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Rehabilitation of Wastewater Collection and Water Distribution Systems

WHITE PAPER

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White Paper on Rehabilitation of Wastewater Collection and Water Distribution Systems

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DISCLAIMER

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EXECUTIVE SUMMARY

As part of the U.S. Environmental Protection Agency's (EPA) Aging Water Infrastructure Research Program, which directly supports the Agency's Sustainable Water Infrastructure Initiative, scientific and engineering research is being conducted to evaluate and improve promising innovative technologies that can reduce costs and improve the effectiveness of operation, maintenance, and replacement of aging and failing drinking water distribution and wastewater conveyance systems (EPA, 2007a). Task Order (TO) 58 (under EPA STREAMS Contract No. EP-C-05-05758) is being conducted by Battelle, in cooperation with the Trenchless Technology Center (TTC) at Louisiana Tech University, Jason Consultants, and Virginia Tech, to perform a comprehensive review and evaluation of existing and emerging rehabilitation/ repair technologies for wastewater collection and water distribution systems, and select and prepare them for field demonstration.

This White Paper provides an overview of the current state-of-the-practice and current state-of-the-art for rehabilitation of pipes and structures within the wastewater collection and water distribution systems. The White Paper discusses the common issues that cut across both water and wastewater applications, including the need for rational and common design approaches for rehabilitation systems, quality control/quality assurance (QA/QC) procedures and acceptance testing during installation of rehabilitation systems, decision support for choice of rehabilitation vs. replacement and choice of rehabilitation systems, and special applications of rehabilitation under challenging conditions such as elevated liner service conditions adjacent to steam lines and high pressure pipe lining systems. It also discusses separate issues for water and wastewater systems in terms of drivers for increased rehabilitation efforts and problems typically encountered. The White Paper examines the state-of-practice for rehabilitation in the water and wastewater sectors and the potential for improvement within the general classes of rehabilitation systems. It identifies some emerging technologies as candidates for potential field demonstration and cross-cutting innovation potential. The organization of a field demonstration program is also discussed.

The document was used as a basis for discussions at an International Technology Forum, which was held on September 9 to 10, 2008, at Edison, NJ as part of the project activities. Participants in the Forum were invited to provide their degree of concurrence with the descriptions of the state of the industries, discuss different viewpoints as appropriate, propose additional issues to be considered, and present information on specific technological advances underway in North America and elsewhere in the world. The White Paper and Forum contributions together provide documentation and analysis of the current status of technology and practice for rehabilitation of water and wastewater systems in North America and elsewhere in the world and clear guidance on how the demonstration activities planned within the project can best contribute to advancing the technology and accelerating the adoption of favorable approaches.

In many ways, the response of government and industry, once the problem of deteriorating water and wastewater infrastructure was fully acknowledged, has shown real progress. A suite of technologies for the rehabilitation of water and wastewater assets that do not require their full excavation and replacement has been developed over the past 30 to 40 years, and these trenchless technologies have made a significant penetration into the U.S. market; estimates of the proportion of rehabilitation work carried out using trenchless techniques range up to 70 percent in the sewer sector and up to 31 percent in the water sector. The variety of tools available to the water or sewer utility engineer today is remarkably different than it was during the 1960s. However, the average rate of system rehabilitation and upgrading is not adequate to keep pace with increasing needs, quality demands and continually deteriorating systems. The opportunity lies in the fact that while the tools being used today are generally effective, there is still considerable room for improvement in existing technologies and/or development of new technologies. Such improvements or new technologies offer the chance to make the investments in rehabilitation more effective and extend the ability of utilities and local governments to fix larger portions of their systems

with current funding levels. A secondary benefit is to increase the political and public will to spend additional money on fixing this problem.

The current EPA research program is aimed at encouraging the introduction of new and improved technologies into the U.S. marketplace for water and wastewater systems rehabilitation. It will also develop the protocols for demonstration projects that will provide exposure and application data for novel and emerging technologies through the planning and execution of two demonstration projects. A broader set of demonstration projects will then follow in the future. The selection of technologies that will benefit from the formal demonstration project and which have a significant potential for market penetration in the future has also been examined. A key aspect of the planned program is that each demonstration will not only record the use of a particular technology but will provide a documented case study of the technology selection process, the project design, the QA/QC, and the preparation for the life-cycle management of the asset.

In summary, this White Paper was intended to document the research team's assessment of the needs and opportunities of water and wastewater infrastructure rehabilitation. The White Paper also aids in the planning and development for technology selection and field demonstrations to address the knowledge gaps identified herein. In addition, comments to this White Paper were solicited from the project stakeholder committee and at the International Technology Forum and incorporated into this final document as appropriate. Finally, the key outcomes and recommendations from the International Technology Forum are presented.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and sub-surface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of eco-systems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

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1.0 INTRODUCTION

1.1 Purpose of White Paper

This White Paper is intended to provide an overview of the current state-of-the-practice and current state-of-the-art for rehabilitation of pipes and structures within the wastewater collection and water distribution systems. Rehabilitation is defined as repair, renewal, and replacement of components to return the system to near-original condition and performance. The document was produced for use as a basis for discussions in an International Technology Forum, which was held on September 9 to 10, 2008 as part of the U.S. Environmental Protection Agency (EPA) project Rehabilitation of Wastewater Collection and Water Distribution Systems (Contract No. EP-C-05-057, Task Order No. 58 [TO 58]). Participants in the Forum were invited to comment on the descriptions of the state of the water infrastructure technology industry, provide different viewpoints as appropriate, propose additional issues to be considered, and present information on specific technological advances underway in North America and elsewhere in the world. The White Paper and Forum contributions together provide a clear documentation and analysis of the current status of technology and practice for rehabilitation of water and wastewater pipe systems in North America and clear guidance on how the demonstration activities planned within the project can best contribute to advancing the technology and accelerating the adoption of favorable approaches. The key Forum recommendations are included in this report in Section 8. While there is also an urgent need to understand system-wide issues in the operation of water and wastewater systems (e.g., the interaction of wet weather flow with wastewater treatment plant operation), this project and White Paper are focused on the rehabilitation of the pipe systems themselves.

1.2 Development of Rehabilitation Practices

Some aspects of drainage and sewer systems can be dated back at least to 4,000 – 2,400 BC. Archeological evidence (Schladweiler, 2002) indicates that in the Mesopotamian Empire, during this period, stormwater drain systems were constructed using sun-baked bricks or cut stone, and clay was molded to form pipes, tees, and angle joints. A later example (dating from approximately 1,500 – 1,300 BC) of a street drainage channel covered over with a stone slab and clay drainage pipes can be found in the archaeological excavations at the site of the City of Troy in present day Turkey (Troia, 1999).

In Roman times, both storm and sanitary sewer systems were already in use; water supply systems involving complex aqueduct systems and lead piping within houses can still be observed in old Roman settlements. The “dark ages” and even the Renaissance period saw this acquired “know how” disappear, resulting in dire unsanitary conditions in urban areas in many parts of the world. Urban conditions were made much worse by the industrial revolution, which brought an influx of poor residents to the cities and resulted in high-density urban development with little access to fresh water or sanitation. Paris introduced sewer pipes and tunnels during the 13th century AD. In 1854, John Snow made the connection between communicable diseases and clean water supply and sanitary conditions in London, which launched a “modern” wave of construction of better water supply and distribution systems and increased attention to sewerage needs. However, it took the “great stink” of 1858 along the River Thames to goad the English parliament into approving the creation of a drainage system to carry the polluted water in tunnels to be discharged well downstream of the capital city. Improved water supply and sewerage systems quickly spread to many other cities in the Western world, although effective treatment of collected sewage often lagged many decades behind the decision to transport and discharge it into receiving waters away from populated areas. Some of the original systems installed in many cities are still in operation and in good condition, but many portions of systems (including portions installed only a few decades ago) are in poor condition and continue to deteriorate.

From this deliberately simplified synopsis, the evolution and persistence of many of the issues that surround the design, operation and maintenance of water distribution and sewage collection systems can be seen. For example:

- Even once systems are created, continued good government and maintenance of know how are necessary to retain effective and operational systems.
- The materials that were used in pre-historical and Roman water and sewer systems (stone, clay and lead) can still be found in useable condition today (i.e., potentially a life of 2,000+ years).
- There appears to be a natural tendency among human groups to solve a pollution or water supply problem only enough to meet the group's own local or near-term needs. This has resulted in unsustainable withdrawal of aquifer water supplies in arid regions, discharge of minimally treated sewage to rivers and coastal waters, and the lack of investment in maintaining systems, resulting in the inter-generational transfer of these liabilities.
- Disastrous events are often the catalyst for the political will to "fix the problem."
- Most modern water and sewer systems are less than 200 years old.
- One can find many pipes over 100 years old still in good condition although functionality may be impaired by such issues as tuberculation in water systems.
- The deterioration of underground piping systems shows a high degree of variation even among nominally the same piping material, due to variations in the quality of the manufactured product over decades, construction quality, joint type, ground conditions, and water or effluent chemistry. This makes age alone an insufficient barometer of the operational health of a system.
- The longevity of the basic elements of many old piping materials is evident, but they may be impractical for continued usage today due to issues of cost, inability to resist settlement, heavy traffic loadings or deep burial, and health related effects (e.g., lead piping). In some cases, adaptations of old piping systems appear to provide effective and long-lived systems (e.g., flexible, gasketed jointing systems for clay pipes).

Other issues affecting the effective maintenance and rehabilitation of water and sewer systems include:

- Innovation provides the path to better piping and renovation systems; however, initially promising materials sometimes turn out later to exhibit serious drawbacks, resulting in changes to a significant element of a piping or renovation system. This could reset the experience clock back to zero.
- Public works has a strong reputation for conservatism in the adoption of new materials and technologies. The desire for uniformity in materials with respect to maintenance and replacement and the fear of repercussions for choosing materials that later turn out to be problematic are key drivers for this conservatism.

1.3 Current Market

The annual market for rehabilitation of wastewater infrastructure in the U.S. in 2003 was reported to be approximately $4.5 billion. This market has shown consistent growth of 8 to 10 percent per annum for approximately 10 years. *Underground Construction* magazine also conducts an annual survey of municipalities and prepared an estimate for the 2007 sewer rehabilitation market at $3.3 billion and the new sewer construction market at $4.4 billion. They further derived from their survey that 69.7 percent of the sewer rehabilitation work was done using trenchless methods compared to 16.1 percent for new sewer construction (*Underground Construction*, 2008) although it was not clear whether the survey responses came mostly from those cities who were using trenchless methods. In any event, it is clear that trenchless methods have made significant penetration into the water and sewer rehabilitation markets.

The sewer rehabilitation market in the rest of the world is approximately as large as that in the U.S., i.e., the U.S. accounts for approximately 50 percent of the world market. Relatively consistent markets exist in Canada, Europe, Japan, Australia, and Singapore. In these countries, the market structure in terms of technologies used is similar to that in the U.S., except for Australia where locally developed technologies using spirally-wound poly vinyl chloride (PVC) profiles (i.e., Rib-Loc) have the major market share. In other countries, there are more individual projects rather than consistent, everyday markets for both conventional (open trench) and trenchless methods. In a few countries (e.g., China, India, Russia), the market appears to be poised for a rapid development into large and sustained markets.

The current rehabilitation market for wastewater is almost entirely in gravity sewers and laterals. Rehabilitation of force mains remains a small market with occasional projects, rather than being a consistent, everyday market. This is the case both in the U.S. and abroad.

The rehabilitation of drinking water distribution systems is an emerging market in the U.S. and abroad. An exception is the U.K., primarily due to privatization of the water utilities in the early 1990s, which resulted in an accelerated adaptation of new rehabilitation methods. This is not to say that the needs for water rehabilitation are small. As presented in the report *Dawn of the Replacement Era: Reinvesting in Drinking Water Infrastructure* (American Water Works Association [AWWA], 2001a):

> *"For the first time, in many of these utilities a significant amount of buried infrastructure—the underground pipes that make safe water available at the turn of a tap—is at or very near the end of its expected life span. The pipes laid down at different times in our history have different life expectancies, and thousands of miles of pipes that were buried over 100 or more years ago will need to be replaced in the next 30 years. Most utilities have not faced the need to replace huge amounts of this infrastructure because it was too young. Today a new age has arrived. We stand at the dawn of the replacement era. Extrapolating from our analysis of 20 utilities, we project that expenditures on the order of $250 billion over 30 years might be required nationwide for the replacement of wornout drinking water pipes and associated structures (valves, fittings, etc). This figure does not include wastewater infrastructure or the cost of new drinking water standards. Moreover, the requirement hits different utilities at different times and many utilities will need to accelerate their investment. Some will see rapidly escalating infrastructure expenditure needs in the next 10–20 years. Others will find their investment decisions subject to a variety of factors that cause replacement to occur sooner or at greater expense, such as urban redevelopment, modernization, coordination with other city construction, increasing pipe size, and other factors."*

These massive financial needs were also reported by EPA, which estimated that $183.6 billion should be invested by 2023 into distribution and transmission infrastructure (pipelines) (EPA, 2003). Estimates of need have escalated since these figures were published due to the increased worldwide demand for key raw materials such as ductile iron, copper, and plastic feedstocks.

1.4 History of Wastewater Rehabilitation

Until the 1970s, any rehabilitation of sewers was limited to man-entry pipes (>36 inches), and the works were comprised mainly of local in-situ repair of damaged sections such as mortar in brick sewers. Smaller sewers or man-entry sewers with more extensive problems were simply replaced in open trench works. Moreover, there were no economic, social, or managerial drivers for sewer rehabilitation programs and such work was unlikely to take place unless collapses had occurred.

However, such collapses and the associated disruption and loss of service became more frequent in the 1960s and 1970s – especially in the U.K. and other Western European countries where the sewerage infrastructure is the oldest. The first cured-in-place pipe (CIPP) lining of a sewer took place in Brick Lane in Hackney, London, in 1971 for the Greater London Council Sewer Department.

This developed into the Insituform System that remains a market leader to this day. As this technique began to penetrate the market, similar systems were developed in competition. However, the market remained small, limited to North America and Western Europe.

On the expiration of Insituform's U.S. patents for the lining and inversion process in 1994, there was a rapid and large increase in the range of available systems; this increased competition led to lower prices and increased cost-effectiveness, and a concomitant increase in market volume. Concurrently, public and political interest in maintaining the wastewater infrastructure more efficiently in order to protect public health and the environment created a strong regulatory driver for the market. This was especially the case in the U.S., where EPA began to enforce the Clean Water Act of 1972 more strongly with respect to sewer system overflows. Similar regulatory drivers began to apply in other countries in which an aging infrastructure is found together with high living standards and sophisticated political institutions. A continuing problem, however, is that the interactions remain poorly understood between pipe deterioration, wet weather peak flows, wastewater treatment processes, and improving the overall system performance in terms of human health and environmental protection. This lack of understanding can lead to less than optimal decision processes for capital investment and asset management of the overall wastewater infrastructure.

1.5 White Paper Organization

Sections 2, 3, and 4 of the White Paper discuss the key issues affecting the cost-effectiveness and progress of rehabilitation efforts in the water and wastewater sectors. Section 2 discusses issues common to both systems, and Sections 3 and 4 discuss wastewater and water systems individually.

Section 5 examines the current state-of-practice for rehabilitation in the water and wastewater sectors and the potential for improvement within the general classes of rehabilitation systems. Section 6 identifies some emerging or novel technologies as candidates for potential demonstration. These technologies provided a starting point for discussion at the International Technology Forum. Section 7 discusses the organization of a demonstration program designed to help improve and speed the adoption of selected rehabilitation technologies. Section 8 provides a summary of key findings and recommendations from the Forum.

Appendix A provides a glossary of acronyms used in the report. Appendices B, C, and D provide descriptions of rehabilitation technologies in both the wastewater and water sectors. Appendix E provides example quality control standards for rehabilitation.

2.0 COMMON ISSUES FOR REHABILITATION SYSTEMS

In this section, key issues will be explored that cut across both water and wastewater applications and that apply to many of the specific technologies used for rehabilitation. Rehabilitation systems are already applied (field installed) widely with good success, but it is believed that improvements in certain areas will provide more consistent design approaches among methods, more competitive bidding and method selection processes, and better quality assurance and quality control (QA/QC) for these systems.

2.1 Need for Rational and Common Design Approach for Rehabilitation Systems

Most rehabilitation methods have been developed as proprietary systems; the standards for their design and use have been developed on a technique-by-technique basis, even though the design principles have many common elements. Many technical innovations start in this way with the design, construction, and many aspects of QC being provided by the company offering the technology. The downside to this approach is the potential lack of common safety factors among methods, the lack of control of design details by owners and their consultants, and the lack of a common playing field for comparison among methods. Over time, most proprietary technologies make a transition from this situation to one in which most aspects of the design process are handled by the design engineer working on behalf of the owner. The contractors then bid to a specific design, which may allow several different rehabilitation products to compete on a common performance basis.

A second aspect of the evolution of design processes in most areas of engineering has been the shift from designs based on an allowable working stress (which includes a global safety factor) to designs based on determining the predicted load at failure and applying partial safety factors to the different aspects of the design process (e.g., loading, structural response, material strength, etc.) according to how accurately these elements are known and what their expected variations would be. This approach allows a consistent treatment for a variety of “limit states” (failure conditions), and the design can be checked that it satisfies all of the required limit states. With this approach it is also easier to compare the performance of different (but somewhat similar) systems on a common basis.

For instance, the design of a cured-in-place (CIP) liner system for sewers currently follows the non-mandatory appendix of the American Society for Testing and Materials (ASTM) F-1216 standard. This standard describes the methodology of a CIP liner system and some QC standards to which the installation should adhere. In terms of structural design, the standard uses two loading mechanisms: one based on loading of the liner by external groundwater pressure and one based on the soil loading being applied to the liner through a “fully deteriorated” host pipe. Two design controls are used, namely the allowable levels of buckling and local bending stresses, but the application of partial safety factors for loadings or material strength/stiffness is not possible. There is no available methodology currently to develop the needed safety factors for CIPP as a function of installation method, curing process, geometrical imperfections, and other factors affecting the mechanical properties of the final product. Furthermore, if a CIP liner is to be used in a pressure pipe, a different ASTM standard (ASTM 2207-02) is used, and different combinations of loadings are considered. Thus, the key loading configurations and the structural response of the liner are addressed in a fragmented manner with no explicit considerations of the variations in safety factors against the different limit states. In addition, there is no rational method to assess the design life of liners that might not meet their original design criteria. In some cases, liners were found to have only 60 to 90 percent of the structural strength specified in the contract.

Currently, there is no rational method to link between the reduced mechanical properties of the installed liner and the potential reduction in service life of the liner. A limit state design approach will provide a quantified approach for evaluating the effect of under-strength liners in terms of increased probability of failure for specific failure mechanisms. The solution is to develop a limit state design approach for various lining categories. This approach requires the development of large experimental databases. Currently the Trenchless Technology Center (TTC) at Louisiana Tech University is developing a limit state design approach for CIP liners. Data were collected from 600 buckling tests conducted by universities and companies around the world over the past 20 years. The data are currently subjected to a rigorous statistical analysis to statistically derive the needed limit state coefficients.

2.2 QA/QC Procedures for Rehabilitation Technologies

To take full advantage of the estimated design life of the various trenchless rehabilitation technologies, it is important that the installer uses proper installation controls and that the finished quality is confirmed by good assurance protocols and/or testing. Qualification (i.e., proof of design) testing is typically performed on the materials and the related installation process to define applicability of a particular technology. The installation process is given control limits by the technology manufacturer that allows the installer to pre-judge the finished quality of the installation during the execution of the work and prior to acceptance testing by the owner. QA and acceptance testing confirm that the installation is consistent with the product that was pre-qualified in the design phase and that it should live up to its design performance expectations.

The design approach must be supported by the systems' qualification type or testing. Depending upon the technology being used, the level of the rehabilitation system's qualification testing varies greatly in the trenchless rehabilitation industry. For instance, the evaluation and testing of the materials for CIPP are given by the requirements of ASTM Standard D5813, Standard Specification for Cured-In-Place Thermosetting Resin Sewer Piping Systems. This standard used in conjunction with one of the many installation method standards (such as F1216, F1743, and F2019) presents a very clear statement of the CIPP system to be used – its range of applications, its environmental performance capabilities, its proper installation, and its proper finished performance properties. Fold and Form thermoplastic PVC piping rehabilitation systems do not have such a qualification standard; they do, however, have a material specification and an installation standard. These "proprietary" standards, however, don't address the qualification testing of the stated cell classes for service in the application of lining pipe; further, there is no long-term performance verification testing required for these thermoplastic materials after going through the known rigors of the deformation/reformation process. Similarly, other material specifications and installation standards are used for high density polyethylene (HDPE) rehabilitation systems (e.g., pipe bursting, sliplining, etc.) and for grouted-in-place lining (GIPL) systems and structural panels. The lack of long-term validation is cited as one of the impediments to using rehabilitation technologies in general.

For CIPP, ASTM D5813 serves as an industry qualification standard, addressing the demonstration of long-term performance of the finished product in an aqueous environment that includes various chemical solutions likely to be found in the sewer or water environment by subjecting the CIPP samples to a battery of tests lasting 10,000 hours in length. The materials are tested for both strain corrosion and chemical corrosion in these hypothetical environments to project performance in service of 50 years (or more). Material systems certified to having been subjected to the testing contained within this standard give the design engineer and system owner the necessary information to make an informed selection for the application under consideration. The standard looks at both the load case classification (Type I, II, or III) and the grade of CIPP required (Grade 1, 2, or 3). The Type I loading condition is a relatively thin lining that prevents exfiltration and provides chemical resistance. The Type II loading condition prevents infiltration as well as exfiltration (thus, it has to be capable of supporting the external hydrostatic load) and provides chemical resistance; this is the F1216 partially deteriorated design condition. The Type III loading condition is the ASTM F1216 fully deteriorated load condition, which is expected to bear all loads placed upon the host pipe. Grade 1, 2, and 3 refer to the resin system used, i.e., polyester, vinyl ester, and epoxy, respectively.

For other lining systems, the suitability of the liner material and the installation process for a particular application must be determined by broadly applicable testing standards for the materials used and/or proprietary testing carried out by the manufacturer for the pipe lining system. Depending on the materials and the application, this combination may result in a very clear and consistent QA/QC approach or it may leave gaps in the QA/QC coverage for particular applications.

QC procedures for the various technologies discussed herein are typically given to the installation contractor by the system manufacturer. To further reinforce a system's commitment to having a quality installation, the manufacturers will develop an ASTM installation standard for their system. Appendix E provides examples of the current extent of coverage of industry-wide standards for rehabilitation systems.

QA is the responsibility of the system owner or the designated project engineer. Whether utilizing prescriptive or performance specifications, it is important that this communication with the installer convey what QA testing will be performed, and then the contract documents need to follow through on this testing. Too often, trenchless technologies have specifications for reasonable assurance testing, but those overseeing the project do not perform the testing. Samples of the finished installation need to be taken to confirm that the minimum mechanical properties have been achieved or have gone unaltered. Fit and finish should be evaluated in light of the prior condition of the host pipe and the system being installed. It is generally preferable that the relationship with the testing laboratory providing the results of the testing resides between the owner and the laboratory; not the contractor and the laboratory.

Current QA testing has its drawbacks. Most CIPP projects require restrained samples to be taken from cured liners where the liner is inflated in a pipe sleeve of like diameter either at an intermediate manhole or the receiving end manhole so that the approximate thickness of the liner during installation after the rigors of its placement can be captured to provide determination of the as-built mechanical properties of the newly installed CIPP. These samples must be properly taken to provide an accurate representation of what is in the ground. They must rest horizontally, with a sufficient heat sink, to simulate the ground during the curing process. The restrained samples are taken in manholes or other access locations and thus the heat loss and/or moderation provided by the host pipe and pipe embedment materials must be replicated by placing a "soil envelope" on the sample tube. Often this is not achievable due to the size and shape of the receiving manhole. Currently there is a change before the ASTM F17.67 sub-committee to add ultrasonic thickness testing as an alternative to using the thicknesses derived from the restrained sample. A method of non-destructive determination of the finished mechanical properties also is lacking. Ultra-wideband pulsed radar systems, ultrasonic measurements, and before-and-after laser profiling are potential methods to provide definitive finished thickness information. However, none of these methods is fully developed for in-pipe liner thickness measurements.

