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Deteriorating Buried Infrastructure Management Challenges and Strategies

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Background and Disclaimer

The USEPA is revising the Total Coliform Rule (TCR) and is considering new possible distribution system requirements as part of these revisions. As part of this process, the USEPA is publishing a series of issue papers to present available information on topics relevant to possible TCR revisions. This paper was developed as part of that effort.

The objectives of the issue papers are to review the available data, information and research regarding the potential public health risks associated with the distribution system issues, and where relevant identify areas in which additional research may be warranted. The issue papers will serve as background material for EPA, expert and stakeholder discussions. The papers only present available information and do not represent Agency policy. Some of the papers were prepared by parties outside of EPA; EPA does not endorse those papers, but is providing them for information and review.

Additional Information

The paper is available at the TCR web site at:

http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html

Questions or comments regarding this paper may be directed to **TCR@epa.gov**.

**DETERIORATING BURIED INFRASTRUCTURE
MANAGEMENT CHALLENGES AND STRATEGIES**

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DETERIORATING BURIED INFRASTRUCTURE MANAGEMENT CHALLENGES AND STRATEGIES

I. Introduction

The findings of several prominent studies forecasting capital investment needs for water systems has brought the subject of buried infrastructure asset management to the forefront of priority issues facing the water industry. The capital investment focus of these studies and numerous other published articles has overshadowed any discussion or concern of the potential health risks associated with deteriorating distribution systems. The United States Environmental Protection Agency (USEPA), in an effort to assess the need for regulatory action, has directed preparation of several White Papers (including this paper) to address health risks related to specific water distribution system topics. The characteristics of deteriorating water distribution systems include the increased frequency of leaks, main breaks, taste, odor and red water complaints, reduced hydraulic capacity due to internal pipe corrosion, and increased disinfectant demands due to the presence of corrosion products, biofilms, and regrowth. Each of these conditions presents the potential for water quality degradation, and the specific causes, health risks and mitigation strategies are appropriately being addressed by individual White Papers dedicated to these topics. This paper will not duplicate that work but rather will compliment these papers by providing a broad assessment of current buried infrastructure management challenges and strategies for addressing them.

These broader challenges associated with buried infrastructure include establishing a means for monitoring and measuring all impacts associated with deteriorating water systems and their relative importance. These impacts include health risks as well as customer service, community disruption, customer confidence, public perception, fire protection, and other less tangible variables. State and Federal subsidies will likely be unavailable or insufficient to fully address this issue, and the needed capital funds will be limited by increasing demands to keep water rates affordable. Investment in buried infrastructure will also be in direct competition with other more visible and regulatory driven infrastructure needs. Historically, buried infrastructure investment, absent regulatory compliance directives, or gross system failures, have been subordinate to regulatory driven investment or capital needs associated with more highly visible projects. The competition for capital funds is made more difficult when a comparison of “direct” costs of repair versus rehabilitation or replacement almost always favors continuing to repair a deteriorated water main. Therefore, a utility must measure and present credible evidence of the indirect costs and impacts associated with poorly performing systems including service interruptions, community disturbance, and health risks in order to support the need for capital investment.

The rate of deterioration of a water system is not a function of material age but rather the cumulative effect of the external forces acting on it. During a recent water system valuation, 70+-year-old unlined cast iron main was found to be in excellent condition with negligible internal or external corrosion. Based on the field observations, there is no reason to believe that these mains will not provide another 70+ years of satisfactory service. Conversely, in another system, cast iron mains less than 50 years old are experiencing excessive and rapidly increasing break rates and severe corrosion activity. Planned replacement of these mains is needed in the

near future. Therefore, broad based decision factors regarding infrastructure replacement, whether based on age, pipe size, pipe material, linings, etc. will not result in an effective use of limited capital resources. Better information and decision making is needed. Lastly, with numerous pipeline rehabilitation technologies and new pipeline materials emerging, the question of how best to remedy a poorly performing water main must be answered. This question can only be answered through actual knowledge of the conditions and service characteristics of the existing main, comparative repair, replacement, and rehabilitation costs, and an understanding of what is being gained via the various rehabilitation techniques available. This paper will address these issues and provide a basis for sound management of buried infrastructure assets moving forward.

II. Buried Infrastructure Challenges Facing the Water Industry

The buried infrastructure challenges facing the water industry are an interrelated mix of technology, financial, customer and community service, and regulatory issues. This section will summarize the condition of buried infrastructure in this country, the positions of various industry groups and organizations including their estimates of needed capital, the concerns with justifying the capital expenditures, and potential new regulations that may affect the future management of buried infrastructure.

A. Current Condition/Status of Buried Infrastructure

The majority of distribution piping installed in the United States, beginning in the late 1800's up until the late 1960's, was manufactured from cast iron. The first cast iron pipe manufacturing process consisted of pouring molten iron into a sand mold, which stood on end in a pit in the ground, similar to how concrete is poured into a form. Pipe manufactured by this method is referred to today as "pit" cast iron pipe. Due to the potential inconsistencies that could occur in the pipe wall thickness, the pipe was designed with a wall thickness that was much greater than that required for the internal working pressure or external loading to which the pipe would be subjected. When installing the pipe in the field, the joints were sealed with rope and lead that was heated, poured in a molten state, and allowed to cool. Although pit cast iron pipe has no interior or exterior corrosion protection, it has performed well within the industry as a result of the added wall thickness.

In 1920, the process of centrifugally casting pipe in a sand mold was introduced. Pipe that was manufactured by this process is referred to as "spun" or "centrifugally" cast iron pipe. The centrifugal forces that are induced on the molten iron alter the molecular composition of the metal and increase its tensile strength. The higher strength coupled with the lack of inconsistencies in the wall thickness resulting from the centrifugal action allowed the pipe to have a much thinner wall than pit cast iron pipe. Interior lining of the pipe with cement to prevent corrosion was also introduced in the early 1920's; however, it did not gain wide acceptance until the late 1930's. The process of centrifugally casting pipe was improved in the early 1930's with the use of a water-cooled metal mold that allows the pipe to be immediately withdrawn from the centrifuge. This process, which is known as the "deLavaud" process, is still in use today for the manufacturing of ductile iron pipe. Although the centrifugal casting process improved pipe strength and minimized casting imperfections, the reduction in wall thickness

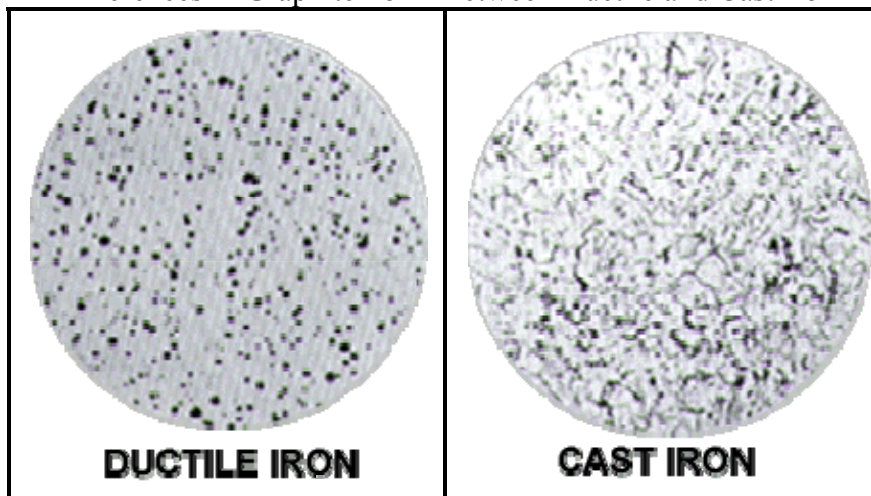
coupled with the lack of exterior corrosion protection has resulted in a failure rate in the industry that is higher than the older pit cast iron pipe.

