pigs** are used to verify the size and ovality of pipelines.
(2) **Transmitter pigs** are any type of pig with an embedded transmitter, for tracing the pipeline, tracking the pig's movement, and finding the location of a struck pig.

CHAPTER 4
CONCEPTS FOR REMAKING SERVICE CONNECTIONS

This chapter presents 6 concepts for lateral reconnections, addressing 6 different rehabilitation methods. The concepts that are described here were either developed or presented in an expert workshop held on January 16, 2003, at the Underground Construction Technology Conference in Houston, Texas. A list of workshop participants can be found in Appendix A. The cases are:

Case 1: Tight-fit HDPE lining – lateral reconnection
Case 2: Pipebursting – lateral reconnection
Case 3: Loose-fit slip lining – lateral reconnection
Case 4: New lateral connection to existing main
Case 5: Tight-fit PVC lining – lateral reconnection
Case 6: Cured-in-place pipe lining – lateral reinstatement and seal

CASE 1: TIGHT-FIT HDPE LINING – LATERAL RECONNECTION

Advantica, part of the former British Gas, developed the concept that will be briefly described in Case 1. They have produced a prototype robot and obtained both U.S. and international patents. Enclosed with this report is a CD with a video presentation, which demonstrates the concept.

Figure 4.1 shows the problem that this concept hopes to solve. Following installation of a bypass piping system, an HDPE pipe has been inserted inside an existing water main. One of several available techniques has been used to insert the pipe and then expand it until it fits snugly inside the host pipe. Typically, there will be no visual indication of where the lateral is located. If a camera were passed inside the HDPE liner pipe, no dimple would be visible. In fact, if there were a protruding tap or ferrule at the lateral, it would be ground off, prior to insertion of the liner, to keep the liner from bulging inward. Thus, locating the lateral and re-establishing the bore is the first problem to be solved. The second problem is to connect the HDPE pipe to the lateral in such a way that water will not leak into the annulus between the liner and host pipes.
The concept proceeds as follows:

1. Working from the meter box, a wire is fed down the existing lateral to the main, stopping at the liner.
2. A radio signal is transmitted on the wire. A robot inside the lined pipe traces the signal, homing in on it, and thereby determines the location of the existing service connection.
3. The robot locks itself firmly into place. The signal detection device on the robot rotates to find the angular orientation of the lateral. The location of the lateral is recorded.
4. The robot then travels a set distance axially along the pipe, moving a drill into position.
5. The robot locks itself into position again, and drills a hole through the liner at the lateral.
6. The wire is removed from the lateral pipe, and a small-diameter tube is fed down the lateral pipe until it penetrates the liner. The insertion end of the small tube has been previously fitted with a PEX[1] nipple.

[1] PEX = Cross-linked polyethylene

7. After the PEX nipple has penetrated into the hole in the liner, the robot rotates a halogen lamp into position, and inserts it into the nipple.
8. Heat from the halogen lamp causes the PEX nipple to expand and contact the edges of hole in the main liner. Continued use of the halogen lamp fuses the PEX nipple to the main liner.

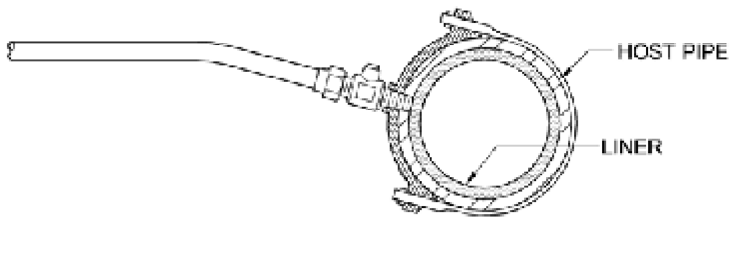

Figure 4.1. Illustrates conditions that exist following HDPE tight-fit slip lining.

The tool that performs these functions is a "robot" in the truest sense of the word. It is self-powered and has an on-board master controller that receives signals and directs operations. To negotiate through small-diameter mains, the robot is constructed as a series of linked modules, with separate functions. Among the modules are drivers, sensors, control, power, drilling, and heat source units. The robot is able to move axially, and units within the robot move rotationally. Once the lateral location is pinpointed, the modules are automatically moved into work positions based on the fixed distances between modules.

Problems Associated with Lateral Lining

Development of this robot and the reconnection concept represents an important step forward in the field of trenchless construction, but several technical limitations have prevented the inventor from bringing the tool to market. Perhaps the biggest limitation has been the use of a liner inside the lateral pipe. As one can imagine, placing any liner inside a lateral pipe would result in significantly reduced capacity. Because the concept was developed initially for the gas industry, such a reduction is diameter might not be as limiting—if the system pressure could be increased, sufficient quantities of gas might still be delivered. However, for a water utility application, a loosely fitting liner pipe inside a lateral pipe would be an unacceptable condition for all but the rarest of circumstances. For a water application, the capacity of the completed lateral would be half of the original lateral, or less. Consider, for instance, a 1-inch (25-mm) lateral. If the lateral liner has an outside diameter of 7/8-inch (22-mm) and 1/16-inch (1.5 mm) wall thickness, then its inside diameter would be 3/4-inch (19-mm). Based on hydraulic calculations, such a lateral liner would deliver less than half the water that the 1-inch pipe provided (assuming both pipes have equal roughness). It's possible that if the original lateral were heavily scaled or turberculated, then the liner pipe might produce flows that are equal or better than the original. However, it needs to be noted that the heavily scaled laterals would first need to be cleaned using a rack feed power bore or similar method (Ellison, 2003), before insertion of the liner.

Using a thin, tight-fitting lateral liner might help ease the capacity limitation just described, but would not fully overcome it. Perhaps only 25 percent of the capacity would be lost, but this still would not be acceptable in most service applications. Indeed, where water mains are being rehabilitated, lateral pipes are frequently undersized by modern standards—they are seldom oversized. It is not uncommon to have 5/8-inch (15-mm) and 3/4-inch (19-mm) lateral pipes to older homes, reflecting a time before dishwashers, washing machines, and multiple showers were common. If a tight-fitting liner were to be used, additional research is needed to determine the most suitable material and thickness, and the process of insertion.

The lining of lateral pipes is a concept that is fraught with various risks. In water systems, the oldest lateral pipes commonly found are composed of steel, cast-iron, or lead. Copper is now the U.S. standard, while in Europe, polyethylene is very common. Old laterals are often choked with tuberculation or scale, and may be well corroded. Compared to mainline pipes, the laterals are often crooked, with bends, and even kinks. There may be various unknown fittings and other invisible conditions between the meter and the main. Televising the pipes is difficult, due to their small diameter. The pipes have thin walls, and can endure only the smallest of external loads without crushing, tearing, or pulling apart. Seldom do records exist which provide reliable information regarding size, material, fittings, or other items of interest.

This is not to say that lateral lining is impossible. In fact, it is currently performed in Europe, where an extremely thin, tight-fitting liner has been developed primarily as a means of protecting against the health effects of lead service pipes. This lateral liner, produced from PET[2], is manufactured with longitudinal ribs that allow the pipe to be inflated up to 2.2 times its original size, to fit snugly in the host pipe. The thickness of the liner pipe is 0.30 mm (0.01 inch), and thus would be considered non-structural—the existing lateral host pipe provides 100 percent of the pressure resistance.[3] It is not known whether such a lateral lining would solve the problem of effectively sealing the annulus between main and liner at the lateral opening. It is very doubtful that the PET material could be joined to the HDPE liner, but a lateral liner of medium or low-density polyethylene perhaps could be made to work. Further research is recommended.

Concept Variation: Lateral Extraction Instead of Lining

Subsequent to the technical workshop described at the beginning of this chapter, one of the workshop participants[4] developed a variation to the Case 1 concept. This variation would avoid the liner within the lateral, and thus does not reduce the capacity of the lateral. Instead of lining the existing lateral, a new lateral pipe would be pulled, from the mainline to the meter, using a cable that is fed down the lateral to the main. The concept of using an old lateral to help pull in a new one is not new. Currently this method is used widely for pulling new laterals between the meter box and the main. However, in these current applications, an excavation at the main is required. The novel idea was to attempt a "no-dig" technique. The lateral would be extracted from inside the main. To our knowledge, this had never been attempted. This concept is described in additional detail in Chapter 7, where bench tests of the concept are described.

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[2] Polyethylene terephtalate

[3] The description of this liner is taken from the technical literature of its manufacturer, Wavin Overseas BV.

[4] Credit for this concept goes to Jim Hopwood, a pioneer in the field of pipeline rehabilitation. Unfortunately, shortly after he shared this idea with the project team, Jim passed away.

The extraction concept is as follows:

1. As described previously, the lateral pipe is located using a robot tracing a signal on a wire.
2. This time a slightly larger hole is drilled by the robot, fully encompassing the threads of the corporation stop.
3. Both the liner and the host pipe are bored (not just the liner). The corporation stop is thereby freed from the host pipe.
4. A steel cable is pushed inside the old service line. The cable is fitted with an “umbrella” at the end that will expand after reaching the inside of the water main.
5. From inside the water main, a HDPE lateral pipe is affixed to the end of the umbrella.
6. The cable is used to pull out the umbrella, simultaneously removing the old lateral pipe and installing the new lateral pipe.
7. After the new lateral pipe emerges from the meter excavation, extraction continues for several more feet, until a flange on the main end of the lateral pipe makes contact with the main liner. CCTV is used to monitor this step to assure that sufficient contact is made, yet the lateral is not over extracted to the point that the flange slips through the hole in the main.
8. The new lateral pipe is then fused to the liner pipe, using electric resistance wires embedded in the flange.

If successful, this lateral extraction method will remove one of the major limitations to the robotic approach developed by Advantica. Furthermore, it is believed that this refinement may open up a wide enough range of applications such that further development and testing of this general method may now be a profitable investment.

CASE 2: PIPEBURSTING – LATERAL RECONNECTION

In Chapter 1, the difficulties associated with developing a no-dig approach to reconnecting lateral pipes following pipebursting were described. In particular, without an excavation at the main, it would be difficult to discern the location of a lateral pipe, much less retrieve it, and somehow attach it to the new pipe, after a main is burst or split. In addition, the lateral pipe is quite likely to be damaged during the bursting operation, making a reconnection even more problematic.

So instead of a no-dig approach, the workshop participants determined that a low-dig approach was needed. The method that is described below follows upon research and development that has been pursued by various organizations and companies in the pipeline rehabilitation area. Particular credit goes to the Gas Technology Institute that has been one of the foremost leaders in this area, commonly referred to as “keyhole” technology.

Step 1 (illustrated in Figure 4.2). After bypass piping is installed to maintain water service to customers, a vacuum excavator is used to dig a hole, approximately 2-feet (0.6 m) square, centered over the corporation stop.[5] The lateral pipe is then severed some distance back from the main.

Step 2 (illustrated in Figure 4.3). A new HDPE pipe is inserted using the pipebursting method. Remnants of the old pipe are removed in vicinity of service pipe.

[5] Pipe locators, as described in Chapter 3, are used before excavation to accurately determine the tap location.

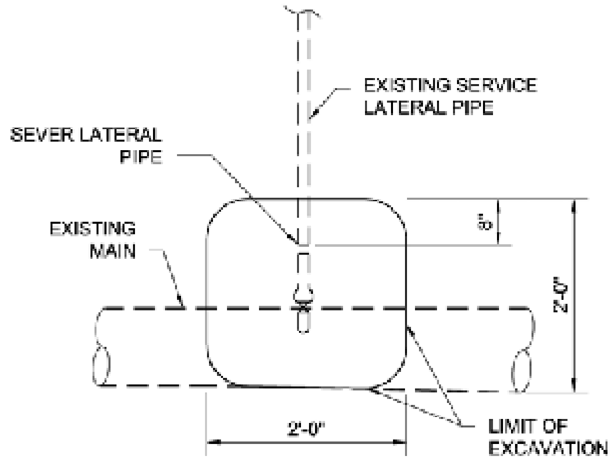

Figure 4.2. Step 1 of Case 2.

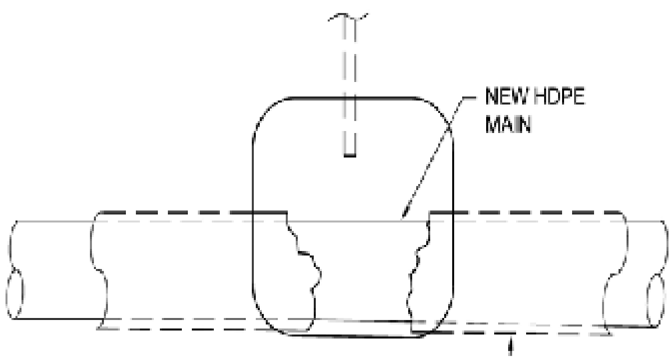

Figure 4.3. Step 2 of Case 2.

Step 3 (illustrated in Figure 4.4). Using long-handled tools, the following is accomplished:

- A standard service saddle is fused to the top of the main. This service saddle is to have a pre-attached "pig tail" of HDPE tubing
- The "pig tail" is connected to the old lateral pipe using a compression coupling
- The built-in hole-cutter within the service saddle is employed to open a hole in the new main. The cutter is then backed out to allow for flow of water.

Field Testing of Keyhole Concept for Lateral Reconnection

Field testing of the concept described above, was conducted in the fall of 2003 at the Los Angeles Department of Water and Power, and is the subject of Chapter 5. These field tests demonstrated that the concept can be applied by contractors and utility crews today, and may be an effective way to reduce the amount of excavation required to rehabilitate a system when pipebursting is used. This reduction in excavation volume should result is a cleaner project that is more quickly executed, with fewer inconveniences to the public.

It is also believed that if pipebursting of water mains were performed as large-scale projects, with 25,000 feet (7500 m) or more of main renewal routinely included in a single construction contract, crews could learn through practice how to efficiently perform the necessary tasks using keyhole techniques. Competition among contractors would then produce significant economies, and the methods and tools would become widely used and significantly refined. Among the advantages to be considered: the use of small-diameter excavations and key-hole tools avoids the need for shoring, which can be a major consideration when mains are more than 4 feet deep.

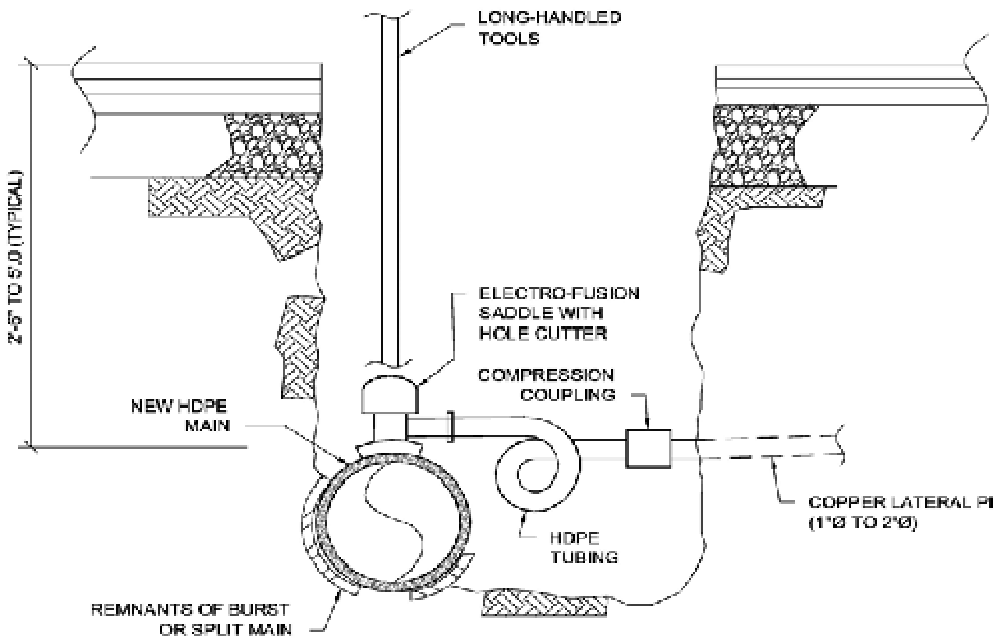

Figure 4.4. Step 3 of Case 2.

Concept Refinement: Pavement Coring and Grouting

Already the field of keyhole work is attracting entrepreneurs. One significant refinement is how pavement can be removed and restored. A Canadian company has developed specialized construction equipment that cores 18-inch (450 mm) holes in the asphalt or concrete pavement. The pavement coupon is then extracted and laid to the side of the hole, as shown in Figure 4.5. After the keyhole work is completed, and the vacuum excavated hole is backfilled, the coupon is grouted back in place, using quick-setting, high-strength grout. According to testing performed at the University of Illinois Urbana-Champaign, the bonded core has sufficient strength to support bus and truck traffic within 30 minutes of the repair (Lange, 2003).

It is interesting to note that the University of Illinois testing was based on the punch-out shear strength of the cores bonded within the existing pavement. The tests showed that the bonded pavement was essentially as strong as the original pavement. Such an assertion certainly cannot be made in the case of conventional pavement repairs, where tests have shown that very little bond will exist between the old and new pavement. As a result, utility trenches are notorious for their deleterious effects on roadway pavements. This lack of bond between new and old pavement in a typical utility trench repair creates a permanent weakness in the pavement that often leads to its failure. Not only does the coring and bonding process solve that problem, but it also mitigates damage to pavement in two other ways: (1) because the hole is circular, the corners are not overcut, and stress-concentration points are not created; and (2) because no jack hammering is performed, the pavement sub-base is not disturbed—another weakness at the juncture between new and old pavement is thus avoided.

Figure 4.5. Keyhole core and replaceable pavement coupon.
Photo courtesy of Utilicor Technologies, Inc.

CASE 3: LOOSE-FIT SLIP LINING – LATERAL RECONNECTION

As described earlier in Chapter 1, several difficulties exist in reconnecting a lateral to a loosely fitting slip-lined pipe. First, a significant gap exists between the new carrier pipe and the lateral. This gap must be bridged with something that prevents water from leaking into the space between the pipes. Second, the geometry is both irregular and unpredictable. Because the carrier and lateral pipes are not concentric, the lateral pipe will seldom be normal to the wall of the carrier pipe. This angle will vary depending on the relative sizes of host and carrier pipes. In fact the angle that the lateral makes with the carrier pipe wall may vary considerably from service to service, even on a single street.

Workshop participants devised the following concept for reconnecting a service when slip lining is performed.

Step 1 (illustrated in Figure 4.6). After bypass piping is installed, an HDPE carrier pipe is pulled inside an existing main. The outside diameter of the HDPE pipe is 1 to 2 inches smaller than the inside of host pipe. For instance, a 6-inch (150 mm) HDPE SDR17 pipe, is pulled inside an 8-inch cast-iron main. The HDPE pipe will have on outside diameter of 6.625 inches (168 mm) and an inside diameter of 5.846 inches (148 mm), and a pressure rating of 100 psi.