Water-tightness is another issue confronting trenchless rehabilitation technologies. CIPP, which is seen as a monolithic structure, from time to time has "leaks through the wall." Joints in just installed thermoplastic panel systems have leaks, especially when machine installed in non man-entry size piping. One question that should be resolved is how leakage testing should be carried out and what level of leakage is acceptable, both from a life-cycle view of the installation and an inflow and infiltration (I&I) perspective. Some recent inspection systems (e.g., the FELL electro-scan system) provide an effective means of finding and quantifying leaks and, perhaps more importantly, potential leaks that are not currently active – but only in nonconductive pipe systems.

As the governing patents expire on many aspects of rehabilitation technologies, more companies are encouraged to enter the marketplace and compete with the established technology providers. This provides increased competition – leading in general to lower prices – but it also may provide an incentive to cut corners on QC as part of the price competition. Also, new entrants into the rehabilitation marketplace may not have as well developed technical "know how" (staff education level and experience). This means that systems that have gone through their learning curve and become highly reliable techniques may exhibit a more variable performance as the marketplace widens. When, and if, this happens, it is important that QA/QC procedures are in place and used effectively – both to provide a high performance and long-lived product and allow contractors who provide quality to compete fairly with those willing to cut corners to win jobs at a lower cost.

In summary, better QA/QC-related technologies and procedures are an important part of providing improved technologies for water and wastewater system rehabilitation, especially as the governing patents expire and proprietary systems become commodity products.

2.3 Decision Support for Choice of Rehabilitation vs. Replacement and Choice of Rehabilitation Systems

Even with a comprehensive set of fully effective rehabilitation technologies, many issues would still remain about how and when to apply the technologies. According to an EPA report (2007a), "System rehabilitation is the application of infrastructure repair, renewal, and replacement technologies in an effort to return functionality to a drinking water distribution system or a wastewater collection system." The circumstances that affect rehabilitation planning and prioritization include the current condition of the system, the extent of critical repair needs, the availability of funding for rehabilitation work, and the ability to inspect and assess the condition and deterioration rate of each element of the system. The broad activities that determine system-wide planning follow asset management principles and life cycle analyses that are being increasingly employed in water and wastewater systems in the U.S. These principles mean that rehabilitation approaches may include partial rehabilitations to extend performance life as well as full structural rehabilitations to reset the life cycle performance clock. Which one is most appropriate and cost effective depends on the deterioration rate of the asset, the ability of the rehabilitation method to extend performance life, and the cost and social/environmental impact of the method against competing approaches. Unfortunately, most of these parameters are poorly understood and require a significant commitment to ongoing inspection and condition assessment within a system before accurate quantitative behavior parameters can be established. The issues relating to condition assessment and system-wide asset management are being addressed under separate task orders within the EPA program. There remain several issues that apply directly to the selection of rehabilitation methods that have a strong bearing on the cost effectiveness of rehabilitation programs and their impact on traffic and environment in the areas where the rehabilitation work is needed.

The key decision needs are to determine:

- Whether to renovate or replace (via trenchless or open-cut construction methods) water and wastewater pipes
- Which of the commercially available rehabilitation methods are suitable for a particular application

Open-cut replacement has been the standard practice in the past, but its preferential use over trenchless techniques has been significantly diminished in the past two decades – particularly in the wastewater sector. Awareness of the indirect and social costs associated with utility work in congested urban areas (i.e., traffic congestion, loss of pavement life, business impacts, noise, and dust) have encouraged the use of "full" costing approaches in determining the choice between open-cut replacement and trenchless rehabilitation or replacement methods. Often, however, the choice of trenchless technologies is driven by acknowledged environmental constraints and expected public pressure rather than by a quantitative calculation of full direct, indirect, and social costs. Also, differences in social and indirect impacts are often addressed in work requirements that reduce or eliminate any cost advantage to open cut in congested or sensitive settings. Such work requirements may include payment for traffic lanes occupied (i.e., A+B bidding method [Gilchrist and Allouche, 2005]), restrictions on work hours, noise barriers, plating of excavations for traffic flow during peak periods, remote storage of excavated materials, reimbursement for business loss and damage to adjacent utilities. The awareness of the issues and the adjustment of working practices have had a significant impact in the wastewater sector where the typical positioning of mainline services (large diameter, deep, and in the center of streets) makes their replacement an operation involving major disturbance and cost. In the water sector, distribution pipes are typically of smaller diameter, shallower and may be at the edge of or behind roadway curbs. But technical difficulties arise in providing a pressure-tight rehabilitation system including the connections of the relined mains to the service lines. This has traditionally required open-cut excavation at connections, which negates some of the benefit of trenchless rehabilitation technologies and has kept the penetration of water main rehabilitation approaches slower than that for sewers.

Selection of trenchless rehabilitation approaches involves a screening process followed by a more detailed evaluation of the technologies. It is generally easy to exclude some technologies as evidently not suitable for a particular application. The remaining technologies may be generally suitable but have different cost, risk, setup area requirements, life cycle performance, compatible materials and environmental impacts. A new element in these considerations is how "green" a product or process is. For example, many trenchless methods have a much lower carbon footprint than open-cut repairs. Evaluation of technology differences in a rational and impartial manner is a persistent but important challenge. Specifying a single technology in request for proposals may have a negative impact on the competitiveness of bids received for the use of that technology. Ideally, a level playing field is created when bidders can propose one of several suitable technologies, so that a fair competition is created with similar performance characteristics specified for each technology.

2.4 Special Applications

There is a wide range of rehabilitation needs within water distribution and sewer collection systems. These needs include rehabilitation of various types of gravity and pressure piping systems and rehabilitation of a wide variety of ancillary structures such as manholes, valve chambers, pumps and lift stations. The most common situations are well provided for in terms of technologies, materials, and design approaches – with some room for improvement in QA/QC approaches. However, certain special application conditions are not well provided for, either in terms of suitable materials or design and QA/QC approaches. Two particular areas are described below as examples of this issue.

2.4.1 Elevated Temperature Liner Service Conditions. The City of New York has extremely congested utility conditions beneath its streets and the range of installed utilities includes steam lines, often running in close proximity to sewer lines. Rehabilitation of the sewer lines is urgently needed; but as a deeply-placed utility, open-cut access from the surface is prohibitive in terms of cost and impact on traffic. Trenchless rehabilitation of the sewer lines is a very desirable option, but a complicating factor is that the steam lines have condensate traps, leaks and venting systems that discharge condensate and/or steam (~220 °F) into the sewers. The high temperature provides a very challenging environment that cannot be met by the current thermoplastic or thermosetting lining materials available in the marketplace. In addition, the temperature differential between the head section of the pipe (which is filled with steam at 220 °F) and the invert of the pipe (covered with water at 40 °F) results in differential strain and unique loading mechanisms (i.e., limit states) not encountered in common applications. Currently, a search for suitable materials and their testing to confirm applicability under the anticipated service conditions is being funded jointly by the City of New York and Consolidated Edison Company of New York (Allouche et al., 2009). It is worth mentioning that this problem is common to some older cities in the U.S. that operate similar thermal energy systems including Boston, Philadelphia, Harrisburg, Milwaukee, and Seattle. In addition to solving this particular class of problems, the research will open a range of new applications for rehabilitation under similar challenging conditions in industrial or power plant applications.

2.4.2 Relining of High Pressure Piping Systems. Rehabilitation systems are available in considerable variety for pressure pipe applications, but most have been designed to handle the pressure levels commonly experienced in water distribution systems. However, there are other applications where high pressure pipelines need to be rehabilitated and for which adequate test data on liner approaches and suitable composite materials do not yet exist. Liners can be designed either as stand-alone replacements for the host pipe, or as "semi-structural" liners that rely on the host pipe for overall structural stability but provide a bridging capability across holes, cracks, and failing joints. The materials used to provide the higher pressure capacity often do not have the same ability to conform easily to the host pipe, which can create ridges in the liners. Poor cleaning of the host pipe prior to lining also can create local deformations in the liner. Both kinds of defects can act as stress raisers within the liner and lower the pressure rating of the liner. To address this problem, it is necessary to gain a fuller understanding of types of defects in pressure liners and better understand their impact on liner performance. This is particularly true for a new class of organic "high-build" coating systems such as polyurea and 100 percent solid polyurethane. These products, which are able to be built to thicknesses of 2 inches within seconds and a pressure rating exceeding 1,000 psi, provide new opportunities to the pipeline rehabilitation industry (Johnson et al., 2002) but require the appropriate qualification and service testing for pressure pipe applications. The procedures for ongoing maintenance, installation of new services, and emergency repairs of rehabilitated pipe sections also are a key concern. This issue is addressed later in Section 4.1.9.

3.0 WASTEWATER SYSTEM ISSUES

In this section, the issues relating to rehabilitation of wastewater systems will be examined in more detail. The water system rehabilitation issues are addressed in Section 4.

3.1 System Characteristics

The U.S. sewer network totals approximately 800,000 miles in length. Force mains comprise approximately 7.5 percent; thus, the force main system is approximately 60,000 miles and the gravity network is approximately 740,000 miles. An estimated 25 percent of the gravity sewer network is more than 40 years old, 77 percent is 12 inches in diameter or smaller, and 44 percent is clay or concrete pipe (Water Environment Research Foundation [WERF], 2004). Tables 1 and 2 provide a percentage distribution of pipe material types within various pipe size ranges for gravity sewers and force mains, respectively (WERF, 2004).

The force main network is not as old as the rest of the sewer network – about 2 percent is greater than 50 years old, while 68 percent is less than 25 years old (WERF, 2008).

The American Society of Civil Engineers (ASCE) gave wastewater infrastructure a grade of D^- in its 2007 annual report card (ASCE, 2007). This was the lowest grade given for any infrastructure category. This is despite the replacement or rehabilitation of approximately 8,000 miles of sewers annually at a cost of some $4.5 billion per year. The system is aging, in many cases well beyond its design life; as a result, it is no longer serviceable at an adequate level. There are also huge differences among different municipalities with some having created a very effective rehabilitation program and some doing little or nothing in terms of system rehabilitation.

Table 1. Gravity Sewer Systems: Percent Distribution by Pipe Material and Diameter Range (WERF, 2004)

Material	Diameter, inches				
	4 to 12	14 to 20	21 to 36	37 to 54	≥ 60
VCP	41	36	23	7.1	3
RCP	18	28	44	64	63
Lined RCP	1.4	3.9	6.2	17	20
PVC	27	15	6	1.6	0
HDPE	1.5	1.4	1	0.9	0
DI/CI	8.6	12	10	4.1	2.5
ACP	3.8	2.6	1.3	5.1	0.1
Brick	0.5	0.9	2.1	3.8	4.2
Other	0.9	1	3	0	6

Notes: VCP = vitrified clay pipe; RCP = reinforced concrete pipe; PVC = poly vinyl chloride; HDPE = high density polyethylene; DI = ductile iron (lined and unlined); CI = cast iron (lined and unlined); ACP = asbestos cement pipe.

Table 2. Force Main Systems: Percent Distribution by Pipe Materials and Diameter Ranges (WERF, 2008)

Material	Diameter, inches				
	4 to 12	14 to 20	21 to 36	37 to 54	>54
DI	46.8	62.5	46.0	13.9	3.1
CI	16.9	12.7	5.3	<0.1	0
PVC	28.4	3.5	0.9	0.1	0
HDPE	2.0	1.0	0.2	0	0
PCCP/CCP	1.0	3.1	26.1	54.6	58.1
Steel	0.5	2.0	10.4	12.9	30.4
FRP	0	0.1	0	0	0
ACP	4.0	12.2	0.7	5.0	0
RCP	<0.1	2.5	10.4	13.4	8.4
Other/not known	0.4	0.5	0.1	0	<0.1

Notes: DI = ductile iron; CI = cast iron; PVC = poly vinyl chloride; PCCP/CCP = prestressed concrete cylinder pipe/concrete cylinder pipe; FRP = fiberglass reinforced pipe; ACP = asbestos cement pipe; RCP = reinforced concrete pipe.

3.2 Drivers for Increased Rehabilitation Efforts

The driver of almost all sewer rehabilitation works in the U.S. is the system of fines and consent decrees imposed by EPA. These generally refer to sanitary sewer overflows (SSOs) and combined sewer overflows (CSOs) in both gravity sewers and force mains. The regulatory system has a variety of elements, and there is a degree of overlap, even contradiction, among them. Greater coordination of the various programs may enable more efficient allocation of resources to achieve the overriding objectives of protecting public health and the environment.

3.2.1 National Pollutant Discharge Elimination System (NPDES). The NPDES permit program controls water pollution by regulating point sources (e.g., collection systems and treatment plants) that discharge pollutants into open waters. The NPDES is part of the 1972 Clean Water Act intended to protect the country's waters and directs EPA to issue rules on implementation. Industrial, municipal, and other facilities must obtain permits if their discharges go directly to surface waters. In most cases, the NPDES permit program is administered by individual states.

3.2.2 Sanitary Sewer Overflows (SSOs). EPA estimates that $88 billion is needed over the next 20 years to control SSOs and that this figure may be even higher if the Agency continues to take a zero tolerance stance on SSOs. Municipalities have made significant progress in improving water quality since the implementation of the Clean Water Act, but the wet weather arena demands a more consistent regulatory and enforcement framework, specifically relating to SSOs. Proposals have been made, e.g., by the National Association of Clean Water Agencies (NACWA) that a national SSO policy should recognize the level of risk posed by SSOs nationally and be modeled after EPA's CSO Control Policy to provide the flexibility necessary to address adverse impacts when manifested at a local level and to direct resources to those areas that will have the most impact (NACWA, 2007).

3.2.3 Combined Sewer Overflows (CSOs). EPA's CSC Control Policy is a national framework for control of CSOs through the NPDES permitting program (*Federal Register*, 1994). The Policy provides guidance to municipalities and State and Federal permitting authorities on how to meet the Clean Water Act's pollution control goals as flexibly and cost-effectively as possible.

The Policy contains four fundamental principles to ensure that CSO controls are cost-effective and meet local environmental objectives:

(1) Clear levels of control to meet health and environmental objectives.

(2) Flexibility to consider the site-specific nature of CSOs and find the most cost-effective way to control them.

(3) Phased implementation of CSO controls to accommodate a community's financial capability.

(4) Review and revision of water quality standards during the development of CSO control plans to reflect the site-specific wet weather impacts of CSOs.

CSO communities have made significant progress in reducing the frequency and size of overflows, but more work remains to be done. EPA estimates that the annual CSO volume is approximately 850 billion gallons, down from over 1 trillion gallons prior to issuance of the 1994 CSO Control Policy. EPA also estimates that approximately $51 billion is still needed over the next 20 years to meet the goals of the policy (NACWA, 2007).

3.2.4 Capacity, Management, Operation, and Maintenance (CMOM) Program. The CMOM regulations are part of the SSO regulations affecting some 19,000 sanitary sewer collection systems throughout the country. Owners of all municipal wastewater collection systems are required to develop procedures to improve system capacity, perform long-term planning for investments in infrastructure, develop better documentation and asset management procedures, and share all of this information with stakeholders more effectively. The CMOM is derived from a need for reducing sewer overflows and the consequent health risks associated with these overflows. The purpose of the CMOM approach is to abate SSOs, reduce health risks, extend the life of sewer system assets, and improve utility customer satisfaction.

3.2.5 Government Accounting Standards Board (GASB) Statement No. 34. The GASB, a non-government entity that defines the criteria that auditors use to judge the adequacy of local and state government financial statements, has changed long-standing practices by requiring that government entities include reporting of their capital assets in their annual balance sheet and income statement. GASB-34, adopted in June 1999, highlights the costs of acquiring, owning, operating, and maintaining public-works infrastructure for government-bond holders and the public at large. GASB-34 requires that the value of infrastructure assets be shown on the balance sheet, and gives governments a choice of adopting either (a) traditional private-sector methods of calculating infrastructure depreciation expenses based on historical acquisition costs, or (b) an effective asset management system. These asset management systems must demonstrate either that maintenance spending is adequate to prevent infrastructure deterioration or that infrastructure condition is being maintained at or above explicitly stated minimum acceptable standards.

3.2.6 Rehabilitation Funding. Federal funding under the Clean Water Act State Revolving Fund (SRF) program has remained flat for the past decade. Congress appropriated between $1.2 billion and $1.35 billion annually from 1995 to 2004. However, in FY 2005, Congress cut wastewater SRF funding for the first time in eight years, reducing the total investment to $1.1 billion. The administration proposed further cuts for FY 2006 and 2007, with a budget submittal calling for an appropriation of only $688 million in FY 2007, a reduction of 37 percent from the FY 2005-enacted level. In March 2007, the U.S. House of Representatives approved the Water Quality Financing Act, 2007, which reauthorized the Clean Water SRF at $14 billion over 4 years (FY 2008 to 2012).

Funding for sewer renovation and maintenance is a major challenge for municipalities throughout the country. The sources of funding are grants, local taxes (rates), or debt (bond) issues. All are limited in amount and are politically sensitive at a local and national level. The competition for funds within municipal budgets is intense, and the budgets themselves are constantly under scrutiny, irrespective of economic conditions. The current economic downturn serves to increase this budgetary pressure; many cities have cut budgets for sewer inspection, maintenance, and renewal.

As a result, municipalities are caught between increasing regulatory demands and lack of adequate funds to meet those demands. Solving this issue requires innovative and visionary thinking in terms of asset management along the lines dictated by GASB-34, but there has been little adoption of this approach in the U.S. Political time horizons, dictated by electoral cycles, militate against implementation of asset management solutions that show benefits over a longer period.

The silver lining is that the need to do more with less creates opportunities for innovation in technology, organization, business processes, and management that will optimize resource allocation in order to achieve the regulatory objectives as efficiently as possible.

3.3 Problems Typically Encountered in Wastewater Pipe Systems

In searching for the most effective rehabilitation approaches, it is important to understand the most frequent types of defects that are present in wastewater pipe systems. These vary by the type of pipe system and by the type of pipe material used. It has been found that defects may vary by period of installation due either to variations in material quality (e.g., thick wall versus thin wall cast iron pipes) or QC and work crew issues (e.g., quality of bedding and backfill control).

3.3.1 Gravity Sewers. Table 3 provides a summary of frequently observed distress in gravity sewer systems (WERF, 2004). Based on survey data on the types of defects observed and taking into consideration the frequency of use of the pipe materials, the priority ranking for problems affecting gravity sewers has been assessed as:

- Cracks
- Internal corrosion
- Grease build-up (plus grit and debris)
- Root intrusion
- Joint misalignment/separation/leakage
- Excessive pipe deflection
- Lateral connection/leakage
- Grade and alignment.

These problems can cause either partial blockages leading to backing-up and overflows upstream, or excessive infiltration leading to surcharge and overflows downstream.

3.3.2 Laterals. As municipalities have worked to rehabilitate their mainline networks using relining or replacement approaches, it has become evident in many cases that the savings in inflow and infiltration (I&I) expected from the rehabilitation work have not always occurred.

The probable cause of the low achievement of I&I reductions has been identified in many cases to be the problems with the private sewer connections to the mainline sewers in the streets (private lateral sewers or "laterals") (WERF, 2006). While the mainline sewers in most cases need urgent attention, the omission of the laterals from the rehabilitation programs results in an incomplete solution. The problem is

Table 3. Main Defects in Gravity Sewer Systems by Sewer Material

Material	Potential Problem/Defect
Vitrified Clay	• Cracks/broken pipe • Root intrusion • Grease build-up • Joint misalignment and/or leakage
PVC	• Excessive deflection • Grease build-up • Joint misalignment and/or leakage • Grade and/or alignment • Lateral connections
Concrete	• Internal or external corrosion of concrete and/or reinforcement • Cracks and fractures • Grease build-up • Joint misalignment and/or leakage • Root intrusion • Missing wall sections • Open joints
Cast Iron/Ductile Iron	• Internal corrosion • External (pit) corrosion • Circumferential breaks • Grease build-up • Joint failure and/or leakage • External corrosion • Longitudinal break/split • Corporation cock failure • Leaking laterals
Concrete with Liner	• External corrosion of concrete and/or reinforcement • Liner failure or separation (including weld failure) (leading to internal corrosion) • Grease build-up • Root intrusion • Cracks • Joint misalignment and/or leakage • Capacity
Prestressed Concrete Cylinder Pipe / Concrete Cylinder Pipe	• Corrosion of prestressing wires • Grease build-up • Root intrusion • External corrosion • Joint leakage • Internal corrosion • Pressure capacity
Polyethylene	• Excessive deflection • Grease build-up • Root intrusion • Grade and alignment • Leaking laterals
Pressure Only	• Pressure capability

Table 3. Main Defects in Gravity Sewer Systems by Sewer Material (Continued)

Material	Potential Problem/Defect
Steel	• Internal corrosion • Weld failure • External (pit) corrosion • Excessive deflection • Joint leakage • Stress fractures
Brick	• Missing bricks • Soft mortar • Vertical deflection and collapse • Cracks • Grease build-up • Root intrusion
Asbestos-Cement	• Internal corrosion • Cracks • Grease build-up • Root intrusion • Joint misalignment and/or leakage
Fiberglass	• Grease build-up • Excessive deflection • Root intrusion • Cracks/delamination

particularly acute under conditions where the sealing of the mainline causes the groundwater table to rise sufficiently to increase the flows into the cracked and leaky laterals – thus circumventing (at least partly) the sealing of the mainline. When projected savings from expensive rehabilitation projects fall short, political questions are raised about the value of such work. In some cases, funding for rehabilitation work has been suspended.

The topic of when and how to address the rehabilitation of private sewer laterals was the subject of a project funded by WERF and carried out by TTC at Louisiana Tech University between 2003 and 2005 (WERF, 2006).

Ownership of sewer laterals varies significantly for municipalities even within a single metropolitan area. As shown in Figure 1 (WERF, 2006), most commonly, the private property owner owns the lateral sewer all the way to the sewer main in the street (55.2 percent in the referenced survey), but there is a split as to who owns the actual connection into the main (often called a sewer "tap"). A smaller percentage (43.1 percent) of property owners owns the lateral only to the property line. There is also a significant difference of opinion as to whether cleanouts should be installed at the private property line. Where cleanouts are installed, these often serve as the demarcation of private and public ownership, but not in all cases. Cleanouts do help greatly with some types of rehabilitation, can assist in maintenance, and also make it easier to determine whether the private or the public section of a lateral is causing the I&I problem.

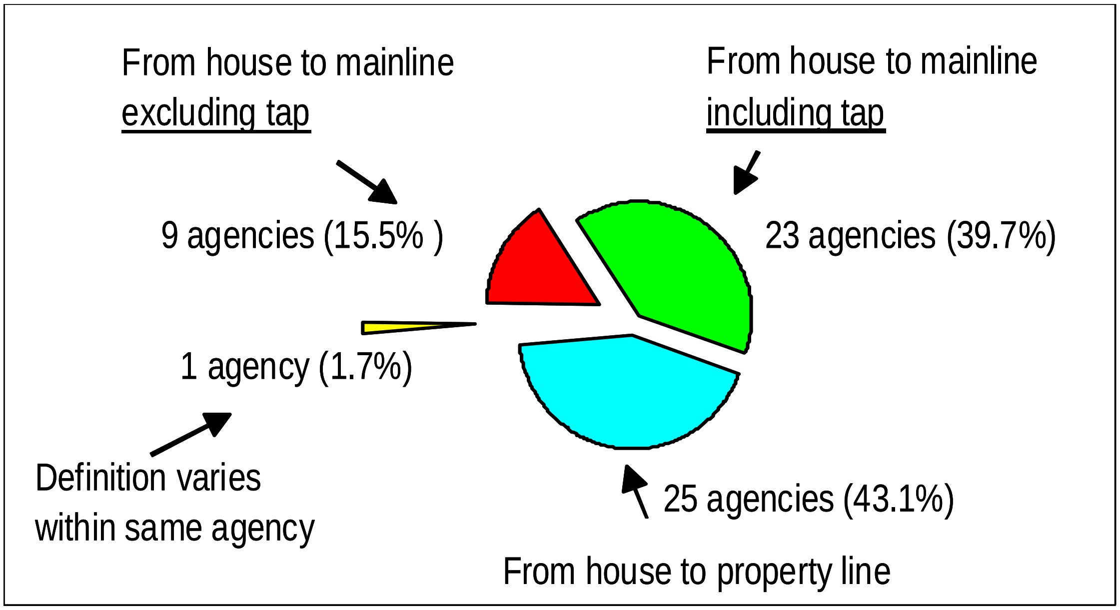


Figure 1. Private Ownership of Sewer Laterals (WERF, 2006)

Even when municipalities conclude that their sewer laterals present a problem that should be addressed in a systematic fashion, there is often a reluctance to move ahead. Dealing with private property owners over sewer lateral repair is a difficult issue. Since most private property owners have no idea of the condition of their sewers, they will see little or no direct benefit from the repair; and the rehabilitation costs are usually significant. Linked to the legal issues of who owns which portion of the lateral, who should pay, etc. are also questions of legal right of access to the private property for inspection and repair work and legal liability for accidents during inspection or repair work. As with the issue of laterals ownership, there are many ways in which this is currently handled as well as many opinions on how it should be handled in the future. Some key issues/options regarding legal and liability matters are:

- Some states prohibit spending public money for private gain (i.e., improving private property by paying for rehabilitation of private laterals). This issue has been addressed successfully in the courts by arguing that the private gain is only incidental to a larger public gain from the reduction in sewer overflows and from savings in sewage treatment costs.
- Many municipalities consider taking any additional responsibility for private sewer laterals as a major concern in terms of additional work and public liaison. Other municipalities are more proactive – seeing themselves as being in the best position to do something about lateral problems by providing homeowner-friendly programs even if they do not take financial responsibility for the work.
- Gaining the political will to force homeowners to comply is often an issue with elected city councils who have to approve the program.