In the late 1920's a plasticized sulfur cement compound was developed as an alternate to lead for sealing the pipe joints in the field. This compound is referred to as "leadite". Leadite was commercially produced up until the early 1970's, and was used extensively from 1941 to 1945 when lead was scarce as a result of raw material needs associated with World War II. Ultimately, leadite was found to be an inferior product to lead for two reasons. First, leadite has a different coefficient of thermal expansion than cast iron and results in additional internal stresses that can ultimately lead to longitudinal splits in the pipe bell. Secondly, the sulfur in the leadite can facilitate pitting corrosion resulting in circumferential breaks on the spigot end of the pipe near the leadite joint. The failure rate in the industry for leadite joint pipe is significantly higher than for lead joint pipe even though the pipe may not be as old.

Beginning in the mid-1950's, improvements in iron pipe manufacturing and technology began to emerge. The first improvement was the advent of the rubber gasketed joint that alleviated shortcomings associated with leadite and rigid joints. The next major improvement was the introduction of ductile iron pipe in the late 1960's. Ductile iron differs from cast iron in that its graphite form is spheroidal, or nodular, instead of the flake form found in cast iron. This change in graphite form is accomplished by adding an inoculant, usually magnesium, to molten iron of appropriate composition during manufacture. Not only is ductile iron pipe stronger than cast iron pipe, it is also more resistant to corrosion. Cast iron pipes, whether pit cast or spun cast, are susceptible to "graphitic" corrosion where which an electrochemical reaction occurs between the cathodic graphite component (flakes) and the anodic iron matrix causing metal loss. Due to its spheroidal graphite form, ductile iron is not subject to graphitic corrosion and also has approximately twice the strength of cast iron as determined by its mechanical properties. Its impact strength and elongation are also many times greater than cast iron. Exhibit No. 1 below shows the molecular differences in ductile iron and cast iron.

Exhibit No. 1

Differences in Graphite Form Between Ductile and Cast Iron



Polyethylene encasement was also introduced about the same time as ductile iron pipe. This even further prevented the potential for external corrosion to occur. In addition to the improvements made in iron pipe technology, the use of both polyvinyl chloride (PVC) and high-density polyethylene (HDPE) in this country began to emerge in the 1970's and 1990's respectively. Although these pipes did not have the strength of ductile iron, their resistance to corrosion is unsurpassed. The advent of all of these new pipe technologies has resulted in a significantly lower failure rate in the industry.

Exhibit No. 2 shows the progression of pipe technology in this country during the 20th century. The first four columns represent 1.) The material from which the pipe is manufactured, 2.) The type of joint, 3.) The interior corrosion protection, and 4.) The exterior corrosion protection.

The concern in the water industry revolves around the three older vintages of cast iron pipe (pit cast, spun cast, and spun cast with leadite joints) that were primarily installed prior to the 1960's (highlighted in yellow in Exhibit No. 2). As technology was thought to be improving the performance of the pipe during this period, it would ultimately be found that the failure rate would increase. The result is that the three vintages of pipe, installed in different time periods, may be reaching the end of their respective service lives at approximately the same time. This will increase the financial burden on the industry, as the cost of replacement will be borne over a shorter time span than that of the original installation period.

Exhibit No. 2
Timeline of Pipe Technology in the U.S. in the 20th Century

MATERIAL	JOINT	Corrosion Protection		1900's	1910's	1920's	1930's	1940's	1950's	1960's	1970's	1980's	1990's
		INTERIOR	EXTERIOR										
Steel	Welded	None	None										
Steel	Welded	Cement	None										
Cast Iron (pit cast)	Lead	None	None										
Cast Iron	Lead	None	None										
Cast Iron	Lead	Cement	None										
Cast Iron	Leadite	None	None										
Cast Iron	Leadite	Cement	None										
Cast Iron	Rubber	Cement	None										
Ductile Iron	Rubber	Cement	None										
Ductile Iron	Rubber	Cement	PE Encasement										
Asbestos Cement	Rubber	Material	Material										
Reinforced Conc. (RCP)	Rubber	Material	Material										
Prestressed Conc. (PCCP)	Rubber	Material	Material										
Polyvinyl Chloride	Rubber	Material	Material										
High Density Polyethylene	Fused	Material	Material										
Molecularly Oriented PVC	Rubber	Material	Material										

Commercially Available
Predominantly In Use

B. Industry Assessment and Estimate of Costs

In March of 2001, the American Society of Civil Engineers (ASCE) released their “Report Card for America’s Infrastructure”. Overall, this report card indicated that the nation’s infrastructure is in poor condition. Drinking Water, Wastewater, and Dams, received very low grades in relation to other categories of infrastructure. The only category receiving lower grades was public school infrastructure.

A number of professional organizations have addressed infrastructure concerns related to drinking water, and some have developed cost estimates. In addition to ASCE, these organizations include the USEPA, the American Water Works Association (AWWA), the Water Infrastructure Network (WIN), and the Help to Optimize Water (H₂O) Coalition. WIN is a broad-based coalition of local elected officials, drinking water and waste water service providers, state environmental and health administrators, and engineers and environmentalists who support the concept of federal financial assistance. The H₂O coalition is comprised of the National Association of Water Companies (NAWC), the Water and Wastewater Equipment Manufacturers Association, and the National Council for Public-Private Partnerships. This coalition recognizes that short term federal financial assistance may be needed, but wants water utilities to be self-sustaining, not subsidized enterprises, over the long term. A summary of the professional organization cost estimates related to drinking water infrastructure are provided in Exhibit No. 3 below. Except where noted, these estimates are for all drinking water infrastructure, including treatment plants, and encompass infrastructure needs due to regulation and deterioration but not new infrastructure associated with growth.

Exhibit No. 3
Cost Estimates for Drinking Water Infrastructure

Professional Organization	Cost Estimate	Period	Comments
ASCE	\$11 B	per year	
USEPA	\$151 B	next 20 years	\$83 B of this amount for transmission and distribution piping
AWWA	\$250 B	next 30 years	
WIN	\$460 B	next 20 years	includes both water and wastewater
H ₂ O Coalition	none	none	believes more analysis is needed

C. Verification of Industry Cost Estimates

In order to conduct a rough, order of magnitude, check of the industry cost estimates, a methodology was used whereby an annual range of costs for buried infrastructure was calculated based on the industry estimates, then verified by comparing it with known information for a large water utility.

First, the USEPA was the only organization that provided a breakdown between transmission/distribution and treatment plant cost estimates. Their transmission and distribution cost estimate was 55% of their total cost estimate (\$83B of \$151B). Thus, it was assumed that approximately 55% of the cost estimates provided by each of the other organizations was allocated for transmission and distribution. Applying this to each of the industry estimates and annualizing them results in a range of costs between \$4.2B to \$6.3B per year.

Second, the population served by community water systems was compared to the population served by the selected utility. As of April, 2000, approximately 264 M people were served by community water systems, and approximately 10M people were served by the selected utility (3.8%). Thus, taking 3.8% of the annualized range of costs calculated above results in an annual range of costs for transmission and distribution piping of \$160M to \$240M per year, with an average of \$200M per year for the utility, based on industry estimates.

Lastly, the selected utility has approximately 40,000 miles of main. Assuming an average pipe installation cost of \$75 per foot, and a range of pipe life between 75 to 100 years, the estimated range of expenditures is \$158M to \$211M per year. This compares favorably with the industry cost estimate range of \$160M to \$240M per year. However, it is important to note that this range of costs would not reflect the degree to which a utility may be behind in terms of pipe replacement. Thus, based on this rough analysis, it appears that the industry cost estimates for buried infrastructure are reasonable.