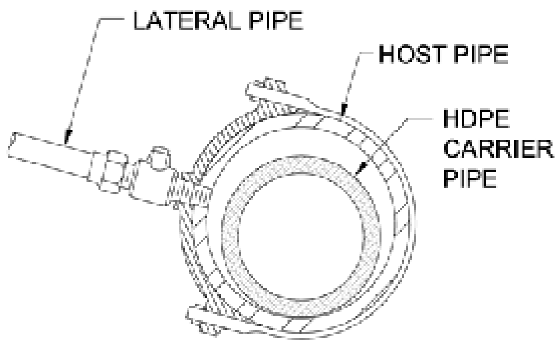

Figure 4.6. Step 1 of Case 3.

Step 2 (illustrated in Figure 4.7). The annulus between host and carrier pipe is grouted. This causes the carrier pipe to "float" to the top of the host pipe. Although grouting the annulus is not always done, and adds to the cost of the rehabilitation, grouting in this case is needed, to stabilize the carrier pipe, and place it nearer to the lateral connection. (In general, lateral taps are found in the top half of most U.S. water mains, because the tapping of a pipe is most easily done from above the pipe.

Step 3 (illustrated in Figure 4.8). The lateral bore is restored using a tool inserted from the meter end of the lateral. To facilitate insertion, the meter is removed. If necessary, the curb stop, street ell and meter box are also removed to allow insertion of the tool directly into lateral pipe. The tool is envisioned as a drill bit or other boring tool on the end of a pipe-cleaning snake, as shown in Figure 4.9. Using this tool, a hole is bored through the liner.

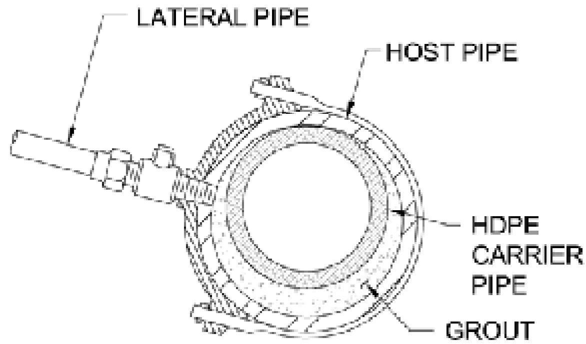

Figure 4.7. Step 2 of Case 3.

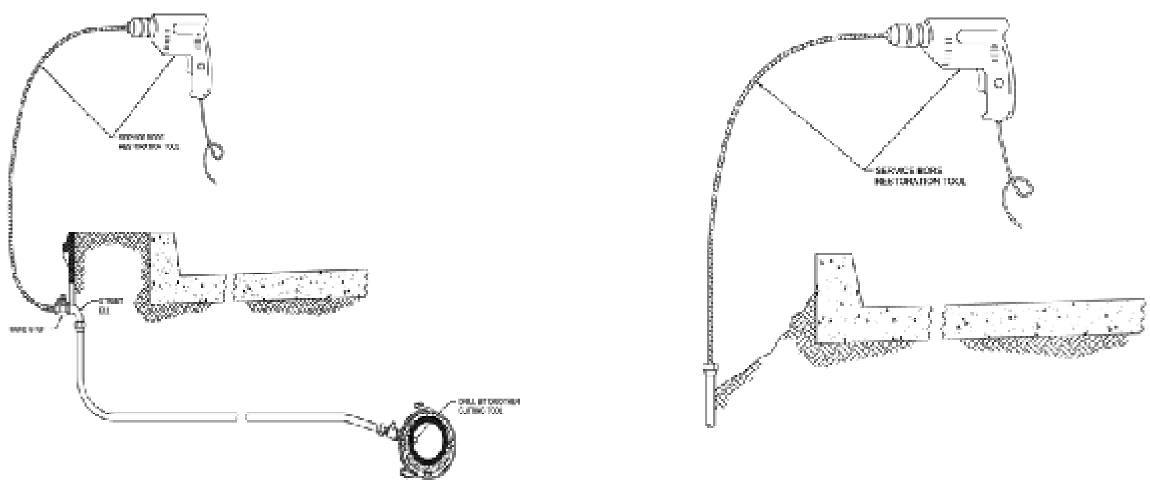

Figure 4.8 Step 3 of Case 3.

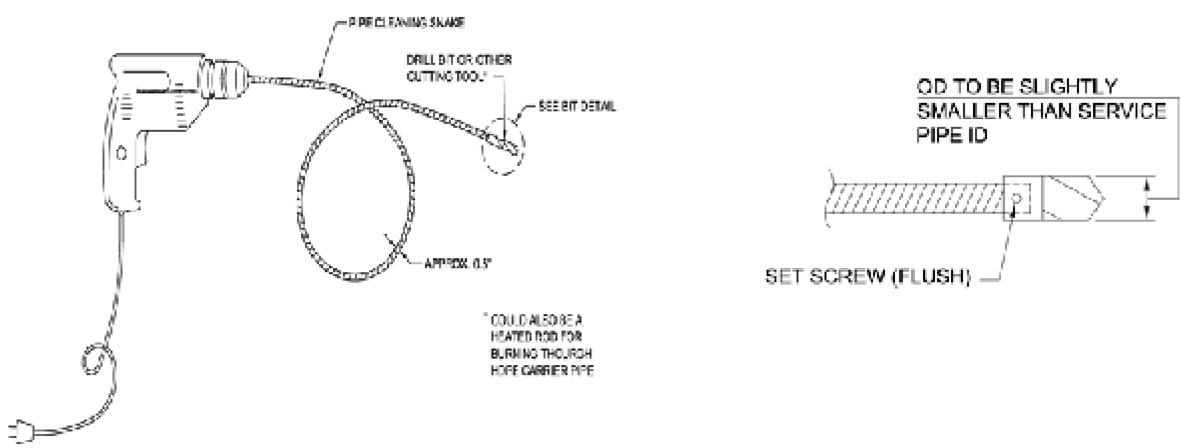

Figure 4.9 Lateral bore restoration tool

Step 4 (illustrated in Figure 4.10). Using a robotic tool from inside the carrier pipe, a “top hat” style connection piece is inserted. This connection piece is somewhat similar in style and function to the Top Hat devices commonly used in the wastewater industry (discussed in Chapter 3), but is very different in construction. The wastewater Top Hats are generally resin-impregnated fiberglass sleeves that are cured in place using ultraviolet light. In this application, the “top hat” style connector would be made of HDPE and would be fabricated as illustrated in Figure 4.11. (The cured-in-place alternative is not feasible for our application, because the resin would not bond to the HDPE carrier pipe.)

On the neck of the top hat are “O” rings set within grooves. These are intended to achieve a seal with either the lateral pipe or with the corporation stop.

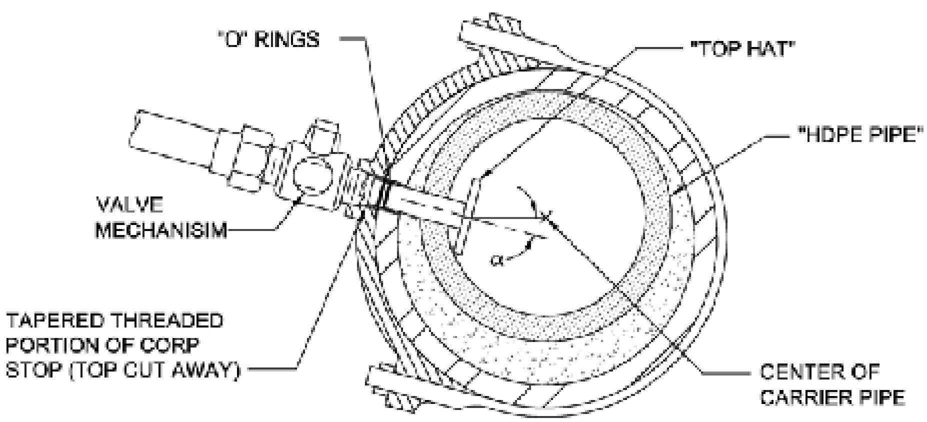

Figure 4.10. Step 4 of Case 3.

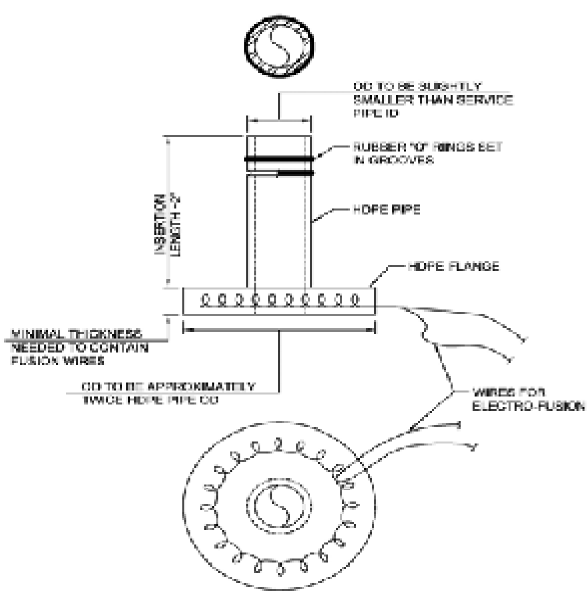

Figure 4.11. Detail of “top hat” style connection piece.

Step 5 (illustrated in Figure 4.12). An inflatable pipe plug is used to push the "top hat" fully into the lateral and to force its flange against the wall of the carrier pipe. The flange is then fused to the pipe wall, by passing an electric current through wires that were embedded in the flange when it was molded (i.e., the electro-fusion process).

The tasks involved in Steps 4 and 5 would be accomplished using a robotic "train", that is, a tool consisting of several specialized modules coupled together with video equipment, and crawlers. The train or its modules would thus have the ability to move axially or to rotate, much as the robot demonstrated in the enclosed CD. The robot's functions would be remotely controlled. CCTV would be used to guide the operator.

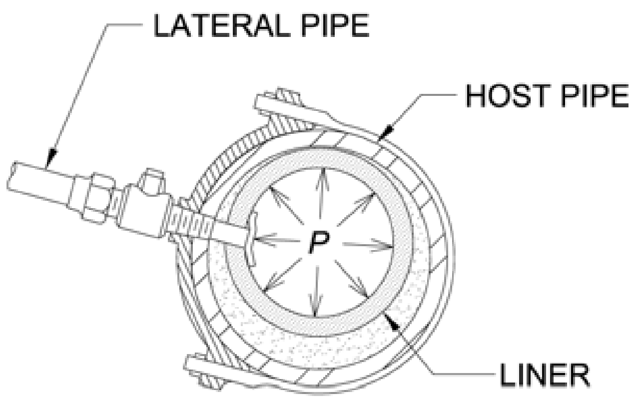

Figure 4.12. Step 5 of Case 3.

Bench Testing of Loose-fit Lateral Reconnection Concepts

The workshop participants recognized that there were many complexities to this concept and considerable research would be needed before a practical application is available to contractors and utilities. Among the questions to be answered were:

- Can a suitably sized opening be established in the carrier pipe using a mechanical bit?
- What sizes of bit (diameters and lengths) are able to negotiate typical bends in the copper service lateral without damaging the lateral?
- Should the lateral restoration tool be mechanical, or should heat (or laser) be used to cut the opening in the HDPE carrier pipe?
- How do the curb stop and corporation stop affect the process?
- Can the "O" rings provide an adequate seal to resist typical water system pressures (up to 150 psi?
- Does the taper of the corporation stop present problems for sealing?
- What would be typical angles "α" (as shown in Figure 4.10) for typical host and carrier pipes? At what angle "α" does the top hat concept appear to be unfeasible?
- What are the maximum recommended thicknesses and diameters for the flange portion of the top hat connection, such that good contact can be made between the flange and the inside of the carrier pipe wall when the pipe plug is inflated?
- For the top hat, what length and "O" ring dimensions are needed to effect a seal.

- Does the "O" ring portion need to penetrate past the corporation stop, or can a seal be made with the valve.
- Can the hole be bored large enough to permit insertion of a sufficiently sized top-hat piece. (Note that the top hat piece must fit very snugly inside the corporation stop to affect a good seal, yet the diameter of the bore may have to be limited to allow passage of the drill bit through the various bends and curves of the service lateral.)

As part of this project, a series of discreet laboratory tests were devised to determine the general feasibility of the concepts, to answer some of the above questions, and to identify issues for additional investigation and research. These tests are described in Chapter 6.

CASE 4: NEW LATERAL CONNECTION TO EXISTING MAIN

If heart surgery can be performed using miniature tools at the end of long catheters, surely we should not need to excavate to connect a new service to an existing main. Routinely, services are constructed and renewed with trenchless methods. Moles, rams, piercing tools and drills are used to bore a path for the lateral, from curb to main. In service pulling, a new lateral is pulled into place, while pulling the old lateral out. Laterals can also be split with pipebursting tools, while new laterals are inserted. Unfortunately, in all these cases, excavations must be made at the main, to complete the connection. Is it possible to install a new lateral without an excavation in the street? One of the workshop groups was assigned the task of developing a concept to accomplish this.

As just noted, getting the lateral from the curb to the main is not the chief problem, since this is done without trenching today, all across North America and Europe. Connecting the lateral to the main, it appears, is the primary problem. If both the lateral and the main are HDPE, then an electrofusion fitting on the end of the lateral could be used to fasten the two pipes together. While HDPE mains are not yet common in the U.S., it is easy to imagine that future water systems might be composed largely of HDPE mains—reportedly HDPE is the material of choice in many European countries.

Perhaps horizontal directional drilling (HDD) might become the routine method of installing water mains. This is not currently a widespread practice, partly because the mains would need to be installed rather deep, to avoid conflicts with other utilities. However, if the laterals could also be constructed and attached without an excavation at the main, an unusually deep main might then become more of a blessing than a curse. A deep main might also then enable the lateral to be bored without fear of interference with other utilities. (It should be noted that in northern latitudes, mains and laterals already are installed relatively deep, to avoid damage from frost.)

How might the lateral be bored into place? A *micro*-micro tunneling device might simultaneously cut a path and pull the lateral. The risk, of course, is that any type of mechanical bore has the potential for damaging other utilities. Similarly, a piercing tool could be used to hammer a path while dragging in the pipe. In both cases, however, the tools would have to somehow collapse so they could be withdrawn through the lateral. To facilitate this, the lateral pipes themselves might need to be larger. The workshop group discussed the possibility of using a combination of vacuum excavation and telescoping casing pipe, to secure a path to the main. The advantage of vacuum excavation, of course, is a lower risk of damage to other utilities.

One of the problems would be directing the tool to the proper location. To achieve a satisfactory connection to the main, the lateral would need to line up reasonably close to the center of the main. An approach that is tangential to the main, would not suffice. Being off-target by one or two inches might be fatal to securing a good connection. Moreover, even if your aim is good, the lateral bore might be diverted from its path by a rock or other obstacle. It would therefore be desirable to steer it back toward the main, using a signal from the main itself.

Unfortunately, there is no current means for transmitting an electromagnetic signal along HDPE mains. Instead, traceability of plastic pipes is typically accomplished with wires that lay along side the pipe, but such wires must be buried with the main, using open-trench construction—exactly what we are seeking to avoid. The development of traceable plastic pipe is a problem that has received some research. Concepts include embedding metals in the pipe that are mated together during the fusion process. Tracers might also be installed within the main, after completion of construction. Certainly, to guide the lateral boring tool, a device might be temporarily inserted within the main, but for this no-dig method of lateral construction to gain wide acceptance, this would need to be done without removing the main from service—industry standards call for the ability to make "hot" taps.

An exciting advancement in this direction was announced recently by the Gas Technology Institute using "magnetic" polyethylene pipe. Such pipe is made from HDPE material with embedded magnetic particles. These particles are magnetized after the pipe is extruded in such a way that a spiral pattern is discernable, marking it as a "gas" pipeline. According to the researchers, the pipeline was locatable at depths of five feet. Thus, it is easy to conceive of a steerable boring device which would be programmed to aim towards an HDPE pipeline with a similarly unique magnetic field.

Is a valve at the main (i.e., a corporation stop) necessary? Workshop participants generally agreed that these valves are chiefly used for the hot-tapping process, and they could be eliminated if a method is devised that achieves the same result. On occasion, a corporation stop is used to stop the leak in a lateral, but the number of instances the valves are used, compared to the number of valves that are installed, is minuscule. Thus, if a lateral and main could be joined together without the need for an excavation, a corporation stop need not be part of the assembly. The actual tapping of the main would be accomplished rather simply, using a device such as shown in Figure 4.9. This could be done through a valve at the curb end of the lateral.

It is apparent that considerable research needs to precede the adoption of Case 4 concepts, however accomplishing this work is not beyond industry capabilities. The only thing needed is sufficient motivation and incentive. Obviously there are plenty of incentives for accomplishing heart surgery with remotely operated miniature tools. The incentives to develop tools and methods for lateral installation are not as strong, but certainly are growing.

CASE 5: TIGHT-FIT PVC LINING – LATERAL RECONNECTION

The concepts in this case were shared by Mark Smith, then the President of Underground Solutions. Underground Solutions holds patents on a process used for tight-fit PVC lining. The Case 5 problem is similar to Case 1. To accomplish a no-dig lateral reconnection following tight-fit PVC lining, the lateral bore must be re-established, and a positive connection between liner and lateral must be provided. Water leakage into the annulus between host and liner pipes must be prevented. The step-by-step process described by Mr. Smith is as follows:

Step 1. Normal preparations are made for the lining process. Depending on conditions, this may include: (1) establishing a by-pass piping system for supplying customers, (2) excavation of holes and removal of pipe sections for access to the interior; (3) removal of line valves, bends, and other lining obstacles, (4) cleaning of the pipe, including removal of tuberculation; (5) video inspection of the pipeline interior, (6) removal of any protruding taps by robotic grinding, and (7) video re-inspection, if needed.

Step 2. A specialized ("parent") robot deposits miniature robots ("children") inside each lateral pipe.

Step 3. Another pipeline robot coats the pipe wall around the tap with a heat-activated epoxy adhesive.

Step 4. The lining of the pipeline proceeds in the normal fashion, which includes:

(1) A pipeline string is created by butt-fusing PVC pipe segments together. The outside diameter of the PVC pipe is significantly smaller than the inside diameter of the host pipe, for ease of insertion.

(2) The PVC pipeline is pulled inside the host pipe.

(3) Steam is circulated through the PVC pipe, until a minimum temperature is achieved.

(4) Pressure within the PVC pipeline is raised, stretching the softened material and expanding the liner, until it fits tightly within the host. Note that when the heated PVC contacts the wall of the host pipe, the pre-placed, heat-activated epoxy material begins to react, bonding the liner to the host pipe, in the vicinity of the lateral tap.

(5) The pressure is maintained while the pipe is cooled. The diameter of the PVC is thus permanently altered.

Step 5. A pipeline robot passing by each lateral activates each of the miniature robots in turn. The activation is accomplished using a radio signal or another type of electro-magnetic field. When activated, these miniature robots bore their way through the liner back into the main pipe, and are collected by the "parent" robot.[6]

Once it is fully developed, this method would appear to be rather efficient. The concept is remarkably simple, and none of the steps would seem to be beyond current technical capabilities. However, considerable time and money must be spent in order to provide a method that reliably works in typical field conditions. The primary hurdles to be overcome are: (1) development of the miniature robots, (2) development of the "parent" robot, (3) selecting an epoxy and applying it in such a manner as to produce an effective, long-lasting seal.