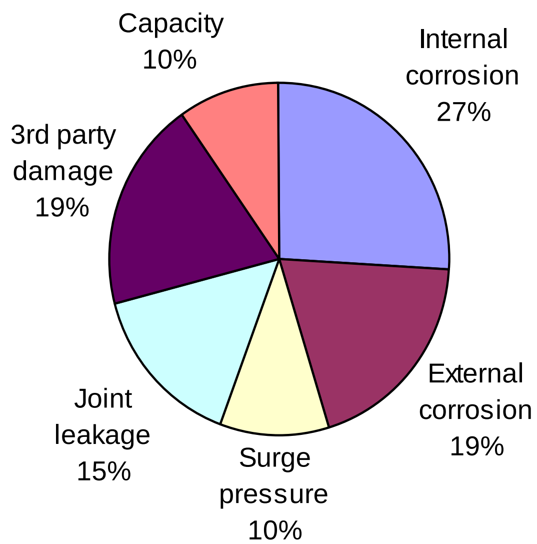
Dealing with sewer laterals in a comprehensive manner can be an expensive undertaking, both for a municipality and for the private property owners involved. The first step is to determine whether a laterals program is justified from the cost-effectiveness perspective, although it can also be argued that a tight and properly functioning sewer system is not just a question of cost-effectiveness of treatment savings versus rehabilitation costs, but that it is required for a good, healthy urban environment. A first step is usually to examine and remove illegal connections of gutters and sumps into the sanitary sewer since these are often the most cost effective initial options. Programs can be much more successful with less public resistance if the financial aspects as well as the legal aspect are given close consideration. Some issues and approaches are listed below:

- For wealthier neighborhoods, financing options can be used to make it easy for the homeowner to say yes and proceed with the repair. For low-income neighborhoods, some kind of financial assistance or deferral of payment until property sale may be essential to allow a program to proceed.
- A few cities have decided that sewer lateral repair provides enough public good that they have put up all the money for such programs.
- Other cities use a warranty or insurance program approach where the homeowner essentially pays an insurance premium against the cost of a malfunctioning sewer system.
- Using a mandatory inspection at time of sale and a requirement to have the lateral in proper condition before the property is transferred allows the cost of lateral repair to be paid at a time when money is available from the property sale. This is true for both low income and wealthy neighborhoods.
- The city can use its program size to bid or negotiate uniform and low costs for the lateral repair. A homeowner can opt to bid the work themselves, but a quick check on an individual price can often convince the homeowner that joining the city program is an opportunity to take care of the problem at a lower price and with little effort on the homeowner's part.

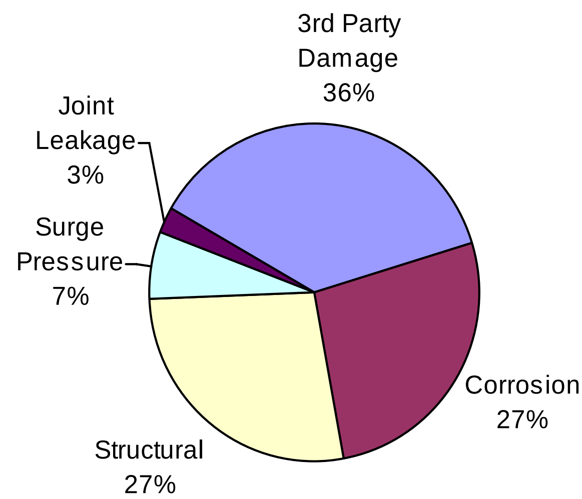
3.3.3 Force Mains. Force mains that carry sewage flows under pressure represent a special set of challenges for sewer rehabilitation. As mentioned earlier, they represent approximately 7.5 percent of the system and typically use materials that are not used elsewhere in the sewer system such as steel, cast iron, and ductile iron. While siphons may be provided with redundancy for cleaning and inspection, most force mains do not have a bypass flow line and hence are difficult to take out of service for inspection or rehabilitation. The combination of corrosion potential, lack of inspection, and severe consequences for a failure make force mains a particular issue of concern. Figure 2 indicates the main causes of failure in ferrous and non-ferrous force mains.

3.3.4 Pump Stations and Lift Stations. Pump stations are usually associated with force mains and are used where it is necessary to move the sewage flows against gravity for some distance. Lift stations are used where gravity sewage lines become too deep for economic installation and it is necessary to lift the sewage so that a new section of gravity sewer line can be installed at a shallower depth. The changing economics of deep sewer installation using microtunneling or directional drilling can make it possible to eliminate some lift stations either during construction of a new system or as a retrofit measure. This can have a significant impact on maintenance and rehabilitation needs for these ancillary structures.

The focus of this report is on the rehabilitation of pipes and structures and hence the issues concerning pump maintenance and replacement schedules are not addressed in detail. It should be noted, however, that pump stations can "age" pipe through surge stresses. For the non-flow areas of pump and lift stations, normal structural rehabilitation issues will apply. The structures are often below ground and may suffer from some groundwater leakage into the structure and condensation during humid weather. Under damp and humid conditions, steel supports and frames may become corroded and equipment may gradually deteriorate. Rehabilitation typically involves working to eliminate the groundwater leakage, and providing new, easily maintained surfaces within the structure. Combinations of grouting, sealing,



(a) Ferrous Force Mains



(b) Nonferrous Force Mains

Figure 2. Main Causes of Failure in Ferrous and Non-ferrous Force Mains

and coating of interior walls are the typical approaches for such rehabilitation. Since the shape of the structures is often rectangular, it is not possible for liners to resist external groundwater pressure by arching action in curved sections; hence, most coating applications require the ability to bond to the existing structure. Further complicating the ability to seal such structures fully are the internal supports for equipment that may be bolted to internal walls and penetrations for venting to pass through the walls of the structure and any waterproofing or sealing layers. Providing a structure that is easy to maintain and keep dry is easiest during the initial design by:

- Keeping external and internal shapes as simple as possible for ease of construction and waterproofing.
- Avoiding sharp, re-entrant corners wherever waterproofing or sealing layers are to be applied.
- Ensuring that internal supporting members preferably slope slightly towards the wall of the structure so that leakage water will be kept adjacent to the wall. The same applies to the floor-to-wall junction.
- Providing an internal drain at the floor-wall junction for confining leakage issues and allowing easy collection and disposal of leakage.
- Carrying out an analysis of pump operations, maintenance, and emergency procedures during the design so that the facility can operate effectively and avoid damage to adjacent pipe sections.

Wet well areas of lift and pump stations are subject to erosion and corrosion concerns, depending on the structural materials used and the level of hydrogen sulfide produced by turbulence in the wastewater flow.

3.3.5 Drop Shafts. Drop shafts are used in wastewater systems to connect a shallow storm or sanitary sewer with a deeper sewer or interceptor tunnel system. Depending on the design of the drop shaft, the flow may be piped to the lower level within the shaft structure or may be allowed to drop freely within the shaft. Piping the flow allows for smooth directional transitions and minimizes turbulence, which can cause excessive hydrogen sulfide release and corrosion/erosion in sanitary systems. In some cases, spiral drop (vortex) structures are used to reduce velocities.

Rehabilitation issues for drop shafts will need to be determined on a case-by-case basis depending on the depth of drop, the internal structures present, and the degree of deterioration.

3.3.6 Manholes and Other Chambers. Manholes are an integral part of wastewater collection systems. Manholes are typically spaced approximately 300 feet apart, but can be less than 100 feet or as far as 500 feet apart. Using these values, the number of manhole structures in the U.S. can be roughly estimated at over 12 million. Older manholes are typically brick or concrete structures and may suffer from a variety of deterioration mechanisms.

- Hydrogen sulfide release may attack concrete manholes and the mortar in brick manholes.
- Manholes may leak allowing soil fines from the surrounding ground to enter the manholes, hence causing soil voids and surface settlement adjacent to the manholes.
- In cold climates, the upper portion of the manhole may be lifted by frost heave in the soil in the winter, thus fracturing the manhole and providing an infiltration path into the manhole.
- Newer plastic manhole materials avoid some of the corrosion issues, but some have been inadequately designed against excessive deflections due to ground loadings.
- Corrosion of ladder access or cast-in-place rungs can be an important safety issue in manholes. Some utilities remove such fixtures during the rehabilitation work.

Rehabilitation approaches use techniques similar to those of piping systems but can take advantage of the person accessibility available. Specific techniques, listed in Appendix D, fall into the following categories:

- Casting a new internal lining using permanent or removable forms
- Sprayed or centrifugally cast concrete linings
- Sprayed polymer linings (coatings or high-build structural linings)
- Cured-in-place lining systems
- Grouting and sealing approaches (including the flood grouting approach used for simultaneous manhole, mainline, and lateral sealing).

Many agencies rehabilitate manholes as they rehabilitate the mainline sewers in an area (unless urgent action is needed on manholes located in other areas). As for mainline and lateral rehabilitation, effective techniques for such rehabilitation do exist and full manhole replacement is an option if the structure is too badly deteriorated for rehabilitation. Special considerations for manholes include:

- The structural thickness requirements of manhole linings vary with the depth below ground level and/or groundwater level. If the thickness of linings is set for the maximum load condition, then the manhole rehabilitation may be more costly than necessary.

- Manhole diameters are much larger than most sewer pipes and hence the thicknesses of liners necessary to resist buckling against external groundwater pressures become significant for the more expensive polymer materials.
- Most calculations for a structural lining do not take any account of bonding with the manhole structure although, for a sealant coating, the bond is critical in terms of the ability of the coating to resist seepage pressures.

3.4 Other Wastewater Issues

3.4.1 Inspection and Assessment. All rehabilitation and replacement works depend on some form of inspection and consequent assessment of the sewer line. A closed-circuit television (CCTV) survey is the predominant method in gravity sewers. However, there are many unmet needs of utilities in terms of equipment and data acquisition when carrying out an inspection. The main issues raised in extensive surveys are:

For gravity pipe systems:

- Improvements in current CCTV systems
- Higher resolution and better lighting
- Tractors better able to negotiate debris, grease, pipe separation, and corrosion
- Improved cleaning procedures undertaken during CCTV work
- Cameras for lateral inspections
- A combination of CCTV and sonar to inspect partially full or surcharged sewers
- A means to determine the remaining thickness of a corroded pipe, or determine the severity of a defect by measurement of the width and depth of a crack or hole in the pipe wall
- The ability to measure the depth of crown corrosion in a concrete pipe
- A method to measure sediment depth in large diameter pipes with heavy flow
- A means to locate sewer laterals accurately
- A means to quantify accurately deformations and out-of-roundness
- A means to quantify joint anomalies – steps and openings
- A means to map sewers that have deviations in line and level, and translate these directly to Geographic Information System (GIS)
- A means to locate buried manholes
- A means to locate voids on the exterior of a pipe.

For pressure pipe systems:

- A means to determine the remaining thickness of a corroded pipe, or to determine other defects such as cracks or pitting in the pipe wall
- A means to determine the magnitude of internal corrosion in a metallic pipe
- A means to locate leakage
- A means to do all of this with the main in service.

In many cases these capabilities already exist, whether within the sewer inspection industry or in others from which they may be adapted, but the awareness of these capabilities remains patchy. In the force main segment, it is seldom feasible to take a main out of service for inspection. No cost-effective technologies exist for inspecting while in service – so, as a result, there is almost no inspection of force mains undertaken.

3.4.2 Inspection and Condition Assessment Standards. Standards for inspection, coding of defects, classification of condition, and rehabilitation itself have been slow to develop in North America. Existing standards are either industry-developed or adaptations of standards and codes developed overseas.

The National Association of Sewer Service Companies (NASSCO) has adapted the UK's WRc pipeline assessment standards to form a Pipeline Assessment and Certification Program (PACP) in an attempt to standardize the interpretation of CCTV inspection findings for sewer mains. They have also released a similar program for manholes, the Manhole Assessment and Certification Program (MACP). The development of standard defect codes, a standard data format, and condition ratings need more widespread implementation. Lack of such standardization causes subjective and inconsistent interpretation of data and precludes the ability to achieve any sort of benchmark of condition even within a single utility, let alone among several. However, the current penetration of PACP usage is still estimated to be low, and some cities complain that, given the high workforce turnover, it is difficult to keep staff sufficiently trained in the system for reliable coding.

3.5 Summary of Wastewater System Issues

Existing technologies for rehabilitation of all elements of the wastewater collection infrastructure (namely main sewers, force mains, laterals, and ancillary structures) are widely used and their performance so far has shown that they do provide extended service life to the infrastructure. The difficulty is knowing the full service life of the rehabilitation and hence its relative life cycle cost compared to full replacement. Here to date there has not been a well documented, unbiased retrospective program aimed at quantifying the condition of previously installed liners so factual evidence can be provided to aid in assessing future service lives. Plus, continuous improvements are being made to these technologies, especially in the less mature segment of laterals and the re-establishment of lateral connections after mainline rehabilitation, so the performance of older technologies may not be indicative of today's products. New structural and semi-structural high-build polymer linings are also being developed and commercialized.

The mature segment of main gravity sewer rehabilitation is dominated by CIPP methods. The use of ultra violet (UV) light curing was developed in Europe and is now entering the U.S. market. This innovation, which has changed the competitive dynamics of the major European markets, is likely to lead to greater cost-effectiveness and improved performance in the U.S. as well. UV-cured products have a long shelf-life after impregnation if kept protected from light. This allows a break in the supply chain between impregnation and installation, which provides flexibility in separating the two activities and the organizations undertaking them, as well as a time separation. Construction footprints are also smaller as large hot water boilers and steam generators are not required to cure the CIPP resin. However, there is little parallel innovation in business models and this continues to be a brake on the market. New technologies, when introduced into the market, tend to use protective business models such as narrow licensing. Adoption of more open models would increase accessibility and the rate of penetration, albeit at potentially lower margins, leading to expansion of the market and greater competition. This phenomenon has already been seen in the trenchless arena when the business model underlying pipe bursting was changed and became more open.

Nevertheless, there remains scope for innovative new technologies to penetrate the market as they are developed. Innovative new technologies need to respond to the need to improve cost-effectiveness so that significantly more sewerage infrastructure can be rehabilitated within available budgets. One technology that could drive such a step change in the market is spray-applied structural lining for gravity sewers. While previous efforts by several developers to commercialize such a technology have failed due to problems with the rapid curing of the resins, several companies across North America are striving to improve both the robotic spray-on technology and the formulation of the spray-on products. The benefit of structural spray-on lining is that it obviates the need for reopening lateral connections after lining and the speed of application of the lining and rapid cure can lead to higher installation productivity.

Better inspection technologies, well-targeted inspection procedures and frequencies, accurate condition assessment, and improved deterioration models will continue to be very important in targeting scarce rehabilitation funding to its most effective use. Newly developed digital scanners and laser profilers are already providing many utilities with new tools to better quantify the condition of their buried wastewater assets and even quantify and track degradation rates over time. On a system-wide level, there is a continued need to understand how to deploy resources for capital investment, maintenance, and renewal among the interlinked processes of collection, storage of wet-weather flows, and wastewater treatment most effectively.

4.0 WATER SYSTEM ISSUES

4.1 Background

4.1.1 Infrastructure Investment Needed. In the May 2001 publication "*Dawn of the Replacement Era, Reinvesting in Drinking Water Infrastructures*" (AWWA, 2001a), AWWA estimated that there were just over one million miles of water mains serving 273 million people in the U.S., and that a staggering $325 billion would have to be spent over a 20-year period to revitalize the aging underground infrastructure. The Government Accounting Office (GAO) in a 2002 report stated that 33 percent of water utilities did not adequately maintain assets and a further 29 percent had insufficient revenues to even maintain current service levels. The EPA's 2002 report "The Clean Water and Drinking Water Infrastructure Gap Analysis" attempted to reach a common quantitative understanding of the potential magnitude of investment needed to address growing population and economic needs (EPA, 2002). Numerous other studies, including the annual ASCE Infrastructure Report Card (ASCE, 2007), clearly show the impact of lack of significant investment on the performance of our aging underground infrastructure. Unless significant action is quickly taken, the problem will only worsen as the average pipe age continues to increase without significant replacement or renewal. As shown in Figure 3, the average pipe age in 2008 is about 38 years old, but by the year 2050 the average pipe age will be 50 years old. This is because of the boom in water pipeline installations that took place after WWII. From 1870 to 1945 less than 20,000 miles of pipe were installed each decade. However, after 1945 this rate increased to over 80,000 miles of pipe. The commonly accepted design life for a water distribution or transmission main was approximately 50 years. Many pipes, especially older cast iron water mains, which had very thick pipe walls compared to today's AWWA standards requirements, have had useful service lives in excess of 100 years. However, minimum wall thickness requirements for ductile iron pipes have dropped over the years due to competitive pressure from thermoplastic materials, resulting in an increased frequency of failures in ferrous pipes. The design basis for thermoplastic and glass-reinforced thermoset pipes is predicated upon applying a suitable factor of safety to the pipe material's predicted tensile strength under a constant load in 11.4 or 50 years, respectively. Many of the ferrous and polymer-based water pipes will provide adequate service for at least 50 years, especially at reduced service pressures, but the frequency of failures will start to increase. For corrosion related failures, the rate of increase can be exponential. Depending on the service conditions, some pipes can be considered "middle-aged" at 50 years, while others must be considered "old" or near the end of their life cycle.

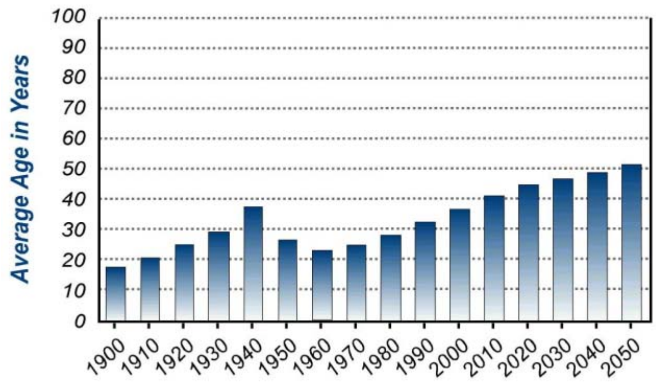


Figure 3. Historical and Projected Average Age of U.S. Water System (EPA, 2002)

4.1.2 Pipe Material Usage. Water mains can be categorized as either distribution piping (2-inch to 10-inch diameter) or transmission mains (12-inch diameter and greater). Approximately 73 percent of all water mains, by length, are distribution pipes. Typically pipe diameters less than 30 inches are considered non man-entry size, so any inspection or trenchless rehabilitation needs to be done remotely. This covers 93 percent of the entire population of water mains. Tables 4, 5, and 6 provide some statistics on the distribution of pipe materials, pipe diameter, and age in the U.S. water distribution network.

Table 4. Water Distribution Systems by Material (AWWA, 2004)

Material	Miles Installed	% of Total
Asbestos Cement	136 196	15.8
Cast Iron unlined	153 415	17.8
Cast Iron cement mortar lined	159 824	18.5
Cast Iron	28 476	3.3
Concrete Prestressed	23 584	2.7
Ductile Iron unlined	35 916	4.2
Ductile Iron cement mortar lined	150 705	17.5
Ductile Iron other lining/lining not known	2 494	0.3
GRP	665	0.08
PE	3 349	0.4
PVC	114 152	13.2
Steel	34 047	3.9
Other/Not known	20 169	2.3
Total	863 000	100

Table 5. Water Distribution Systems by Diameter (AWWA, 2004)

Diameter Range, inches	Miles Installed	% of Total
<6	107 200	12.4
6 to 10	523 200	60.6
12 to 16	138 600	16.1
18 to 24	29 700	3.4
30 to 48	57 700	6.7
> 48	6 600	0.8
Total	863 000	100

Table 6. Water Distribution Systems by Age (AWWA, 2004)

Age, years	Miles installed	% of Total
0 to 10	245 000	28.4
10 to 25	325 500	37.6
25 to 50	156 500	18.1
>50	137 000	15.9
Total	863 000	100

Up to the 1940s, water mains were chiefly unlined cast iron and steel. Cast iron (CI) pipe eventually gave way to ductile iron (DI) pipe and ceased being used altogether in the mid 1980s. Today, 56 percent of all underground water mains are CI pipe. The primary problem with unlined CI pipe is both internal and external corrosion. Internal corrosion causes tuberculation, which can lead to water quality issues and reduced flow and pressure. Internal corrosion can also result in wall thinning that weakens the pipe and holes to cause leakage or eventually rupture. CI pipe is also susceptible to external corrosion if not protected. Graphitization of CI pipe is a type of corrosion that weakens the pipe wall by the removal of iron, leaving graphite behind. Graphitization is not easily detected, because the appearance of the pipe remains unchanged. Weakened pipes can fail under much smaller fluctuations in pressure (i.e., surge), frost heave, ground movement or thermal stress (due to rapid changes in water temperature). Also, the relative thickness of CI pipe was gradually reduced over the years as production and material technology improved. For unprotected ferrous pipes, the National Standards Bureau found the rate of corrosion to be similar for all ferrous pipe types. Consequently, younger unprotected CI pipe with thinner walls can actually pose a greater failure threat as less time is needed to penetrate the reduced wall thickness. CI pipe is also susceptible to failure at corporation stops due to galvanic action between the two dissimilar materials, which leads to leakage. If the leakage continues over time, the underlying bedding may be compromised and bending loads induced by loss of beam support (e.g., as a result of loss of bedding), which result in circumferential cracks.

Asbestos cement (AC) was initially developed in Italy and introduced to the U.S. market in the late 1940s. Being non-metallic, AC pipe was not subject to galvanic corrosion. However, soft water will remove calcium hydroxide (free lime) from the cement and eventually lead to deterioration of the pipe interior (softening accompanied by release of asbestos fibers). External exposure to acidic groundwater (e.g., mine waste) or sulfates in the soil can also lead to deterioration of the cement matrix. Type II Portland cement, which reduces the negative impact of sulfate, was not always used. The production of AC pipe ceased in the U.S. in 1983. However, despite the cessation of production, approximately 15 percent of all water mains today are asbestos-cement. This percentage is much higher on the West coast (closer to 20 percent) where AC pipe was more widely used.