D. Justifying Capital Investments

One of the key components of infrastructure assessment is the estimate of the useful life of the asset. When is it time to replace the pipe? The following case history illustrates this challenge in more detail. A large mid-western water utility has done considerable work in their efforts to manage main breaks over the last few years. The system serves over 300,000 customers with a distribution system of over 4,000 miles of mains. They currently experience about 2,000 breaks per year. This equates to about 5½ breaks per day. In December 1999 during a particularly cold period, it experienced 1,000 main breaks. Exhibit No. 4 shows that main breaks in the system have been increasing over the years, especially the rigid joint, spun cast iron pipe. Using this data, an engineering economic analysis was performed by analyzing data from a computerized leak database containing over 30,000 records since 1983. The result was a main break forecasting model for individual mains in the system and an engineering economic model to estimate the total life cycle costs of each pipe with three or more breaks.

Exhibit No. 4
Main Breaks Since 1965

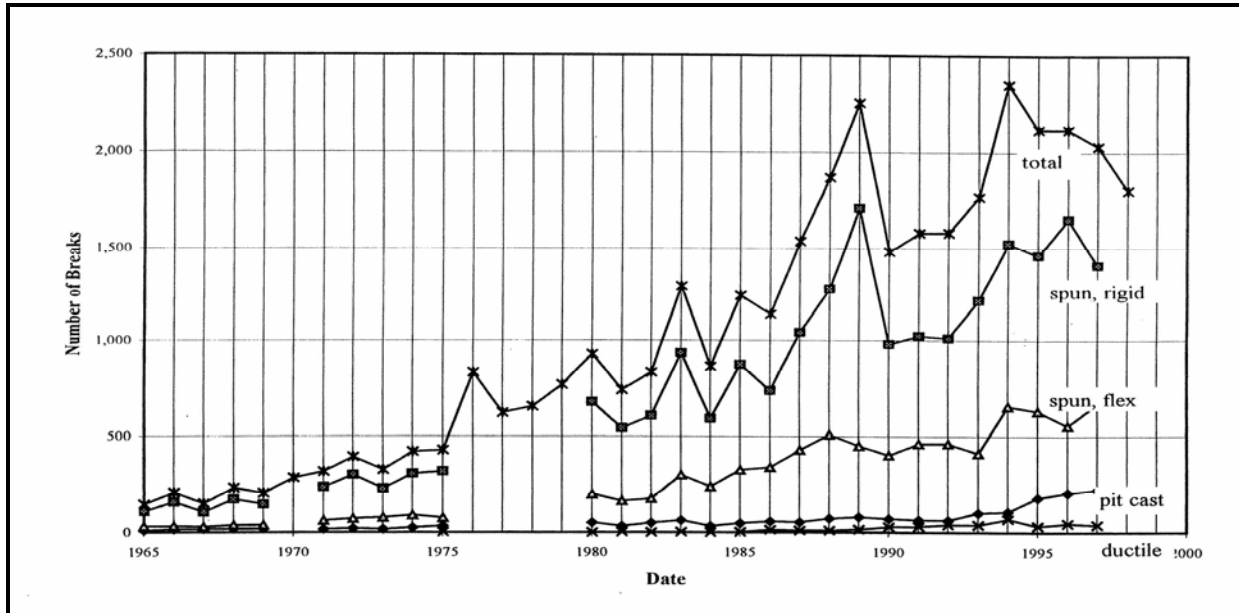
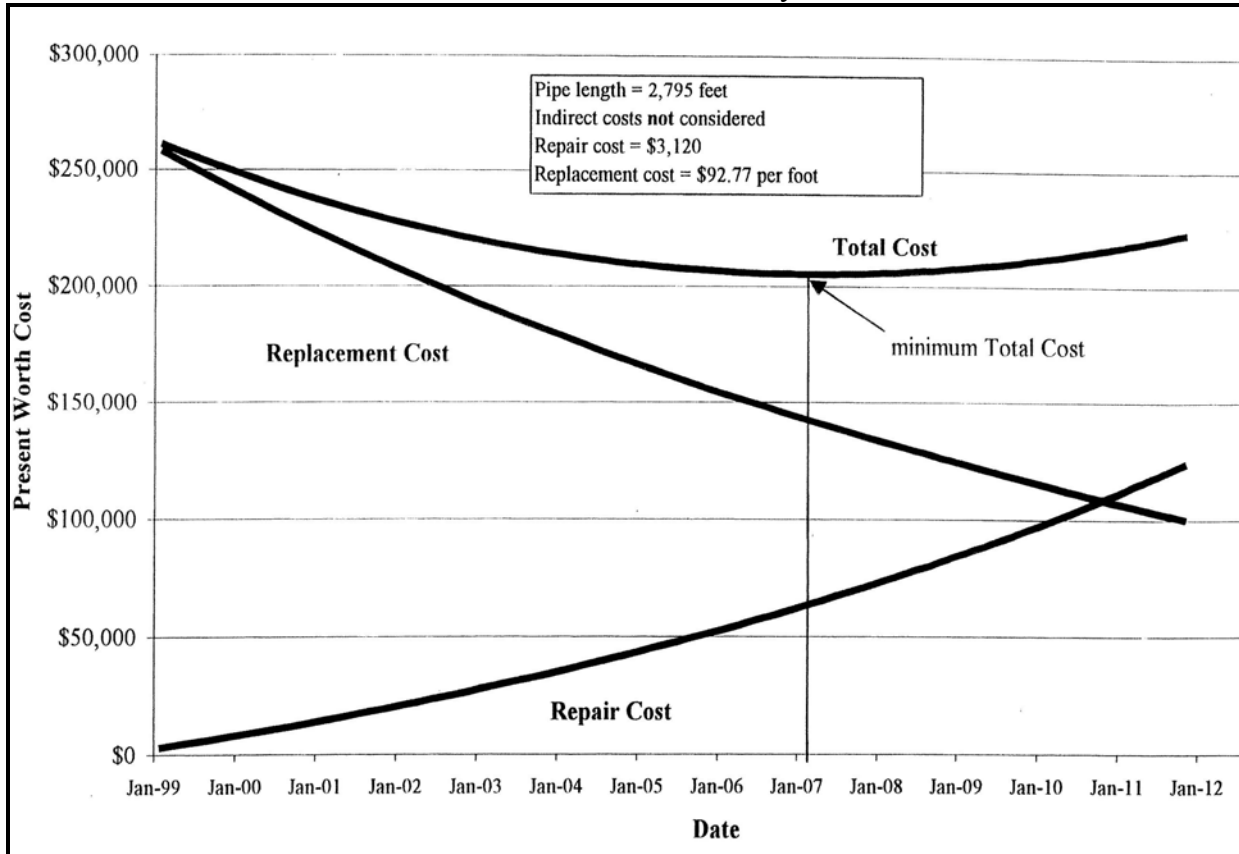


Exhibit No. 5 presents an example of a pipeline’s total life cycle costs derived from the model. The line sloping downward indicates the present worth of the replacement cost. The line sloping upward indicates the cumulative costs to repair the pipe. The top line indicates the addition of the other two curves, which represents the total life cycle cost of the pipeline. In other words, it shows how much money must be set aside today to finance the continual repair and/or eventual replacement of this pipeline. From the graph, it can be concluded that the optimal time to replace the pipe is when the total life cycle cost reaches a minimum.

By applying this approach the utility could support that 146 miles of pipe should be replaced today, and furthermore, could identify the individual pipes that should be replaced. Although more analysis is required, the initiative is moving forward to phase in an accelerated main replacement program.

Exhibit No. 5
Economic Break Even Analysis



This is an extraordinary case due to the unusually high number of main breaks. Most water utilities are not experiencing main breaks at such a rate and cannot economically justify replacement over repair. It also is important to note that the economic model is based on standard engineering economics, and does not incorporate financial factors such as taxes on capital investment and depreciation. If these additional factors were considered, the analysis would slant further in favor of repairing instead of replacing mains.