The sealant challenge is not an insignificant one. Can such a seal last 50 years? That would be the hope of most utility managers. Certainly the performance of epoxy lining is well known, but here it would be used as an adhesive as well as a sealant and coating. This raises the question of what kind of loadings would the adhesive be subject to? In addition, the epoxy would need to bond well with PVC[7] and the common host pipe materials (cast-iron, steel, asbestos cement, concrete) and pipe linings (cement mortar, asphaltic, and bituminous), yet be suitable for potable water.

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[6] Instead of miniature robots, another idea is to deposit a transmitter or other device within each lateral that would enable a pipeline robot to locate and bore precise holes at the taps.

[7] A distinct advantage of PVC over HDPE is that materials can adhere to it, but adhesion to any smooth surface is difficult, unless a chemical bonding occurs.

One particular concern raised by Mr. Smith himself, is that the liner would not be directly connected to the lateral. The liner would be bonded to the host pipe that is connected to the lateral. Thus a small piece of host pipe becomes part of the system, and needs to endure to maintain system integrity. A further complication occurs when the host pipe has a cement-mortar lining. Even if the PVC were to bond well to the cement-mortar lining, the cement-mortar may not be well bonded to the host pipe. If the cement mortar were applied in the factory and had been thus been compacted by rapidly spinning the pipe, it can argued that little leakage into the annulus can occur, but the author's personal observation is that even factory lined cement mortar has minimal bond to the steel. This is likely not an insurmountable problem—perhaps the epoxy can be applied in such a way to effect a seal of the annulus—but it is another issue to be addressed.

CASE 6: CIPP LINING – LATERAL REINSTATEMENT AND SEAL

Cured-in-place pipe (CIPP) lining is believed to be the most common method of pipeline rehabilitation used in the United States. It is largely applied in the wastewater field to gravity-flow pipelines. Its use in potable water pipelines is much less common, because it generally is not designed for pressurized applications, and is less cost effective than cement-mortar and epoxy linings for normal corrosion protection applications. However, there are at least two commercially available systems that are designed specifically for water systems and are rated for pressure. These systems utilize fabric tubes of woven polyester fibers. A third pressure choice may also soon exist—at least one company claims to offer an application with carbon-fiber reinforcement, but to date, no small-diameter mains have been lined with this product.[8]

One of the reasons that CIPP has been less cost effective in water pipeline applications is that lateral reconnection is not simple. Compared to other non-structural applications (cement-mortar and epoxy), CIPP lateral reinstatement is considerably more difficult. As described in Chapter 2 of the report, no effort is needed for lateral reinstatement after epoxy lining, and only an air blast is needed after cement-mortar lining. Compared to applications in wastewater pipes, CIPP lateral reinstatement in water pipes is more difficult because a visible "dimple" is not discernable at the lateral tap. Finding where the lateral tap is located—and doing so with precision—is therefore the first problem to be solved.

Workshop attendees thought that finding the lateral was a solvable problem. One possible method is to use a tool similar to the remote field eddy current (RFEC) devices that are now used for finding defects in cast-iron mains. The development of these tools arose from another AwwaRF project (Jackson, et al, 1992), and several subsequent AwwaRF investigations have researched their applications and effectiveness (Ellison, 2001 and Reed, et al, 2004). It has been reported that with proper calibration, these tools have been able to detect and precisely locate corrosion defects in water mains that are as small as a dime. It is therefore believed that these tools have the ability to detect and locate service taps. A service tap with attached corporation stop and lateral pipe represents a relatively large anomaly and should cause significant disruption of the electrical field.

Additional research is needed to determine whether RFEC could be effective for this application. If RFEC does not work, other possible methods that might be used include

[8] Portions of large-diameter pipelines have been reinforced with carbon fiber reinforced plastic. In these cases, the reinforcement has been hand-applied from inside the pipes.

ultrasonic and magnetic flux leakage. If all else fails, a signal can be transmitted down the lateral from the meter box, using a direct connection to the metal pipe, or to a wire that is inserted into the pipe, as described in Case 1. There is also the idea of depositing transmitters into the laterals prior to lining.

Once the lateral is located, a pipeline robot equipped with a mechanical drill can be employed to re-establish the bore. This technology is also described in Case 1, and is demonstrated on the CD which is included in this report.

The other Case 6 problem to be solved is the sealing of the annulus. As discussed earlier, research conducted for the City of Baton Rouge (Bakeer, et al, 1997) has shown that an annular space exists in most (if not all) CIPP applications. Through this annulus, water can migrate, even under pressures as low as 5 psi. With normal water system pressures, extensive leakage would be expected, negating the benefit of the CIPP liner as either a corrosion barrier or as structural reinforcement. However, if the annulus can be sealed at the lateral opening, both the corrosion protection and the structural benefit of the lining are enhanced.

Chapter 3 describes tools and techniques that have been developed for other applications that may have benefit to the problem of remaking water service connections in a no-dig or low-dig manner. Among these tools and techniques are pipeline robotic devices used for injection of chemical grouts, resins, and other sealants. Many of these devices have been specifically adapted for applying grouts and resins at lateral connections, to address concerns about leakage through the annulus. The existing devices essentially inject the grouts and sealant under pressure between temporary pipeline seals. It is believed that developing appropriate sealant applicators for water mains and laterals is largely a problem of scaling the existing designs for the smaller pipes found in water systems.

While "chemical" grouts composed of hydrophilic polymers are the most common injection materials, they typically form a fairly porous foam-like material of relatively low strength. This would not be effective in water systems with typical system pressures of 50 to 100 psi. The chemical grouts work by permeating the soil surrounding a leak, filling void spaces all around. This inhibits infiltrating water from reaching the pipe. The long-term performance of these grouts has been a subject of considerable research over the years, but the cost of chemical grouting is relatively low.

For sealing within water pressure pipes, epoxy or urethane sealants are more likely to be effective. An effective sealant will be one that adheres well to the host pipe, adheres well to the liner, does not contaminate the water, does not impart a taste or odor to the water, and is long-lasting. In at least one regard, sealing laterals may be easier in water pipelines than in wastewater pipelines, because grease and other contaminants should be less prevalent.

Again, research is needed to determine what sealants would be most effective, and how they could be applied. All sealants as well as liners, will need to be tested and approved by the appropriate agencies, such as the National Sanitation Foundation.

CHAPTER 5
FIELD TESTING OF KEYHOLE METHODS

This chapter describes a successful field trial of "keyhole" methods for reconnecting services following the pipebursting replacement of a water main. The concepts for these field tests were developed by participants at the expert workshop, and were described in Chapter 4, Case 2. The field testing was performed on an actual water system, completed successfully, and the connections are now delivering water to customers. A CD showing the progression of the work is enclosed with this report.

Many organizations and companies contributed to this effort. Work was performed using common tools and a typical utility crew, in conjunction with specialized tools, equipment, and specialized labor. A list of the organizations and key individuals who contributed to these tests is found in the acknowledgments section of this report.

BACKGROUND

Prior to the field work, activities were planned, tools were developed, mock tests were performed, and procedures were debated. All told, 10 weeks of preparations and planning preceded any work in the field. Participating in the planning effort were engineers and managers of the various contributing organizations, but key to the overall success was preparation by a handful of field personnel, who spent hours of their own time contemplating the tasks to be performed and developing the long-handled tools needed to accomplish the work.

The use of keyhole techniques is not new. The Gas Technology Institute and several companies have been experimenting with these techniques for many years. Several papers and magazine articles have been written on the subject. The company that performed the work for this project is considered one of the foremost leaders in this field, so some of the tools and techniques described here have been used before. However, because these techniques had never been applied before to the remaking of water system service connections, the majority of tools described and shown in this report were uniquely adapted to this trial.

The location of the project was a dead-end residential street in Los Angeles, where an existing 4-inch cast iron main provided service to 5 houses. This main was specifically selected because if problems arose few customers would be affected and work would not affect other portions of the system.

The old cast-iron main had been installed in 1926, and heavy tuberculation had accumulated over the years. Figure 5.1 shows a portion of the main that was removed for access. Two other items are worth noting in the picture: (1) the pipe walls are abundantly thick, reflecting the manufacturing processes of the time, and (2) graphitization and cracking is visible, making the main unsuitable for cleaning and cement mortar lining.

Figure 5.1. Section of 4-inch Water Main to be renewed.

The Los Angeles Department of Water and Power (LADWP) offered this main for our experiment, provided the services of a main replacement crew, and purchased the materials. In exchange, LADWP obtained a fully-functional, rehabilitated main. Had this main not been replaced using pipebursting, conventional open-trench methods would have been used. Most of the other services required for this test were donated by pipeline rehabilitation companies and suppliers.

BYPASS WATER SYSTEM

The first step was to install a bypass piping system, to keep customers supplied during the duration of the construction, which was expected to take as long as one week. Installation of the bypass system was started several days in advance, as super-chlorination and bacterial testing is required before the temporary main can be placed in service. Once testing confirmed the absence of contaminants, each service was connected to the bypass system, by closing the curb stop, removing the meter, and using hoses to connect the service pipe to the bypass system. A typical installation is shown in Figure 5.2. The installation of the bypass system was accomplished by a specialty contractor working for LADWP. The specialty contractor was used rather than utility labor, because such contractors have the needed bypass pipelines, hoses and connections readily on-hand, along with crews that are well practiced in their installation.

PREPARATION OF THE HDPE PIPE

While the bypass system was being installed, the HDPE pipe segments were delivered and butt-fusing of the pipeline commenced. Normal construction equipment (a backhoe) was used to offload the material and maneuver it into the fusion machine. Although the LADWP crew was not experienced in the use of HDPE piping, it is common practice for the material supplier to provide the fusion machine and its operator. Thus, no special tools, equipment, or knowledge was needed for this fairly typical utility crew to fuse HDPE pipe together. As the pipe was fused, sections were laid along the gutter of the street, until needed.

Figure 5.2. Bypass water system installation.

Figure 5.3 shows the butt-fusion machine. Butt-fusion of HDPE pipe is accomplished as follows:

(1) The ends of two pipe sections are placed into this machine. Clamps are lowered over the pipes, to hold them firmly in place. With the pipes clamped firmly, they can be pushed together and pulled apart, as the process proceeds.

(2) A rotating tool is lowered between the two pipe ends. As the ends of the pipe are pushed against this tool, their surfaces are planed, removing the outer layer of material. By removing this outside layer of plastic, contamination is removed and "virgin" plastic is exposed.

(3) The planing tool is then removed, and the two ends of the pipe are placed together to verify alignment.

(4) A heating iron is placed between the pipes, which are then pressed against the two sides of the iron. The heating time and temperature are closely controlled and monitored.

(5) After a sufficient portion of the two pipe ends has been softened, the pipes are pulled apart, and the iron is removed.

(6) The pipe ends are then brought together and pressed firmly end-to-end, causing the softened portions to fuse. As the compression force is maintained, beads form on the inside and outside of the pipe at the weld. The force and duration of this compression step are carefully controlled and monitored.

(7) The pipe is then visually inspected all around. A weld bead of a properly fused joint will exhibit certain visible characteristics.

Although HDPE pipe is still considered somewhat exotic by many U.S. water utilities, the tools, equipment and processes have been used extensively in the gas industry and in European water systems for many years.

Figure 5.3. Butt-fusion machine.

PREPARATION FOR PIPEBURSTING INSERTION

The excavation of entrance and exit pits was started shortly after fusion of the pipe was started. Since the existing water main was relatively straight from one end of the street to the other, only two pits were planned—one at each end of the 300-ft (90 m) run. (Had there been intervening valves or bends, additional excavations would have been needed to temporarily remove these items.) After the bypass system was up and running, and all services switched over, a valve was closed, and sections of the main were removed within the entrance and exit pits, to provide access to the interior of the pipe.

In this case, a rodding machine (Figure 5.4) was needed to insert a nylon rope through the existing main. Because the main was so heavily tuberculated, other methods[1] of rope insertion would not have worked. (These rodding machines are not generally in the inventory of water utilities, but their sister wastewater utilities often have such equipment on hand.) The nylon rope was then used to pull in a heavy-duty wire rope.

Next the HDPE pipe string was prepared for insertion. An air line was inserted inside the HDPE pipe, which was then connected to the bursting tool. The bursting tool was affixed to the end of the pipe, and the wire rope was securely connected to the nose of the bursting head.

[1] Among the other methods used to insert ropes in pipes: (1) using compressed air and a plastic grocery bag "parachute" to propel a rope from end to end; (2) floating a rope through the pipe with flowing water; and (3) using a motorized toy car to pull the rope.

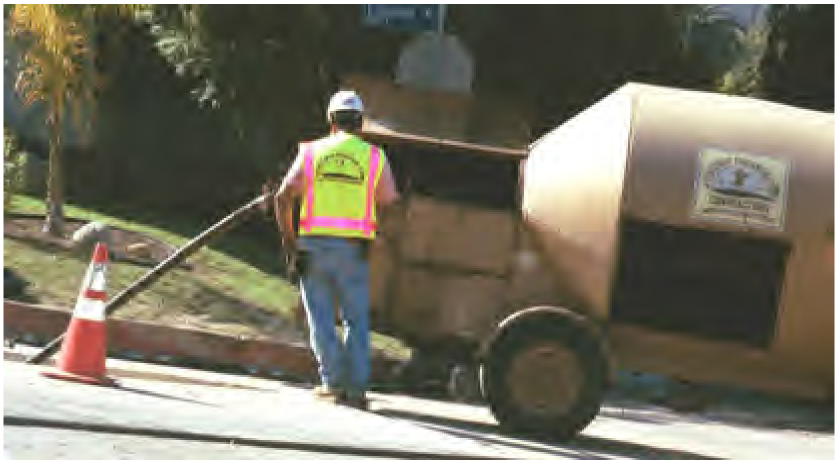


Figure 5.4. Rodding machine, used to bore through tuberculated pipe and pull back rope.

Because LADWP crews had never performed pipebursting before, this equipment, like the pipe fusion machine, was not in their inventory. But like the pipe fusion machine, the bursting equipment (bursting head and constant tension winch) can be readily procured through arrangements with the equipment manufacturer, who also furnished a skilled technician to guide the work. In our case, the manufacturer donated these services. In most cases, they would be paid for by the hour. The only other equipment needed for this type of pipebursting is a normal construction-style air compressor.

Pneumatic type pipebursting equipment was used in this application. This equipment has an air-driven hammer in the bursting head, which breaks the cast-iron pipe and helps propel the assembly forward. There are several other types of pipebursting systems, including "static" pull systems, wherein the winch (or puller) provides all of the pulling and bursting force. Using the pneumatic hammer reduces the amount of pulling force that is required.

Figure 5.5 shows the pipe string with both the bursting head and wire rope connected. Figure 5.6 shows the constant tension winch used to pull the tool through the pipe.

PREPARATION OF KEYHOLES

Before bursting of the main could be started, the keyholes needed to be excavated, the lateral pipes severed, and the corporation stops removed. This was necessary to prevent the bursting operation from damaging the service lines, which were intended to be reused. Preparation of the keyholes involved the following steps at each of the 5 service connections:

(1) The service lines and mains were traced using pipe locating equipment, and the exact location of the main/lateral connections were marked on the pavement.

(2) The limits of demolition were then marked, and the pavement was broken up using jack hammers.

(3) Vacuum excavation equipment (Figure 5.7) was used to excavate a hole, approximately 2 feet x 2 feet in plan, centered over the corporation stop. Soil was also cleared around the connection.

(4) Using channel lock pliers with long extension bars fastened to the handles, the flared fitting connecting the corporation stop to the lateral pipe was disconnected. A sledge hammer was then used to break the corporation stop from the main. (Figure 5.8 shows the result to this point.)
(5) A grinder on the end of a pole was used to cut the "U" bolts on the service saddles. This last step was done to facilitate the pipebursting process.
(6) After each hole was prepared, a small (3 feet x 3 feet) traffic plate was placed over the hole. A distinct advantage of using keyholes is the relative ease of placing and removing these relatively small traffic plates.

Although this task just described may sound complicated, each keyhole was prepared in 30 minutes or less.

Figure 5.5. Bursting head assembly.

Figure 5.6. Constant tension winch.

THE PIPEBURSTING INSERTION PROCESS

Like many pipebursting insertions, this one had a few hitches. Although the insertion initially proceeded with the pipe advancing about 1 foot per minute, after 4 hours the progress slowed to half that rate. As mentioned earlier, the overall run was 300 feet. Figure 5.9 and Figure 5.10 show the pipebursting work in progress.

Figure 5.7 Vacuum excavation. **Figure 5.8 Key-hole ready for pipebursting.**

A nominal 6-inch pipe (6.625 inch O.D.) had been selected to replace the 4-inch cast iron pipe. This is not a large “upsizing”, but it is significant, given difficult soil conditions. The original pipe trench had been cut through bedrock and backfilled with a sandy material. This created considerable resistance to the pipebursting tool, which must expand the bore by pushing the fractured pipe outward and compressing the surrounding material. The other condition that impeded progress was the uphill pull. When given a choice, it is always better to pipeburst going down hill, allowing gravity to help and not hinder the work. On this street, there was no choice. There was no space at the top of the hill to lay out the pipe string.

Like many pipebursting insertions, this one also got hung up by an unknown obstruction. Repair clamps, saddles, and other difficult to break items will sometimes become wrapped around the bursting head, and get pushed along, creating significant resistance to advancement. In our case, the resistance came in the form of a concrete manhole, the walls of which had been cast around the water main. This caused a one-hour delay, as first a pavement saw was called in, and then a backhoe. Despite these difficulties, 300 feet of pipeline was still installed in one day.

Had this single-street pipebursting project been put out to contract, the cost probably would not have been very economical—and the change orders might have been high. However, had the project also included dozens of streets, the unit costs could have been quite low, and the change orders might have been minimal. One reason is that during most of the work, when the pipebursting insertion was underway, only a single person is needed to attend to it. This frees up the rest of the crew to attend to other work on the adjacent streets (setting up for the next pipebursting insertion, for instance, or completing connections on an insertion that was just completed). Then, when obstructions are encountered, the person monitoring the pipebursting work simply needs to call the crew over to assist with the problem. Moreover, if projects are large enough and are bid frequently enough, it becomes difficult for contractors to claim difficulties are “unexpected”, when they are really quite common. On a large project, several repair clamps perhaps should be expected, and these hindrances then get “averaged out” over the whole project. While some streets within a large project would be difficult to complete—others should be easy.

Figure 5.9
Pipebursting insertion, as viewed from the rear.

Figure 5.10
Pipebursting, as the insertion is started.

RECONNECTING THE SERVICES USING KEYHOLE TOOLS

Connection Design Revision. As the pipebursting insertion proceeded, the specialty crew that had been selected to perform the keyhole work was making final preparations. For weeks, this crew had considered their objectives, contemplated what conditions would be encountered, and crafted the tools they believed would be needed. These efforts had resulted in significant changes to the connection "design" that had been formulated in the workshop.