Approximately 22 percent of the existing underground water main infrastructure is DI pipe. DI pipe was introduced to the utility market in 1955 and eventually displaced CI pipe completely. Initially, DI pipe was unlined, but by 1975 most DI pipe marketed for water service was lined with cement mortar. Also, as external corrosion issues were observed, unbonded loose polyethylene (PE) sleeves were later made available for field application to electrically isolate the pipe from the soil; and these sleeves have performed with varying degrees of effectiveness (Szeliga, 2007). The U.S. DI pipe industry currently does not offer DI pipe with bonded coatings, as done by the steel pipe industry. The industry, as represented by the Ductile Iron Pipe Research Association (DIPRA), contends that external corrosion protection is not normally required for DI pipe, and when corrosive soil conditions exist, the PE sleeves are totally adequate and cathodic protection unnecessary. A bonded coating to the exterior surface, in conjunction with cathodic protection to handle any inadvertent holidays (e.g., pinholes or voids) in the coating, is generally considered to offer the highest level of corrosion protection (National Association of Corrosion Engineers [NACE], 1984; Sloan, 2001).

Thermoplastic pipes, initially in the form of PVC and more recently PE, have also found use as underground water mains. In the U.S., PVC represents 10 percent of the underground water main infrastructure and is definitely the thermoplastic leader in this market. Acceptance for PE pipe, which is actually higher in Europe than that for PVC pipe, is growing slowly as utilities gain more experience with the material. Thermoplastic pipes are not subject to electrochemical or galvanic corrosion. PVC pipes have experienced premature fatigue-related failures when used in cyclic pressure applications (e.g., irrigation systems and force mains). A Water Research Foundation (formerly American Water Works Association Research Foundation [AwwaRF]) study titled “Long-Term Performance Prediction of PVC Pipes” provides evidence that the longevity of a PVC pipe is directly related to its resistance to slow crack growth (SCG), which is dependent on the pipe’s fracture toughness and distribution and size of defects in the extruded pipe wall (Burn, 2006). Most PVC pipe failures tend to be brittle, not ductile, which tends to support the conclusions of the AwwaRF study.

The performance of PVC pipe produced in the U.S. has been shown to be superior to that initially used in Australia and the U.K., where problems have been experienced. AwwaRF also completed a similar study on PE pipe, titled "Long-Term Performance Predictions of PE Pipes", where the pipe's longevity was also found to be dependent on the rate of crack growth, which is functionally tied to the fracture toughness of the material (Davis et al., 2008).

Thermoplastic pipes, as well as AC and concrete pipes, have been shown in studies carried out in the Netherlands to allow low molecular weight hydrocarbon molecules to migrate through the pipe wall. The rate of migration is dependent on the molecular structure of the pipe material. The AWWA standards for PVC (AWWA C900 and C905) and PE (AWWA C901 and C906) contain warnings on the use of these materials in drinking water supply systems if the pipes pass through contaminated soils. Rubber ring gaskets are also susceptible to the migration of low molecular weight hydrocarbons, so caution needs to be taken with the use of other pipe products that use rubber gasket joints in contaminated soils. Exposed surface areas are generally much smaller for a rubber gasket joint mitigating the severity of the problem.

Thus, the million miles of aging water mains are made of a vast array of different types of pipes, with and without corrosion protection systems. The failure mechanism of each type of pipe is different meaning that rehabilitation solutions must be tailored to match the problems experienced by a specific type of pipe material, or be flexible enough to cover a multitude of performance problems. The latter is not as likely.

4.1.3 Drivers for Water System Rehabilitation. The U.S. water industry has an environment different from the wastewater industry when it comes to the amount of rehabilitation undertaken or even contemplated. Formal enforcement action by EPA on communities with excessive CSOs and SSOs during wet weather has definitely been a spur to action. For example, the threats of hefty fines for overflows or spills is driving many communities to undertake I&I reduction programs that often involve some form of sewer main rehabilitation. Without the threat of such external and costly enforcement actions, the political environment in many communities would make it difficult to raise the necessary funds to improve the condition of its wastewater system to an acceptable level. Water systems also are harder to inspect as ordinary visual inspections will reveal little about the structural condition of the mains, and require expensive and/or time consuming temporary services and disinfection in conjunction with rehabilitation. With well-developed emergency repair strategies, many water utilities currently find the repair option cheaper than establishing a systematic rehabilitation program.

In the U.S., approximately 160,000 public water systems are subject to the Safe Drinking Water Act (SDWA). The SDWA requires EPA to establish National Primary Drinking Water Regulations (NPDWR) for contaminants. Mandatory maximum contaminant levels (MCLs) and non-enforceable maximum contaminant level goals (MCLGs) are established by EPA. The 1996 Amendment to the SDWA established the Drinking Water SRFs. States can use the funds to help water systems make infrastructure improvements or assess and protect source water. Unfortunately, the amount of money allocated to the revolving funds has decreased over the years. The amount of money available in the SRFs is miniscule compared to the amount needed to rebuild the infrastructure.

Primacy states have administrative penalty authority, and many types of formal enforcement actions are possible. However, fines are small in comparison to those for wastewater overflows, so utility efforts tend to focus more on source water and treatment issues rather than distribution and transmission improvements. For example, service interruptions as a result of a failure, inadequate flow, or low pressure, all of which can be very upsetting to the utility customers, but do not warrant enforcement action under the SDWA.

The main driver pushing utilities to undertake any rehabilitation work on their underground infrastructure is the direct and indirect costs associated with cumulative failures in a water main. As an example, the City of Cleveland, Ohio has experienced two breaks in a 36-inch CI water main located in the center of the business district. The Cleveland press reported that the cost to repair the first break, and restore damage done from flooding, combined with the business losses associated with a complete shutdown for two days, was about $1.5 million. After the second failure, the City decided to aggressively take action to upgrade this line because the estimated cost to rehabilitate was less than the costs associated with these failures. More common types of failure involve the repeated failure of a pipe, aggravating customers and causing repeated repair to become economically unfavorable in comparison to renewal.

4.1.4 Funding for Rehabilitation. As stated earlier, SRFs are insufficient to cover the costs for rehabilitating an aging water system. Rate structures for pubic water utilities typically are not designed to provide the level of funds needed either. Water rates are politically sensitive and, without significant increases over the years, often do not even cover the cost of providing clean water to stakeholders. One of the paradoxes of the water industry is that life is impossible without water, yet we are only willing to pay a fraction of the cost of what it takes to deliver safe, clean water to our homes and offices. Public utilities will need to find a way to raise rates to match the value of water to society so that money becomes available for renewing the aging infrastructure. In recent years, the federal government has been unwilling to step in and provide those funds. In the coming years, a renewed interest in infrastructure provision and the need for an economic stimulus may change the funding outlook.

Regrettably, it may take a significant disaster, as occurred in Walkerton, Ontario, to force politicians to take action on rate increases. An outbreak of *E. coli* due to operator error in Walkerton, Ontario, in May 2000 resulted in the death of seven people from drinking contaminated water. Two thousand people suffered from the symptoms of the disease. The disaster prompted a surge of regulations and other enforcement measures, resulting in water rates tripling in many Canadian municipalities (Holme, 2003). Utility operators have commented, however, that there were actually few documented water quality events related to pipe failure (with new regulations in place concerning “boil water” orders).

4.1.5 Potable Water – NSF International (NSF)/American National Standards Institute (ANSI) Standard 61. Federal and State governments encouraged the development of a consensus standard that could filter out products not suitable for use in the conveyance of potable water. The NSF International in Ann Arbor, Michigan spearheaded the development of NSF/ANSI Standard 61, which covers products in direct contact with potable water. Pipe and joining materials must undergo a searching evaluation of formulation, toxicology, and product use and a rigorous testing program that includes water immersion under controlled conditions and testing for migration of contaminants, odor, and taste. The testing protocol can take up to six months and the cost to the supplier interested in getting an NSF listing against Standard 61 may reach many thousands of dollars. In the U.S., it is virtually impossible to supply a pipe, liner, or sealing mechanism (i.e., gasket) for a potable water application that is not NSF/ANSI Standard 61 listed. The exception is products that have been grandfathered due to extensive past usage, such as cement mortar linings. Products that are made from organic compounds, such as polyester resins and their catalyst systems, especially if they incorporate styrene, have particular difficulties in this regard. When the chemistry is brought to the field and curing is done under non-laboratory or less controllable conditions, it becomes even more difficult to get an NSF/ANSI Standard 61 listing. Only a few CIPP suppliers have NSF 61 listings. They have usually achieved acceptance by using epoxy resins, which are more costly than polyester resins, or by incorporating a polyethylene or polyurethane coating that separates the resin body from the potable water stream. Initially there was only one spray epoxy resin system that had an NSF 61 listing, now there are a dozen approved systems, but it has taken 15 years to achieve that level of acceptance. Some spray polyurethane resin systems, which use the same application process as epoxy, have also gained NSF 61 listings. A more streamlined testing program, and at lower cost, would allow other concepts to be tested easily and quickly – broadening the number of rehabilitation options available and eventually at lower cost.

4.1.6 Service Connections. Water mains, especially distribution pipes and service lines, may be buried with as little as 30 to 36 inches of soil cover in non-frost areas. In some northern areas, where frost penetration dictates deeper burials, up to 8 feet depths may be required. With water service connections every 25 to 50 feet, many water utilities feel that it is just as cost-effective to dig up and replace the entire main as to rehabilitate the main using trenchless methods if every service connection has to be excavated to be reinstated. In-line fittings almost always have to be replaced, which requires open-cut excavation, again minimizing the value of using trenchless techniques.

Several vendors have introduced products and procedures for remotely reinstating service connections from inside a lined main. Insituform's iTap mechanically locks the new liner to the existing corporation stop from inside the main without excavation. Sanexen has also developed a procedure for remotely sealing the area between the new liner and the service connection. Both of these are promising and may encourage more utilities to attempt trenchless rehabilitation over outright replacement. Another area of recent development has been in the application of keyhole "soft" excavation techniques to core through the road pavement and dig small diameter holes down to the service connection. Repairs to the line or new service connections are then made using special long handled tools within the keyhole excavation. These techniques have been pioneered mostly within the gas industry, but they also can be used in the water and wastewater sectors.

4.1.7 Experienced Contractors. The U.K. and Australia are often considered to be about 10 years ahead of the U.S. when it comes to asset management and water main rehabilitation. The majority of water main rehabilitation in the U.S. has consisted of cleaning and lining (cement mortar lining) of mains or replacement. Most lining used to date is a nonstructural rehabilitation method (thin internal coating) suitable only for pipes that have internal corrosion issues contributing to water quality or flow problems. Many contractors are experienced with CIPP lining gravity sewer mains, but only a handful have pressure pipe experience. Likewise, the use of close-fit PE and PVC liners, and other new rehabilitation technologies, has been very limited to date in the water industry, so finding experienced contractors can be difficult. Experienced contractors must also be familiar with installing temporary bypass systems and protecting water quality integrity. Many utilities incorporate experience requirements in tendering documents, which makes it very difficult to find a local contractor that meets those requirements.

It is very difficult to introduce a new rehabilitation technology into the U.S. water market. There is tremendous inertia to follow past practices and not consider new technologies or methods that might draw criticism if unsuccessful. Well documented and publicized demonstration projects by credible organizations can be important in overcoming this conservatism in addition to making available suitable standards and specifications for the new techniques.

4.1.8 Standards. As mentioned above, one way to overcome the reluctance of U.S. municipal engineers to try new rehabilitation technologies is through well developed consensus specifications that cover all of the necessary short-term and long-term performance requirements, along with the tests that demonstrate conformance to these requirements. Currently, these are significantly lacking for water rehabilitation technologies. At present, there are no AWWA specifications for rehabilitation of water mains, with the exception of cement mortar lining. For any national or consensus rehabilitation specifications or standards, one has to turn to NASSCO or use the available ASTM standards. NASSCO only has sewer specifications and derives most of its specifications from vendors or groups of vendors. ASTM has several specifications for the lining of pipes with cured-in-place liners (F-1216, D-5813, F-1743, F-2019, and F-2207). AWWA has just released C620-07, Spray Applied Epoxy Liners (AWWA, 2008). It has also been reported that the AWWA Rehabilitation Standards Committee is working on standards for pipe bursting and interior joint seals, which are nearing completion. However, many other types of pipe liners such as close-fit PE and PVC, spray epoxy or polyurethane, etc., are not adequately addressed by any national standard. Even more to the point, there are no national standards covering the full range of structural design issues for liners in deteriorated pipes. The design of the liner is dependent on the condition of the host pipe. The norm is to refer to the condition of the host pipe as either partially deteriorated or fully deteriorated, but the determination of these conditions is largely subjective. Either the liners are semi-structural, designed to bridge or span holes of a given dimension, or they are fully structural and capable of carrying the full internal design pressure should the host pipe fail completely.

Once again, the guidelines for determining what type of rehabilitation liner is needed are vague. The ASCE Pipeline Infrastructure (PINS) committee was attempting to establish better guidelines for the design of pressure and non-pressure liners, but the committee's report lacked sufficient detailed guidance and consequently has not been found very useful by the engineering community.

4.1.9 Maintenance Concerns. The operations and maintenance (O&M) staff of a utility are given the task of repairing failures that occur in a water main. They also have to operate the system, which often means cutting in new valves or taps for new services. Field crews are trained to work with the type of pipe materials that the utility has in its system. Repair clamps, mechanical couplings, and spare pipe sections are usually kept in inventory to handle emergency repairs. Instructions for repairing a pipe that has been lined with a close fit PE liner or CIPP are not widely publicized or known. As a consequence, O&M staff will tend to favor replacement of a deteriorated main with a pipe with which they are familiar, even if at a significant cost premium over a renovation lining technology. Until vendors can demonstrate practical methods for repairing damaged or failed mains that incorporate these new innovative liners, there is going to be continued reluctance on the part of O&M personnel to accept them as viable options to outright replacement.

4.2 Summary of Water System Issues

The water infrastructure in North America is older than the wastewater infrastructure. At the current pace of replacement (less than 1 percent per year) and installation of new pipes, the average age of the underground pipe infrastructure will gradually approach the commonly accepted design life of 50 years in 2050. Many pipes have been known to operate longer than their design life, but the frequency of failures increases with the age of the infrastructure. This means that unless a more aggressive rehabilitation program is adopted now, communities are going to be hit with significantly increasing repair costs in the not too distant future. The current drivers that exist in the wastewater side of the industry, including punitive actions for CSOs and SSOs, do not exist in the water industry. Water rates have historically been set at levels that do not truly reflect the value of this precious commodity, and politicians have been reluctant to adopt rate structures that would provide the necessary funding to make water utilities self supporting and sustainable.

Leadership in the area of design standards development for renewal and trenchless replacement technologies has been slow to evolve in North America. The design of a liner can be non-structural, semi-structural, or fully structural dependent on the level and type of deterioration in the host pipe. This determination is entirely subjective with little guidance provided by the expert community.

Techniques for the repair of pipes with liners are not well understood by those in charge of maintenance and operations in a water utility, and adding new materials and/or technologies is not readily welcomed by those who receive failure calls at 3 a.m. It will be many more years before a large body of contractors with significant water main rehabilitation experience exists – similar to what exists today in the wastewater side. Communities are reluctant to try new technologies especially with inexperienced installers who are also in the process of learning.

Streamlining the NSF Standard 61 approval process such that vendors can get more products screened quicker, and for less money, might open the door to more innovation in the industry.

Effective inspection and condition assessment of water pipe is generally difficult or extremely costly to carry out. Targeting mains for rehabilitation and replacement is largely centered on performance assessment: main break frequency or severity, water quality problems or poor hydraulic characteristics. Recently, emphasis on structural defects has shifted to improved leak-detection technologies that seek to reduce the loss of water and quickly identify faulty pipe to reduce the cost of repair and consequence of failure. Predictive models for deterioration based on pipe materials, ground conditions and failure history are considered useful in identifying the extent of the present and near future needs for rehabilitation.

5.0 CURRENT TECHNOLOGIES AND POTENTIAL FOR IMPROVEMENT

A wide variety of techniques exist to prolong the performance life of water and wastewater system assets or effectively replace the assets in situ. In practice, the applicability of each technique is evaluated based on the condition of the existing asset, site circumstances, cost, track record and local availability of the technique, and its expected ability to meet new performance requirements over an extended life cycle. Each technique has found its market niche and some technologies compete with others over a wide range of applications. In trying to improve the performance and cost-effectiveness of rehabilitation technologies, current methods represent the standards against which new technologies or the evolution of current technologies must be measured.

Descriptions of the wide range of commercially available methods for rehabilitation of wastewater collection and water distribution systems are provided in Appendices B and C, respectively. The emphasis is on methods that are in use or being introduced within the U.S. For each method, a very brief description of the method is given together with examples of the commercial providers of this method.

Rehabilitation includes both replacement and renovation or renewal of an existing pipe. Emphasis will be placed primarily on the renovation/renewal side of rehabilitation (including trenchless replacement via pipe bursting) although replacement by open cut, microtunneling and horizontal directional drilling (HDD) methods must also be considered. For water systems, the need for installation of temporary services lines is a major cost issue.

The range of technologies and their potential applications is summarized in Tables 7, 8 and 9. The application conditions are not intended to be absolute indicators but rather to represent the common range of practice. Taken together, these methods vide the state-of-the-practice for rehabilitation in the water and wastewater sectors and the opportunities to provide substantially increased value to utilities. They provide a wide range of innovative and cost-effective solutions, but there is still plenty of room for extension and refinements of existing methods and the addition of new approaches. Each of the categories of rehabilitation technologies is evaluated below in terms of the potential for additional advances or refinement in the near- to mid-term (i.e., less than 5 years or 5-10 years).

5.1 Sliplining

This is a mature technology with a number of pipe products available for use in sliplining. Changes in technology that would allow more cost-effective installations could include the ability to negotiate moderate bends within the length of a sliplined section, improved sliplining pipe materials and/or improved grouting materials. One innovation is sliplining a prefilled, pre-disinfected pipe in drinking water applications which can greatly speed the return to service of the water line. The use of ductile iron pipe for sliplining and fusible PVC are relatively new alternatives to HDPE pipe. Remote reinstatement of service connections would also be a major benefit.

5.2 Spiral-Wound Liners

This technology spans the range between ungrouted circular liner systems for small, circular pipes to non-circular, custom-profiled liners for large pipes and tunnels. Most of the experience with the systems has been overseas, but the technologies have been used in the U.S. over a full range of pipe sizes and for both circular and non-circular profiles. Since the profiles, their locking mechanisms, steel reinforcing strips, etc., vary from system to system, there is still a need to provide a performance history tied to the specific attributes of each lining configuration.

5.3 Cured In Place Pipe Liners

This is a mature technology in one sense, since CIPP liners have been installed since 1971. However, changes in the technical and operational aspects of CIPP lining continue to evolve. These are driven partly by technical innovations and partly by the need to stay competitive both within the CIPP market and in terms of competition with other liner systems. Recent innovations applicable to the U.S. market are in the introduction of UV-cure liner systems, the increased use of steam cure in place of water cure, the refinement of site operations to recycle hot water used for curing, the introduction of composite liner technologies and the expansion of the number of industry providers of CIPP installations. The challenges are the increasingly stringent controls on chemicals that may enter the aqueous or air environment and to maintain high levels of QC in a more commodity-driven business environment.

5.4 Close-Fit Liners

Close-fit liners involving the fold-and-form or symmetrical reduction system have a long track record of use in wastewater and water systems in the U.S. Swagelining and Rolldown systems have mainly been applied in water pipe rehabilitation. A factory-manufactured pipe is installed, but careful QC is still needed in the field during pull-in and expansion to fit the host pipe. Protruding service connections may also be a concern. Insituform Blue has recently introduced its PolyFlex and PolyFold products for the water industry which are HDPE close fit liners. The Insituform Blue products use 4710 (PE100) grade polyethylene, which has a 25 percent higher hydrostatic design basis (HDB). The newest entry to this sector is the Tight-in-Pipe (TIP) system which is more-or-less a hybrid of sliplining in conjunction with a minimal pipe bursting operation.

5.5 Grout-In-Place (GIP) Liners

The Trolining system remains relatively novel in the U.S. despite a number of years experience in use in Europe – especially in industrial applications. The system has significant flexibility in terms of total liner thickness, structural capacity, and leak containment and detection capabilities. An emerging technology in this category is the Mainsaver system which uses a thin studded polyethylene sheet that is anchored into a grout layer. The grout is distributed along the liner at the same time that the liner is inflated to fit tightly against the host pipe.

The liner offers relatively low cost installation with some level of structural bridging capability (Type II[1] liner as defined in AWWA M28 Rehabilitation of Water Mains (AWWA, 2001b).

5.6 Panel Liner Systems

Several structural panel lining systems are available in the U.S. market. These are essentially site fabricated, modular structures. There is still scope for innovation in terms of specific materials and installation procedures. An important issue is loading characteristics that should be considered for the liner design for deteriorated but still structurally adequate host pipe or tunnel systems. This issue also applies to most large-diameter liner systems.

5.7 Sprayed Coating and Liner Systems

The difficulty of providing a clean, sound surface for bonding of sprayed linings is a major impediment to the use of thin sprayed linings for corrosion control. Clean surfaces are particularly of concern in the

[1] Type II liners are semi-structural, not capable of independently sustaining the full operating pressure on a long term basis but able to span holes and joint gaps, resistance to external loads depends on adhesion to the host pipe.

wastewater sector. High-build linings can develop sufficient ring strength and stiffness and can function even with a poor bond. This is probably the growth area for sprayed linings in the wastewater sector – both using traditional materials such as shotcrete in culvert rehabilitation and using high-build polyureas and polyurethanes in pipe rehabilitation. In the water industry, sprayed polymeric compounds are having increasing success and achieving rapid cure times. In the water sector, the emphasis is shifting towards use of sprayed coatings as semi-structural and structural spray linings. Also available are carbon fiber reinforced pipe liners (CFRP) that can be used for local reinforcement of person-entry pipelines or a seismic upgrade of sections of pipelines.

5.8 Flood Grouting

Flood grouting is another wastewater rehabilitation system that has been used far more extensively in Europe than in the U.S. Three systems are potentially available for use, but more, well-documented field experience will help to increase confidence in the use of the technique and will provide comparative performance with separate mainline, lateral and manhole sealing systems.

Table 7a. Overview of Sewer Pipe Rehabilitation Methods—Mature Technologies

	Pipe Parameters		Work Requirements						Features		
Method	ID Diameter Range**	Repair Length	Plugging	Pit Excavation	Resin/ Coating*** Cure Time	Annular Space Grouting	Structural Repair	Excavation for Laterals Reopening	Cross Section Change	Removal of I&I	Corrosion Protection
1. Level of Cleaning required: Good / Very Good											
CIP, standard	8-96”	<2500’	Yes	No	Yes	No	Yes	No	Decrease	Yes	Yes
CIP, Top Hat	4-20” M 4-8” L	1’	Yes	No	Yes	No	No	No	Decrease	Yes	Local
Reinforced gunite	≥35”	<500’	Yes	No	Yes	No	Yes	No	Decrease	Yes	Yes
Spraying, epoxy	3-36”	<400’ typ.	Yes	No	Yes	No	No	Varies	Decrease	Yes	Yes
Robotic repairs	8-30”	24”	No	No	Yes	No	Local	No	Same	Yes	Local
2. Level of Cleaning required: General											
Sliplining	4-150”	<5,000’	No	Yes	No	Yes	Yes	Yes	Decrease	Yes	Yes
Fold and form	3-30”	<1500’	Yes	No	No	No	Yes	No	Decrease	Yes	Yes
Deform-reform	3-59”	<1,000’	Yes	No	No	No	Yes	No	Decrease	Yes	Yes
Compression-based SR*	4-20”	<3,000’	Yes	No	No	No	Yes	Yes	Decrease	Yes	Yes
Tension-based SR*	3-36”	<3,000’	Yes	No	No	No	Yes	Yes	Decrease	Yes	Yes
Chemical grouting	6-144”	Varies with diameter	Yes	No	Yes	No	No	No	Same	Yes	Yes
Spot repair sleeves	36-108"	18-36"	Yes	No	No	Varies	Local	Yes	Decrease	Yes	Yes
GRP panels	Man entry	No Limit	Varies	Yes	No	Yes	Yes	No	Decrease	Yes	Yes
2. Level of Cleaning required: None / Not Applicable											
Pipe bursting, static	2-54”	<750’	Yes	Yes	No	No	Yes	Yes	Same/ increase	Yes	Yes
Pipe bursting, pneumatic	2-54”	<750’	Yes	Yes	No	No	Yes	Yes	Same/ increase	Yes	Yes
Pipe bursting, hydraulic	2-20”	<750’	Yes	Yes	No	No	Yes	Yes	Same/ increase	Yes	Yes
Pipe extraction	1-60”	<200’	Yes	Yes	No	No	Yes	Yes	Same/ increase	Yes	Yes
Pipe reaming	4-24”	<600’	Yes	Yes	No	No	Yes	Yes	Same/ increase	Yes	Yes

* SR = Symmetrical Reduction; ** M = Mainline; L = Lateral; *** Not grouting. Table entries should be considered indicative of applications but not definitive for all products.