Consider the following example where actual direct costs for replacement and repair are compared. Average replacement costs are approximately \$100/foot for 6-inch main. Therefore, for a 1,000-foot main, total replacement costs would be approximately \$100,000. If the utility expects to recover that investment, the annualized revenue requirement or cost would be \$10,000 to \$15,000, depending on financing cost or economic regulation (investor-owned utilities). Repair costs on the main are approximately \$3,000 per break. Consequently, in order to justify replacing that pipe purely from a cost standpoint, the main must experience breaks at a rate of approximately 3 to 5 per year. A rate of 4 breaks per year is a break every 3 months for a length of pipe slightly longer than a city block. Such a high break rate is very unlikely and certainly would not be tolerated by customers subjected to such frequent service and traffic disruptions. Therefore, other factors such as the stakeholder and liability costs associated with main breaks must also be considered.

Liabilities associated with main breaks can be quite significant. A single break can incur liability costs that total more than the replacement cost of the main. Service disruptions can result in lost revenue and other risks to customers that depend on reliable water service (e.g. hospitals, restaurants, commercial properties, laundry mats, etc.). Traffic disruptions equate to lost time from work for stakeholders. Consideration should also be given to the monetary value of water lost during the break, including pumping, chemical, and waste disposal costs. These costs can be significant for large main breaks, especially if they empty tanks. One study estimated that these indirect costs could equal 20% to 40% of the repair costs.

Other important issues should be considered, including effects on water quality and the reputation of the utility. Main breaks can cause loss of system pressure, which poses the threat of contamination. Neglected distribution piping often breeds poor water quality due to corroded pipelines, resulting in numerous customer complaints. These problems result in poor customer service that can damage the reputation and credibility of the utility.

It is difficult to justify replacement of mains on direct costs alone. Although this can be done in some circumstances where break rates are excessive and/or replacement costs are very low, for most pipelines it will be less costly to continually repair the main than to replace it if direct costs alone are considered. However, direct costs do not present the full impact to the utility. Instead, we must consider the indirect costs and stakeholder issues discussed above in order to maintain system integrity and reliability so that acceptable customer service can be assured.

E. Regulations Affecting Buried Infrastructure

1. *Potential Health Effects*

In addition to this paper, other White Papers being prepared in response to the USEPA assessment of health risks and the need for distribution system regulation include:

- a. Contamination of New or Repaired Mains
- b. Permeation and Leaching
- c. Intrusion into Pipes
- d. Microbial Regrowth/Biofilms
- e. Covered Storage Vessels
- f. Decay of Water Quality in Pipe with Time
- g. Cross Connections
- h. Nitrification

Papers a through d above cover the specific causes, health risks, and mitigation strategies associated with the characteristic signs of deteriorated water distribution systems. These papers discuss the deleterious effects of internal corrosion on water quality and also address external sources of contamination and the potential pathways into the distribution system during repair activities or during negative pressure events associated with water hammer occurrences. In general, internal corrosion by-products, including the formation of tubercles (oxidized metals at the anode deposited back on the pipe wall), cause taste, odor and color problems and impart a

disinfectant demand on distributed water. Additionally, corrosion by-products can shield microorganisms from disinfectants and serve as a nutrient and physical substrate for their growth. Leaking mains and repair activities introduce pathways for external contamination including pathogen and harmful chemical intrusion. Sources of these contaminants include adjacent soils harboring microbial activity, leaking sanitary sewers, storm water runoff, chemically contaminated soils, and exposure to animal wastes. The findings of these papers needs to be incorporated in the overall management planning for aging distribution systems and used to clearly support the need for capital investment.

2. *New Accounting Regulation*

The Governmental Accounting Standards Board (GASB) was formed in 1984 to develop and improve financial reporting rules for the 85,000 state and local governments in the United States. It operates under the auspices of the not-for-profit Financial Accounting Foundation, which oversees, funds, and appoints the members of the GASB, as well as the Financial Accounting Standards Board (FASB). GASB is not part of the government, federal or otherwise. Its rules are required in most states for financial reporting at the local and state level. GASB rules also are required to be followed when a state or local government's audit reports that it follows Generally Accepted Accounting Principles (GAAP). Bond covenants associated with government debt often require them to follow GAAP.

GASB Statement No. 34 (GASB 34) was modified in June 1999. It requires, for the first time, that governments begin including infrastructure assets on their balance sheets. After estimating the initial cost of each infrastructure asset and including that cost in the balance sheet, governments will be required to either depreciate those assets, or manage them using an asset management system. GASB 34 prefers that municipalities implement an asset management system referred to as the "modified approach" because it better models the way infrastructure should be treated. There are specific requirements for the implementation of the asset management system, and reporting that must be produced.

Whichever method is used, a fundamental requirement is a good inventory of assets. The inventory must include the actual or estimated historical cost of construction. The most straightforward method for valuing assets is depreciation, but this method ignores the extended life of the asset provided by continued maintenance. The modified approach incorporates the benefits, or value, of such maintenance activities. GASB 34 provides the following minimum guidelines as to what the modified approach should include:

- a. The assessed physical condition of infrastructure assets (governments must perform such assessments at least every three years, and disclose the results of at least the three most recent condition assessments).
- b. Descriptions of the criteria the government uses to measure and report asset condition.
- c. The condition level at which the government intends to maintain the assets.
- d. A comparison of the annual dollar amount estimated to be required to maintain and preserve the assets at the condition level established by the government with the actual expenses, for at least the last five years.

Although not prescribed in detail, GASB 34 requires that governmental entities use “consistent” and “reasonable” methods for valuing assets. The GASB 34 rule should have a positive effect on addressing aging infrastructure by continuously measuring the condition of a buried water system and quantifying investment needs and past deficiencies.

Municipalities must be in compliance with GASB 34 by July 2001, 2002, or 2003 depending on the government’s annual revenue base in 1999. Only new infrastructure (added or reconstructed) need be included beginning on those dates. An additional four years are granted before pre-existing infrastructure need be reported. If revenue base was less than \$10 million in FY 1999, a municipality is encouraged, but not required, to report pre-existing infrastructure.

III. Buried Infrastructure Technical Considerations

In order to address the concerns raised by the water industry, it is first necessary to further understand the technical aspects of buried infrastructure in order to develop appropriate management strategies. This section will address the failure mechanisms of pipe, potential rehabilitative and preventative technologies, and recommendations for pipe materials for future use.

A. Recommendations for Extending Pipe Life

In order to minimize main failures and maximize the life of the assets, it is necessary to understand the failure mechanisms of pipe. These failure mechanisms, which are a result of either Operational/Physical or Chemical means, are identified in Exhibit No. 6.

Exhibit No. 6
Pipe Failure Mechanisms

Operational/Physical	Applies to	Options	Chemical	Applies to	Options
Manufacturing defects	M,P,C	No	Internal corrosion	M,C	Yes
Improper design/installation	M,P,C	No	External corrosion - soil	M,C	Yes
Geologic instability	M.P.C	No	External corrosion - other	M,C	Yes
Higher operating pressures	M,P,C	Yes	Leadite corrosion	M	Yes
Hydraulic transients	M,P,C	Yes	Leadite expansion	M	Yes
Change in water temperature	M	Yes	Material incompatibilities	M	Yes
Excessive external loads	M,P,C	No	Gasket deterioration	M,P,C	Yes
Damage from digging	M.P.C	No	Material fatigue	P	No

M = Metallic (ductile iron and/or cast iron)

P = Plastic (PVC or HDPE)

C = Concrete (RCP or PCCP)

This exhibit indicates the type of pipe to which the failure mechanism is applicable (metallic, plastic, or concrete) and whether there are any options to reduce or eliminate the failure mechanism for pipes that are already installed in the ground. If so, these are addressed in a subsequent exhibit. Nearly all of these failure mechanisms can be addressed or controlled for new installations as a result of newer pipe materials, current manufacturing technology, and improved utility operational practices.