The workshop participants had envisioned that an electrofusion saddle connection would be fitted with an HDPE "pigtail". (This was shown in Figure 4.4, which has been reproduced on the next pageas Figure 5.11, for easy reference.) The "pigtail" was an acknowledgement of the fact that considerable field adjustment would probably be needed, given that the orientation and position of the existing lateral pipes were both unknown and highly variable. Indeed, during this particular field test, on a street with just five houses, there were five substantially different configurations for the lateral pipes. Some laterals had originally been tapped to the top of the main, some were tapped horizontally, and others tapped at an angle somewhere in between. How this "pigtail" would be formed, and how it would be made to fit the existing piping was a detail that the managers and engineers in the workshop, had left to the imagination.

One thing was certain, making this HDPE "pigtail" work, was not going to be easy. HDPE, afterall, is not *that* flexible. It can be made somewhat pliable with heat, but it also has a tendency to remember earlier shapes and forms, and try to revert to them. This might cause such a "pigtail" to pull out of the compression coupling that was envisioned as attaching it to the copper lateral pipe. Recognizing this problem, various suggestions were offered by various project participants, but most options had one or more significant flaws. Hose materials, for instance, might not be durable enough, might not be NSF approved, and might be prone to collapse or kinking, particularly if the main were ever depressurized.

The field crew came up with a better idea. Instead of using HDPE as the transition material, copper would be used. With a series of elbows, nipples, and copper compression fittings, an assembly was devised that allowed for virtually any configuration of lateral pipe that might be encountered. Figure 5.12 shows one of these connection assemblies. Figure 5.13 shows the materials used to construct the connection assembly, how it could be adapted to various configurations of lateral pipes.

Thus while the pipebursting insertion was progressing, the keyhole crew was taking various measurements and making various observations of the exposed lateral pipes, verifying that the prefabricated saddle connection assemblies would work. In one case, it was necessary to customize the assembly because the existing lateral pipe near the main had been damaged during the original construction, so a longer connection piece was needed.

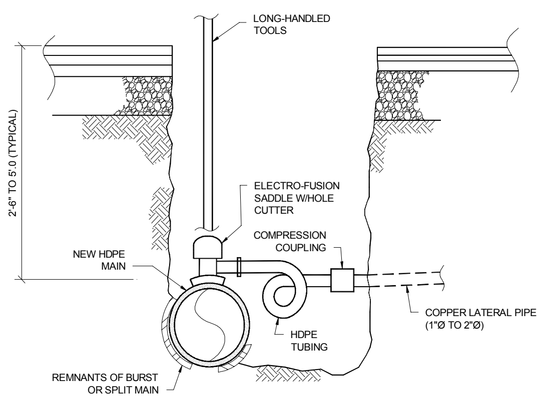


Figure 5.11
Connection as conceived, showing "pig tail."

Figure 5.12
Electrofusion saddle, with copper pipe and fittings.

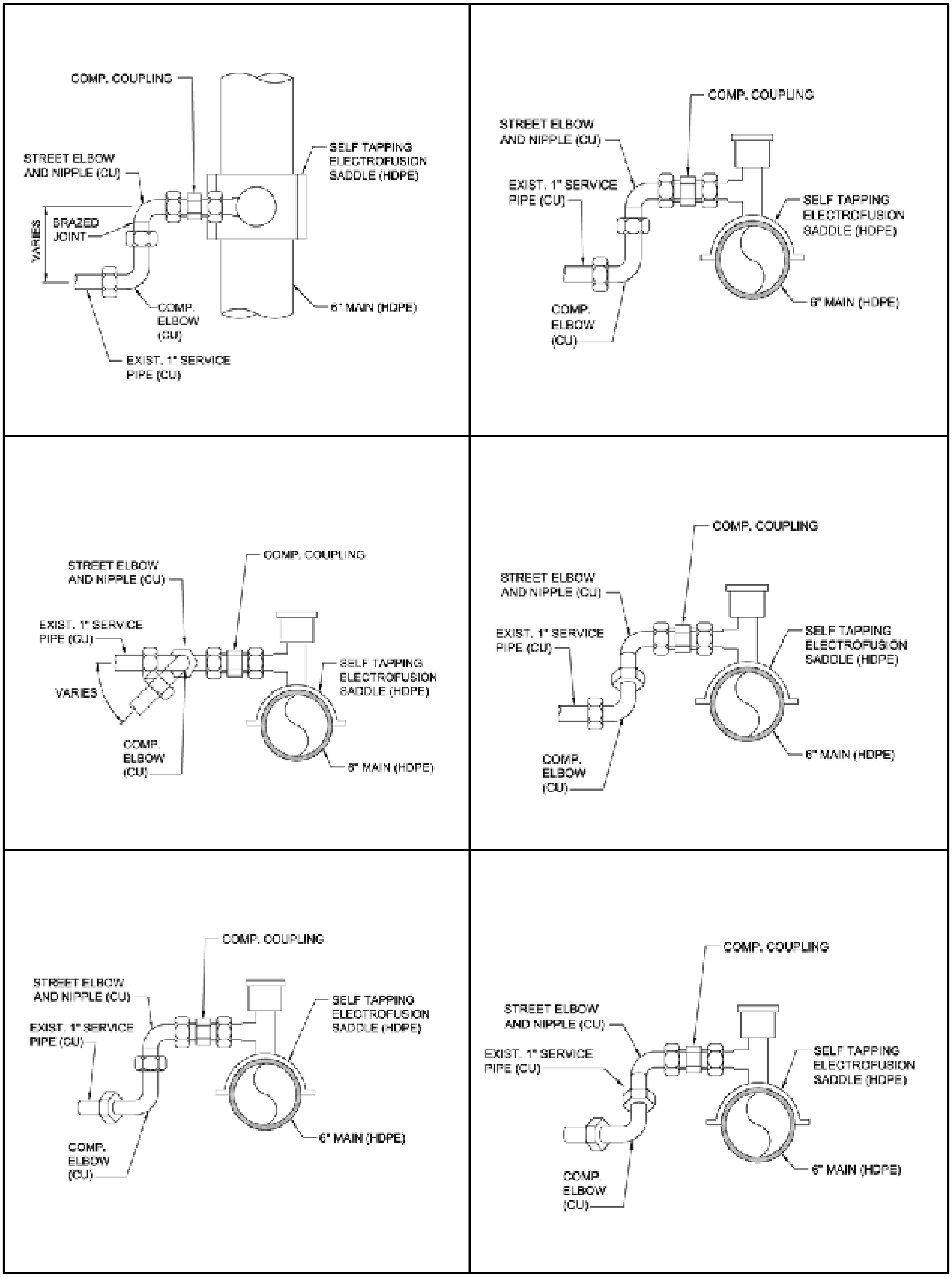


Figure 5.13. Various configurations of electrofusion saddle, with copper pipe and fittings.

Also while the pipebursting work was going on, the keyhole crew was preparing the lateral pipes to receive the connections. This generally entailed cutting each pipe to remove the flared end, and then cleaning the pipe surfaces to assure a good seal with the compression fitting. One of the more clever keyhole tools was a long-handled copper tubing cutter used to remove the flared ends of the existing lateral pipes. A demonstration of this tool is found in the accompanying CD. This tool and others are displayed in Figure 5.14.

The Fusion Clamp Problem. An issue of significant concern was how to temporarily hold the electro-fusion saddle in place, while fusion occurred. Normally a clamp wraps around the bottom of the pipe, holding both sides of the saddle, as shown in Figure 5.15. Lowering and maneuvering this clamp into place, and then activating the handle appeared to be a difficult task to accomplish through a keyhole. Figure 5.16 shows a different style of clamp that would have been much easier to apply. This clamp is essentially a large "C" clamp. Lowering it into position appeared to be relatively easy. However, the manufacturer of the fusion saddles insisted that the 6-inch saddles which we needed could not be effectively installed with confidence, using the "C" clamp. This is thus an area where opportunities for improvements exist.

COMPLETING THE CONNECTIONS USING KEYHOLE TOOLS

Once the pipebursting process was completed, the keyhole crew was able to start installing the connections, using only the long-handled tools. As expected, the first connection was somewhat challenging, but with each succeeding attempt, the connections became easier. Granted, the relatively shallow depth of mains in Los Angeles[2] makes the keyhole process less difficult than other locales, but, in these other locales, conventional large-excavation methods are also more difficult, particularly when shoring is needed for soil stability and worker protection in a deep excavation.

Figure 5.14. Various keyhole tools used to complete the work.

[2] The top of the main was 30 to 36 inches below the pavement surface.

Figure 5.15. Wraparound fusion clamp.

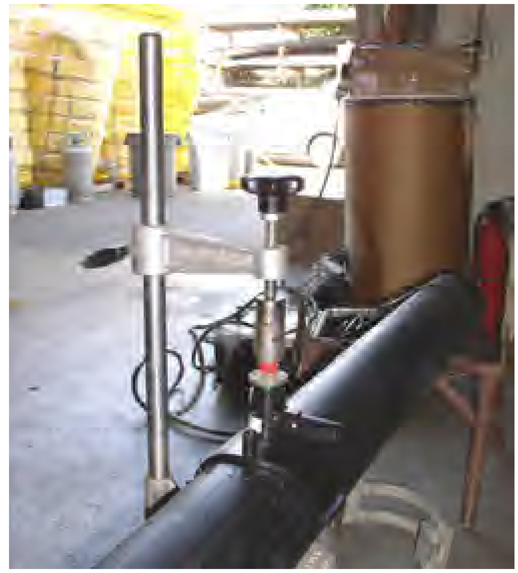


Figure 5.16. "C" style fusion clamp.

The keyhole connection process proceeded as follows (see Figures 5.17 and 5.18):

(1) The saddle and copper fitting assembly was lowered into the hole to check general alignment, and to determine where the saddle would land on the HDPE main.

(2) The connection assembly was then removed and a disc sander on the end of a long pole was used to prepare the top of the main to receive the saddle. A long-handled brush was then used to whisk away any dirt and debris.

(3) The nut and compression bushing from the compression coupling was then slipped onto the end of the existing lateral pipe. This step tended to be difficult, because the bushing is made to fit very snugly onto the pipe. Thus it is difficult to get the bushing positioned just right, and then pushed onto the pipe. However, one can imagine a simple tool that could accomplish this task with relative ease.

(4) The connection assembly was lowered again into place, with fusion wires connected.

(5) The connection to the existing copper lateral was then completed, using the compression nut and bushing installed in (3).

(6) The wrap around clamp was installed. The clamp itself was lowered using baling wire. Long-handled hooks were used from various angles to pull the clamp into position below the pipe, and lift it up to pipe. Then the crew moved the clamp laterally, down the main, sliding it over the "ears" on the saddle. The handle on the clamp was then engaged, again using the long-handled hooks.

(7) The fusion process was completed by:

   a. Scanning the bar code on one of the saddles. This gave a computer within the fusion machine the information needed to determine the proper amperage and duration of fusion.

   b. The start button on the fusion machine was pressed.

c. The computer was monitored for error messages, and to confirm that appropriate cool down was reached, before removing the clamp.

(8) All the copper compression fittings were then tightened. Channel lock pliers with long extensions wired to the handles were used. (Pipe wrenches have also been adapted to key-hole use.)

(9) Finally, the main was tapped, using the built-in cutter that is standard on these types of saddles. This was easily accomplished using a standard wrench fitted onto the end of a "T" bar. The cutter, which is at the top of the saddle, was screwed down, cutting the pipe wall, then backed out, to allow water to pass. The plastic cap was then placed over the cutter assembly.[3]

Figure 5.19 shows one of the completed assemblies. On the date that this report was written, each of these connections had worked satisfactorily for more than two years.

Figures 5.17 and 5.18. Keyhole methods in progress

[3] This cutter can also function as a corporation stop; by screwing the cutter back down, flow is stopped.

Figure 5.19. Completed keyhole connection.

Testing of the connection. Prior to tapping the main, another step should be considered. Before the tap is made, the individual connections could be easily pressure tested using water or air pressure delivered down the lateral pipe from the meter box. A simple testing unit could be made to connect directly to the curb stop. Pressure testing the lateral connection before tapping into the main would enable the crew to promptly address any problem with the installation. Then if no problem was noted, the main could then be tapped, and the hole filled with backfill (or sand-cement slurry), allowing a cleaner construction site. As it was, pressure testing and disinfection was done after the main was tapped. Thus, the connections were tested and disinfected along with the main, and then placed back into service. It should be noted that the sequence of these activities is somewhat flexible since customers are supplied through the bypass system until successful test results are obtained.

CONCLUSIONS

1. The field trial demonstrated that keyhole techniques can be applied today, to reduce the impacts and possibly the costs associated with remaking service connections. This trial applied keyhole techniques to a pipebursting project, but the tools and techniques are transferable to many other types of trenchless main renewal.
2. Ample opportunities exist to improve upon the techniques presented here, and to develop new tools for special tasks. All that is needed are the incentives to do so. With sufficient refinement and practice, these low-dig methods should be cost effective.
3. The methods shown here could be further enhanced, if coring and grouting of the pavement were used, as described in Chapter 4, Case 2.

4. The field trial also demonstrated that a utility construction crew could successfully execute a pipebursting project without any special training. Such crews already have most of the skills, tools, and equipment that are needed. The fusion machine, fusion machine operator, pipebursting head, winch, and pipebursting technician are readily obtained from companies that specialize in this area.

CHAPTER 6
BENCH TESTING OF
LOOSE-FIT SLIP LINING CONNECTION CONCEPTS

A concept for a no-dig method of reconnecting service laterals following a loose-fit slip lining rehabilitation was presented in Chapter 4 as Case 3. This concept was developed by participants in an expert workshop hosted for this project. At the time the concept was developed, difficulties were foreseen in its implementation. The fundamental problems to be overcome were similar to other rehabilitation methods—namely re-establishment of the service opening and making a positive connection between the lateral and main liner. However, the complex geometry that occurs when host and liner pipes are not concentric, and the need to bridge a rather wide annulus between the host and liner pipes, make the perfection of a no-dig connection for loose-fit slip lining particularly challenging. It was therefore determined that a few modest bench tests would be appropriate to verify the validity of several of the key ideas included in this concept.

This chapter describes the bench testing that was conducted in Louisiana Tech University's Trenchless Technology Center (TTC) by Drs. Aziz Saber and David Hall, under the guidance of Dr. Ray Sterling. Two series of tests were conducted. The first series investigated whether various boring tools at the end of a plumber's snake could be used for re-establishment of the service opening. The second series investigated whether a small flanged pipe with "O" rings could be used for an effective connection between liner and lateral.

RE-ESTABLISHMENT OF THE SERVICE OPENING

Figure 6.1 shows what is believed to be a fairly typical configuration for a loose-fit slip lined water main, except that the annulus space has been grouted, causing the liner pipe to "float" to the top of the host pipe. The grouting of the annulus is considered necessary if a positive connection is to be made between liner pipe and lateral pipe, otherwise movements caused by thermal expansion and contraction of the HDPE liner pipe would likely damage any type of connection. The grouting also serves two other purposes: (1) it holds the liner in a firm position for boring and (2) it stops a boring tool inserted from the corporation stop from glancing off the side of the lateral. An unfortunate consequence of the grout is that some of it will inevitably be deposited into the corporation stop and lateral pipe, making the re-establishment of the service opening even more difficult.

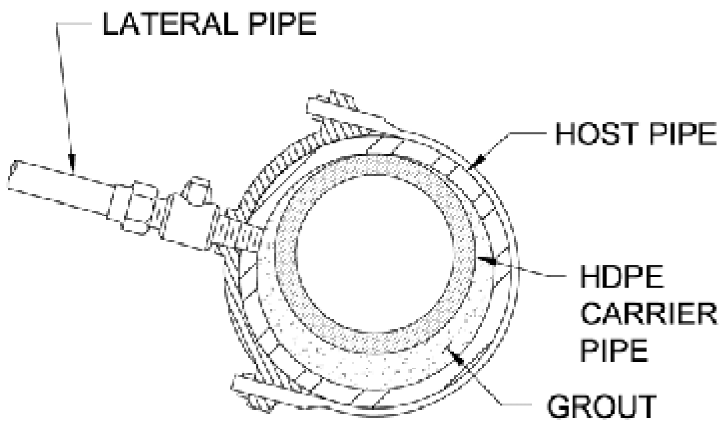


Figure 6.1 – Sli pliner readied for reconnection

For the tests performed at the TTC, two simplifications were assumed. First the lateral connection was positioned at the top of the main, so that it was normal to the liner pipe. Second, for most of the tests, a straight lateral was used. Neither of these assumptions reflects configurations that would be typically encountered in the field, but they allowed the researchers at the TTC to more easily accomplish their first objective, which was to test various boring tools. Figure 6.2 shows one of several 6-inch steel mains set up for testing, with a 4-inch HDPE liner pipe and grout.

The original concept was to use a common steel drill bit affixed to the end of a long plumber's snake for boring a hole in the liner, working from the meter end of the lateral pipe. The TTC team reported that their attempts to utilize such a tool were unsuccessful—the tool was simply too flexible. Apparently, a plumber's snake is not capable of delivering enough normal force to the drill bit to cause it to cut into the HDPE material. Thereafter, a simple ¼-inch diameter steel rod replaced the plumber's snake as the drive shaft for various boring tools that were tested. While such a rod might be capable of negotiating some lateral pipes, it should be recognized that this tool would not be suitable for the vast majority of applications. More thought and research is thus needed to find a suitable driver for the boring tool.

Among the boring tools tested for boring holes in the liner pipes were (1) a simple steel bit, (2) a steel bit aided by pilot hole, (3) a step-bit, and (3) a hole saw.

Simple steel bit. To bore a one-inch hole in the liner pipe, a one-inch bit is required. In practice, a bit of this size proved difficult to use, particularly if a long, flexible drive shaft is to be employed. A bit of this size requires considerable normal force in order to cut into the base material. Applying such a force did not appear feasible even with the solid steel drive used at the TTC.

Figure 6.2 - Six-inch host pipe with 4-inch liner pipe and grout.

Steel bit aided by a pilot hole. The TTC then tried using heated rods (modified soldering irons), pushed through the lateral, to create a pilot hole in the liner. With a pilot hole, it was believed that the steel bit would be able "bite" into the liner. For this test, two types of soldering irons were used. A problem was soon discovered: centering the pilot hole in the lateral. Although this problem could likely be solved with ingenuity, a simpler tool was available—the step-bit.

Step-bit. In considering ways of keeping the pilot hole centered in the lateral, the TTC team came upon the idea of using a stepped drill bit (Figure 6.3). Such a tool bores successively larger holes, starting with a pilot that is automatically centered. Standard step-bits are available in 1-inch and 1¼-inch diameters and can be custom manufactured in virtually any size. This tool appears capable of making the needed hole in the liner. It is not known, however, if the bit would be suitable for negotiating the bends that might be typically found in a service lateral. The tapered shape of the bit should allow it to negotiate moderate bends, but its length of about 2.5 inches may cause it to bind in a bend with a short radius.