Table 7b. Overview of Sewer Pipe Rehabilitation Methods—Emerging Technologies

	Pipe Parameters		Work Requirements						Features		
Method	ID Diameter Range*	Repair Length	Plugging	Pit Excavation	Resin/ Coating Cure Time	Annular Space Grouting	Structural Repair	Excavation for Laterals Reopening	Cross Section Change	Removal of I&I	Corrosion Protection
1. Level of Cleaning required: Good / Very Good											
CIP, T-liners	6-24” M 3-6” L	<160’	Yes	No	Yes	No	Yes	No	Decrease	Yes	Yes
Spraying, polyurethane	Varies	Varies	Yes	No	Minimal	No	Varies	Varies	Decrease	Yes	Yes
Spraying, polyurea	Varies	Varies	Yes	No	Minimal	No	Varies	Varies	Decrease	Yes	Yes
2. Level of Cleaning required: General											
Spiral winding	6-180”, 12’×15’	<650’	No	Varies	Varies	Yes	Yes	Yes	Decrease	Yes	Yes
Grout-in-place (GIP)	6-80”, >80” (panels)	<525’	Yes	No	Grout only	Yes	Yes	No	Decrease	Yes	Yes
Internal joint sealing	14-216”	7-10”	Yes	No	Varies	No	No	No	Same	Yes	Yes

* M = Mainline; L = Lateral. Table entries should be considered indicative of applications but not definitive for all products.
Emerging technologies are defined here as those that have been used commercially in a substantial number of applications in the U.S., but not yet recognized as a mature technology.

Table 7c. Overview of Sewer Pipe Rehabilitation Methods—Novel Technologies

	Pipe Parameters		Work Requirements						Features		
Method	ID Diameter Range*	Repair Length	Plugging	Pit Excavation	Resin/ Coating** Cure Time	Annular Space Grouting	Structural Repair	Excavation for Laterals Reopening	Cross Section Change	Removal of I&I	Corrosion Protection
1. Level of Cleaning: Good / Very Good											
CIP, composite	24-96”	<700’	Yes	No	Yes	No	Yes	No	Decrease	Yes	Yes
2. Level of Cleaning: General											
Flood grouting	Not specific	Not specific	Yes	No	Yes	No	No	No	Same	Yes	Yes
3. Level of Cleaning: Minimal											
Tight in place (TIP)	8-15”	500’	Yes	No	No	No	Yes	Yes	Decrease	Yes	Yes

* M = Mainline; L = Lateral; ** Not grouting. Table entries should be considered indicative of applications but not definitive for all products.
Novel technologies are defined here as those that have only been used at the pilot-scale, in a few commercial applications, or are new to the U.S. market.

Table 8. Overview of Water Pipe Rehabilitation Methods

	Pipe Parameters			Work Requirements				Features		
Method	ID Dia. Range*	Repair Length	Working Pressure psi	Pit Excava-tion	Resin/ Coating** Cure Time	Annular Space Grouting	Excavation for Service Reopening	AWWA Classifi-cation	Cross Section Change	Status of Technology (U.S.)
Level of Cleaning Needed: Very Good										
Woven PE/epoxy lining	3-24”	Varies	150	S/N	Yes	Adhered	No	II	Minor	Emerging
Level of Cleaning Needed: Good										
CIP	8-96”	<2,500’	200	S/N	Yes	No	No	III	Minor	Mature
Deform-reform, PRP	3-12”	<1,000’	230	S/N	No	No	No	III	Minor	Novel
Deform-reform, PE	3-48”	<1,000’	150	S/N	No	No	No	III	Minor	Mature
Spraying, cement mortar	3-24” and up	<1,000’	NK	S/N	Minimal	No	No	I	Minor	Mature
Spraying, epoxy	3-36”	<1,000’	NK	S/N	Yes	No	No	I	Minor	Mature
Spraying, polyurethane	3-48”	<1,000’	NK	S/N	Yes	No	NK	II	Minor	Novel
Spraying, polyurea	3-36”	<1,000’	NK	S/N	Minimal	No	NK	IV	Decrease	Novel
Level of Cleaning Needed: General										
Sliplining	>4”	<5,000’	360	L	No	Varies	Yes	III	Decrease	Mature
Compression-based SR*	4-20”	<1,000’	New pipe	M/L	No	No	Yes	IV	Minor	Emerging
Tension-based SR*	3-36”	<1,000’	New pipe	M/L	No	No	Yes	IV	Minor	Emerging
Grout-in-place (GIP)	4-12”	<600’	NK	L	Yes	Integral	No	III	Decrease	Novel
Level of Cleaning Needed: None or Not Applicable										
Pipe bursting, static	2-36”	300-400’	New pipe	L	No	No	Yes	IV	Same/ increase	Mature
Pipe bursting, pneumatic	2-36”	20-500’	New pipe	M	No	No	Yes	IV	Same/ increase	Mature
Pipe bursting, hydraulic	2-36”	NK	New pipe	M	No	No	Yes	IV	Same/ increase	Mature
Pipe extraction	1-60”	NK	New pipe	M	No	No	Yes	IV	Same/ increase	Rare
Pipe reaming	4-24”	1,600’	New pipe	M	No	No	Yes	IV	Same/ increase	Mature
Carbon fiber reinforced pipe (CFRP)	Man entry	NA	High pressure	M	Yes	No	Yes	IV	Minor	Emerging
Spot repair / joint repair	4-54”	12-36”	Varies	S/N	Minimal	Adhered or none	N/A	IV	Same/ decrease	Mature

* SR = Symmetrical Reduction; NK = Not known; S/N = Small or none; M/L = Medium or large; L = Large;
AWWA classification of potable water rehabilitation systems I = Nonstructural; II = Semi-structural without inherent ring stiffness (depends on adhesion); III = Semi-structural with inherent ring stiffness (self supports); IV = Structural.

Table 9. Overview of Manhole Rehabilitation Methods

Method	Manhole Parameters		Requirements and Features of Rehabilitation Method						Technology Status in U.S.
	ID Diameter Range	Height Range, ft	Annular Space	Duration	Invert Repair	Bench Repair	Removes Infiltration/ Inflow	Structural Repair	
Preformed manhole units	3.5–6 ft	3–25 ft	Yes	6-8 hrs	Yes	Yes	Yes	Yes	Mature
Poured-in-place concrete	Any	Any	No	8 hrs	Yes	Yes	Yes	Yes	Mature
Cured-in-place manhole (CIPM)	2.0–19 ft	Any	Yes	4-8 hrs	Yes	Yes	Yes	Yes	Emerging
Grout-in-place liners	Any	Any	No	8 hrs	Yes	Yes	Yes	Yes	Mature
Cementitious coatings, spincast	8”-12 ft	Any	No	2 hrs	Yes	Yes	Yes	Yes	Mature
Cementitious coatings, sprayed	Any	Any	No	2 hrs	Yes	Yes	Yes	Yes	Mature
Coatings, epoxy	Any (sprayed)	Any	No	2.5-6 hrs	Yes	Yes	Yes	Yes	Mature
Coatings, polyurethane/polyurea	Any (sprayed)	Any	No	½ -1 hr	Yes	Yes	Yes	Yes	Novel
Coatings, modified polymer skin panels	Any (sprayed)	Any	No	1 hr	No	Yes	Yes	Yes	Emerging
Flood grouting	Any	Any	No	8 hrs	No	No	Yes	No	Novel
Dish inserts, Grade rings	Any	NA	No	Varies	No	No	Yes	Localized	Mature
Chimney seals, mechanical	Any	NA	No	Varies	No	No	Yes	Localized	Mature
Chimney seals, CIP	Varies	2-3 ft [a]	No	Varies	No	No	Yes	Localized	Novel
Chimney seals, polymer	Varies	NA	No	Varies	No	No	Yes	Localized	Novel
Barrel joint seals, mech., cementitious, polymer	Varies	NA	No	Varies	No	No	Yes	Localized	Mature
Channel inserts	Any	NA	No	Varies	Yes	No	Minor	Localized	Mature

(a) 5” into the cone.

6.0 EMERGING AND NOVEL TECHNOLOGIES

In this section, a series of emerging technologies or technological/management advances that will assist in the effective rehabilitation and management of water and wastewater systems are highlighted and other potential advances are discussed. Emphasis will be placed on those technologies that are new or emerging in U.S. applications.

6.1 Potential Technology Candidates for Demonstration

Tables 10, 11, and 12 provide a list of those technologies that are considered potential candidates for demonstrations. The suitability of these technologies for demonstration in terms of their stage of development and their potential breadth of application were discussed during the International Technology Forum.

Table 10. Novel and Emerging Trenchless Pipeline Rehabilitation Methods

Method	Example Technology	Area of Innovation	Diameter Range	Repair Length	Application
		Relining			
Spray lining-ESL	Copon Hycote (E. Wood)	High build epoxy for semi-structural renovation, bridge holes	4” - 12”	500’	Water pipe (AC/ferrous)
Spray lining – PSL	Heitkamp	Polyurethane lining cures in 30 min., outage reduced to 6 hours	4” - 12”	500’	Water pipe (ferrous)
CIPP, inversion	Iplus Composite™ (Insituform)	Composite liner (carbon/fiberglass) resulting in thinner tube, started in 2005	24” - 84”	1,000’	Sewer pipes, gravity
CIPP, pulled in	AquaPipe® (Sanexen)	Robotic reinstatement of services, in U.S. since 2005, NSF 61 Listing	6” - 12”	500’	Water pipes
CIPP, pulled in	Blue-Tek™ (Reline America)	Factory pre-impregnated, UV cured, in U.S. since 2005. Working on the applicability in water pipelines.	4” - 48”	1,000’	Sewer pipes, gravity or pressure
Hose Lining-non adhesive back	Thermopipe™ (Insituform)	Thin PE liner reinforced with woven polyester fiber. Rated to 150 psi.	3” - 12”	700’	Water or sewer pipes, pressure
Compression symmetrical pipe reduction	Rolldown PolyFlex™, (Insituform)	HDPE pipe pulled in with diameter reduced up to 20% (round shape), in U.S. since 2006	4” - 48”	800’	Water pipes
Grout-in-place	MainSaver™	Composite liner (MDPE liner pulled in, cement grout in annular space), in U.S. since 2006	4” - 12”	350’	Water pipes

Table 10. Novel and Emerging Trenchless Pipeline Rehabilitation Methods (Continued)

Method	Example Technology	Area of Innovation	Diameter Range	Repair Length	Application
Close fit PVC	Duraliner™ (UGSC)	Expansion of PVC pipe to form close fit reorients molecular chain increasing strength, NSF 61 Listing	4" - 30"	1000'	Water pipes
Grout-in-place	Trolining®	Composite liner (HDPE liner pulled in, cement grout in annular space), in U.S. since 2005	6" - 120"	650'	Sewer pipes, gravity
Sliplining, continuous	Fusible C900™ (UGTC)	PVC pressure pipe butt fused and pulled into host pipe	6 - 36"	3000'	Water pipe, pressure
Sliplining, segmental	Push-and-Drive (IPEX/TT Technologies)	PVC pipe pulled in place, close fit, coming on the market soon	6" - 12"	500'	Sewer pipes, gravity
Sliplining, segmental	Channeline	FRP panels usually 3' or 6' long, for man-entry pipes, tongue-and-groove or bell-and-spigot, was offered in U.S. 2002-2005 (Hobas)	36" - 20 ft	No limit	Sewer pipes, gravity
Spiral Wound	SPR (Sekisui)	PVC spiral-wound, in U.S. since 2005	36" - 12' x 15' and larger	1,000'	Sewer pipes, gravity
		Pipe Replacement - online			
Pipe Bursting/ Splitting	Impactor® (HammerHead)	Merging of pipe bursting with HDD for faster replacement and less excavation (in U.S. since 2002), upsizing by 25% possible	4" - 48"	Over 3,000'	Sewer and water pipes
		Pipe Replacement - offline			
Direct PipeTM Hybrid	(Herrenknecht)	HDD/Pipe jacking hybrid. Novel system to thrust pipe by external gripping.	8" - 144"	700'	Sewer pipes, gravity and pressure pipes
Horizontal Directional Drilling (HDD) for on-grade sewer	Various	Directional drilling with HDPE or PVC pipe pulled into hole during pull back. Mature for water applications, emerging for on-grade sewer applications	4" - 54"	3000'	Water pipes, pressure and gravity sewer with sufficient grade tolerance.
		Flood Grouting			
Flood grouting	Sanipor®	Simultaneous main/manhole/lateral sealing, limited use in U.S.	Any	No limit	Sewer pipes, gravity

Note: Refer to Tables 7, 8 and 9 for a more complete listing of technologies. This table only lists some technologies that are considered more novel or still emerging in the U.S. market.

Table 11. Novel and Emerging Technologies for Manhole Rehabilitation

Method	Example Technology	Technology Outline
	Relining	
Cured-in-place liners (CIP)	MultiPlexx Liner™ (Terre Hill)	Patented composite CIP liner (PVCP = PVC polyester) developed around 2002. In addition, MultiPlexx Layup™ is a segmented MultiPlexx Liner™ used in hard to reach places.
High Build Polyurenthane / Polyurea	SprayrockTM Innov. Painting & Waterproofing	High build, quick setting sprayed polymer linings suitable for structural repairs as well as corrosion protection.

Note: Refer to Tables 7, 8 and 9 for a more complete listing of technologies. This table only lists some technologies that are considered more novel or still emerging in the U.S. market.

Table 12. Novel and Emerging Trenchless Methods for Rehabilitation of Wastewater Laterals

Method	Example Technology	Area of Innovation	Diameter Range	Repair Length
		CIP Relining		
UV cured CIPP lateral liner	InFlex Liner™ (Reline America)	Factory preimpregnated, UV cured, in U.S. since 2007	2"-8"	≤150'
CIPP, T-liners	LMK T-Liner®	Full circle mainline seal (16") added, in use since 2004	3"-6"	≤160'
		Pipe Replacement		
Pipe bursting/ splitting	Tric™ Trenchless, TT Technologies	Equipment scaled for effective use in laterals	4"-8"	20'-200'
		Chemical Grouting		
From main, long bladder	Logiball Connection	Long bladders, available since 2004	4"-6"	5'-30'
		Flood Grouting		
Flood grouting	Sanipor®	Simultaneous main/manhole /lateral sealing, limited use in U.S.	Any	No limit
		Robotic Repair		
Robotic repairs	Janssen	Structural repair with surrounding soil stabilization, in U.S. since 2005	4"-12"	2'

Notes: Refer to Tables 7, 8 and 9 for a more complete listing of technologies. This table only lists some technologies that are considered more novel or still emerging in the U.S. market.

6.2 Cross-Cutting Innovation Potential

As discussed in Sections 2, 3 and 4, there are many aspects pertaining to the rehabilitation of water and wastewater systems that are not specific to any particular technology. These issues are summarized below.

6.2.1 New Materials. Most techniques could benefit from the availability of new or improved materials – with enhanced strength, stiffness, corrosion resistance, short installation, curing time, etc. Most new materials, however, would need to be applied using one of the existing approaches for creating a liner inside a pipe, manhole or ancillary structure. New materials using carbon nanotubes are likely to be too expensive for use in the wastewater industry. Clay nanotubes are much less expensive and may prove to have uses in wastewater rehabilitation. However, recently released work on the health effects of carbon nanotubes indicates that there may be long-term asbestos-type health issues if the nanotubes are inhaled. Geopolymers can provide a grout or concrete-like material for use in the wastewater sector that have rapid strength gain and much higher corrosion resistance than concrete. They represent very environmentally friendly materials since their principal constituent is the waste fly ash from coal-fired power plants. Research is underway to adapt and control the flowability, set time, curing conditions, etc., so that the materials can be used successfully in cast, spray or grouting operations.

6.2.2 Wastewater Innovations. Anticipated innovations or continued technology developments that are specifically related to wastewater are:

- Enhanced understanding of realistic loading scenarios and their probabilities and risk. This is probably the weakest area of current design approaches for rehabilitation technologies. Some research is underway, but much remains to be done.
- Consistent design and specifications across rehabilitation technologies. Such work is necessary so that competing rehabilitation technologies can be fairly evaluated in terms of cost, risk, and performance.

6.2.3 Water Innovations. Anticipated innovations or continued technology developments that are specifically related to water are:

- Reliable liner-service connections made without excavation at each service connection
- Service connections made using keyhole technologies where internal reconnection is not feasible
- Trenchless rehabilitation and replacement of service lines without street excavation
- Spray on structural liners
- Thinner composite liners that reduce the amount of cross section loss
- Methods that reduce or eliminate the need for temporary service lines.

6.2.4 Decision Support. A utility owner must choose the appropriate range of rehabilitation options for any project from the wide range of possibilities described in this White Paper. In addition to the performance and cost of the rehabilitation method, such decisions derive strongly from the utility's overall asset management strategy, available rehabilitation technologies, and the assessed condition and predicted deterioration rate of the pipe or structure under consideration.

Rehabilitation technologies include a broad spectrum of approaches that attempt to return the system to near-original condition and performance:

- A repair technique is used when the host pipe/structure is structurally sound and provides acceptable flow capacity.
- A rehabilitation technique is used where improved hydraulic conditions and structural strength are needed.
- A replacement technique is undertaken when the pipe/structure is severely deteriorated, and/or an increased flow capacity is needed.
- Choices among repair, rehabilitation and replacement also need to consider the estimated life cycle cost of the facility under each option.

- The asset management and condition assessment aspects of decision support are being evaluated elsewhere. Only the aspects that relate to choice of the rehabilitation technology will be discussed here.

The following are the key issues:

- For water and wastewater systems, the current system goals, existing pipe/structure condition, corrosion level and flow quality must be known in sufficient detail to address and determine whether a structural, hydraulic and/or a water quality problem exists.
- For wastewater systems, the above determination may depend on the planned phasing of work across the system and whether consent decrees with time limits for I&I reductions are in effect. For example, a grouting program to reduce I&I may provide immediate I&I relief at a reasonably low cost, permitting a less hurried approach to sector-by-sector evaluation and rehabilitation.
- Site and soil conditions, neighboring structures, geometrical configuration, and structural condition of the host pipe will limit the choices of the renewal technologies applicable to any particular project.
- While an engineer experienced in water or wastewater renewal could quickly arrive at the appropriate set of technologies that are applicable, this step can take considerable amount of research and effort for designers that are not familiar with all of the available rehabilitation technologies. Also, an experienced engineer may be unfamiliar with new technologies that are just being introduced.
- The selected technologies and materials must be acceptable to the utility.
- Once the applicable technologies have been narrowed to an acceptable list, organizations must be able to be competitively bid on a level playing field in terms of specifications, and there should be a reasonable likelihood of available bidders for each technology.

Some decision support software is already available to assist in this process (Matthews and Allouche, 2007), but significant refinements are possible that, for example, could directly import condition assessment information and incorporate system-wide preferences into job-by-job selections. Selection of current renewal techniques should be based on the structural, hydraulic, joint leakage, or water quality problems of the main. As part of the project, additional information will be collected: (1) to identify the decision criteria used by each utility for choosing water and sewer main pipes for repair, rehabilitation, or replacement; and (2) to obtain descriptions of the technologies previously selected and the reasons for their selection. For water systems, based on the AWWA M28 Manual (AWWA, 2001b), the key elements of a decision model to renew a structurally deteriorated pipe must include:

(1) The exact nature of the problem
(2) The hydraulic and operating pressure required for the rehabilitated main
(3) Materials, geometry and dimensions of the main
(4) Types and locations of valves, fittings, and service connections
(5) Length of time for which the main can remain out of service
(6) Site-specific factors

An example of a decision tree for the rehabilitation/replacement of a structurally deteriorated water pipe is shown in Figure 4 (AWWA, 2001b).

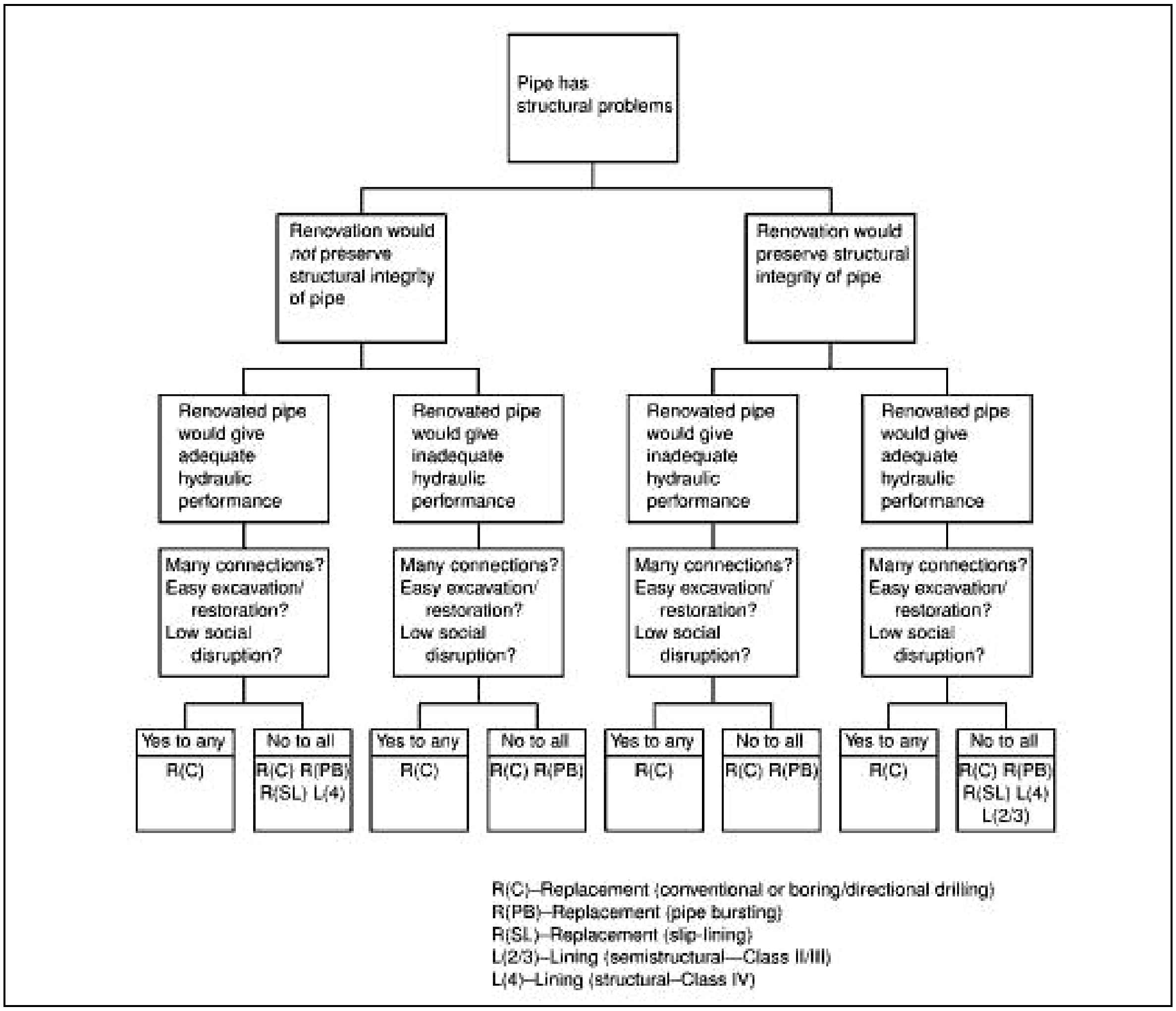


Figure 4. Selection of Rehabilitation Techniques to Solve Structural Problems [AWWA, 2001b]

It is proposed that a multi-criteria evaluation methodology be used for an enhanced decision-making process. Multi-Criteria Evaluation (MCE) is a set of procedures designed to facilitate decision-making. The basic purpose is "to investigate a number of choice possibilities in the light of multiple criteria and conflicting objectives" (Voogd, 1983). The objective of a multi-criteria methodology is to find the proper balance of repair, rehabilitation, and replacement options and to select the "best" option and/or a ranked order of options. "Best", in this context, could be interpreted as a function of the condition improvement, cost effectiveness, water quality, practicality, degree of disruption, risk reduction, and other criteria. Figure 5 shows a conceptual framework for selecting appropriate technologies.