A few of these failure mechanisms warrant additional discussion as follows:

1. Hydraulic Transients: Hydraulic transients (water hammer) occur as a result of a sudden change in flow velocity. Some ways that this can occur are due to a sudden starting or stopping of a pump, closing or opening a hydrant too quickly, or sudden starting and stopping of water usage by large customers. As a rule of thumb, for every 1 ft/sec instantaneous change in flow velocity, the pressure can change by 100 ft (43.3. psi). It is important to understand the variables which effect the magnitude of the pressure change as defined by the Joukowsky equation:

$$H = \frac{4660}{\left(1 + \frac{M_w * ID}{M_p \text{ th}}\right)^{0.5 * g}} * (V_i - V_f) \quad \text{where:}$$

H = pressure increase (ft)
Mw = bulk modulus of water (psi)
Mp = bulk modulus of pipe materials (psi)
ID = inside diameter of the pipe (in)
th = wall thickness of the pipe (in)
g = acceleration due to gravity (ft/sec²)
Vi = initial water velocity (ft/sec)
Vf = final water velocity (ft/sec)

It can be seen in this equation that the materials of construction (Mp) and the geometrical strength of the pipe (ID/th) also affect the magnitude of the pressure change. With the same change in velocity, a stronger, more rigid pipe will experience a higher pressure change. The second item to note is that water hammer is independent of volume. It is also important to be aware of operational situations that could promote hydraulic transient events as listed below:

- Pipeline velocities > 5 ft/sec
- Non-networked pipelines (transmission mains)
- Dead end pipelines and closed (no tanks) systems
- Undulating topography
- Combination vacuum relief/air release valves of the same size
- Pumps with swing check valves or no control valves
- Frequent power failures at pump stations

2. Change in Temperature: Utilities with cast iron pipe typically experience an increase in main failures with freezing temperatures. Although plastic pipes also are affected by a change in temperature due to their high coefficient of thermal expansion, it is less of an issue due to the flexibility of the pipe, and the phenomena of concern discussed here applies only to iron pipes. One theory of why iron pipes fail in freezing temperatures is that the ground movement imposes a stress on the pipe. Although this may be true, the primary reason for the failures relates to the differences in thermal expansion between water and iron. As water and the pipe cool, they are both contracting until the temperature reaches 39 deg

F. At this point, the pipe continues to contract, but the water begins to expand. This can result in a stress equivalent to that of increasing the hydrostatic pressure in the pipe by approximately 200 psi.

3. Corrosion (internal): Internal corrosion of water distribution systems leads to two major problems for water utilities. The first is the failure of distribution system pipes which can result in water leakage, loss of pressure, and potential contamination during main installation and repair. The second problem is an unwanted change in water quality as the water is being transported through the distribution system (Snoeyink et al, 1996). Corrosion can occur without metals leaching, i.e., oxidized metals released at the anode can be deposited back on the pipe wall in the form of tubercles (Snoeyink et al, 1996).

During iron corrosion, the metal dissolves and the electrons are accepted in cathodic reactions such as those involving the reaction of protons and oxygen. These reactions are shown in Equations a through c (Snoeyink et al, 1996).

- a. $\text{Me} \leftrightarrow \text{Me}^{z+} + z e^{-}$
- b. $2\text{H}^{+} + 2e^{-} \leftrightarrow \text{H}_2$
- c. $\text{O}_2 + 2\text{H}_2\text{O} + 4e^{-} \leftrightarrow 4\text{OH}^{-}$

According to Benjamin, Sontheimer, and Leroy (1996), the corrosion of iron piping in distribution systems can be either uniform or localized. Localized corrosion can be caused by local nonuniformities in the pipe or the water quality adjacent to it, and often leads to tuberculation.

When potable water containing dissolved oxidants (such as oxygen or chlorine) is in contact with metallic iron, there is a driving force for active corrosion under any realistic water quality conditions (Benjamin et al, 1996). The authors also state that the corrosion rate is probably limited by the rate at which oxygen is provided to the surface, which in turn is limited by molecular diffusion through the layers of stagnant water and scale adjacent to the metal.

Ferrous ions or compounds in scales can be oxidized directly or microbially mediated, resulting in a variety of end products. These corrosion products can be released into the water due to physical or water quality factors, and therefore the iron release rate often bears no relation to the overall corrosion rate (Benjamin et al, 1996). Corrosion and the release of corrosion products can lead to chemical, physical, and microbial degradation of distribution system water quality.

The internal corrosion of cement-based materials can impact both water quality and infrastructure integrity. Cement-based materials include reinforced or prestressed concrete pipes, cement-mortar linings, and asbestos-cement pipe. Two general components of cement-based materials include the aggregates and the binder. The binder consists of calcium silicates and calcium aluminates in various proportions depending on the type of the cement (Leroy, Schock, Wagner, and Holtschulte, 1996).

Several types of degradation of cement materials can occur in the presence of acid waters or waters aggressive to calcium carbonate (Leroy, Schock, Wagner, and Hultschulte, 1996). Degradation can result in weakening of the material as well as leaching of calcium carbonate and metals into the water. Water quality impacts associated with lime and metals leaching from cement-based materials are discussed further under Metals and Chemical leaching. Health effects associated with the release of asbestos fibers from asbestos-cement pipe are addressed in the Phase II National Primary Drinking Water Regulations (USEPA, 1991).

Microorganisms have the ability to induce or promote corrosion as well as take advantage of corrosion deposits as growth habitats (Snoeyink et al, 1996). Corrosion by-products such as tubercles, iron oxides, and other precipitates can shield microorganisms from disinfectants and can serve as a physical substrate for growth. Organisms such as *Bacillus*, *Escherichia coli*, *Pseudomonas*, and *Citrobacter* have the ability to reduce Fe(III) to Fe(II) and have been found in tubercles, but the role these organisms play in the corrosion process has not been delineated (Snoeyink et al, 1996). Microbial regrowth and associated health effects are discussed in a separate White Paper.

Internal corrosion can result in leaking or failure of distribution system pipes. Leaks and breaks can serve as pathways for contamination from harmful organisms originating exterior to the pipe environment. Potential health impacts associated with pathogen intrusion are discussed in a separate White Paper.

4. Corrosion (external): The two basic types of external corrosion which can occur in a water system are galvanic and electrolytic. The galvanic corrosion process occurs when electrons flow from one metal (anode) to a dissimilar metal (cathode) via an electrolyte (soil) with a return current path (the pipe). Electrolytic corrosion is similar to galvanic corrosion with the exception that the return current path includes a direct current source (stray current) which drives the reaction.

Some of the specific types of external corrosion in pipelines include:

- a. Pitting Corrosion - Occurs when protective films covering a metal break down.
- b. Bacteriological Corrosion - The result of sulfate reducing bacteria giving off sulfides which are excellent electrolytes.
- c. Soil Corrosion - Mostly occurs in soils with high electrical conductivity.
- d. Graphitic Corrosion - Corrosion can occur in any metallic pipe. However, the potential for corrosion is higher in cast iron pipes than in ductile iron pipes. The corrosion phenomenon that occurs in cast iron (pit cast or spun

cast) is called graphitic corrosion. Graphitic corrosion of cast iron is a form of selective leaching where the iron matrix corrodes, leaving behind porous graphite mass. The process affects buried cast iron pipe in relatively mild aqueous environments. The corrosion mechanism involves an electrochemical reaction between the cathodic graphite component and the anodic iron matrix. Graphitic corrosion generally is a slow process. It can cause significant problems since no dimensional or physical changes occur which are visible, yet the cast iron loses its strength and becomes brittle.