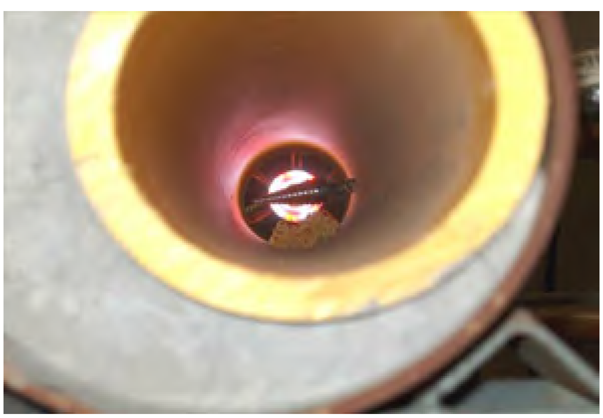


Figure 6.3 – Step Bit

Figure 6.4 – Hole Saw

Hole saw. A standard hole saw was also tested successfully (Figure 6.4). A hole saw typically is guided by an integral drill bit at the center, which may not be needed for this application, since the bore of the lateral pipe and corporation stop may be sufficient for guiding the saw. For the TTC tests, the saw which was used was guided by a ¼-inch bit that protruded about 3/8-inch beyond the end of the saw. The hole saw offers two distinct advantages: (1) because the tool works by coring and not cutting, less material must be physically cut, and the process can be done more quickly; and (2) the cylindrical shape of the saw provides better assurance that the hole will be positively centered. The disadvantages are: (1) passing the tool though bends in a lateral pipe may be more difficult due to its non-tapered cylindrical shape, and (2) the tool must be at least as long as the material that is cored. Thus, if the lateral enters the main from the side, a rather long tool will be needed to traverse the grouted space and cut through the wall of the liner. Alternatively, the tool would have to be intermediately withdrawn to remove cored material and then reinserted for completion of the hole.

It is not known which tool, the step-bit or the hole saw, would be more effective in cutting through grout that enters the corporation stop and lateral pipe when the grouting is initially performed. In either case, if considerable grout enters the lateral pipe, the boring of the hole will no doubt be significantly impeded, and some means of removing material from the pipe would probably be required. Perhaps air jets on the side of the stepped bit could be used to blow the pulverized grout from the lateral. Another problem to be solved is engineering a tool to effectively cut the abrasive grout (assuming that standard sand-cement grout is used) without rapidly dulling the tool.

Conclusion. This first series of tests at the TTC demonstrated that re-establishing the lateral bore may be possible using a tool inserted from the meter side of the lateral, but it will certainly be problematic. Among the questions still need to be answered:

- What is a suitable drive shaft for the boring tool? The shaft must be flexible enough to pass through various bends, but stiff enough to allow the boring tool to work.
- What size of boring tools can negotiate typical bends in service laterals? To facilitate a tight connection with the "top hat" connector (as discussed below), the boring tool must be nearly as large as the inside diameter of the lateral. Thus any ovality created by bends in the pipe may obstruct tool passage. Additionally, the longer the tool, the longer the radius of bend must be to allow for its passage.
- How would grout inside the corporation stop and lateral pipe affect the process?

CONNECTING THE LINER TO THE LATERAL

The next problem to be solved is to make a positive connection from the liner to the lateral. One concept for making this connection is to insert a short HDPE "top hat" connector into the bored hole, where the flange on the top hat is bonded to the liner by electrofusion and the seal at the corporation stop is obtained using one or more "O" rings, as depicted in Figure 6.5.

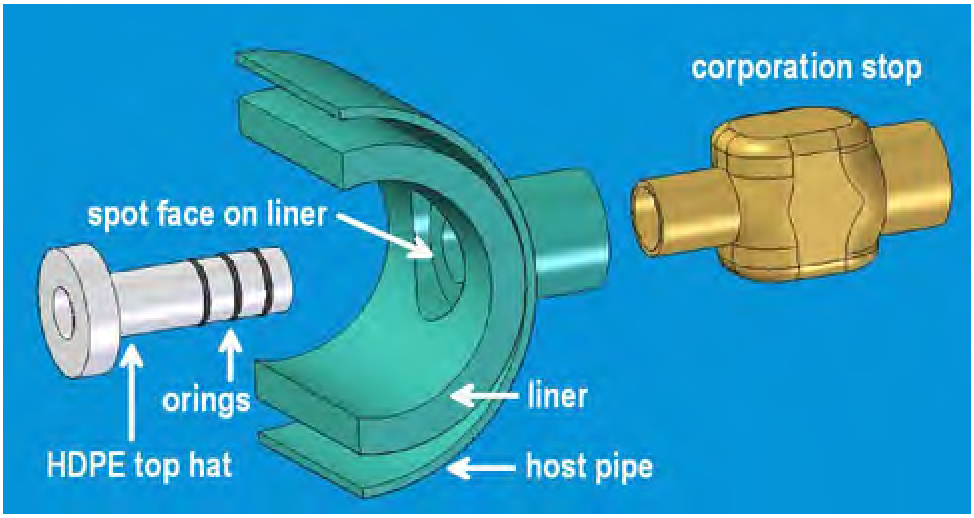


Figure 6.5 – Exploded view of the top hat lateral sealing technique.

Fabrication of the top hat. Several HDPE connectors were fabricated to the dimensions shown in Figure 6.6. The shaft of each was machined to a diameter of 0.95 inches to provide a small clearance when inserted into the 0.971 inch bore of the corporation stop. Figure 6.7 shows the connector being drilled out to an internal diameter of 0.703 inches (using a 45/64 inch drill bit). The thickness of the material between the bottom of the "O" ring grooves and the inside bore of the top hat was roughly equal to that of one-inch diameter black HDPE tubing (wall thickness ≈ 0.06 inches). The dimension ratio (DR) was thus 11.7, providing a pressure rating of approximately 160 psi.

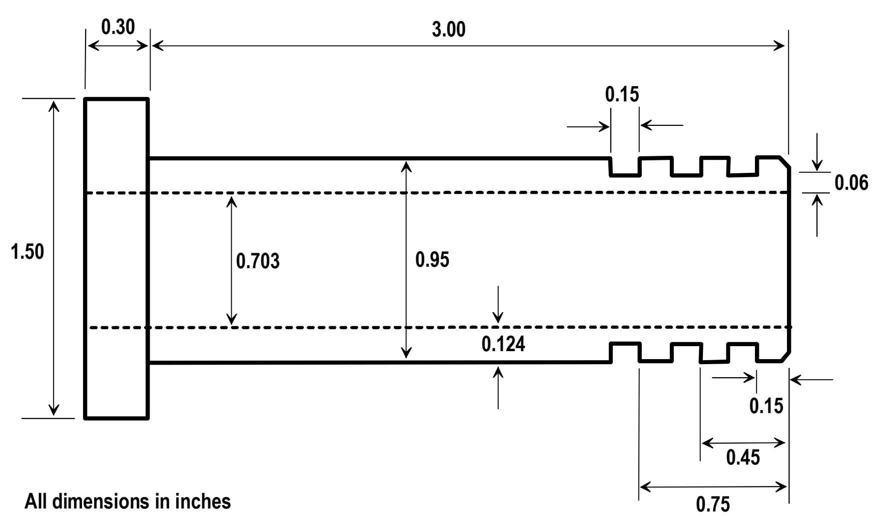


Figure 6.6 – Dimensions of the top hat connector.

Figure 6.7 – Center drilling of the top hat. **Figure 6.8 –Spot facing the HDPE liner.**

Preparation of the slip lined pipe. To simulate field conditions, the top hat was installed in a one-foot long segment of slip lined pipe. Prior to lining, two holes were drilled in the six-inch diameter steel host pipe. One of the holes was 2-inches in diameter and provided access to the inner surface of the liner during the subsequent spot facing and electrofusion operations. It should be noted that in practice, no such access hole would exist, and the spot facing would need to be performed by a pipeline robot. The second hole was 1.25 inches in diameter and was drilled directly across from the first hole. A one-inch diameter iron pipe coupling was welded over this second hole, and a 1-inch diameter corporation stop was screwed into the coupling. Several holes were drilled into the coupling to allow for leak detection during testing. The purpose of the 2-inch hole was to facilitate spot facing of the liner (as described later).

Following the preparation of the steel host pipe, a 3.645-inch internal diameter HDPE liner with a 0.425-inch wall thickness was slipped into the host pipe and grouted into place adjacent to the 1.25-inch diameter hole for the lateral connection. After the grout set, a two-inch diameter hole was drilled through the liner using the two-inch diameter hole in the steel pipe for access, and a one-inch diameter hole was drilled through the liner from the iron pipe coupling. The liner was then spot faced with a 1.625 inch Forstner bit, as shown in Figure 6.8. The spot facing was slightly larger than the 1.5-inch diameter flanged portion of the top hat to provide the clearance needed for proper seating of the top hat.

This spot facing was done to provide a flat surface for seating of the flange. Otherwise the flange would need to be bent to conform to the curvature of the liner pipe. (In the original concept developed at the expert workshop, a thinner, larger flange would be bent to conform to the liner. The practicality of this idea is questionable.)

Electrofusion of the top hat to the liner. High resistance, 22-gage chromel wire was attached to the inner flanged portion of the top hat to allow for electrofusion bonding to the HDPE liner. Figure 6.9 shows the two different winding configurations tested: several straight spirals around the top hat (left) and a single loop of wavy winding around the top hat (center). The wired top hat was then pressed through the one-inch hole in the liner until the flange of the corporation stop was completely seated in the spot face and the "O" rings fit snugly inside the bore of the corporation stop. The high resistance wire on the top hat was connected to a direct current. power supply, and 5 volts were applied for 5 minutes to melt the plastic at the interface. Pressure was applied to force the top hat into the liner using a threaded rod attached to a handle at the top and a spherically hinged foot at the bottom, as shown to the right in Figure 6.9.

Figure 6.9 – Wire winding patterns (left and center) and pressure application during electrofusion (right).

Testing the connection. After electrofusion, the pipe segments were plugged at both ends by tapered aluminum cylinders that were drilled and tapped in the center to accept an all-thread tie bar. As the two tapered ends were tightened on the all-thread, the tapered cylinders were wedged tightly into the ends of the pipe liner to prevent leakage. The inside of the pipe segment was then filled with water to remove any trapped air, and a pressure gage and manual water pump was attached at the corporation stop, as shown in Figure 6.10.

Three testing trials were carried out for the straight spiral winding configuration (far left in Figure 6.9), and these tests failed to hold more than 50 psi. Testing was repeated for the single wavy loop (center in Figure 6.9), and the top hat held 160 psi on the first attempt before leaking through the holes in the iron pipe coupling.

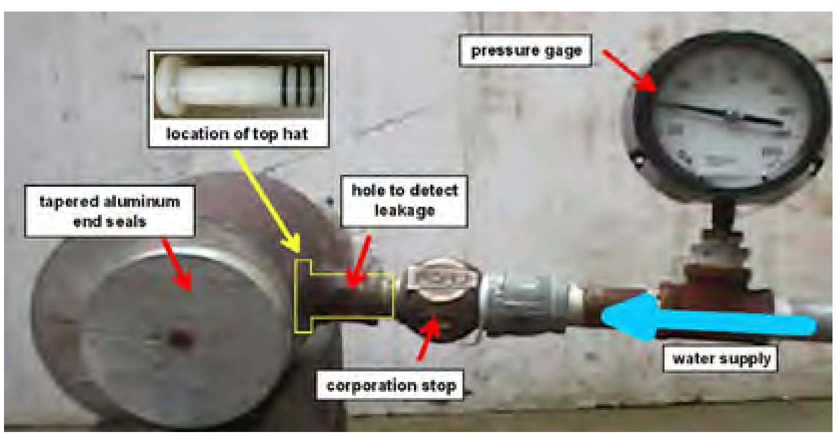


Figure 6.10 - Experimental setup for top hat testing.

Discussion. The electrofused top hat with the single wavy loop of heating wire held 160 psi before leaking. This indicates a strong positive seal between the “O” rings and the inner bore of the corporation stop and at the electrofused joint between the top hat and the spot face on the liner. It should be noted that these joints were prepared under dry laboratory conditions. The presence of moisture, scale, and other debris could present significant obstacles in actual field applications. It appears from the testing that the weak link may have been the electrofusion connection rather than the “O” ring connection. This is good news. Because several companies are experienced in engineering electrofusion materials, obtaining a better seal should not be overly difficult.

The important design variables controlling the seal between the “O” rings and the corporation stop include the clearance between the shaft of the top hat and the inner bore of the corporation stop, the depth of the “O” ring grooves, and the size of the “O” rings themselves. Increasing the clearance between the “O” ring and the corporation stop with all other variables held constant will loosen the seal, eventually resulting in leakage as the clearance becomes excessive. Decreasing the clearance will result in tighter and tighter “O” ring seals, but this decreased clearance may lead to cutting of the “O” rings as they enter into the corporation stop. One approach to allow for more variation in the bore of the corporation stop would be to use a slightly tapered top hat shaft where the first “O” ring had the smallest OD, the next “O” ring had a slightly larger OD, and so on. Using this idea, if an “O” ring was too large, it would simply be cut during the insertion process, and the smaller “O” ring in front of it would do the sealing.

These tests were performed with the lateral pipe in a position that would be rarely encountered in actual practice. More commonly, the axis of the service lateral would not intersect the axis of the liner. In those cases, the flange on the top hat will not be correctly seated in the spot face. One possible solution to this problem is to use a spherical joint between the flange of the top hat and the shaft of the top hat, as shown in Figure 6.11. Here, the spherical joint would be electrofused in place when the top hat was electrofused to the lining.

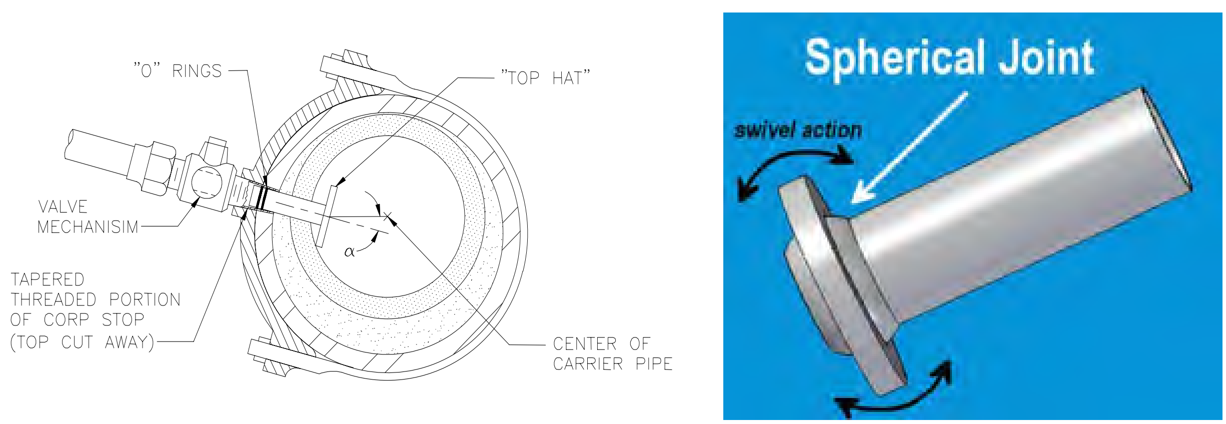


Figure 6.11 – Problem of misalignment of the service with the liner and a potential solution.

The quality of the electrofusion joint depends on the relative melting points of the top hat material and the liner material. Early trials used a top hat material with a melting point significantly higher than that of the liner. The performance of these joints was not good. The melting temperatures of the two materials were more closely matched for the successful test.

SEALING WITH SELF-TAPPING FITTINGS

The TTC also explored the idea of connecting to the liner pipe using a self-tapping fitting. Such a service could potentially be reconnected without accessing the inside of the water main. A self-tapping connection would not require a counter-bore on the inside of the liner to create a seal, so the hole could be drilled from the service-side rather than from within the main. However, for this method to work, technologies for installing the fittings from the surface would need to be further developed.

Preparation of the fitting and experimental setup. To perform a simple proof-of-concept test, a ½-inch hose barb to ¾-inch NPT fitting was modified to develop a prototype of the self-tapping fitting, as shown Figure 6.12. Four slots were milled around the circumference of the threaded end using a 3/16-inch diameter end mill. The slots were approximately 5/16-inch long and a few thousandths deeper than the valley of the threads. These slots provide cutting edges much like the cutting edges on a standard threading tap. For testing, a hose was then attached to the barbed end of the fitting and held in place with a hose clamp.

The pipe sample, shown in Figure 6.13, was prepared by drilling a 47/64-inch hole through the wall of the HDPE pipe. The fitting was then tightened using a pipe wrench, creating threads with each turn. The tapered pipe threads allow the seal to get tighter and tighter with each turn.

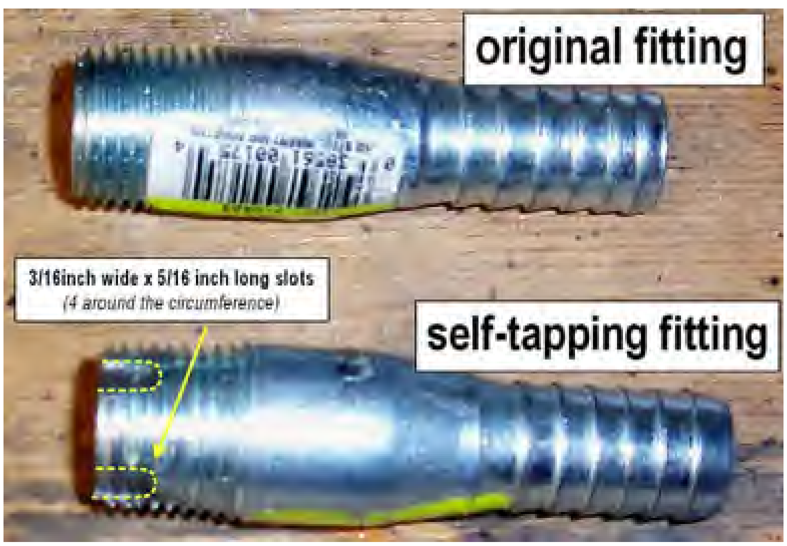


Figure 6.12 – Preparation of the self-tapping fitting by milling slots.

Figure 6.13 – Specimen ready for pressure testing.

Testing of self-tapping fitting. Water pressure was applied to the fitting using the same pump and piping system as for the top hat fitting. The self-tapping connection proved leak free for pressures less than 150-psi. Leaking began slightly above 150-psi, and the fluid appeared to be running around the thread pattern and escaping at the top of the thread.