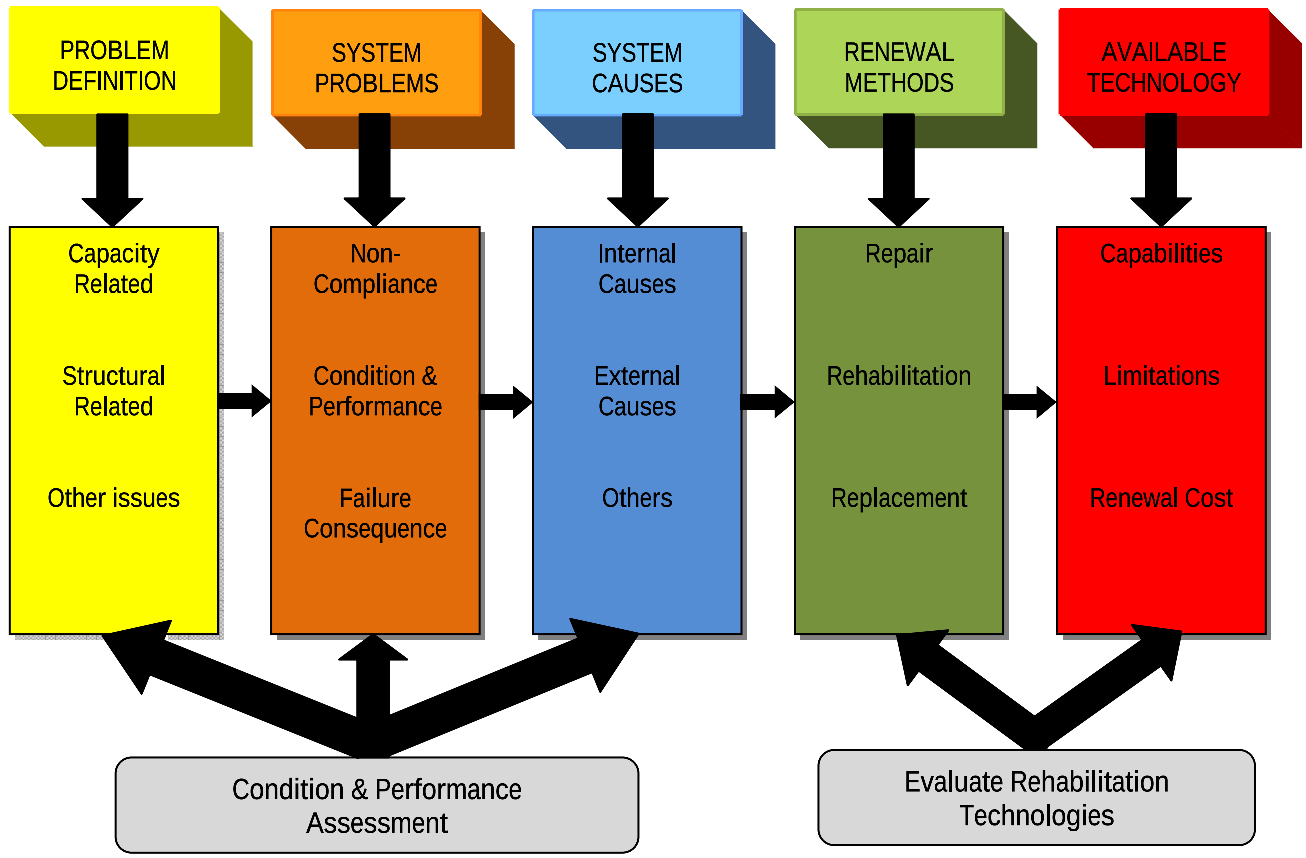


Figure 5. Conceptual Framework for Selecting Appropriate Technologies

6.2.5 Accelerating Adoption of New Technologies. Technologies with a clearly recognized advantage over existing methodologies will eventually be embraced by both industry and the owners. However, the advantage of a proactive approach to evaluating and introducing technologies is to shorten the timeframes for adoption of beneficial technologies and reduce failures during the commercialization process. The pitfalls for a new technology on the way to commercial success are extensive and will not be re-examined in detail in this white paper. The major pitfalls include:

- Initial application(s) attempted are not successful, although the method could have been successful under less challenging conditions and the same challenging conditions could have been mastered later in the product life cycle.
- Overcoming experience requirements, owner conservatism, competing industry resistance, etc.
- Overselling the technologies leading to inappropriate applications and failures
- Developmental and testing costs exceed the ability of the technology developer to underwrite and sufficient external investment is not raised.
- Technology is under capitalized, i.e. with insufficient funding to survive the market introduction process whereby the product must be accepted more-or-less on an owner-by-owner basis across the country.

There are many facets to the introduction of a new technology to water and wastewater industry, whether invented from scratch or being introduced from another industry or country. Appropriate specifications and standards must be created, local technology demonstrations typically are required, standard and specialized testing (short- and long-term) will need to be conducted or evaluated by organizations accepted by the owners, and cost and performance data prepared to show the benefits of the new technology.

It is possible, however, for government and other organizations to greatly assist in the process of speeding up technology introductions and reducing unnecessary and duplicative costs for the technology developers. The following are some examples of programs that have proved successful in assisting the technology introduction process.

EPA Environmental Technology Verification (ETV) Program. The ETV program was developed by EPA to provide a voluntary but consistent methodology whereby new technologies could establish their environmental performance. The technology can then be "verified" as meeting this standard of performance which helps to overcome some of the barriers to introducing novel technology.

Civil Engineering Research Foundation (CERF) Program. During its years of operation, CERF developed an exemplary technology evaluation program to help bring new technologies to the marketplace. Key aspects of the program included a review panel drawn from major potential users of the technology, and support from an expert consultant or organization. The panel developed the testing program and reviewed the results that were executed by the company and the consultant.

California Pipe Users' Group. It is typically far more efficient for both the potential users of new technologies and for their developers to carry out new product assessment activities in a group setting. The appropriate personnel in a variety of user organizations and their consultants can share application information and develop consensus approaches to new product acceptance.

Trenchless Technology Municipal Users' Forum Program. In a similar fashion to the California Pipe Users' Group, the TTC at Louisiana Tech University organizes local/regional forums across the country which is designed to stimulate the sharing of information among the potential users of trenchless technologies. Successes and problems can be shared leading overall to a higher effectiveness for rehabilitation efforts.

Center for Innovative Grouting Materials and Technology (CIGMAT), University of Houston. CIGMAT has been active in research and testing related to buried piping systems for more than a decade. It has been a active partner in the development of test protocols for use in the EPA Environmental Technology Verification program.

The University of Louisville Center for Infrastructure Research. The center was formed in August 2002 through a partnership between the University of Louisville, the Metropolitan Sewer District and the Louisville Water Company. The intent of the center is to leverage the limited resources of these sponsors and additional sponsors to solve common problems and then to disseminate the learned information.

Accelerated Pavement Testing Programs. Accelerated Pavement Testing (APT) programs have been conducted by State Departments of Transportation (DOTs) across the country. DOTs have gained immensely by instituting such APT programs that particularly have made significant headway in terms of quantifying pavement performance characteristics under various field conditions. Florida DOT in particular has an exemplary APT program. This model could be adapted to develop a program.

EPA Science To Achieve Results (STAR) Program. The STAR program targets the encouragement of research to advance environmentally related technologies with a mission to include U.S. universities and non-profit groups in the EPA research program to ensure the best possible quality of science in areas of highest risk and importance to EPA. Sub-programs include: targeted research grants, exploratory research grants, graduate fellowships and research center competitions.

Small Business Innovation and Research (SBIR) Grants. The SBIR program targets assistance to small businesses in conducting research and developing technological innovations. Similar programs are operated by many federal agencies and they also encourage the collaboration of small business with academic researchers.

AwwaRF/WERF Research. AwwaRF and WERF have sponsored relevant research and field demonstrations in this area. For example, a field demonstration program was held to evaluate various trenchless technologies as alternatives to open-trench rehabilitation and replacement of water mains. The objective was to identify conditions under which each technology could be best applied (Deb et al., 1999).

6.2.6 Observations on Successful Programs. The programs above address issues involved in gaining the approval for the use of a new technology and expanding its marketplace of application by providing:

- User input for defining the standards that new technologies must meet before they are considered acceptable
- Independent verification of the claims of technology developers
- Sharing of information about new technologies among peer user groups
- Accessing the talents and resources of the nation’s universities
- Easing the financial burden on a technology developer in bringing a new product to geographical and organizational diverse market.

7.0 EPA DEMONSTRATION PROJECTS

7.1 Purpose of Technology Demonstration

As discussed in the previous sections, the water infrastructure in the U.S. is deteriorating at an accelerating rate. Some important factors behind the deterioration are reduced funding, poor installation resulting from insufficient QC, little or no inspection and maintenance, and a general lack of uniformity and improvement in design, construction, and operation practices. To meet the challenge of ongoing and increasing needs for maintenance and repair of the water and wastewater systems, many utilities are seeking innovative technologies to replace, renew, or extend the life of their systems, and to meet more stringent regulatory requirements. Unfortunately, information on new and emerging technologies is not always readily available or easy to find, especially when applied under actual field conditions.

Lack of knowledge on the performance of innovative and emerging rehabilitation technologies and the limited ability to determine the most cost-effective, long-term rehabilitation methods for water distribution and wastewater collection systems were identified as critical gaps by the key stakeholders participating in the March 2006 EPA *Workshop on Innovation and Research for Water Infrastructure for the 21st Century* (EPA, 2006a). To help fill these gaps, a demonstration program on emerging and innovative rehabilitation technologies was proposed, in collaboration with water and wastewater utilities, to gather reliable performance and cost data during applications of these technologies under a wide range of field conditions (EPA, 2007b).

Demonstration of emerging and innovative rehabilitation technologies at selected sites in the U.S. can make the capability of these technologies better known to the water and wastewater industry, allowing their applications to be promoted in the U.S. The impartial assessment on the effectiveness, longevity, expected range of applications, and life-cycle cost of the demonstrated technologies can assist the utilities in determining whether rehabilitation or replacement is more cost effective and in selecting which rehabilitation technology to use.

7.2 Previous Demonstration Projects and Benefits of Demonstration. There are many case studies and laboratory-scale and pilot-scale evaluations on innovative and emerging rehabilitation technologies and materials (EPA, 2006b), but only a handful of field demonstration projects have been conducted to date. Two examples are illustrated below:

- **Demonstration of Innovative Water Main Renewal Techniques.** The AwwaRF sponsored this field demonstration project in 1999 to evaluate three trenchless technologies for water main renewal and identify conditions under which each technology could be best applied (Deb et al., 1999). It successfully demonstrated a pipe bursting technology to burst an existing 6-inch CI pipe and replace it with an 8-inch DI pipe (i.e., a bell-less microtunneling push pipe).
- **Demonstration of Decision Support Tools.** Computer Aided Rehabilitation of Sewer Networks (CARE-S) and Computer Aided Rehabilitation of Water Networks (CARE-W) are European Commission-developed rehabilitation decision support systems that have been adapted by water utilities to set up strategic and tactical rehabilitation plans. It is important to evaluate the applicability of these tools in a range of utility types and sizes and optimize data collection. Researchers at the Polytechnic University of New York recently conducted a demonstration project of CARE-W at Las Vegas to develop a cost-effective system for maintaining and repairing the water distribution networks. The project has developed performance indicators, a failure forecasting model, a hydraulic

reliability model and long term economic simulation tools, and an annual rehabilitation planning program (Vanrenterghem-Raven, 2007).

From these and other past demonstration projects, it suggests that well documented and publicized demonstration projects by credible organizations can play an important role in accelerating development, evaluation, and acceptance of new technologies. A successful demonstration project will not only generate good quality data, which is useful to the research communities, but also provides substantial value to the utilities, manufacturers/technology developers, and consultants/service providers. The benefits of the technology demonstration to these various groups are summarized below:

- Benefits to Utilities
  - Reduced risk of trying new technologies and new materials on their own
  - Increased awareness of emerging technologies, particularly those from overseas, and their capabilities
  - Assistance in setting up strategic and tactical rehabilitation plans
  - Identification of regulatory and quality control issues.

- Benefits to Manufacturers/Technology Developers
  - Opportunity to advance technology development and commercialization
  - Opportunity to accelerate the adoption of new technologies in the U.S.

- Benefits to Consultants and Service Providers
  - Opportunity to compare performance and cost of similar products in a consistent manner
  - Access to standards and specifications for the new techniques
  - Education of best practices on pre- and post-installation procedures and testing

7.3 Special Aspects of Planned EPA Demonstration Project

While the technology demonstration project is intended to evaluate the capability and performance of the technology, it also provides an opportunity to address/examine several key issues identified in Sections 2, 3, and 4. Special aspects of the EPA demonstration project are discussed below, aiming to bring added value to the water and wastewater rehabilitation industry within a five to 10 year timeframe.

7.3.1 Demonstrate Application of Consistent Design Methodologies and Decision Support Approaches to the Selected Technologies. The need for consistent design methodologies and decision support approaches for different rehabilitation systems is discussed in previous sections. Because of the rapid evolution of rehabilitation technologies, standards and codes often lag behind, which poses a great challenge to the design work. Types of qualification testing and consistent test protocols for the selected technologies are also needed to ensure conformance of the rehabilitation technology to the specifications. Standards and Codes of Practice do exist overseas and the adaptation of these measures to the North American market is one way to quickly advance the development of standards and codes. An important role of the EPA demonstration project is to identify/develop common specifications for the selected technologies and apply consistent design methodologies based on the specifications. It may require collaborations with organizations such as NASSCO, ASTM, Water Environment Federation (WEF), and ASCE in identifying and developing the specifications.

7.3.2 Demonstrate Application of Appropriate QA/QC and Post-Installation Procedures. The success of a rehabilitation project depends largely on the proper installation controls and post-installation inspection and assessment. The level of the qualification testing and QA requirements vary from technology to technology; sometimes there is no clear industry quality standard. The demonstration project provides an opportunity to examine the current QA practices and identify areas for improvement. For the technologies lacking an industry quality standard, QA/QC procedures developed by the manufacturers and utilities shall be reviewed and adopted (as appropriate) to the demonstration project. The demonstrations will allow the QA/QC protocols to be tested.

Post-installation tests range from taking samples from finished installation for mechanical properties testing, air-pressure testing, water exfiltration testing, to non-destructive testing (NDT) using CCTV and ultrasonic technologies. Preferences shall be given to NDT approaches for the demonstration project.

Some rehabilitation technologies do have reasonable QA testing specifications; however, system owners often do not execute them at the end of the rehabilitation because they assume design performance can always be achieved. The process to identify installation deficiencies through application of QA protocols will be documented through the demonstration project, which can be useful to educate the utility owner of the importance of good QA practices for an effective rehabilitation.

7.3.3 Demonstrate Life-Cycle Plan for Ongoing Evaluation of Rehabilitation Performance. Data on the long-term effectiveness and longevity of rehabilitation technologies are difficult to obtain from the field demonstration directly due to the short timeframe of the project versus the long service life of many rehabilitation technologies, i.e., the design life for CIP liners is estimated to be 50 years or more (WERF, 2006). It is important for the demonstration project to lay the groundwork by assisting the utilities in developing a life cycle plan for ongoing evaluation of rehabilitation performance. For example, the project shall collect relevant environmental and performance data before and immediately after rehabilitation (e.g. water quality in water systems or infiltration estimates in sewer systems) to provide a baseline for long-term evaluation. Many operational and environmental factors, such as soil conditions, stress conditions, groundwater levels, sewage/soil acidity, and dissolved oxygen levels for wastewater and water quality for water, may have negative impacts on the effectiveness and longevity of rehabilitation. It is important to characterize these factors on a long-term basis.

Indirect metrics, such as long-term laboratory coupon tests and accelerated aging tests combined with model simulation, may be useful in evaluating the long-term effectiveness of new materials/ technologies. Recommendation and suggestions were solicited from the Forum participants to identify additional metrics to assess the long-term effectiveness of rehabilitation technologies.

7.3.4 Document Data from Demonstration. The demonstration project shall collect the following data/information at each demonstration site:

- Installation process, procedures, and problems encountered
- Performance data: collect short-term data and establish procedures for tracking long-term effectiveness, and projected longevity
- Labor requirement and cost information for conducting demonstration, including design, capital, and O&M costs
- Comments and feedback from utility owners and consultants

Such information will be included in a project report available to the project participants.

7.3.5 Provide an Assessment of Selected Technology, Expected Range of Applications, Avenues for Improvements. The demonstration project will assess the short-term and long-term effectiveness and life-cycle cost of the selected technologies in comparison with the respective vendor specifications and identify conditions under which each technology can be best applied. It will also provide suggestions on necessary improvements for the technology itself, the installation procedures, and QA/QC procedures. The expected range of applications claimed by technology vendors can be verified based on demonstration results of a single technology at multiple sites.

7.4 Demonstration Approach

One key objective of the International Technology Forum was to solicit input from the participants on the technical approaches for conducting the demonstration project. This section provides a basis for discussion at the Forum. The input from the Forum participants is summarized in Section 8.

7.4.1 Technology Selection Criteria. The term "innovative technologies" includes innovative designs, components, systems, methods, and procedures. The technology selection criteria may vary with respect to different types of technologies, but shall follow the general guidelines below:

- **Performance.** This criterion will be evaluated based on capabilities and limitations of the technology, the advances over existing and competing technologies, the strength of supporting performance data (full-scale data carry more weight than pilot-scale data), feedback from previous installation sites, and patent citation, if applicable. The potential of the proposed technology as a compliance strategy for the specific conditions should be identified. Third party evaluations and appropriate QA information are important components of the supporting data.
- **Cost – Direct and Indirect Cost.** A critical factor in the evaluation of technologies is the cost of installation (direct cost) and cost for periodic inspection and cleaning (indirect cost). The typical installation cost on a per-unit basis (i.e., cost per linear foot) shall be provided. Warranties or guarantees on performance should be provided. Tracking social costs such as the disruption of traffic is beyond the scope of this study.
- **Complexity.** The complexity of the technology refers to the level of training required for the installer, pre- and post-installation requirements, and maintenance requirements. An estimate of the time and cost for maintenance should be provided.
- **Maturity.** Depending on the stage of development for each technology, it can fall into developmental/emerging, innovative, or established category. New technologies that are commercially available overseas, but not yet widely applied in the U.S. market, are considered to be emerging with respect to U.S. applications.
- **Potential Benefits.** Potential benefits gained from implementing a rehabilitation technology may include capital savings, operational savings, I&I reduction, SSO/CSO reduction, restored structural integrity, leakage reduction, and improved maintenance tracking/management, etc. Technologies with a high potential to improve a utilities' ability to cost-effectively repair, rehabilitate, or replace water mains and sewers have the greatest benefits.

Efforts were made to solicit candidate technologies at an international level through the Technology Forum input, via a comprehensive literature search, and through member societies of the International Society for Trenchless Technology (ISTT). This generated a list of candidate technologies that will continue to be updated with input and feedback from EPA, the project stakeholder group, and Forum participants. The final selection of the demonstration technologies will be made jointly by EPA, a peer-review expert panel, and the demonstration host sites.

7.4.2 Site Selection Criteria. To ensure the field demonstration results are acceptable and useful to the user community, the selected demonstration scenarios must be representative of typical applications for a given technology. The environmental conditions (i.e., soil, groundwater, and surface conditions) of the host sites also shall be representative. Another key criterion in site selection is the utilities' willingness to participate, which depends largely on their needs to improve their water or wastewater systems, their understanding of present problems, their time and resources available to contribute, and their desire to advance the state of the technology. Decisions will also depend on the receptivity of the corresponding city/county for demonstration and the accessibility of the potential demonstration sites.

The following factors shall be considered in developing site selection criteria:

- Utilities' willingness to participate
- Known problems with water and/or wastewater systems
- Maintenance and operation history
- Pipe age
- Pipe sizes and materials
- Site accessibility, including traffic control requirements
- Security of testing equipment/instrument
- Local hydraulic and soil conditions
- Technology vendor's stated application limitations
- CCTV or other inspection technology reports available at the site
- Proximity of site to high-voltage power lines. These may impact some of the instrumentation readings
- Proximity of site to high-pressure lines, for example natural gas, gasoline lines (mainly for safety considerations)
- Proximity of site to contaminants/toxics in the soil or groundwater
- Proximity of site to high decibel noise sources
- Proximity of site to fault zones or active faults
- Closeness to fire and police protection, including fire lines
- Restrictions to access (right-of-way)
- Receptivity of local city or county or municipality for demonstration
- Representativeness – how typical is the field demonstration to problems commonly faced by most utilities
- Regulatory climate – how willing are local and state officials to work with the researchers and utility concerning requirements (NSF approval, etc.) to permit use of an innovative technique.
- Perceived value – number of interested utility participants; regional-scale versus national-scale (e.g., value to each user times total number of users).
- Feasibility of measuring performance and cost – Special considerations shall be given to ensure that the selected site will allow evaluation of the effectiveness of the rehabilitation approach. For example, it is challenging to evaluate the effectiveness of a sewer lateral

rehabilitation by the reduction in I&I volume. This is because in a normal practice of mixed mainline and laterals system, I&I volume from a specific lateral cannot be quantified due to the existence of other I&I sources in the system (WERF, 2006). With a special site that would allow temporarily (up to several hours) plugging the mainline upstream of the rehabilitated lateral, I&I volume from the lateral can be evaluated in a rainfall simulation, using a flow monitoring equipment installed in the mainline immediately downstream of the lateral connection (WERF, 2006).

7.4.3 Demonstration Protocols and Metrics. The demonstration of new or emerging technologies will require clear and repeatable testing criteria if the new technologies are to be understood and eventually accepted as reliable industrial tools. Bridging the gap from prototype or bench scale technology performance to field performance can only be credibly accomplished if demonstration projects are carefully designed and executed. A demonstration protocol provides guiding principles and a consistent approach for conducting safe and appropriate demonstrations and documentation of rehabilitation technologies in a manner to encourage acceptance of the test results by water and wastewater utilities.

The demonstration protocols will be specific for the chosen demonstration technologies, but also be general enough in nature to accommodate future technology field demonstrations. The protocols will have three major sections: (1) Planning, (2) Field Demonstration, and (3) Data Assessment and Reporting. The Planning section will include objectives of the demonstration, capabilities, features, and limitations of the technologies and site conditions. The Field Demonstration section will include standardized field testing methods and procedures for the rehab technology to be demonstrated. The Data Assessment and Reporting section will include specific guidelines addressing how performance and cost data are to be gathered uniformly and analyzed and the format of the report. The protocols will also provide specific guidelines for the preparation of site- or technology-specific tests plans, quality assurance project plans (QAPPs), and health and safety plans.

7.4.4 Demonstration Trials. As part of the project, the field demonstration of at least two innovative technologies is planned to take place in 2010, which will provide an opportunity to implement and refine the selection criteria, protocols, and metrics developed for future large-scale demonstrations. Based on the Project Team's experience and an extensive literature search, several technologies have been identified as potential candidates for field demonstration in three categories: pipeline rehabilitation (water and wastewater), manhole rehabilitation, and wastewater laterals. The preliminary list of candidate technologies was presented at the Forum and updated with input from the Forum participants (see Section 6). Initial contacts with vendors and utilities have been made to solicit their interest in participating in the project and providing in-kind contribution for 2- or 3-day field trials held at utilities in close proximity to the vendors' offices and where they have established working relationships. An alternative approach is to collaborate with utilities having on-going rehabilitation projects using innovative technologies where EPA can subsidize the testing, monitoring, QA/QC, data analysis, and reporting parts of the projects. The final selection of technology and host sites is yet to be made by EPA and the project stakeholder group.