5. Leadite Corrosion and Expansion: As previously discussed, leadite has a different coefficient of thermal expansion than cast iron resulting in stress on the pipe which can ultimately result in longitudinal splits in the pipe bell. Secondly, the sulfur in the leadite allows for bacteriological corrosion that can lead to circumferential breaks on the spigot end of the pipe near the leadite joint.
6. Material Fatigue: There is no measurable relationship between ductile iron's applied tensile strength and time to failure. However, both PVC and HDPE pipe experience a reduction in strength over time.

Exhibit No. 7 identifies the strategies for reducing or eliminating pipe failures for those pipes that are already installed in the ground. The potential for implementing these strategies is also indicated.

Exhibit No. 7
Operational Strategies for Reducing or Eliminating Pipe Failures

Failure Mechanism	Strategy	Potential
Higher operating pressures	Redistribution of pressure zones	Low
Hydraulic transients	Surge control and operator training	Medium/High
Change in water temperature	Blending with ground water sources, where possible	Low
Internal corrosion	Cleaning and lining	High
External corrosion - soil	Cathodic protection	Medium
External corrosion - other	Cathodic protection	Medium
Leadite corrosion	Replace the joint only	Low
Leadite expansion	Replace the joint only	Low
Material incompatibilities	Install dielectrics at corporation stops	Medium
Gasket deterioration	Replace the joint only	High

Additional information regarding some of the potential rehabilitation or prevention strategies (e.g. cleaning and lining, cathodic protection) is discussed subsequently in this section.

B. Rehabilitation Technologies

Once a water main has been identified as failing to meet its service requirements, the method of replacement or renewal should be considered. Currently, the majority of water main replacement is performed using open-cut or open-trench methods. Conventional open-trench construction is still the most frequently and cost-effective method of water main replacement in the United States, and therefore, contractors are usually easy to find and locally available. For

many water utilities, the practice is to install the new main in a trench parallel to the old main. In some cases, removal of the old main is not worthwhile or necessary, and old, damaged water mains are simply abandoned or given to electric or cable utilities. Because the old main is kept in service until the new main is in place and ready for connection to the customers' service lines, service interruptions are minimized. In those cases where the old main has to be shut down before the new main is in place, bypass pipes can be laid to provide uninterrupted service to customers.

Though popular, open-cut methods can create considerable inconveniences to customers, businesses, residences, and traffic in the area. In some cases these inconveniences can also become very costly. As a result, trenchless technologies have attracted the attention of the water industry as an alternative to open-trench methods. Based on the site-specific main replacement, trenchless technologies can frequently reduce both direct rehabilitation costs and the additional financial and commercial costs associated with holes in the road.

For over 20 years, trenchless renovation technologies have been steadily increasing and playing an increasingly important role in the wastewater and gas industries, and for many of those utilities, it is now their method of choice. In the United Kingdom, where extensive privatization of the water supply industry has greatly accelerated rehabilitation expenditures, numerous trenchless techniques are in widespread use. There is; however, some reluctance on the part of U.S. water utilities to use trenchless technologies due to their inexperience with the technology and questions regarding the use of the materials in a potable water system.

Recently, the AWWA Research Foundation (AWWARF) and a number of AWWA technical committees have evaluated alternative rehabilitation technologies for application in the water utility industry and developed guidelines for those technologies that have a proven track record within the industry. The following paragraphs will briefly describe the alternative technologies that could be considered by American Water utility subsidiaries to successfully rehabilitate water mains and identify conditions under which each technology can best be applied within American Water.

Alternative rehabilitation techniques can be classified into three categories according to their effect on the performance of the existing pipe. The three categories include: non-structural systems, semi-structural systems, and structural systems.

1. Nonstructural Lining Techniques

One of the most common and effective renewal methods used in the piping industry is the application of a non-structural protective lining on the interior of the water main. Nonstructural lining systems are used primarily to protect the inner surface of the host pipe from corrosion and tuberculation. They have no effect on the structural performance of the host pipe and have a minimal ability to bridge any existing discontinuities, such as corrosion holes or joint gaps. Hence, non-structural lining systems have minimal effect on leakage. Their use is indicated in pipes that are structurally sound and leak tight at the time of lining and expected to remain so for the foreseeable future. Examples of nonstructural techniques include cement-mortar lining and epoxy resin lining. Statements regarding the effect of service connections, valves, bends, and

appurtenances on efficiency and the expected service life extension from non-structural pipe lining apply to both lining methods discussed.

The advantages of non-structural pipe lining are that a smooth protective non-structural coating is applied to the interior surface of the pipe that restores hydraulic capacity to the water main. A limitation is that service connections, valves, bends, and appurtenances will affect the cost of lining projects. The expected service life of the pipe with reasonably good structural condition can be extended 30 to 50 years with cement mortar lining or epoxy lining procedures. Cement mortar lining is the most common rehabilitation technique in use today and is effective and reliable. Cement mortar linings were first installed in existing pipelines using the centrifugal process in the mid-1930s to rehabilitate pipelines. However, this method was limited to pipes large enough for a person to enter. In the 1960s, remote lining processes were introduced. Today, cement mortar is applied to new ductile iron pipes and most new steel pipes before installation, making this method a standard in the water industry. Service lines and laterals less than 2 inches in diameter must be cleared after the lining application. This is done about 1 hour after the lining is completed, using compressed air to blow open the service line at the connection to the main. Laterals over 2 inches are not plugged by centrifugal lining and do not require excavation or blow back. Cement mortar lining may increase the pH of water and therefore is not recommended for soft or aggressive water.

The process for in-situ epoxy resin lining of iron and steel pipelines was developed in the United Kingdom in the late 1970's and has been performed in North America since the early 1990's. The process has been used effectively to rehabilitate old, unlined water mains. Epoxy lining of water mains is also classified as a nonstructural renewal method. As with other lining techniques, pipelines must be thoroughly cleaned and dried before application of the epoxy lining. The epoxy resin is applied to the interior of the pipeline using a centrifugal method. A spinning head is winched through the pipeline at a constant rate spraying a thin (1 mm) liquid epoxy coating onto the inner wall of the pipe. The coating cures in 16 hours and provides a smooth and durable finish resistant to mineral deposits and future tuberculation buildup. Several epoxy-lining materials are currently approved for use in the potable water systems under ANSI/NSF 61. Epoxy resin linings do not normally block service lines and laterals. They do not affect the pH of the water and may be used for soft water supplies. Problems can occur if water is accidentally introduced in the main during the lining process. The lining will be damaged and may cure incorrectly, creating water quality problems. Mix ratio errors will also cause failures in the lining.

2. Semi-Structural Lining Techniques

Semi-Structural renovation systems generally involve the installation of a thin plastics-based lining tube that achieves a "tight fit" to the pipe wall. Since the stiffness of the liner is less than that of the host pipe, all internal pressure loads are almost entirely transferred to the original pipe. Such a lining is required only to independently sustain internal pressure loads at discontinuities, in the host pipe, such as corrosion holes or joint gaps. Semi-structural lining techniques are best suited for long transmission mains with few service connections and for situations in which obstacles such as buildings, underground utilities, and railroads do not permit the excavation of the old pipes. Mains with corrosion holes and leaks, which would not be suited

for cement mortar or epoxy lining but that have not experienced structural failures (i.e. breaks), are good candidates for semi-structural lining. Semi-structural liners do reduce the effective cross-sectional area of the pipe. Therefore, post lining flow requirements must be considered when deciding to slip-line. However, the reduction in the friction factor of the liner pipe as compared to the old, unlined pipe should compensate for the reduced cross sectional area. In addition, the flow rate will not be reduced by corrosion over time. The geometry of the unlined pipe must also be considered, as liners generally do not turn well through elbows. Excavations will be required at branch connections, bends and service connections in order to complete the installation. Examples of semi-structural lining techniques include: slip-lining, close-fit slip-lining and cured in place pipe lining

3. Structural Lining Techniques

Structural lining techniques are capable of sustaining a long-term (50-year) internal burst strength, when tested independently from the host pipe, equal or greater than the Maximum Allowable Operating Pressure (MAOP) of the pipe to be rehabilitated. Additionally, structural linings have the ability to survive any dynamic loading or other short-term effects associated with sudden failure of the host pipe due to internal pressure loads. Structural lining techniques are sometimes considered to be equivalent to the replacement pipe, although they may not be designed to meet the same requirements for external buckling or longitudinal/bending strength as the original pipe.