Discussion. The leakage that occurred during this short-duration test could be expected to occur at lower pressures during longer tests, due to the relaxation of the plastic. Different types of threads may help to eliminate such leakage, and more severely tapered threads would tend to create a tighter seal at the outside of the liner. Another approach to eliminate leakage may be to bond the fitting and liner together. If the self-tapping fitting were made of metal thread-cutting edges followed by plastic threads, the plastic fitting could be electrofused to the liner (in the case of HDPE) or chemically bonded to the liner (in the case of PVC). It is believed that a simple mechanical bond without electrofusion or chemical bonding may not hold pressure for a long period of time due to creep deformation of the fitting and liner in response to the applied pressure.

OVERALL CONCLUSIONS REGARDING LOOSE-FIT LINING CONCEPTS

The bench testing performed at the TTC demonstrated:

- a step-bit boring tool is likely the best choice for re-establishing the service opening, if working from the meter end of the lateral, and
- an effective seal to the corporation stop may be possible using "O" rings
- an electrofused flange can be used for connecting to the liner, provided that spot facing has occurred.

As expected, the technical details of completing a no-dig lateral connection following a loose-fit slip lining appear difficult. Among the problems yet to be solved are:

- determining an effective drive shaft that can negotiate typical bends in lateral pipes
- testing a cutting tool where the lateral is not normal to the liner, and where grout has entered the corporation stop and lateral
- developing a means for removing pulverized grout and other cutting debris from the lateral
- developing and testing a “swivel” joint for the top hat connection piece
- testing each step in the concept in succession on a single mock up—determining that the hole made by the boring tool is compatible with the top hat connection piece
- developing a robot that is capable of spot facing the liner, inserting the top hat, applying pressure, and activating the fusion
- testing the method on real mains and laterals, where water, corrosion, sediment or other extraneous material may create difficulties

CHAPTER 7
BENCH TESTING OF LATERAL EXTRACTION CONCEPT

The technique of using an old lateral to help pull in a new one is widely practiced in the utility construction industry, but excavations are required at both the meter box and the main. This method is thus only marginally less intrusive than open-trench construction of a new lateral. In contrast, Chapter 4 presented the concept of a "no-dig" technique for connecting a new service to a tight-fitting HDPE liner without digging a pit at the main.[1] This technique involves:

(1) Releasing the corporation stop from the main by using a robot to drill around the tap.
(2) Pushing a steel cable down the lateral from the meter box. At the leading end of the steel cable would be a "gripping device" that would be pushed through the corporation stop.
(3) Pulling out the existing service and corporation stop while simultaneously pulling in a new HDPE lateral pipe. (This new lateral pipe would be extracted from within the main itself.)

This chapter summarizes laboratory testing of the concept, using a pulling rig designed and fabricated in the Trenchless Technology Center (TTC) at Louisiana Tech University, by Drs. David Hall and Ray Sterling.

GRIPPING DEVICE

To successfully extract a typical water system lateral pipe with a corporation stop attached would require more pulling strength than the typical lateral pipe could provide—particularly one that had been in the ground for many years and possibly weakened by corrosion. Moreover, the connection between the corporation stop and the lateral pipe was not considered strong enough to extract the corporation stop. Thus came the idea of using a strong cable with a "gripping device" on the end, which would be pushed through the lateral, from the meter box to the main.

Originally, the gripping device was envisioned as resembling a small umbrella that would spring outward after being pushed through the lateral and corporation stop and into the main. Instead, the TTC designed and fabricated a device utilizing a spring-loaded latch that would extend outward, after extending into the main. An exploded solid model of the device is shown in Figure 7.1 and a photograph of the fabricated device is shown in Figure 7.2. The device was designed specifically for extracting a one-inch copper lateral and corporation stop.

[1] This is found in the "Case 1, Concept Variation" found on page 61.

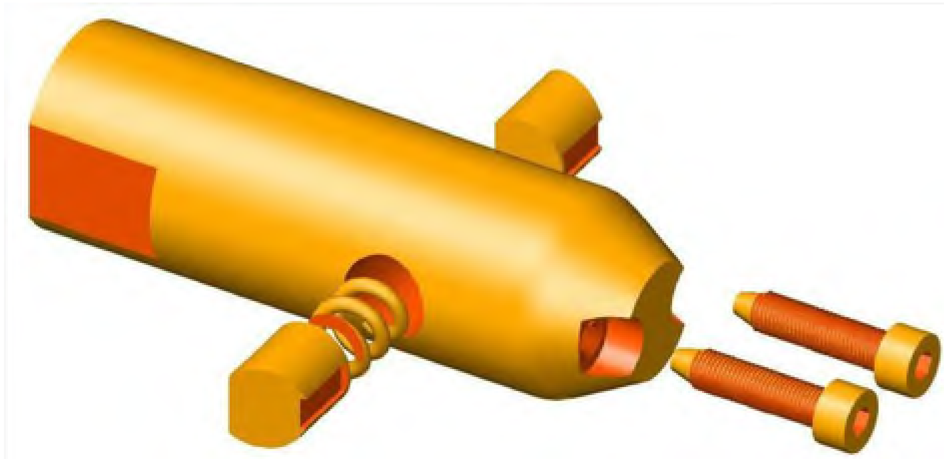


Figure 7.1. Exploded solid model of the gripping device.

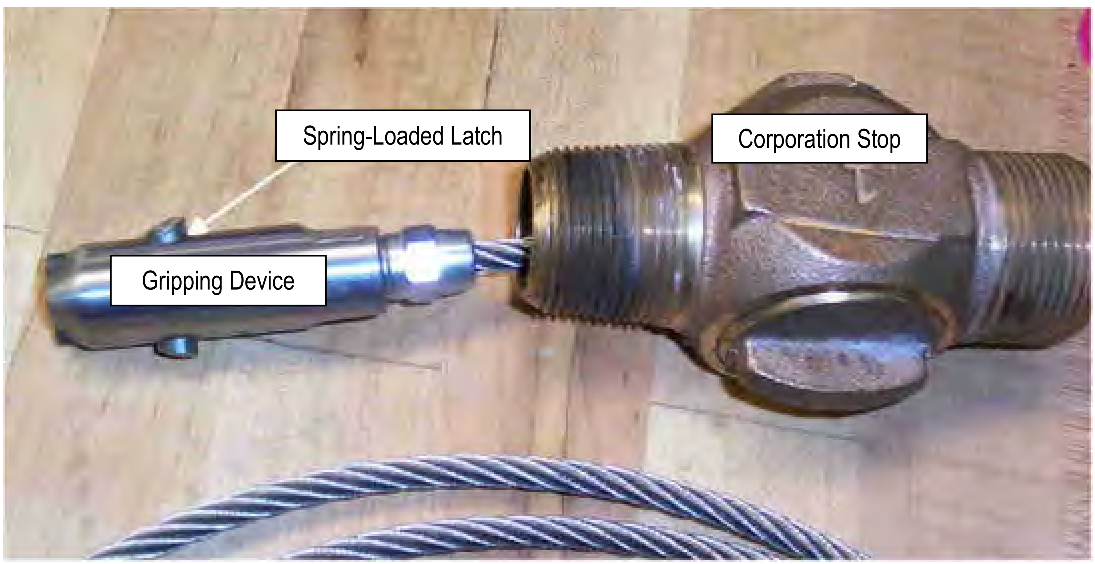


Figure 7.2. Photo of the gripping device attached to a cable.

From Figure 7.1, it can be seen that the gripping device consists of a cylinder, two opposing cylindrical latches, a compression spring, two screws, and the hardware to attach the cable. Each of the latches on the device works like a latch on a door lock. As the device is passed through the bore, the spring between the two latches is compressed (shortened) so that the latches move radially inward. However, when the device passes through the corporation stop bore at the main, the compression spring pushes the two latches outward. The distance between the tips of the fully extended latches is greater than the ID of the corporation stop, thus preventing the device from being pulled back through the corporation stop when tension is applied to the cable. The latches are prevented from falling out of the body by the two screws that catch at the bottom of the groove in each latch.

The pulling cable employed in the testing was a 7x19 class strand core, ¼ inch diameter, Type 304 stainless steel wire rope with a breaking strength of 6,400 lbs. The wire rope fitting used to connect the cable to the gripping device was a 9/16-inch diameter sleeve with 18 threads per inch. The sleeve was part of a standard positive-grip cable-end fitting. The cable was fed through the sleeve, frayed and wrapped around a plug that prevented the cable from pulling out after it was screwed into the body of the gripping device. A dimensioned drawing of the body of the device is shown in Figure 7.3. The prototype device used for field-testing was machined from 1020 steel.

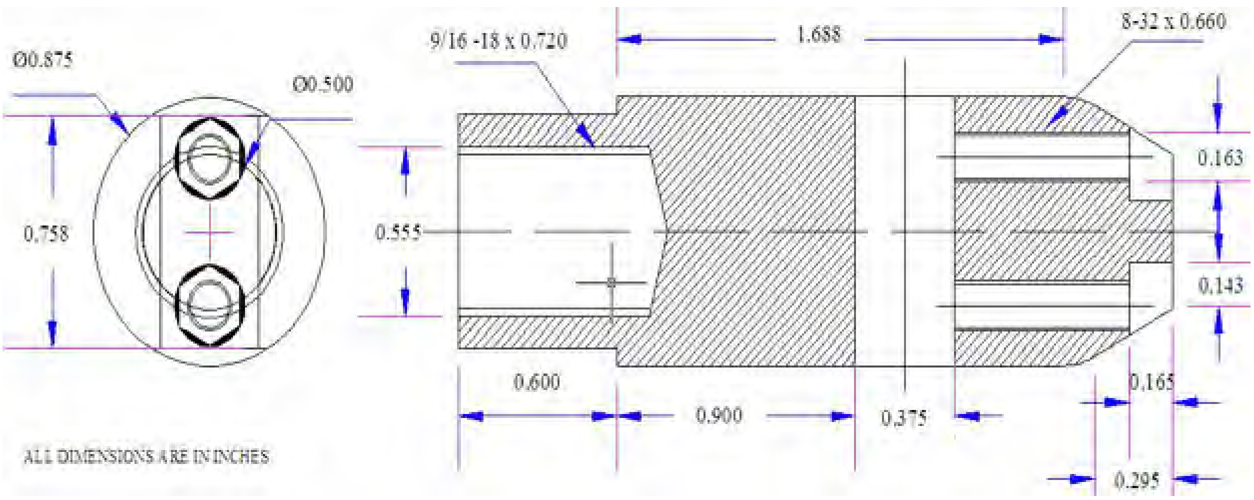


Figure 7.3. Drawing of the gripping device.

HYDRAULIC PULLER

A hydraulic puller was designed to apply tension to the gripping device. Figure 7.4 shows the hydraulic puller, assembled and in place, ready for pulling a pipe. It consists of three main sections: the tower, lateral frame, and bearing plate.

Tower Assembly. The tower, shown more closely in Figure 7.5, provides the housing for the moving components in the design – the hydraulic cylinder and the pulley. The tower slides into the lateral frame during assembly and is secured with a pin at the base.

A manual hydraulic pump sends hydraulic pressure to the cylinder. The cylinder subsequently transmits force through the cable grip to the cable. The pulley directs the cable from the bearing plate through which the pipe is pulled. The hydraulic pump provides the force to retract the cylinder during a pulling stroke (the cylinder assembly shortens during pulling), and a pressurized pneumatic tank was used to provide the force to re-extend the cylinder after completing a stroke.

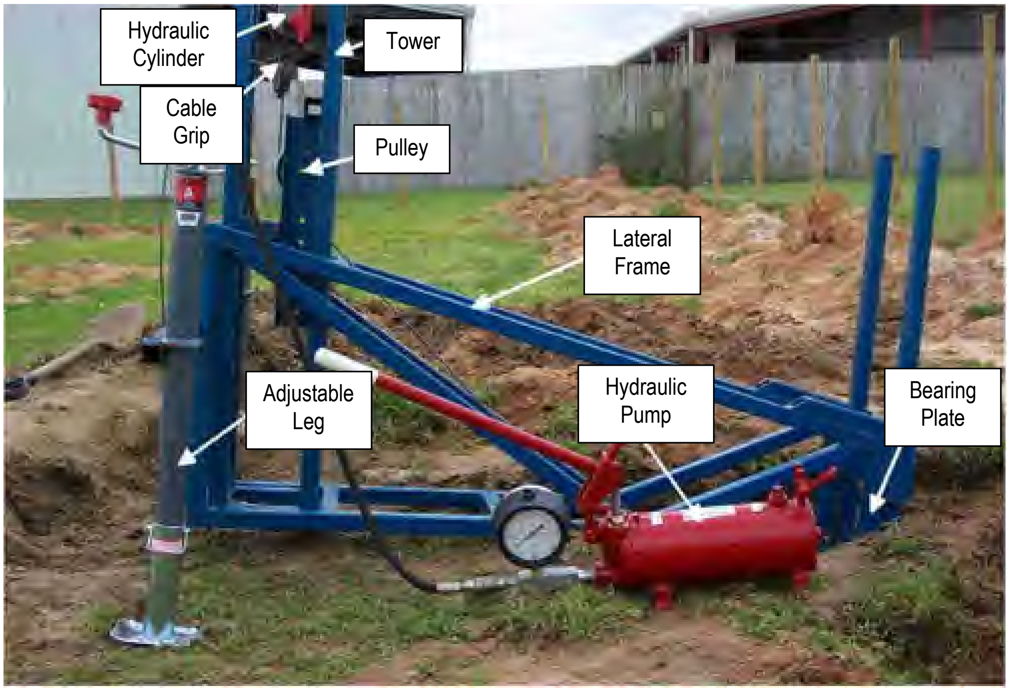


Figure 7.4. Hydraulic puller assembly in place for pulling.

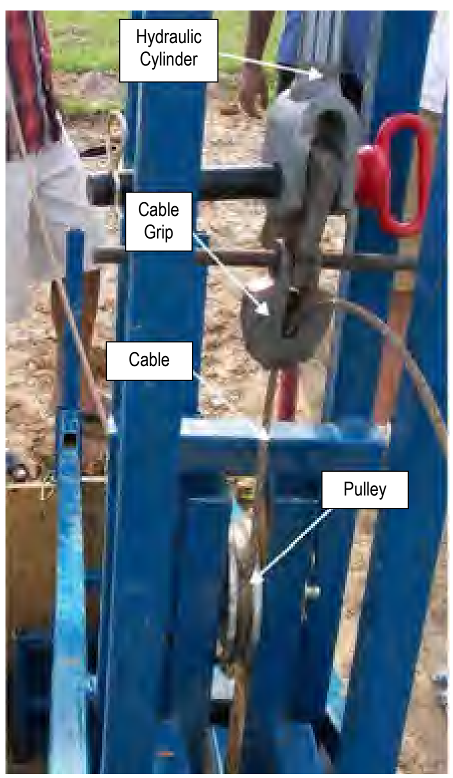


Figure 7.5. Tower assembly during pre-pull procedures.

It was not possible to re-extend the cylinder by hand. Figure 7.6 shows a pneumatic re-extension tank along with the hydraulic pump. After completing a stroke, the hydraulic pump's valve can be opened, allowing the fluid to reenter the pump reservoir and the air pressure to extend the cylinder. In actual practice, motor-driven winches or pumps of various configurations might be used instead of the TTC apparatus. However, the simplicity of the set up shows that equipment may be relatively inexpensive. (One particular objective of the TTC set up was the need to effectively measure the pulling force required to extract the lateral.)

Prior to the assembly and placement of the tower assembly, the gripping device is pushed from the meter side (Figure 7.7), down the length of the lateral and through the corporation stop. Once it is pushed all the way through, the spring-loaded latches deploy and allow force to be applied at the corporation stop. The corporation stop and the service lateral are therefore in compression during the pull. The corporation stop helps distribute the pull forces. As previously explained, in many if not most circumstances, the strength of existing service laterals are believed to be insufficient to pull the corporation stop from the ground without the assistance of a gripping device and cable.

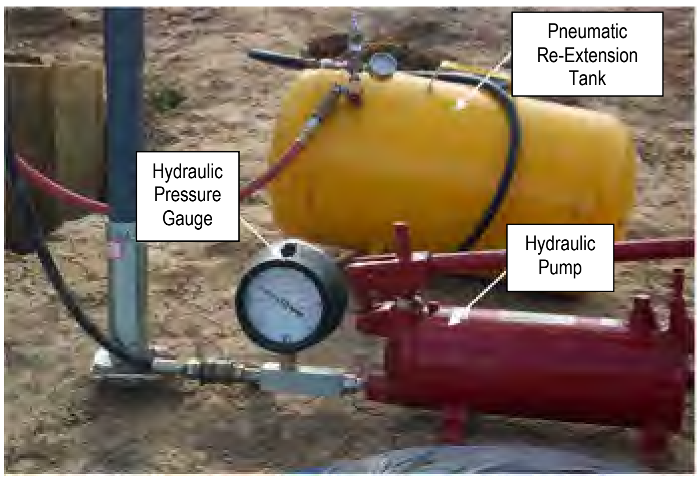


Figure 7.6. Hydraulic and pneumatic pressure sources.

Figure 7.7. Gripping device being inserted into the lateral.

Lateral Frame. The lateral frame together with the bearing plate is shown in Figure 7.8. The frame supports both the tower and the bearing plate, and resists the large moments created during pulling. The main function of the lateral frame is to provide space to cut and remove the pulled pipe from the pulling cable before it reaches the pulley.

Bearing Plate. The bearing plate, also shown in Figure 7.8, has a hole through which the lateral pipe is extracted. It features a guide that redirects the force horizontally while allowing the pulled pipe to gradually bend around it toward the pulley. There are also guide tabs that restrain the cable and pipe to prevent misalignment.

EQUIPMENT ASSEMBLY AND SETUP

The assembled hydraulic puller is shown in Figure 7.9. The hydraulic puller can be assembled in approximately 15 minutes by two people, once the access pit has been prepared. The steps involved in setting up the puller are given below:

1. Excavate a 2-foot wide pit that extends 6-inches below the lateral for insertion of the bearing plate. (In practice, much of this pit will already exist, as this is where the meter box would be.)
2. Push the gripping device through lateral until it exits the corporation stop.
3. Place the bearing plate in the pit with the plate side facing the main, threading the cable through its opening.
4. Put the lateral frame behind the bearing plate, and slide the bearing plate arms into the square channels on the lateral frame.
5. Insert retaining pins into the bearing plate arms to restrain movement during pulling.
6. Lift the tower and place it within the large square receptacle area at the rear of the lateral frame.
7. Place the support pin through the lateral frame and the base of the tower for vertical support.
8. Lift the hydraulic cylinder into place at the top of the tower and secure the cylinder with a pin.
9. Secure the cable grip to the hydraulic cylinder using the link plate and two pins.
10. Install the pulley and thread the cable around the pulley and through the cable grip, pulling it snug.
11. Attach the hydraulic line to the lower cylinder port.
12. Attach the pneumatic line to the upper cylinder port.