7.4.5 Invitation to Apply and Selection Process for Future Demonstration. For the large-scale demonstration project to be conducted in the future, it is important that the application and selection process be objective and transparent to the utilities and technology vendors. General approaches can be adopted from a large-scale EPA Arsenic Removal Technology Demonstration Program, which is being conducted at 50 sites in 24 states (EPA, 2008a). The invitation to apply for participation in the demonstration project can be announced in the *Federal Register* and/or the EPA website requesting interested water/wastewater utilities and vendors to submit Letters of Intent and technology proposals, respectively. The announcement should be linked to the websites of other research organizations or industrial trade associations (i.e., WERF, Water Research Foundation, North American Society for

Trenchless Technology (NASTT), etc.) for additional dissemination. An independent technical panel will be convened by EPA to review the utilities' information and vendors' proposals according to the selection criteria discussed above and provide recommendations to EPA on the sites and technologies appropriate for demonstration. Depending on the funding level and other factors, multiple sites and multiple technologies will be selected for demonstration.

8.0 FORUM OUTCOMES AND RECOMMENDATIONS

A companion EPA report titled "*Forum Report for Rehabilitation of Wastewater Collection and Water Distribution Systems*" is available, which fully documents the Forum discussions (EPA, 2008b). The major outcomes and recommendations from the Forum are summarized below.

State of Infrastructure. The consensus of the Forum was that the current state of buried water and wastewater assets in the U.S. continues to deteriorate. The main impediments to faster improvement were as follows:

- Increased Funding Needs. Increased funding received a high ranking from Forum participants. Out-of-sight and out-of-mind was seen as a political barrier to more funding. Utilities must use their limited existing funds for repair/rehabilitation wisely and improved decision tools were needed to help them make cost/benefit calculations for rehabilitation – especially in relation to inflow/infiltration (I/I) control.
- Improved Technology Needs. Better technologies received a medium to high ranking from Forum participants. It was indicated that technology needs were especially high for water pipeline rehabilitation. It was also suggested that vendors should demonstrate their technologies up front to meet the pre-qualifying needs of utilities.
- Improved Training and Education. Improved training needs and education received a medium to high ranking. Participants are looking for increased information and knowledge sharing about rehabilitation technologies. They would place extra weight on evaluation data from an independent source. Participants also suggested that a "lessons learned" central database be developed on rehabilitation technologies.
- Increased Staffing Needs. Increased staffing needs received a low to medium ranking. Participants recognized the challenge of ageing professional staff and the need for increased recruitment and professional education. In large part, staffing needs would be expected to be resolved with adequate funding, although the shortage of civil engineering professionals impacts the availability of appropriate staff.

White Paper Review. The Forum participants suggested some changes to the content of the White Paper as summarized in this report, but there were no major disagreements with the overall sense of the White Paper. Written comments were received from stakeholders and Forum participants and incorporated into the Final White Paper as appropriate.

State-of-Technology (SOT) and Key Rehabilitation Issues. Forum participants shared case studies and information on emerging, innovative, and international rehabilitation technologies for water and wastewater. These additional technologies were reviewed for inclusion in the White Paper. Specific needs were identified on how to increase adoption and overcome barriers to the use of innovative rehabilitation technologies. A few of these needs are listed below:

- Operation and Maintenance (O&M) Needs. Addressing concerns associated with ongoing O&M needs is crucial for a wider acceptance of rehabilitation methods. Rehabilitation technologies need to include how to maintain and repair restored piping. Repairs of rehabilitated pipelines need to be performed by the utilities' regular maintenance crews.

- Challenging Pipe Configurations. Wastewater rehabilitation faces several challenges with difficult pipe configurations such as large diameter, non-circular sewers with angles and bends that can be rehabilitated while remaining in service.
- Disinfection and Service Reconnections. Water main rehabilitation will continue to lag sewer rehabilitation in the U.S. unless practical solutions can be developed for addressing rapid disinfection and customer service reconnections of rehabilitated piping.
- Design and Quality Assurance/Quality Control (QA/QC). A systematic approach to design and QA/QC is lacking in the rehabilitation industry. There is a great need for collecting, analyzing, and publicizing performance information which will provide a strong incentive for QA/QC at all levels (i.e., design, manufacturing, and installation). Cost-effective methods and protocols for collecting quantitative in-situ data regarding the baseline (initial) performance of the rehabilitated pipe are critical and will facilitate the establishment of successful installation QA/QC and long term performance monitoring programs among utilities. Better inspection and assessment methods of the rehabilitated pipe are crucial for a wider acceptance of water and force main rehabilitation methods.
- Need to Integrate Sustainable/Green Technology Concepts. It is not enough to repair or rehabilitate one pipe. A watershed-based, system-wide approach should be adopted as part of the decision-making process, especially for I/I control issues. Research should look at the integration of green and grey water technologies. Trenchless rehabilitation technologies can often reduce the overall “carbon footprint” of a construction project and/or reduce overall impacts to the environment and indirect costs to the community.

Rehabilitation Information and Knowledge Sharing. There is a desire for EPA to become or facilitate a technology transfer center for rehabilitation technologies with the ability to provide information on emerging technologies as well as existing technologies. Information must be sufficient enough to allow for a clear understanding of these technologies including proper application parameters and demonstrated life-cycle information. The EPA could provide impartial information based on pre-requisite technical data and field performance.

Technology Demonstrations. A technical panel of vendors and utilities was invited to provide feedback on how to conduct the field demonstration of emerging and innovative rehabilitation technologies in order to maximize benefit to the user community. The vendor and utility panel and group discussions led to several conclusions. A few of these are summarized below:

- Demonstration Impact and QA/QC Protocols. Demonstrating only a handful of novel and emerging technologies is going to have only a limited impact. The demonstrations need to have a broader impact (e.g., on design and QA/QC practices) rather than just showing that a technology can be successfully installed.
- Technology Selection Criteria. Forum participants indicated several criteria that should be considered for inclusion of a technology in an EPA Demonstration Program including emerging technologies which are commercially-ready; adaptability and widespread benefit for small- to medium-sized utilities; ease of installation; truly novel and more than incremental improvement over conventional methods; environmentally-friendly; and used to reduce frequency of breaks for water utilities.
- Technology Performance Metrics. Forum participants indicated several metrics that should be used to document rehabilitation system performance including unit cost of the technology application; installation time and social disruption; QA/QC plan and outcome;

manufacturer stated performance versus actual performance; durability; physical strength; visual appearance; flow properties and friction factors; and I/I reduction for sewers.

- Controlled Technology Performance Assessment. Results from controlled technology performance assessment via the development of a test bed would reduce the perceived risk to municipal engineers. When trying a new technology, often these engineers are expected to assume the entire risk, putting their reputation and budget on the line. There was great interest among the participants in the presentation on Germany's Institute for Underground Infrastructure (IKT) which conducts controlled performance trials for rehabilitation vendors including a "Consumer Reports" type testing for sewer lateral rehabilitation technologies.

Long Term Performance Assessments of Rehabilitation Projects. There was a strong feeling that revisiting previously installed rehabilitation projects with a detailed investigation and estimation of deterioration versus as designed and installed condition would be valuable (despite the expected lack of post-installation data). Long-term data regarding the performance of various rehabilitation systems is badly needed; the availability of such data will enable decision makers to make fully informed cost-benefit decisions.

Rehabilitation Decision-Making Tools. Utilities at the Forum expressed an interest in sharing information on how they make decisions regarding the replacement versus rehabilitation of their wastewater collection and/or water distribution systems. Of particular concern was how to estimate the cost/benefit for I/I reduction projects achieved from rehabilitation. The project team will collect case study information from 10 to 15 utilities on their rehabilitation prioritization approaches and decision-making methodologies. The resulting case study report will build on existing decision models for water and wastewater utilities. A generalized methodology will be developed based on these case studies, along with recommendations for improvements to current practices.

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APPENDIX A

Abbreviations

AC	asbestos cement
ACP	asbestos cement pipe
ANSI	American National Standards Institute
APT	accelerated pavement testing
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AWWA	American Water Works Association
AwwaRF	American Water Works Association Research Foundation (changed name to Water Research Foundation since January 1, 2009)
CARE-S	Computer Aided Rehabilitation of Sewer Networks
CARE-W	Computer Aided Rehabilitation of Water Networks
CCP	concrete cylinder pipe
CCTV	closed-circuit television
CERF	Civil Engineering Research Foundation
CFRP	carbon fiber reinforced pipe
CI	cast iron
CIGMAT	Center for Innovative Grouting Materials and Technology
CIP	cured-in-place
CIPP	cured-in-place pipe
CMOM	capacity, management, operation, and maintenance
CSO	combined sewer overflow
DI	ductile iron
DIPRA	Ductile Iron Pipe Research Association
DOT	Department of Transportation
EPA	United States Environmental Protection Agency
EPDM	ethylene propylene diene M-class rubber
ETV	Environmental Technology Verification
FRP	fiberglass reinforced pipe
GAO	Government Accounting Office
GASB	Government Accounting Standards Board
GIP	grout-in-place
GIPL	grouted-in-place lining
GIS	geographic information system
HDB	hydrostatic design basis
HDD	horizontal directional drilling
HDPE	high density polyethylene
I&I	inflow and infiltration
IKT	Institute for Underground Infrastructure
ISTT	International Society for Trenchless Technology
MACP	Manhole Assessment and Certification Program
MCE	multi-criteria evaluation
MCL	maximum contaminant level
MCLG	maximum contaminant level goal

NACE	National Association of Corrosion Engineers
NACWA	National Association of Clean Water Agencies
NASSCO	National Association of Sewer Services Companies
NASTT	North American Society for Trenchless Technology
NDT	non-destructive testing
NPDES	National Pollutant Discharge Elimination System
NPDWR	National Primary Drinking Water Regulation
NRMRL	National Risk Management Research Laboratory
NSF	NSF International
O&M	operation and maintenance
OD	outside diameter
PACP	Pipeline Assessment and Certification Program
PCCP	prestressed concrete cylinder pipe
PE	polyethylene
PINS	pipeline infrastructure
PRP	polyester fiber reinforced polyethylene
PVC	polyvinyl chloride
PVCP	polyvinyl chloride polyester
QA/QC	quality assurance/quality control
RCP	reinforced concrete pipe
SBIR	Small Business Innovation and Research
SCG	slow crack growth
SDWA	Safe Drinking Water Act
SRF	State Revolving Fund
SSO	sanitary sewer overflow
STAR	Science to Achieve Results
TIP	tight-in-place
TO	Task Order
TTC	Trenchless Technology Center
UV	ultraviolet
VCP	vitrified clay pipe
WEF	Water Environment Federation
WERF	Water Environment Research Foundation

APPENDIX B

Wastewater Pipe Rehabilitation Technology Descriptions

Sliplining is a method of pipe rehabilitation in which a new pipe of smaller diameter is inserted directly into the deteriorated pipe by pulling or pushing. With this method, an annular space between the host pipe and the liner is created, which is generally grouted with a cementitious material. The method can be categorized into:

- ***Segmental sliplining*** – A liner is assembled from short pipe segments at the entry point into the existing pipe, from where the liner is pulled or pushed into the pipe segment by segment.

  Sliplining pipes are typically manufactured from PE, HDPE, PP, PVC, GRP, or CCFRPM.

- ***Continuous sliplining*** - A liner is manufactured as a continuous pipe or assembled in the field prior to insertion (e.g., by fusing HDPE pipes) to match the entire length of the existing pipe.

  Sliplining pipes typically are PE, HDPE, PP, PVC, or PE/EPDM.

  Example technology: Akkerman SLS 50/100 Sliplining, Vylon® PVC Slipliner Pipe, Hobas® SewerLine®, etc.

Spiral winding is a method of pipe rehabilitation in which a liner is fabricated in the field from a continuous plastic strip. The joint between strips is mechanical (the strip has male and female edges which self-interlock). The strips, made of PVC (with or without steel reinforcement) or HDPE, have external ribs to increase the stiffness of the liner section. These liners may be installed without grouting or they may be grouted in place – in which case the external ribs serve to anchor the liner into the cement grout.

Example technology: Rib Loc® Expanda, Sekisui SPR, etc.

Cured-in-place (CIP) lining is a method in which a resin-saturated tube is inserted into the pipe by inversion or winching, then expanded using air or water pressure, and then the resin is subsequently cured at ambient or elevated temperature (using steam or hot water), or using ultra violet light, to create a pipe within the pipe. The method creates a minimal annular space and no grouting is performed.

Conventional CIP – A tube is made of a needled felt or equivalent material (in most systems) or a fiberglass reinforced material (e.g., Advantex™). The resin is usually unsaturated polyester, epoxy vinyl ester, or epoxy with catalysts. Based on the liner shape (which is determined by the part of sewer system to be relined), the following are different types of conventional CIP liners:

Standard CIP – The liner is shaped as a simple tube. These liners are used in sewer mainlines and laterals.

Example technology in mainlines: Insituform® CIPP, Inliner® , National Liner, Blue-Tek™ etc

Example technology in laterals: PermaLiner™, MaxLiner™, Inflex Liner™, etc.

Top Hat Liners – For relining a lateral-to-mainline connection, the liner is shaped in the form of a top hat. It creates a small brim (approx. 3 inches) in the mainline around the opening and extends for a short distance (approx. 6 to 12 inches) into the lateral.

Example technology: Top Hat®

T-Liners – For relining both a lateral-to-mainline connection and a lateral, the liner is made from two parts: a short mainline CIP (approx. 16 inches) and a standard lateral CIP (up to 160 feet).

Example technology: LMK T-Liner®

- ***Composite CIP*** – A tube is a composite made of a conventional CIP material sandwiched between layers reinforced with carbon fiber (high stiffness) and/or glass fiber (corrosion resistance), with a protective coating (PP) on the inside of installed of installed liner (increased surface smoothness and additional corrosion protection). The system is used for medium to large diameter pipes.

Example technology: Insituform's iPlus® Composite CIPP

Close-fit lining is a method of pipe rehabilitation in which a liner pipe is temporarily deformed before its insertion into an existing (host) pipe and subsequently restored to its original diameter forming a close fit with the original pipe. This method is also referred to as modified slip lining. The method can be categorized as follows:

- ***Fold-and-form***: A PVC pipe is deflected during the manufacturing process into a flat shape (SDR 26-32) or an H shape (SDR 55-60) and expanded after insertion using pressurization (steam to relax and recover the round shape, followed by air pressure to press the liner against the host pipe).

  Example technology: Ultraliner PVC Alloy, EX Method®, AM-Liner II®.

- ***Deform-reform***: A PE pipe is deflected during the manufacturing process, or on site, into a C-shape (flexible PE pipe) or a U shape (semi-rigid PE pipe, and is held in this shape by a sleeve or plastic bands). By this process, the diameter is reduced by approximately 35 to 40 percent for easy insertion. The pipe is expanded in place after insertion by the application of pressurized steam or water. The PP bands burst open during this process.

  Example technology: U-Liner, Subline, Polyflex.

- ***Symmetrical reduction:*** The liner is an HDPE pipe, which is temporarily reduced in diameter just prior to insertion for easy insertion and is reverted to its original diameter after the insertion (either naturally due to the material's viscoelastic recovery properties or by applying pressure to assist the process). The following methods have been developed:

  Tension-based symmetrical reduction (TBSR) – The pipe (SDR 17) is pulled through a swage die to reduce its diameter (typically by 7 to 15 percent of OD). With the pipe under tension, there is some change in pipe length. After the pull in is completed, the winch is disconnected relieving the tension and allowing the liner to viscoelastically recover towards its original diameter and hence form a tight fit within the host pipe.

  Example technology: Swagelining™

  Compression-based symmetrical reduction (CBSR) – The pipe (SDR 11) is hydraulically pushed through a series of compression rollers to reduce its diameter (typically by up to 10 percent of OD). With the pipe under compression rather than tension, there is little change in pipe length; however, there is a corresponding increase in the pipe wall thickness. The pipe diameter does not immediately try to recover its original shape and the diameter recovery is initiated with cold-water pressurization.

  Example technology: Subterra, Rolldown, Polyflex

  Tight-in-pipe (TIP) – Static pipe bursting equipment, lightweight and easily transported, is used where space is limited to slipline a failing pipe with a new pipe, which is temporarily reduced in diameter for easy insertion (a special tensioning device is used to put a liner pipe into tension). Short-module pipes (PVC in U.S., PP in Europe) assembled into a continuous pipe on site or a fusion-welded HDPE pipe can be used. The bursting unit has a specially designed guiding sleeve with rollers, which pulled through the pipe restores the pipe's circular profile as necessary and the new pipe attached to it is simultaneously pulled in.

  Example technology: TT Technologies' TIP system using Grundoburst 400s/Burstfix tensioning system.

Grout-in-place (GIP) is a method in which a liner (an HDPE pipe or panels from PP, PVDF, or ECTFE) has anchors (V-shaped studs) on the outside of the liner that serve as a spacer to the inner surface of the pipe, and the annular space created is filled with a high-strength, cementitious grout.

Example technology: Trolining®, Sure Grip®, etc.

GRP segmental lining is a method of large pipe rehabilitation (man-entry) in which interlocking glass fiber reinforced plastic (GRP) pipe segments are assembled inside the host pipes. The segments are manufactured from corrosion resistant isophthalic resin and can be designed for almost any pipe profile (circular, oval, vertically sided, symmetrical or non-symmetrical) as one piece, two piece, or multi-piece systems.

Example technology: Channeline Sewer Systems.

Gunite/Shotcrete is a concrete lining (mixture of sand, aggregate, water, and cement) that is applied by spraying layers to the required thickness. Gunite has only fine aggregate while shotcrete contains larger-sized aggregate. Reinforcing can be provided by spraying the concrete onto a cage of reinforced steel positioned and anchored into the sewer wall or by including reinforcing fibers in the shotcrete mix. It is normally applied through hand spraying, but robotic shotcrete lining technologies have been developed for non-person-entry pipes.

Example technology: Shotcrete Technologies, Inc.

Sprayed polymer lining is a method of pipe rehabilitation in which a layer of coating material is sprayed onto the surface of damaged pipe in sufficient thickness to create a high-built (HB), semi-structural liner. The method can be categorized as follows:

- *Epoxy lining* – An epoxy layer is centrifugally cast onto the pipe surface through a spray head, which is attached to a plural-component hose and winched through the host pipe. The thickness of application ranges from 40 to 400 mils (1 to 10 mm).

  Example technology: 3M Scotchkote 162PX, Scotchkote 134, 206, or 6233

- *Polyurethane lining* – A polyurethane (fast cure, 100 percent solids) is applied centrifugally onto the pipe surface in a thickness typically between 120 and 200 mils (3 and 5 mm). An air-driven spray head (the spinner head) is passed through the pipe to create the lining.

  Example technology: Copon Hycote 169 HB, 3M Skotchkote 169 HB (currently aimed at the water market).

- *Polyurea lining* – A polyurea (a plural component, fast cure, 100 percent solids elastomeric systems) is applied onto the pipe surface using a robotic application system or by conventional hand applied procedures in multiple thin layers to build a pipe inside a pipeline with wall thickness between 20 and 500 mils (0.5 and 12.5 mm) or greater.

  Example technology: PolySpray Structural Liner.

Flood grouting is a method in which an isolated section of sewer is consecutively flooded (completely filled) with two chemicals, which exfiltrate into the soil through pipe and joints defects, and chemically react with each other creating a water-tight seal. The method seals manholes, mainlines, and laterals simultaneously in one setup.

Example technology: Sanipor®.

Spot repairs involve a variety of methods that typically or exclusively repair relatively short sections of pipe, defective joints or defective lateral connections:

- ***Chemical grouting*** – A chemical grout is injected under pressure through cracks and defective joints into the surrounding soil to seal the defective pipe and protect against infiltration/inflow. In small diameter pipes (up to 24 inches), the method is applied with packers as a test-and-seal procedure. Although basically a spot repair, the method can be used to seal the entire pipe by repeating the test-and-seal procedure along the pipe.

  Example technology: Logiball Test-and-Seal Packer.

- ***Robotic repairs*** – Robots are used for mechanical work (e.g., cutting off or grinding protruding laterals, grinding of damaged pipe to expose the virgin pipe material) and for applying a repair material (resin or mortar) without or with pressure to the prepared surface, which cures into a material compatible with the host pipe and becomes an integral part of the pipe. If pressure is applied, the material penetrates the soil behind the defective pipe where a sealing collar is created around the pipe. Robotic repairs are carried out as spot repairs anywhere in mainlines or at lateral connections.

  Example technology: KA-Te and Jansen Lateral Rehabilitation.

- ***Spot repair sleeves*** – Prefabricated stainless steel or PVC sleeves are positioned inside the pipe while folded and then jacked (snapped) into an expanded shape. The sleeves offer a structural repair of damaged pipe but can also restore missing pipe sections without excavation or provide infiltration sealing of joints. Although multiple sleeves can be used adjacently, this method is typically used to repair relatively short sections of pipes.

  Example technologies are Link-Pipe Grouting Sleeve™ and Insta-Liner™ (made up from short links of stainless steel sleeves)

- ***Internal joint sealing*** **-** A flexible rubber seal is positioned over a leaking joint and compressed against the inside diameter of the pipe on both sides of the joint with expansion bands.

  Example technology: Amex10®/Weko-Seal® and NPC Internal Joint Seal.

Trenchless pipe replacement is a method of replacement of a deteriorated pipe with a new pipe of the same or slightly larger diameter along the existing pipe alignment. This may also be referred to as “on-line” replacement, but this term can be confused with work done “on line” – meaning “in service.” The bursting tool (bursting head) is passed through the pipe breaking it into fragments if the pipe is brittle (pipe bursting) or slicing through it if the pipe is ductile (pipe splitting), and the new pipe is simultaneously pulled in place. The old pipe, whether fractured or sliced open, remains in the ground. The new pipe is usually an HDPE pipe, but segmented pipe can be used with modified pipe insertion arrangements. The method can be categorized as follows:

- ***Static bursting*** – The bursting head is hydraulically pulled or pushed through the existing pipe.

  Example technology: TT Technologies Grundoburst®, Hammerhead HydroBurst®, etc.

- ***Pneumatic bursting*** – The bursting head applies repeated impacts onto the existing pipe driven by compressed air (delivered through air supply hoses inside the replacement pipe).

  Example technology: TT Technologies Grundocrack®

- ***Hydraulic bursting*** – The bursting head is hydraulically expanded breaking the pipe, contracted, and slid forward to repeat the process incrementally along the existing pipe.

  Example technology: XPANDIT system.

- ***Pipe insertion by pushing*** – The hydraulic jacks are used to push a new pipe in place of the existing deteriorated pipe. The lead equipment (a bursting head) positioned ahead of the new pipe penetrates, fractures, and expands the old pipe. The system utilizes the column strength of segmented jacking pipe for the newly installed line and only rigid pipe materials can be used (clay, ductile iron, polycrete, Hobas, steel and stainless steel).

  Example technology: Tenbusch Insertion Method (TIM)™.

Trenchless pipe removal is a method of on-line pipe replacement in which the existing pipe is removed from the ground as the new pipe is being pulled in place. The method can be categorized as follows:

- ***Pipe reaming*** – HDD equipment is used (standard equipment plus a modified back reaming tool). During back reaming, the existing pipe is fragmented using pick cutters and the fragments are carried out by the drilling fluid along with other excess particles.

  Example technology: Nowak's InneReam System®.

APPENDIX C

Water Pipe Rehabilitation Technology Descriptions

Sliplining is a method of pipe rehabilitation in which a new pipe of smaller diameter is inserted directly into the deteriorated pipe by pulling or pushing. The method can be categorized into:

- ***Segmental sliplining*** – A liner is being assembled from short pipe segments at the entry point into the existing pipe, from where the liner is pulled or pushed into the pipe for the length of each added segment. The annular space is grouted. Sliplining pipes can be HDPE, PVC, CC-GRP pressure pipe (Hobas), and ductile iron.

  Example technology: Certa-Lok™ Yelomine™, Hobas® WaterLine®, etc.

- ***Continuous sliplining*** - A liner is manufactured as a continuous pipe or is assembled in the field prior to insertion to match the entire length of the existing pipe. Sliplining pipe can be HDPE or fusible PVC pressure pipe. One system has been developed that uses a PVC pipe with smaller diameter than the host pipe for easy pull in and subsequently applies heat and pressure to expand the PVC pipe tightly against the interior walls of the host pipe thus eliminating the annular space.

  Example technology: Duraliner™.