Structural linings will be used in circumstances similar to those for semi-structural lining, but their use is essential for host pipes suffering from generalized external corrosion where the mode of failure has been, or is likely to be, catastrophic longitudinal cracking. Examples of structural lining techniques include structural slip lining and pipe bursting. Structural slip-lining techniques are similar to the semi-structural slip lining methods, but with varying design parameters for the new pipe regarding wall thickness, pressure rating, and operating requirements.

Pipe bursting is a patented process of replacing existing water mains by breaking and displacing them and installing a replacement pipe along the same route and in the void created. The pipe bursting technology is a total pipe replacement method. The pipe bursting process replaces the original pipe with a new pipe of the same diameter or larger. The system consists of a pneumatic, hydraulic or static bursting unit that splits the existing pipe while simultaneously installing a replacement pipe of the same or larger diameter and pressure rating. The pipe-bursting tool is designed to force its way through the existing pipe by fragmenting or splitting the pipe and compressing the materials into the surrounding soil as it progresses. The use of high density polyethylene pipes as the replacement pipe is desirable due to their flexibility, especially when the pipes to be replaced are not straight. Pipe-bursting demonstrations using ductile iron pipe have not been proven successful. All service connections should be completely disconnected and isolated from the existing pipe before pipe-bursting operations begin. All service connections, valves, bends, and appurtenances must be individually excavated and connected to the new main. A temporary bypass system is usually provided to maintain service to consumers. Breaking of existing repair clamps may also be a problem. If the pipe-bursting heads cannot break a repair clamp, the pipe needs to be excavated and the repair clamps must be

removed or cut with a pipe saw.

4. Cost Considerations

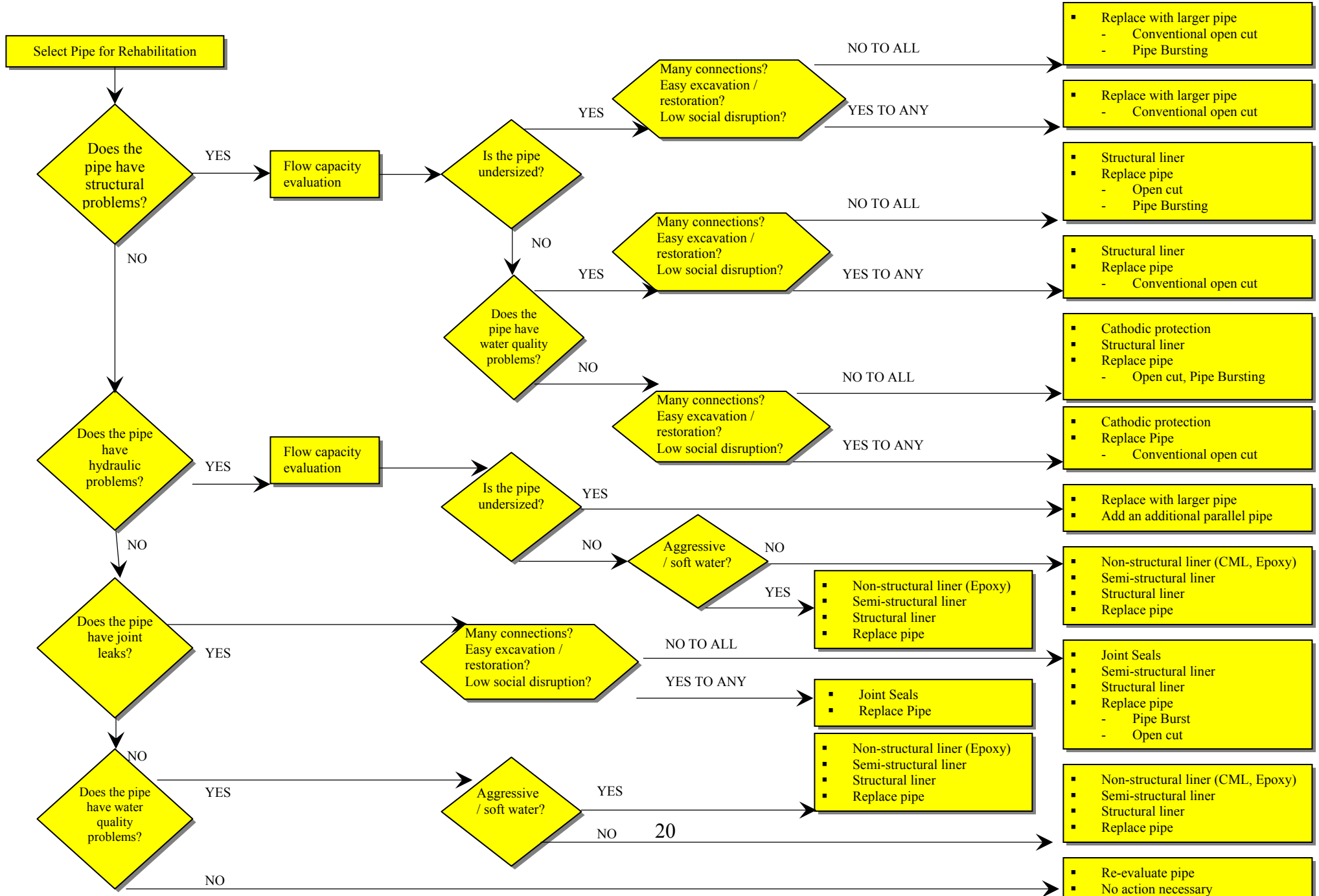
Compared to open-cut pipe replacement methods, the potential cost savings for alternative rehabilitation methods are dependant on the minimization of site restoration activities and the number of service connections on the existing main. All trenchless technologies require excavations for insertion and receiving of pipes, and local excavations for service connections. However, there are usually less excavations for alternative technologies than compared with traditional open cut replacement methods. In order to avoid disruption of water supply to customers, temporary service connections may be required to serve customers during the construction period. Equipment and crew mobilization costs, length of mains being replaced, and the “learning curve” all affect the unit cost of the alternative methods.

In order to satisfy the rehabilitation and replacement needs of water mains, it is essential for the water utilities to consider alternative rehabilitation technologies along with traditional open-cut technologies for cost-effective construction. Trenchless technologies will create less disruption of public life than open-cut methods, although they may not be suitable for all pipe rehabilitation and replacement. Key elements in the selection of a rehabilitation method are:

- a. The exact nature of the problem(s) to be solved.
- b. The hydraulic and operating pressure requirements for the rehabilitated main.
- c. The materials, dimensions, and geometry of the water main.
- d. The types and locations of valves, fittings, and service connections.
- e. The length of time in which the main can be taken out of service.
- f. Site-specific factors.

The selection of renewal technologies depends on pipe characteristics and site characteristics as well as the techniques themselves. The aim of the selection process is to consider all these factors to arrive at the most cost-effective, technically viable solution. Ideally, the cost estimate should include not only direct contracting and related costs, but also indirect costs associated with public disruption and longer-term maintenance. The most cost effective technology can then be selected using present worth (PW) analysis or equivalent uniform annual cost (EUAC) analysis. One approach to rehabilitation/replacement technique selection is summarized in Exhibit No. 8. This chart provides a framework for selecting or rejecting groups of techniques, depending on the nature of the performance problems, hydraulic requirements, and some site-specific factors.