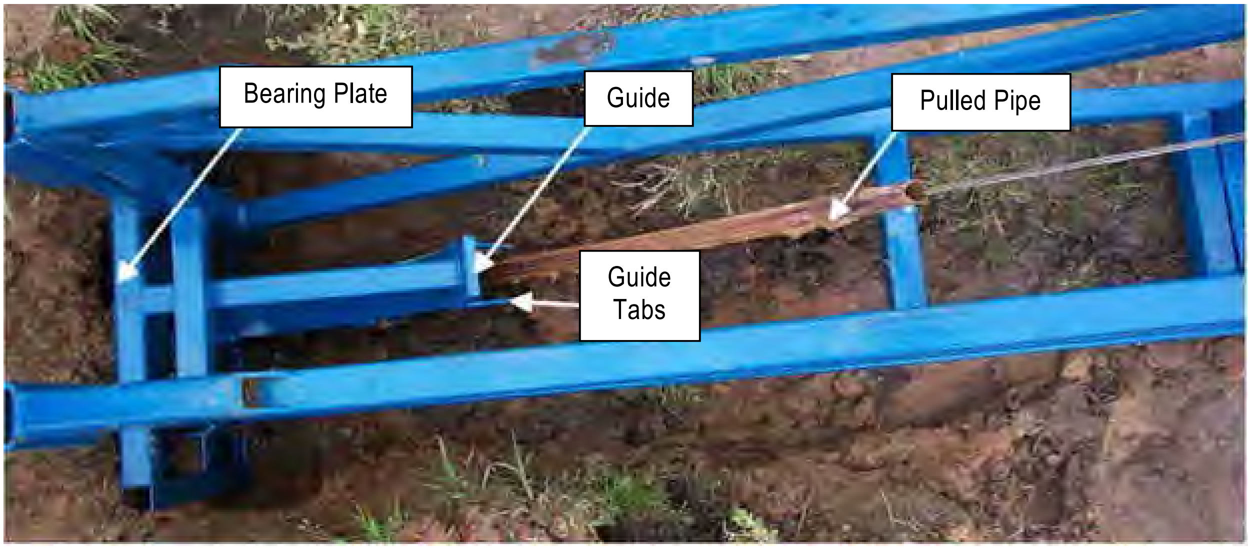


Figure 7.8 – Top view of lateral frame and bearing plate assembly during a pulling operation.

TRENCH PREPARATION

To test the general extraction concept and the equipment just described, lateral pipes were buried in the TTC's field laboratory, under various conditions. A total of six laterals were buried, including both straight and bent pipes in three different soil types (clayey, silty and sandy). All laterals were 10-feet long. The three trenches were prepared on the same day and in the same general manner. The steps for preparing the trenches are given below:

1. Using a backhoe, a 24-inch wide by 32-inch deep trench 13-feet long was excavated, as depicted in Figure 7.10.
2. A 6-inch layer of the specified soil was compacted into the bottom of the trench.
3. The straight and bent sections of pipe were laid in the trench on the newly packed layer, making sure that the corporation stops were attached and open.
4. A 6-inch layer of the desired soil was placed on top of the pipes, and compacted well in the same manner.
5. An additional 8-inch layer of the desired soil was placed and compacted on top of the previous layer.
6. The remainder of the trench (12-inches) was filled with the most convenient soil and compacted.

The threaded portion of the corporation stop on the "main" end of the lateral was inserted into an 8-inch diameter HDPE drainage pipe so that the soil could be packed the full length of the lateral. Plywood held in place by wooden stakes was used to support the soil on the meter end of the lateral.

Figure 7.9. Puller assembled and in place for pulling a service line.

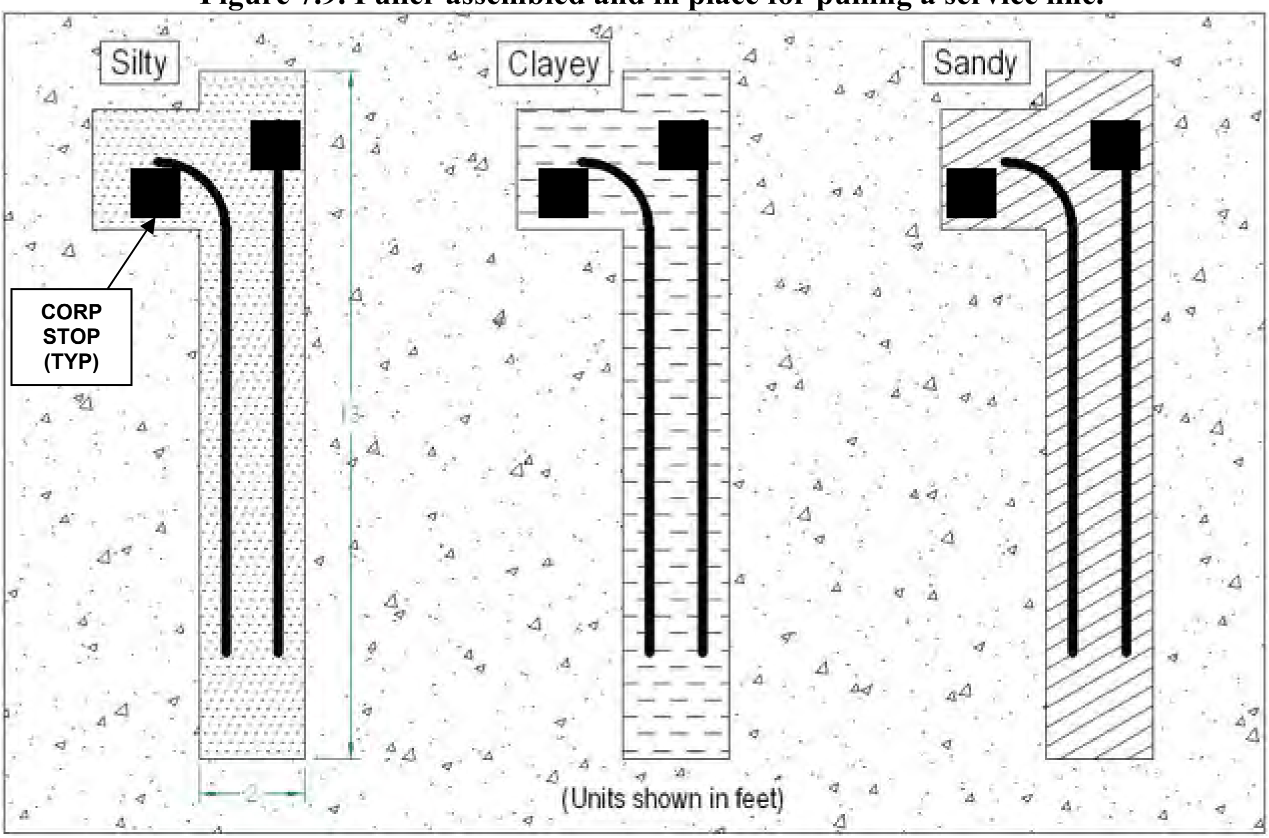


Figure 7.10. Schematic of straight and bent pipe trench layouts.

PULLING PROCEDURE

After setup of the hydraulic puller, the following procedure was followed to simulate extraction of a lateral:

1. Close the hydraulic pump's valve.
2. Pump the hydraulic pump until the cylinder reaches its highest position.
3. Open the hydraulic pump's valve, and the air pressure will automatically extend the cylinder.
4. Close the hydraulic pump's valve when the cylinder is fully extended.
5. Pull the slack out of the cable through the cable grip.
6. Repeat steps 2 through 5, until the entire lateral, including the corporation stop, is pulled from the ground.

Because the pipe cannot bend around the pulley, approximately every two pulls, the pipe must be cut before it enters the pulley area. This was done using a common copper tubing cutter. The section that is cut off between the bearing plate and the pulley was then removed from the cable by unthreading the cable from the cable grip and slipping the cut piece of pipe off the end of the cable. The cable was then re-threaded through the cable grip, pulled tight, and pulling resumed as normal. After a few iterations, this process of cutting and removing sections of pipe was accomplished easily, in less than one minute.

Table 7.1 below provides the data that were collected during the pull testing.

Table 7.1

Data Collected During Testing

Data Collected Per Pull Cycle	Data Collected Per Trial
Hydraulic Pressure (psi)	Soil Type (clayey, silty, or sandy)
Pneumatic Pressure (psi)	Service Line Condition (straight or bent)
Significant Events (cutting, corporation stop entry)	

ANALYSIS AND RESULTS

Pneumatic pressure was applied at the extension port of the cylinder, and hydraulic pressure was applied at the retraction port. For pulling to occur, the force exerted by the hydraulic fluid had to overcome the air pressure as well as the pulling forces. The equation used to compute the net pulling force, F, exerted on the pipe is as follows:

$$F = P_H \cdot A_H - P_P \cdot A_P \tag{7.1}$$

where P_H and A_H are the hydraulic pressure and area, respectively, and P_P and A_P are the pneumatic pressure and area, respectively. A free body diagram of these pressures is given in Figure 7.11. The specifications of the hydraulic cylinder which are needed in the above equation were provided by the vendor of the cylinder (Table 7.2). The maximum pull forces encountered for each soil type and pipe configuration are given in Table 7.3.

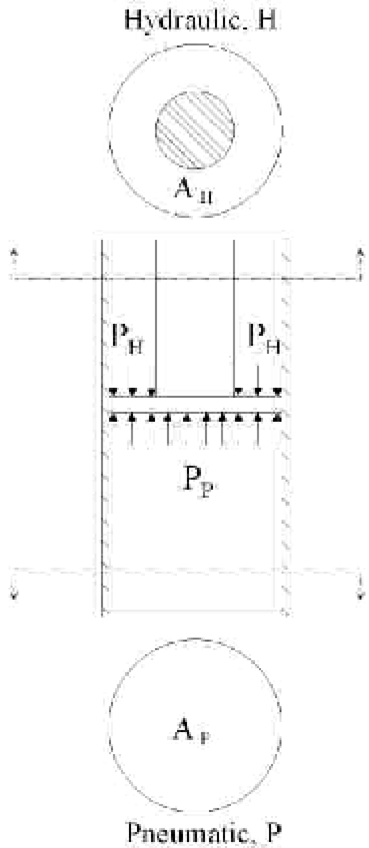


Figure 7.11. Free body diagram of the hydraulic cylinder used for pipe pulling.

Table 7.2

Diameters and Cross Sectional Areas of the Hydraulic Cylinder

Diameter, in		**Area, in^2**	
Outer Bore	Rod	Outer Bore	Rod
2.5	1.25	4.91	1.23

Table 7.3

Summary of Maximum Pulling Forces Measured

Test	Soil Type	Pipe	Force (lbs)
1	silty	straight	1460
2	silty	bent	1620
3	clayey	straight	1250
4	clayey	bent	2000
5	sandy	straight	2630
6	sandy	bent	3830

These results showed that in all cases, the lateral pipes with attached corporation stops could be extracted with the application of moderate forces that are well within the capacity of commercially available wire rope.[2] The maximum pulling forces ranged from 1,250 lbs. to 3,830 lbs. These pulls were made through relatively moist soil, and the pipes had been buried for only 10 days prior to pulling. The pulling forces might be significantly higher for dry soil and for pipes buried for a period of years. The sandy soil offered the greatest average pull resistance, being about double the pull resistance of the other two types of soil.

As expected, the bent pipes offered more resistance to extraction than the straight pipes. These pipes were bent to simulate what may be encountered in the field, where "goosenecks" are often found in the pipes just before they connect to the mains. The profile of the bent pipes as tested is given in Figure 7.12, which shows a minimum radius of curvature of 17.4 inches. In silty soil, the bend added about 11% to the pull load of the straight pipe as opposed to about a 60% increase for clayey soil and 45% increase for the sandy soil.

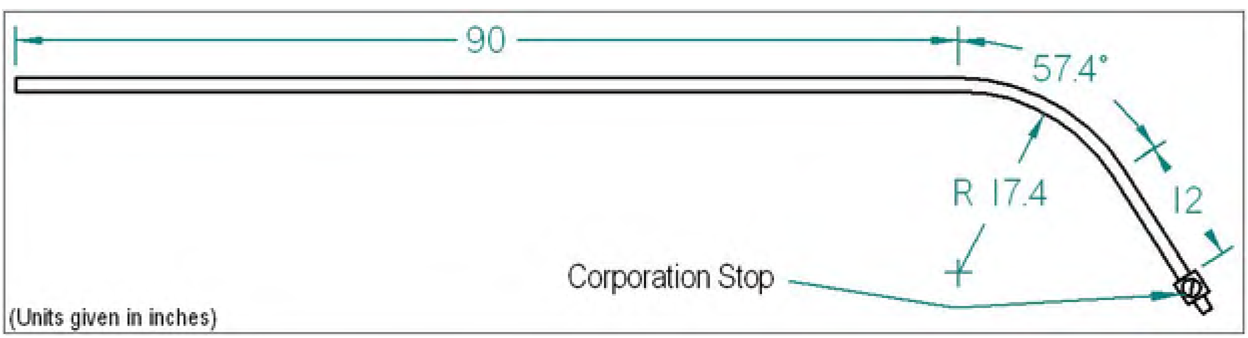


Figure 7.12. Profile of bent pipes in test trenches.

[2] Although these tests used 1/4-inch rope with a breaking strength of 6400 lbs, the breaking strength of 3/8-inch is 12,000 lbs, and 1/2-inch rope has a strength of 22,000 lbs. An adequate factor of safety against cable break, should thus be achievable.

The gripping device worked very well and was able to handle the highest pulling loads without damaging the device. However, as the testing progressed and the device became loaded with soil, it became difficult to feed the gripping device from the meter side with the flexible 7 x 19 class strand core cable. Stiffer cable configurations are available and would likely provide for significantly higher pushing forces and improved overall performance. The cable grip held the cable very tightly and cut some cable strands at the higher pulling loads. Using another cable configuration and different gripping jaws on the cable grip would likely lead to less cable damage.

OTHER CONCEPT DEVELOPMENT ISSUES

The tests just described are one part of a larger concept for remaking service connections without excavating at the main. This concept would apply to a pipe that has been lined with a tight-fit HDPE slip liner. The complete concept involves the following steps:

1. A pipeline robot (similar to the Advantica model shown in the enclosed CD) precisely locates the corporation tap by homing in on a signal emitted by a transmitter that is pushed from the meter box through the lateral.
2. The robot then cores a hole though the liner and the host pipe. The hole is large enough to fully encompass the threads of the corporation stop. The corporation stop is thereby freed from the host pipe.
3. A steel cable is pushed inside the old service line. The cable is fitted with a gripping device at the end that expands after reaching the inside of the water main.
4. From inside the water main, a new HDPE lateral pipe is affixed to the end of the gripping device.
5. The cable is used to pull out the gripping device, removing the old lateral pipe, the corporation stop, and simultaneously installing the new lateral pipe.
6. After the new lateral pipe emerges from the meter excavation, extraction continues for several more feet, until a flange on the main end of the lateral pipe makes contact with the main liner. CCTV is used to monitor this step to assure that sufficient contact is made, yet the lateral is not over extracted to the point that the flange slips through the hole in the main.
7. The new lateral pipe is then fused to the liner pipe, using electric resistance wires embedded in the flange.

The tests described in this chapter have shown that laterals can be extracted by applying moderate force to a gripping device attached to a cable. To more fully test the overall lateral extraction concept, the following additional research is needed (please refer to Figure 7.13 at the end of this chapter for illustrations that depict current overall concepts):

1. **Pipe pulling head design**. For the overall concept to work, the gripping device must be equipped to grab one end of the new lateral pipe, in addition to gripping the corporation stop. One concept is for the front of the gripping device to be equipped with a female fitting that would receive and snap tightly around a male fitting that is pushed into it, much as pneumatic hose couplings currently operate. These fittings should not need to deliver large forces, since the pulling resistance of the HDPE lateral should be relatively low, given that the corporation stop will produce a large bore though the soil as it is extracted.

2. **Bending the lateral to exit the main.** To extract the lateral pipe from the main, the lateral will need to make a very sharp bend as it is pulled though a hole in the main. It is believed that the hole in the main will be just a little larger than the lateral itself. Making this sharp bend may not be easy. If the lateral becomes kinked, it may not pass through the hole.

   As discussed in Chapter 1, this study focuses on lateral pipes that are 1-inch and smaller, and mains that are 6-inch and larger. In the United States, the most typical combination of lateral and main pipes is 1-inch and 6-inches. Thus, if we are to execute the overall concept, the lateral pipe will need to bend at a radius that is less than 6 times its diameter. This is an extremely tight bend even for relatively flexible HDPE pipe,[3] and would likely cause the pipe to kink. A kink in the pipe would likely bind in the exit hole and the pipe could then be damaged as it is pulled.

   One concept for overcoming the kinking problem is to reduce the inherent stiffness of the HDPE lateral pipe. This can be done by flattening the pipe, like a soda straw under a vacuum. Flattening the pipe reduces its moment of inertia, allowing it to bend with relative ease, without kinking. However, because a flattened 1-inch lateral pipe would be about 1.5-inches wide, it would need to be further deformed into a "U" shape in order to pass through the hole in the main (this is analogous to deformed/reformed HDPE liners used in the wastewater industry). It is best that this "U"-shape deformation occurs just prior to entering the hole, to provide maximum flexibility in making the 90-degree turn.

   After the pipe is in place, it would then be re-rounded using air or water pressure. For this purpose, the flange on the main end of the lateral could also serve as a temporary cap, to be bored out by the pipeline robot after the process is completed. Once it is re-rounded, the HDPE pipe has a "memory" and will retain the round shape in which it was originally extruded, particularly if pressure is maintained.

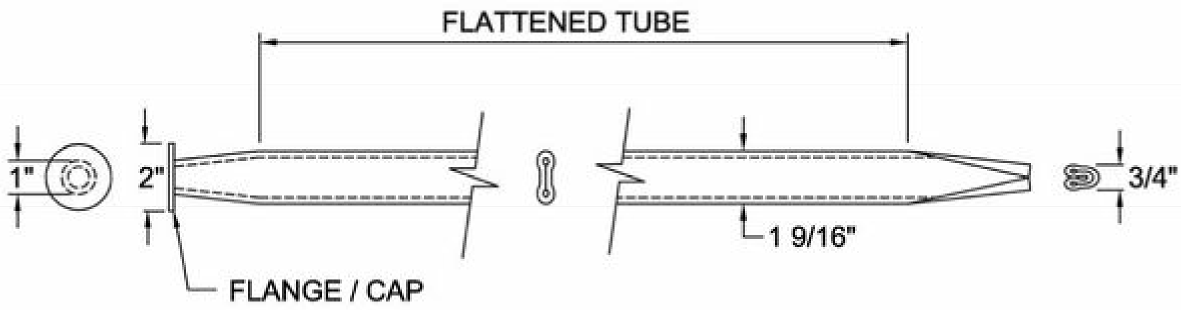
3. **Robot development/adaptation**. The enclosed CD illustrates that pipeline robots can be designed to find and bore holes at service taps. To fully execute the concept described herein, this robot (or a companion robot) would need to perform the following additional functions:
   a. Attach the new lateral pipe to the end of the gripping device.
   b. Monitor the extraction of the new lateral, to verify that the flange/cap at the end of the lateral makes contact with the wall of the main liner. (This is a critical step. A lateral that is insufficiently extracted will result in poor contact and eventual joint leakage. A lateral that is pulled too hard may result in extraction of or damage to the flange.)
   c. Fuse the flange/cap on the lateral pipe to the wall of the main liner, by applying an electrical current to wires embedded in the flange.
   d. Bore a hole in the flange/cap to allow the flow of water after the previously flattened lateral has been re-rounded using pressure. (Conversely, the flange could be pre-bored, and the robot then used to plug the flange when the re-rounding step is undertaken.
4. **Additional Pull Tests**. The testing performed for this report only scratches the surface of lateral extraction testing that should be performed. This testing should include numerous lateral pipes installed within actual operating water systems in various locales. Such testing

[3] Recommended minimum bending radii for long-duration installations range from 20 to 40 diameters, based on the SDR of the material. For short durations, smaller radii may be used.