Cured-in-place (CIP) lining is a method in which a resin-saturated tube is inserted into the pipe by inversion or winching, then expanded using air or water pressure, and the resin subsequently cured at ambient or elevated temperature (using steam or hot water), or using ultra violet light, to create a pipe within the pipe. For water applications, the tube can be PE woven material or glass-fiber reinforced, flexible felt, and the resin is epoxy. Service connections can be reinstated internally without excavating (e.g., iTAP™)

Example technology: Insituform PPL®, RPP™ Aqua Pipe.

Woven PE/epoxy lining is a method in which seamless woven-fabric PE flexible tubing with PE coating is inverted into the pipe (via air pressure) and glued to the interior wall of the pipe with a solvent -free, thermosetting, two-component epoxy adhesive. The gluing operation requires that the interior wall of the pipe be clean.

Example technology: Starline®1000 *Nordipipe*

Close-fit lining is a method of pipe rehabilitation in which a liner pipe is temporarily deformed before its insertion into an existing (host) pipe and is subsequently restored to its original diameter forming a close fit with the original pipe. This method is also referred to as modified slip lining. The method can be categorized as follows:

- ***Deform-reform***: A PE pipe is deflected during the manufacturing process or on site into a C or a U shape to reduce the diameter by approximately 35 to 40 percent for easy insertion. The pipe is expanded in place after insertion by the application of pressurized steam or water. If PP bands were used to hold the shape prior and during the installation, they burst open during this process. Two different categories can be distinguished based on the level of structural repair provided:

  Polyester fiber reinforced polyethylene (PRP) – A thin reinforced PE pipe (the polyethylene matrix encapsulates and surrounds the polyester reinforcement) is supplied as factory-folded into a “C” shape. It is installed by winching into the host pipe and reverted into the circular shape applying air and steam pressure.

  Example technology: Thermopipe®

  Polyethylene (PE) – A thin PE pipe is used.

  Example technology: Insituform PolyFold™, Subline®.

- ***Symmetrical reduction:*** The liner is an HDPE pipe, which is temporarily reduced in diameter just prior to insertion for easy insertion and is reverted to its original diameter after the insertion (either naturally due to the material's viscoelastic recovery properties or by applying pressure to assist the process). The following methods have been developed:

Tension-based symmetrical reduction (TBSR) – The pipe is pulled through a swage die to reduce its diameter (typically by 7 to 15 percent of OD). With the pipe under tension, there is some change in pipe length. After the pull in is completed, the winch is disconnected relieving the tension and allowing the liner to viscoelastically recover towards its original diameter and hence form a tight fit within the host pipe.

Example technology: Swagelining™, Polyflex™

Compression-based symmetrical reduction (CBSR) – The pipe is hydraulically pushed through a series of compression rollers to reduce its diameter (typically by 10 to 20 percent of OD). With the pipe under compression rather than tension, there is little change in pipe length; however, there is a corresponding increase in the pipe wall thickness. The pipe diameter does not immediately try to recover its original shape and the diameter recovery is initiated with cold-water pressurization.

Example technology: Subterra Rolldown, Insituform PolyFlex™.

Grout-in-place (GIP) is a method in which a liner (an MDPE pipe) has anchors (closely spaced hooked tabs) on the outside of the liner (the side facing the pipe wall) that serve as a spacer to the inner surface of the pipe, and the annular space created is filled with a cementitious grout. For installation, the liner is pulled into the pipe folded, the grout is injected into the space between the liner and the host pipe, and a rounding swab is passed through the pipe (applying air pressure) both rounding the liner tube and distributing the grout evenly against the interior surface of the host pipe.

Example technology: MainSaver™.

Sprayed lining is a method of pipe rehabilitation in which a thin layer of coating material is sprayed onto the surface of damaged pipe. The method can be categorized as follows:

- *Cement mortar lining* – A continuous lining of cement mortar is applied to protect against corrosion (thickness $^1/_8$ to $^3/_4$ inch per pass is attainable). The method can be applied as a centrifugal process (the lining unit has a rotating head that disperses the mortar and a series of trowels to smooth the surface) or a mandrel process (the mortar is applied by compressed air and smoothed by a conical mandrel). In man-entry pipes, an operator riding on a machine through the pipe controls the centrifugal unit.

  Example technology: Mk II (Dakota Pipelining Systems).

- *Epoxy lining* – An epoxy lining is centrifugally cast onto the pipe surface through a spray head, which is attached to a plural-component hose and winched through the host pipe. The thickness of application is between 1.0 and 5.0 mm and typically about 3.0 mm ($^1/_8$ inch). The lining is non-structural and provides a corrosion protection.

  Example technology: CuraFlo Spincast System™, Hunting Waterline Epoxy.

- *Polyurethane lining* – A polyurethane (fast cure, 100 percent solids) is applied centrifugally onto the pipe surface from an air-driven spray head (the spinner head) passed through the pipe. Polyurethane can be applied as a non-structural (thickness up to 1.0 mm) or as a structural lining (thickness range of 40 to 200 mils, i.e., 1.0 to 5.0 mm).

  Example technology: Copon Hycote 169 PWX, 3M Skotchkote 169 HB (currently waiting for NSF approval).

- *Polyurea lining* – A polyurea (a plural component, fast cure, 100 percent solids elastomeric systems) is applied onto the pipe surface using a robotic application system or by conventional hand applied procedures. Polyurea can be applied as a non-structural or as a structural lining. As a structural lining, polyurea is remotely applied in many thin layers using a reciprocating and rotating application head to build a wall thickness in the range of 20 to 500 mils (0.5 to 12.5 mm) or greater.

Example technology: PolySpray Structural Liner.

- *Calcite lining* – A supersaturated solution of calcium carbonate is applied onto the pipe wall creating a calcite liner. Portions of municipal water main systems can be closed off, lined quickly and put back in service. The method was used by WSSC and LWC.

Spot repairs involve methods that repair relatively short defective sections of pipe:

- ***Spot repair sleeves*** – Prefabricated stainless steel sleeves are positioned inside the pipe while folded and then are jacked (snapped) into an expanded shape. The sleeves offer a structural repair of damaged pipe, but can also restore missing pipe sections without excavation or provide infiltration sealing of joints. Although multiple sleeves can be used adjacently, this method is typically used to repair relatively short sections of pipes.

Example technology: Link Pipe Hydro-Seal™ Sleeve.

Trenchless pipe replacement is a method of replacement of a deteriorated pipe with a new pipe of the same or slightly larger diameter along the existing pipe alignment. This may also be referred to as "on-line" replacement, but this term can be confused with work done "on line" – meaning "in service." The bursting tool (bursting head) is passed through the pipe breaking it into fragments if the pipe is brittle (pipe bursting) or slicing through it if the pipe is ductile (pipe splitting), and the new pipe is simultaneously pulled in place. The old pipe, whether fractured or sliced open, remains in the ground. The new pipe is usually an HDPE pipe, but segmented pipe can be used with modified pipe insertion arrangements. The method can be categorized as follows:

- ***Static bursting*** – The bursting head is hydraulically pulled or pushed through the existing pipe.

Example technology: TT Technologies Grundoburst®, Hammerhead HydroBurst®, etc.

- ***Pneumatic bursting*** – The bursting head applies repeated impacts onto the existing pipe driven by compressed air (delivered through air supply hoses inside the replacement pipe).

Example technology: TT Technologies Grundocrack®

- ***Hydraulic bursting*** – The bursting head is hydraulically expanded breaking the pipe, contracted, and slid forward to repeat the process incrementally along the existing pipe.

Example technology: XPANDIT system.

- ***Pipe insertion by pushing*** – The hydraulic jacks are used to push a new pipe in place of the existing deteriorated pipe. The lead equipment (a bursting head) positioned ahead of the new pipe penetrates, fractures, and expands the old pipe. The system utilizes the column strength of segmented jacking pipe for the newly installed line and only rigid pipe materials can be used (clay, ductile iron, polycrete, Hobas, steel and stainless steel).

Example technology: Tenbusch Insertion Method (TIM)™**.**

Trenchless pipe removal is a method of on-line pipe replacement in which the existing pipe has been removed from the ground as the new pipe is being pulled in place. The method can be categorized as follows:

- ***Pipe extraction*** – A winching system attached to a cable with embedded pulling heads (or a cable that is grouted into the pipe to be extracted) pulls the pipe out of the ground. The new pipe is pulled into the ground as the old pipe is pulled out. Lead water pipes are typically extracted.

    Example technology: TT Technology's Grundomat piercing tool equipped with a pipe pushing adapter

APPENDIX D

Manhole Rehabilitation Technology Descriptions

Preformed manhole units are used to "slipline" existing manholes. The chimney and corbel/cone area must be removed, and all infiltration in the bench area and around pipes must be stopped prior to the installation. The installation can often be done without sewage bypassing or diversion.

Monolithic units are one-piece monolithic fiberglass units.

Example technology: Flowtite® Fiberglass Rehabilitation Manhole

Composite units consist of a cover section (concentric, eccentric or flat) and riser sections (typically each 5 feet high to facilitate installation) made of fiberglass reinforced epoxy resins.

Example technology: Sewer Shield® Manhole Insert

Poured-in-place concrete creates thick-wall, seamless concrete liners inside manholes that extend from the bench to the frame. Segmented, stackable forms (steel or plastic, available in different nominal diameters and height increments) are positioned into the manhole and the concrete is carefully poured inside the forms (in 3 to 20-foot lifts, depending on the system). After the concrete has sufficiently cured, the forms are disassembled and removed. The repair can often be done with active flows.

Example technologies: Permaform®, Mono-Cast™, Monoform

Cured-in-place manhole (CIPM) relining is a method in which a manhole liner, prefabricated to fit the structure and resin-saturated at the jobsite, is lowered into the manhole interior, a flexible diaphragm is inflated, and the resin is heat cured forming a protective liner within the manhole. The resin is typically an epoxy, whereas the liner material differs depending on the system: a laminate containing a non-porous membrane bonded between the structural layers of fiberglass (Poly-Triplex®), or PVC polyester (MultiPlexx™ PVCP). Manhole preparation includes water pressure cleaning and chemical grouting to eliminate infiltration/inflow (if applicable).

Example technologies: Poly-Triplex®, MultiPlexx™ PVCP Liner.

Grout-in-place manhole liners are constructed from panels (HDPE or PVC) with anchors (V-shaped studs) on the outside of the liner, which serve as a spacer to the manhole surface that create the annular space filled with a high-strength, cementitious grout.

Example technologies: Trolining®, Sure Grip®.

Cementitious coatings are generally used for structural restoration in low-level corrosion environments. They are applied by spraying or spincasting from the center of the manhole (Permacast®) in layers approx ¼ inch thick to a total thickness of ½ inch for I&I elimination or 1 to 4 inches for structural repair. These coatings can be made with Type I Portland cement (pH 3.0 or higher) or calcium aluminate cement (pH 2.0 or higher). Cement mix and aggregate choices (e.g., a blend of 100 percent pure fused aluminate clinker with a minimum aluminate content of 46 percent and calcium aluminate cement) can further lower the pH where the corrosion can be avoided (pH 1). Manhole preparation includes water pressure cleaning and chemical grouting to eliminate infiltration/inflow (if applicable). The full cure is achieved in 28 days, but the flow plugging is required only for 24 hours.

Example technologies: Strong -Seal®, Permacast®, etc.

Polymer coatings are used primarily for corrosion protection (they can be applied in conjunction with cementitious coatings). They are applied by spraying or spincasting, in thickness range of 80 to 500 mils (approx. $^1/_8$ to $^1/_2$ inch). Generally, only 100 percent solids, solvent-free products are used for safety and performance. Surface preparation is critical for success. The following are different types:

- ***Epoxy coatings*** – These coatings have good adhesion property, excellent chemical resistance, and are moisture tolerant. Epoxies are also used as primers for ureas and urethanes. Cure time varies, and is usually 5 to 6 hours (Raven) or, if the epoxy is preheated, about 2 hours regardless of ambient temperature (Warren). They are typically applied in thickness 120 mils, although some recommend minimal thickness 250 mils (Warren).

Example coatings: Raven Lining Systems, Warren Lining Systems etc

- ***Polyurethane/polyurea coatings -*** These coatings have good-excellent chemical resistance, but are moisture sensitive. All infiltration must be stopped and the surface completely dry to ensure adhesion to the substrate. For corrosion protection, they are typically applied in two layers: polyurethanes to thickness 150 mils (75 mils/layer) and polyurea to thickness 180 mils (90 mils/layer). Gel times are very short (several seconds to minutes). The flow can be reinstated in 30 to 60 minutes.

  Example coatings: Sprayroq (polyurethane), PCSI Polyurea Manhole Coating

- ***Modified polymer skin panels -*** Systematic layering of polymer resins imparts structural strength due to "Stress Skin Panel" effect. The lining system consists of a moisture barrier (silicone-modified polyurea), a surfacing coat to fill voids, eroded areas and missing mortar joints (polyurethane/polymeric blend foam), and a final corrosion barrier (silicone-modified polyurea). The coats are spray-applied and can be installed in any shape or configuration. Fast curing allows lining of a typical, 7-foot deep manhole to be completed about one hour.

  Example technology: **SpectraShield™**

Chemical grouting is a method in which chemical grouts are used to seal leaking, non-structural defects in manholes. The method can be categorized as follows:

- ***Acrylamide/acrylate grouts***: Gel type chemical grouts are injected with hand-held injection equipment through cracks to the soil surrounding the manhole to form a gel curtain around the outside of the manhole. Acrylates are alternatives to the acrylamides, which are toxic in the gel phase (before polymerization). Acrylates are not as strong as Acrylamides, have a little higher viscosity and not as good gel-time control, and are more expensive.

  Example: AV-100 Acrylamide, Geo/chem AC-400 Acrylate

- ***Polyurethane grouts*** – Liquid type chemical grouts are used to close active leaks or stabilize the soil around the manhole. Polyurethane grouts are water activated. Two types can be distinguished: which cure forming either an expansive foam (flexible or rigid):

  Hydrophilic grouts will absorb the water they find in the concrete or soil. Based on formulation produce either expansive foam or non-expansive gel. The foam is used to seal the leaks from the outside in: the resin is injected under pressure through the manhole wall into the water (a hole is drilled near the leak) and, as the resin reacts with water, the expanding foam is pulled back into the structure creating the seal through the entire manhole wall. The resin that produces gel is used when the leak is not strong enough to pull the grout into the structure: both resin and water are delivered through a manifold, mixed briefly, and injected directly into the crack. In both cases, a tight flexible seal is formed that expands and contracts as pressure or temperature changes cause the crack to open or close.

  Example grouts: Prime-Flex 900XLV, 900LVSF, and 970 Hydro Gel SX

  Hydrophobic grouts will repel the water after activation and push it away. They require a catalyst to cure and expand, and form rigid foam (if the structure moves, the leaks can reappear). With low viscosity, controlled setup time, and high expansion, hydrophobic grouts are best for filling voids and stabilizing soil.

  Example grouts: Prime-Flex 910 and 920.

- ***Epoxy grouts*** – 100 percent solids, two-component epoxy systems are used for grouting and sealing of cracks. With ultra-low-viscosity, they are designed specifically for pressure injection. Epoxies are moisture insensitive and can be applied on damp surfaces, which must however be free of standing water.

Example grout: Denepox 40 Epoxy

Flood grouting is a method in which an isolated section of sewer is consecutively flooded (completely filled) with two chemicals, which exfiltrate into the soil through pipe and joints defects, and chemically react with each other creating a water-tight seal. The method seals manholes, mainlines, and laterals simultaneously in one setup.

Example technology: Sanipor®.

Manhole under cover inserts involve placing an insert under the manhole cover on top of the manhole frame. No special tools are required for installation, but the frame rim must be cleaned of any loose rust or scale, and any debris with a wire brush. The inserts can be:

Dish inserts – HDPE or stainless steel inserts are installed to eliminate inflow, debris and dirt into the manhole, and reduce odors and manhole cover rattle noise.

Example technologies: Sewer Guard® Manhole Insert, No Flow In Flow, Cratex Inflow Dish, InflowShield® (stainless steel)

Grade rings – HDPE rings, flat or sloped, are installed to adjust the manhole cover up to the exact height of roadway surface.

Example technology: Ipex Lifesaver™ (24 to 34 inches).

Chimney seals involve measures focused on sealing joints in the manhole frame-chimney area. The following types can be distinguished:

- ***Mechanical*** – Most chimney inserts are flexible rubber sleeves, which are pleated and secured in place with stainless steel expansion bands (the bends are placed in the band recesses and individually expanded) providing a watertight seal. In addition, inserts in the form of telescopic liners are available, which are made of PVC, easily installed without special tools, and can accommodate grade adjustment rings.

Example technology: Cretex Internal Manhole Joint Seal, FlexRib Frame–Chimney Seal, Water-Lok™ (telescopic PVC liner)

- ***CIP*** - The CIP liner capable is used to reline the entire chimney with an overlap typically of 5 to 6 inches onto the cone section. The liner is made from stretchable "one size fits most" coated polyester (22 inches in diameter will stretch to as much as 60 inches), vacuum impregnated with a 100 percent solids silicate resin, and cured under ambient temperature and pressure in about one hour. Surface must be very clean to ensure bonding of the liner with the manhole.

Example technology: LMK CIPMH™ Chimney

- ***Polymer*** – These coatings are applied with trowel in the chimney area and ambient cured

Polysufides - A two-component, trowel-grade polysulfide, 100 percent solids, chemical resistant and flexible coating.

Example technology: Perma-Flex Manhole Chimney Seal

Epoxy - A 100 percent solids, zero VOC resin is applied with trowel at 20 to 500 mills in a single pass.

Example technology: Neopoxy NPR-5301

Grade adjustment ring area seals involve measures focused on sealing cracks in this manhole area.

- ***Polymer*** – A urethane coating is applied with a brush about 3 inches above the bottom of the frame to 3 inches below the bottom of the grade adjustment ring. Two different coats leave final thickness of the sealant typically 170 to 250 mils.

  Example technology: Flex-Seal Utility Sealant®

Barrel joints seals involve measures focused on sealing joints or repairing defects in the manhole barrel. The following types can be distinguished:

- ***Mechanical*** – Flexible rubber sleeves are used over the barrel joints, fixed firmly with the stainless steel expansion bands to provide a watertight seal.

  Example technology: Cretex Internal Manhole Joint Seal

- ***Cementitious –*** Rapid-setting (1 to 20 minutes) cement-based mortars can be used to stop water seepage through cracks in concrete.

  Example technology: Thoroc® mortarts

- ***Polymer*** – Urethane coatings are applied with brush to the manhole joints (from 3 inches above the joint to 3 inches below the joint) to a dry and clean surface in two different coats, with final thickness of the sealant typically 170 to 250 mils.

  Example technology: Flex-Seal Utility Sealant®

Channel inserts involve measures focused on rehabilitation of inverts. For lining invert flumes in manholes, a plastic composite system can be used. Modular components made of fiberglass (the flume sections) and PVC (the pipe ends) bolt together with minimal tools.

Example technology: Reliner® Channel System

APPENDIX E

Example Quality Control Standards for Pipe Rehabilitation

The installation of CIPP is governed by the ASTM standards F1216, F1743, and F2019. Fold and form PVC installations are governed by ASTM F1867 and F1947; and deformed reformed HDPE is governed by ASTM F1606. There is currently no ASTM installation standard for pipe bursting; pipe bursting is given its installation criteria by the equipment manufacturers. Additionally, NASSCO's International Pipe Bursters' Association division has published a guideline entitled *Guideline Specification for the Replacement of Mainline Sewer Pipes by Pipe Bursting*. GIPL are installed using ASTM F1698 or F1741, depending on whether the PVC material is hand assembled or machine assembled in the pipeline.

The differences between ASTM F1216, F1743, and F2019 center on the type of installation to be carried out. F1216 focuses on the inversion method of installation while F1743 and F2019 provide guide for a pulled in place installation. The thermosetting resin systems used for CIPP are hardened by heating the fluid used in the installation process (water or air) or by UV light. The key control points of a CIPP's installation are given by these standards but may not be readily obvious to those not involved in the details of the day-to-day installation process. The key control points for CIPP are as follows:

- Proper Saturation. The resin system must be impregnated into the fabricated tube such that at least 95 percent of the void space is taken up by the resin. This is accomplished by placing the tube under a vacuum and distributing the resin equally by running the tube through a set of calibration rollers. The amount of resin required is given by the tube manufacturer to the contractor. The length of tube saturated and the resin quantity used confirm proper saturation.
- Proper Catalyzation. Polyester and vinyl ester resin systems use initiators to start the free radical polymerization process that leads to the resin hardening. Initiators are added to the resin system by mixing just prior to saturation. A gel test is done routinely throughout the saturation process to insure that the resin has been properly catalyzed.
- Finished Thickness and Fit Control. The tube manufacturer provides the contractor with the required heads to be used during the inversion or pull in place installation procedure to insure that the saturated tube fully expands to tightly fit the existing pipeline while achieving the proper finished wall thickness. By using these parameters, the contractor can properly pre-plan his installations to comply with these parameters.
- Proper Curing and Cooling. The standard in the industry is to use initiators that commence curing at around 140°F. By using thermocouple wires placed in the interface between the CIPP and the host pipe, the installation personnel can observe the exothermic reaction commencing in the liner and monitor the progress of the curing. The resin manufacturers in conjunction with the CIPP system manufacturers have developed an empirical relationship between the readings observed and the time required to cure the resin past the observed exotherm. In order to properly anneal any residual stresses from the curing process the liner is cooled down at a steady rate consistent with its thickness. Both the length of curing and the cool down timing are given to the installer in terms relating to the readings indicated by the thermocouples.

ASTM F1867 and F1947 dictate the proper installation of a fold and form PVC rehabilitation. The key installation control points given by it are as follows:

- Maximum Pull-in Force. The winching operation is to be monitored by the installation personnel continuously during the insertion process. At no point during the installation is the pulling force to be allowed to exceed one-half of the allowable tensile strength of the piping being used for the rehabilitation (50 percent of the tensile yield strength at 212°F).
- Proper Expansion. The time, temperature, and the pressure must be sufficient enough to overcome the extrusion memory of the PVC material being used. These parameters have been given to the contractor by the system manufacturer. They are stated in terms of the in situ parameters encountered.

- Cool Down. The piping shall be cooled steadily to below 100°F using compressed air and an after cooler. The pressure is not to be released prior to the liner being at or below this point.

GIPL's are typically used in pipes ranging from 10 inches in diameter to 78 inches in diameter; though they are currently beginning to see more use in larger diameter piping. Examples of GIPL's are the Danby System, RibLoc, Sekisui SPR, the 3S Panel system, and Trolining. These systems place a relatively thin thermoplastic material that has been extruded with a profile to greatly improve its bending strength. The placement is either by machine winding into place; or by hand placement. The resulting annular space must be filled with a cementitious grout material to form a composite structure (lining/grout/host pipe). The installation of this type of rehabilitation system currently has two ASTM specifications; one for hand installation and one for machine installation. They are ASTM F1698 and F1741, respectively. The key control points of the installation process are as follows:

- Thermoplastic Material Placement. The strips or panel sections are assembled in the host pipeline to the design I.D. Depending on the design thickness of the grout layer, shims are employed to properly position the assembled liner within the host pipeline. Shimming also serves to providing proper alignment and grade of the lining's placement. These are checked prior to commencing grouting.
- Grout Placement. Grout placement is absolutely crucial to the quality of the finished installation. With the exception of the 3S Panel System, the installer is blinded by the opaque nature of these panels or the procedure used for grouting (Trolining fills the lining with water) to confirm complete filling is taking place. To that end the installer is advised to make holes in the lining to confirm that grout has reached a certain level in the annulus. The 3S Panel System uses a translucent color to allow the installer a real time indicator of the grouting operation.

Pipe bursting gets its installation controls from the piping manufacturer and the bursting equipment manufacturer. As mentioned earlier, the IPBA division of NASSCO has published a guideline specification that gives the installer guidance regarding pipe bursting:

- Pull-in Force. The bursting equipment has a real time reading of the tensile force being applied to the plastic piping, etc. during the pulling in operation. The installer has the necessary information from the pipe manufacturer as to the maximum tensile force allowed.
- Grade is essentially that of the existing pipeline, which is controlled by alignment of the pulling cable inside the host pipe.