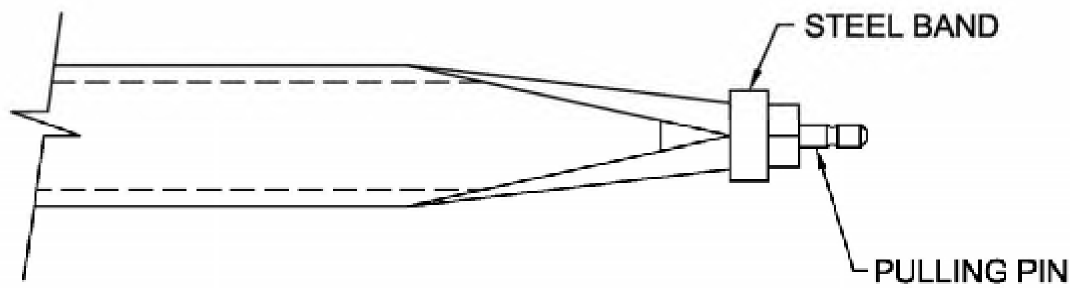
will provide a better understanding of the nature of the resistance forces that might be encountered. Particular focus should be on extracting (1) longer lengths of pipes, (2) pipes buried for many decades, (3) deeper pipes, (3) pipes of various materials, and (4) other configurations.

5. **Lateral splitting**. The piece-meal cutting and removing of sections of lateral pipe slows the overall extraction process. One way of avoiding this would be to spit the lateral pipe before the wire rope enters the pulley. This would speed the process, but raises additional issues. If the lateral were to be split, the required force on the gripping device would be significantly higher. The resulting added compressive force on the pipe being extracted could lead to buckling or local failure of the old pipe just ahead of the corporation stop. This becomes an even greater concern if steel, lead, or other hard-to-spit laterals are extracted.
6. **Different pulling devices**. Various other types and configurations of pulling devices can be envisioned, using commercially available winches and other equipment, along with custom fabricated items. For instance, a common construction backhoe might be successful in extracting laterals under certain circumstances. Backhoes are presently the pulling machines most commonly used for lateral splitting and pulling.

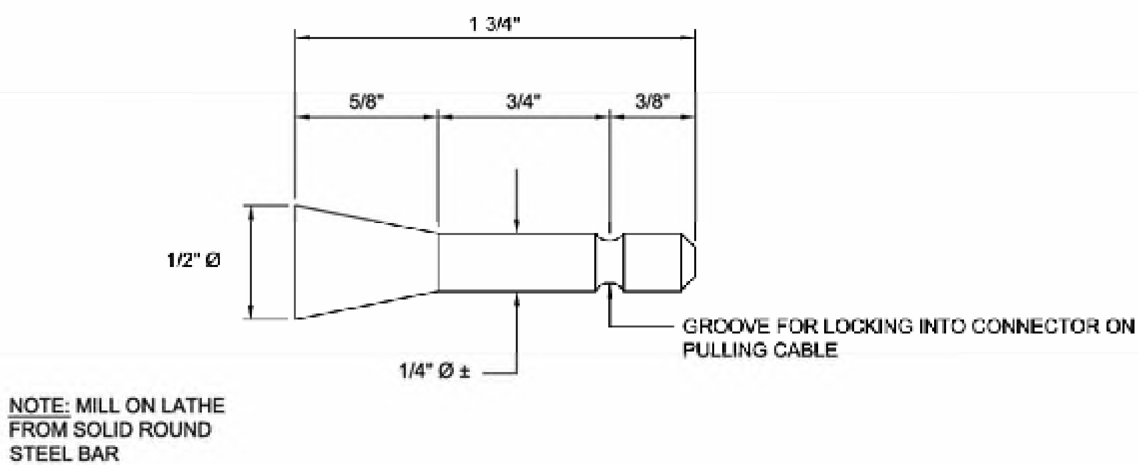
On the next 2 pages, Figure 7.13 illustrates the various steps involved in service lateral extraction, as currently conceived.



LATERAL PIPE DETAIL

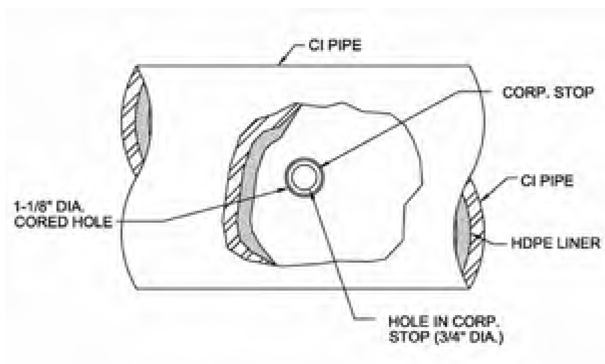


PULLING HEAD DETAIL

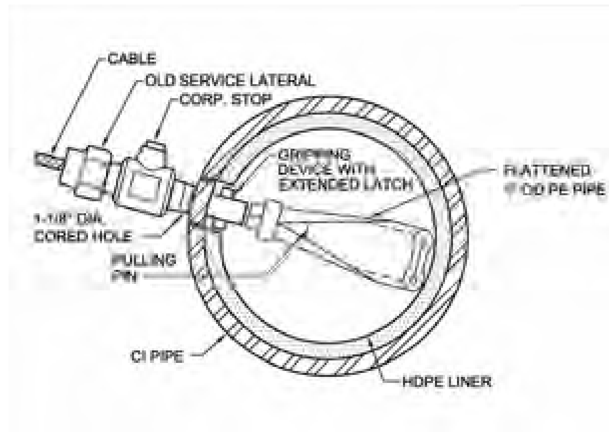


PULLING PIN DETAIL

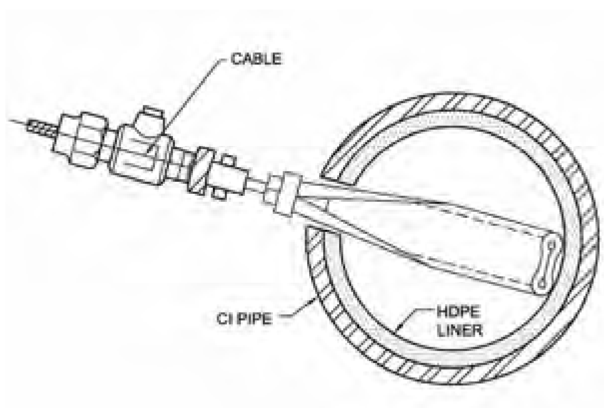
Figure 7.13. Steps and details required for service lateral extraction (continues on next page)



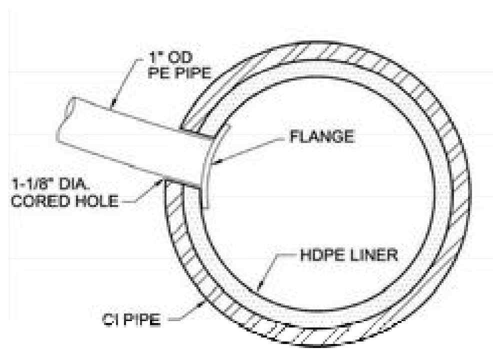
STEP 1. Locate and core hole around corporation stop.



STEP 2. Insert gripping device and attach pulling head.



STEP 3. Extract old lateral and corp stop. Simultaneously install new pipe.



STEP 4. Fuse lateral flange to main. Bore hole through cap.

Figure 7.13. Steps and details required for service lateral extraction (continued from previous page)

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

This report has demonstrated the *general* feasibility of remaking service connections using no-dig and low-dig methods. Considerable work is needed before these methods become commonplace, but if recent history is a guide, most of the technical problems will be solved in time, given adequate incentives.

THE WASTEWATER INDUSTRY EXAMPLE

The trenchless construction industry has made great strides in the last few decades, particularly in the wastewater field. Pipeline rehabilitation was a more "natural" fit for the wastewater industry than it was for the water industry. Compared to the water industry, the greater depth of wastewater pipelines makes their replacement relatively costly, and the general availability of manholes, the non-pressure nature of the systems, the larger pipe sizes, and other characteristics make the use of robotics relatively easy. However, advancements in trenchless wastewater technology still did not suddenly spring into existence. It took a combination of pioneers (inventors, contractors, and utility managers) who were willing to take risks, and sufficient incentives for taking the risks. These pioneers were often not rewarded. Forgotten are the many inventions that failed, projects that lost money, and systems that didn't live up to their promises. Despite these failures, the attempts were noble. As the wastewater industry has shown, eventually, experience is gained, risks are diminished, and a market is created, producing forward momentum. The key was developing market value. With this comes subsequent investment, leading to more research, more products, greater industry acceptance and more market value.

It is difficult to predict how far away the water industry is from the point where similar momentum occurs in the pipeline rehabilitation field. With renewal needs in the hundred of billions of dollars, adequate incentives should exist to propel a rapid growth in trenchless innovation. However, the present rate of infrastructure investment is well short of where it should be. By some estimates, we may be spending almost a full magnitude less than we ought to. As discussed earlier, water utilities in the United States currently renew about 0.5 percent of their pipeline assets per year. As a long-term rate, this is clearly inadequate, but the infrastructure on average is relatively young, so we get away with it. Each year, as renewal rates fail to keep up with the infrastructure, our investment deficit grows larger. The danger is that the money we save by not renewing pipe, is not placed in the bank. When the time comes, and the pipes themselves demand to be replaced, there may not be enough funding to go around, or enough tolerance by the public, to allow the work to be accomplished. In Europe, and in older cities on the east coast of the United States, the industry may be approaching this point. Main breaks are now a subject of political debate in some cities. In the U.K., water leakage became such a hot political issue that regulatory standards were established (Lambert and Preston, 1999). It is probably not a coincidence that most of the new pipeline rehabilitation methods are being developed in Europe, where the basic infrastructure is older.

THE NO-DIG AND LOW-DIG POTENTIAL

The Potential of Pipebursting. The use of pipebursting, as a water main renewal method, appears to be the one method quickly building momentum. With the recent expiration of the basic patent, the cost of using this technique has decreased, and the ability for additional innovation has increased. Ten years ago, few in the industry had even heard of pipebursting. Since then, it has reached the point where few in the industry have not considered it.

The field tests presented in Chapter 5 show that, if nothing else, a water utility crew already has 90 percent of the knowledge, tools, and equipment needed to successfully execute a water main pipebusting project. More importantly, the 10 percent of resources that they do not have can be acquired quickly and easily from specialty vendors and subcontractors. This case study also demonstrated the potential use of simple, clever keyhole tools, in completing the work in a low-dig manner. With the potential of reducing costs and community impacts, keyhole techniques could become an important way of accomplishing service reconnections. Probably all that is needed for these techniques to gain wider use is a larger market. If pipebursting projects with 25,000 to 50,000 feet of water main were routinely put out to bid in large cities, the contractors who compete on this work would soon discover and innovate the tools that are cost effective.

The Potential of Tight-fit and RCIPP Linings. Tight-fit lining techniques have not yet gained the same momentum. This is at least partly because tight-fit lining presently has few advantages and several disadvantages, when compared to pipebursting. In particular, tight-fit methods typically result in some reduction in hydraulic capacity. They also typically produce only a *semi*-structural rehabilitation of the pipe (particularly when HDPE is used). With pipebursting, on the other hand, it is often possible to upsize the pipe, and the completed product will always be fully structural. However, tight-fit lining has the potential to outpace pipebursting, if the no-dig techniques and tools are perfected for reconnecting services. This would present a marked advantage over pipebursting for a typical water distribution main. Currently, a water main that supplies houses on both sides of the street can easily average a service connection every 25 feet.[1] Avoiding the need to excavate every 25 feet along the main could tilt the market to tight-fit methods. It is clear that tight-fit and RCIPP lining techniques have the potential of avoiding these excavations. Pipebursting, on the other hand, will likely always require at least keyhole excavations.

Ultimately the lining of water mains could as commonplace as the lining of sewer mains. The tests and techniques discussed in this report (and shown in the enclosed CD) show that no-dig methods are possible. All that is needed is more investment in development of the concepts presented in this report. There is a chicken-and-egg quandary, without a larger market, the investment is not attractive to entrepreneurs, yet the market cannot grow without the investment.

The potential of reinforced cured-in-place liners is similar: no-dig methods of lateral reconnection appear very feasible. If these connections can be made successfully and routinely, a growing demand for this type of lining should result. One manufacturer claims to have done this, and done it quite readily. However, a protruding lateral tap was needed to provide a visible guide for drilling a hole in the liner. When such a visible clue is not available, another means will be needed of finding the lateral. Some possible methods are described below.

Lateral Bore Reinstatement. The basic problem of reinstating lateral bores appears readily solvable. Three techniques have been presented in this report:

[1] Assumes lots are 50 feet wide.

(1) Working from the meter box, a coring bit at the end of a long "snake" is fed down the lateral pipe. This technique was tested successfully at the Trenchless Technology Center (TTC), as described in Section 6.
(2) A pipeline robot locates the lateral by homing in on a radio signal that is transmitted down the lateral (or emitted from a transmitter that is placed inside the lateral). Once located, the robot locks itself in place, and drills the required hole. This technique is demonstrated on the enclosed CD and discussed in Chapter 4. Alternatively, the robot finds the lateral location, using remote field eddy current technology, as described in Chapter 3.
(3) Miniature robots are deposited in each lateral before the main is lined, then activated by a "mother" robot that travels along the main. After they drill their way through the liner into the main, the "mother" robot retrieves them for reuse. This technique was described in Chapter 4.

Connecting the Liner to the Lateral. Whichever lining method is used, restoration of the lateral bore is the first step toward a no-dig method of reconnecting laterals. The next step is making sure that water does not leak into the annulus between the liner and the main. Several possible methods have been identified that either seal the liner at the lateral opening, or directly attach the liner to the lateral. These methods include:
(1) Voids between the liner and the host pipe are filled at the lateral opening, using epoxy, urethane, or a similar polymer sealant. This would be done using robotic devices similar to the lateral grout packers currently used in the wastewater industry. This method would not be applicable, however, if the liner is HDPE.
(2) Adhere the liner directly to the host pipe all around the lateral tap. This can be done using epoxy that is placed around the tap prior to lining (as described in Case 5 of Chapter 4), or with a well adhering CIPP product (as is claimed by a current product manufacturer). Again, this method would not be applicable if the liner is HDPE.
(3) Use a "top-hat" style connector that connects the liner positively to the lateral, without relying on existing lateral tap on the old main. Two types of "top hats" appear feasible:
   a. A hybrid CIPP/HDPE connector. A product of this type is already commercially available for wastewater-size laterals. Similar connectors for water laterals appear very feasible.
   b. A top-hat with fusible brim and "O" ring seals, similar to the one that was bench tested at the Trenchless Technology Center, as described in Chapter 6.

The Potential of Loose-fit Slip lining. The near-term potential for loose-fit slip lining is much lower. As discussed in Chapter 2, there are many difficulties to overcome before the reconnection of services in a no-dig manner can be accomplished routinely after a main is slip lined with a loose-fitting HDPE pipe. Some of the technical problems were partially solved in the TTC bench testing (Chapter 6), but a simple, one-size-fits-all solution is not likely to emerge soon. The geometry of the problem is both too complex and too variable.

This should not considered a major setback for the trenchless cause, because the market for loose-fit lining will always be rather small. A typical loose-fit lining of a distribution main would have only about one-half the hydraulic capacity of the host pipe (assuming the host is not heavily scaled).[2] Such a capacity reduction is rarely acceptable. If anything, old distribution

[2] The Hazen-Williams formula shows that a 6-inch cast-iron main can deliver 2.5 times the flow of a 4-inch HDPE liner, assuming equal head conditions.

mains tend to be undersized by modern standards, particularly for the delivery of fire flows. This large reduction in hydraulic capacity can generally be avoided by using one of the other techniques (pipebursting, tight-fit slip lining, or RCIPP), none of which are substantially higher in cost.[3] The main advantage of slip lining—that it is non-proprietary and can be performed without special equipment—is not sufficient to overcome its disadvantages.

This combination of technical difficulties and a small potential market for slip lined distribution mains probably mean that the problems with remaking service connections in a no-dig manner will remain unsolved for many years. Notwithstanding, the concepts and bench tests outlined in this report should prove beneficial in addressing various issues that apply to tight-fit and RCIPP lining methods too.

CLOSURE

It is hoped that this report will prove to be a valuable resource for others who are interested in the subject. By considering the concepts, seeing what has been tried, and pondering what other steps might be taken, the reader is invited to become one of the pioneers who helps lead the industry to new, more efficient, less disruptive methods of renewing water mains. As described in the report, many people have contributed to this effort, and many more are welcome to join. Only through the efforts of many will the numerous small technical details be worked out, and effective no-dig and low-dig methods emerge.

[3] Much of the process is similar (and costs are similar), no matter which method is used. The steps include: (1) installing bypass piping system, (2) excavating entry and exit holes, (3) pipe cleaning, (4) installation of liner, (5) resealing, chlorinating, and testing.

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ABBREVIATIONS

AC	asbestos cement
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
AwwaRF	Awwa Research Foundation
CCTV	closed-circuit television
CI	cast iron
CIP	capital improvements program
CIPP	cured-in-place pipe
CML	cement mortar lined
Cu	copper
DR	Dimension ratio. The ratio between outside diameter and wall thickness for a pipe.
EPA	Environmental Protection Agency
ft	feet
ft/s	feet per second
GTI	Gas Technology Institute
gpm	gallons per minute
GPR	ground penetrating radar
GPS	geographical positioning system
HDPE	high density polyethylene
HDD	horizontal directional drilling
ID	inside diameter
in	inches
LADWP	Los Angeles Department of Water and Power
lbs	pounds
m	meters
m/s	meters per second
min	minute
mm	millimeters
NASTT	North American Society for Trenchless Technology
NSF	National Sanitation Foundation

OD	outside diameter
PE	polyethylene
PET	polyethylene terephtalate
PPI	Plastic Pipe Institute
PRP	polyester reinforced polyethylene
Psi	pounds per square inch
PVC	polyvinyl chloride
Q	flow
RCIPP	Reinforced cured-in-place pipe
RFEC	remote field eddy current
SDR	Standard dimension ratio. See DR.
TTC	Trenchless Technology Center, Louisiana Tech University
UCT	Underground Construction Technology
UK	United Kingdom
US	United States
WRc	Water Research Center (United Kingdom)

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