Exhibit No. 8 Rehabilitation Decision Tree



Generally four types of problems (structural, hydraulic, joint leaks, and water quality) need to be evaluated in determining the options available for the pipe. This evaluation is performed in a hierarchical order, with the most critical pipe problems being addressed first and any remaining problems associated with the pipe being addressed by default. The following pipe problems should be evaluated when selecting renewal technologies:

- a. If the problem is structural (loss of strength), the options are replacing the pipe (same size or larger) or installing a structural liner. Using these options will also address hydraulic, joint leak, and water quality problems.
- b. If the problem is hydraulic (lack of adequate flow capacity) the options are replacing the pipe (same size or larger) or installing a structural, semi-structural, or non-structural liner provided the existing pipe diameter is adequate. Using these options will also address joint leak and water quality problems.
- c. If the problem is joint leaks, the options are replacing the pipe (same size or larger), and installing a structural or semi-structural liner. Using these options will also address water quality problems.
- d. If the problem is water quality, the options are replacing the pipe (same size or larger), and installing a liner. The lining can be structural, semi-structural, or non-structural.

Once the pipe problem and available renewal options have been determined, the applicable renewal methods should be selected based on pipe and site characteristic information. Exhibit No. 9 lists a summary of the technologies discussed and recommended applicable use.

Exhibit No. 9
Summary of Applicable Technology and Recommended Use

Technology	Recommended Application
Cement Mortar Lining	<ul style="list-style-type: none"> • Prevent scale formation, internal corrosion and reduce pipe roughness (improve Hazen Williams C-value). • Considered with hydraulic and wq problems when there are no structural and joint leaks and original pipe material is cast iron, ductile iron or steel. • Should not be considered when soft or acidic water is conveyed due to possible deterioration of CML.
Epoxy Resin Lining	<ul style="list-style-type: none"> • Protects original pipe against corrosion and provides an increased Hazen-Williams C-value. • Considered with hydraulic and water quality (WQ) problems when there are no structural and joint leak problems.
Conventional Slip Lining	<ul style="list-style-type: none"> • Effective diameter of pipe is reduced, with a new pipe have a smooth interior surface. • Excavations are required for service connections, entrance pits and exit pits. • Various pipe materials (DI, PVC, HDPE and steel) may be used as new pipe. No strength is added to the host pipe in conventional slip lining.
Close-Fit Slip-lining	<ul style="list-style-type: none"> • Classified as structural or semi-structural lining depending on the thickness of the liner. The inserted pipe add strength, prevents further internal corrosion and improves Hazen-Williams C-value. • Considered for hydraulic, joint leak and water quality problems with no structural problems are involved.
Cured in Place Pipe	<ul style="list-style-type: none"> • Compared to close-fit lining, the thickness of CIPP liner is typically less than a close-fit liner. • As with the close-fit liner, the loss of diameter is compensated for by an improved Hazen-William C-value. • As opposed to epoxy lining, CIPP also provides a certain measure of leakage protection. • Considered a semi-structural liner and is applicable for hydraulic, joint leak and water quality problems when no structural problems are involved.
Pipe Bursting	<ul style="list-style-type: none"> • Pipe bursting is a structural lining technique and is considered suitable for CI, PVC, AC and thin wall steel pipes. • Pipe Bursting recommended for deep mains with sufficient cover to avoid heaving. • Host pipe should not have offset pipe joints or clamps with bolts. • Applicable for replacing pipes of the same diameter or larger. • Excavations are required for service connections, entrance pits and exit pits.

Generally, conventional open-cut methods would be the preferred method of main rehabilitation. Installation of polyethylene encased ductile iron pipe has an anticipated service life well over 100 years. However, when the situation (financial or technical) warrants the use of an alternative technology, a potential cost savings may be realized. Industry and vendor cost estimates for the various alternative technologies indicate a potential savings as follows:

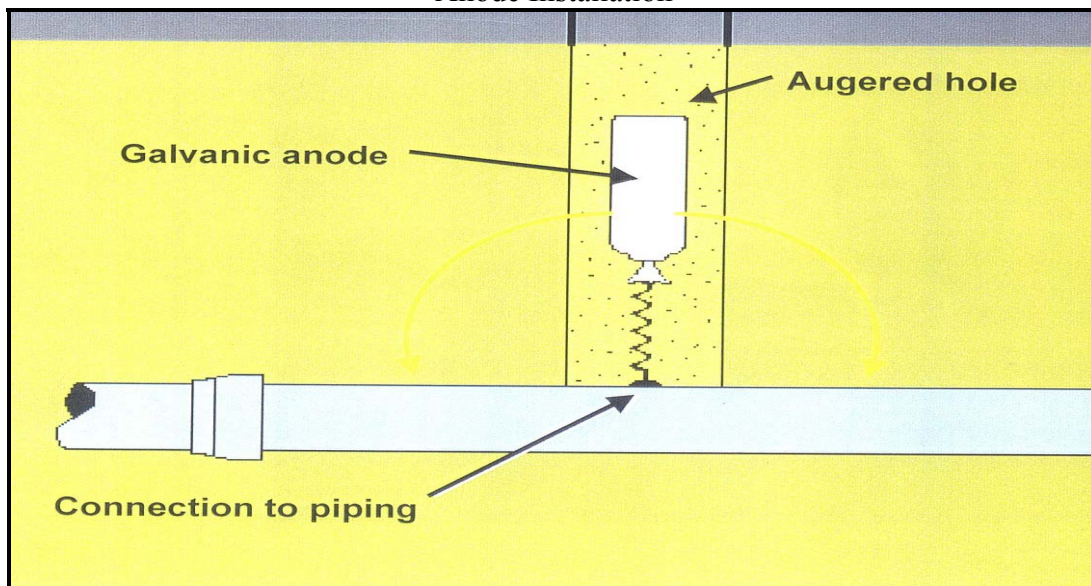
- a. Non-structural (cement mortar and epoxy lining) – 40%-60% less than conventional open cut replacement.
- b. Semi-structural (slip lining and close fit slip lining) – 30%-40% less than conventional open cut replacement.
- c. Structural (pipe bursting) – 20%-30% less than conventional open cut replacement.

Selecting the optimal solution to a specific pipeline problem is a complex process involving both technical and economical considerations. AWWARF is currently developing a computer-based decision tool to assist utilities in this selection process. The computer model is expected to be published by AWWARF in the Spring, 2002 and will provide guidance to utilities in considering the important criteria for selecting suitable technologies and pipe materials based on present worth and environmental considerations. The computer model is expected to assist utilities in selecting several renewal technologies that are appropriate for the pipe and site characteristics of the associated project, allowing utilities to compare different technologies that they may not have considered in the past.

C. Preventative Technologies

Cathodic Protection is a technology for reducing corrosion of a metal water main by turning the entire main into the cathode of a galvanic or electrolytic corrosion cell. Normally, sacrificial anodes are used as the galvanic cell to minimize the effects of external corrosion on existing metal water mains, thus reducing water main breaks and extending the useful life of the mains. A sacrificial anode system does not stop the process of corrosion but rather redirects the corrosion from the water main to the anode. Exhibit No. 10 shows a typical installation of a galvanic anode. Sacrificial anode protection may be used in selective “hot spot” (highly corrosive soils) areas that have been located by soil-survey procedures. In corrosive soils, sacrificial anodes should be installed during the repair of water mains. Typically this would only increase the total cost of the repair by approximately \$200 - \$300 per break.

Exhibit No. 10
Anode Installation



As a preventative maintenance program, sacrificial anodes are typically installed at 40-foot spacing (at every other joint) to be cost effective. This requires that rubber-gasketed joints be electrically bonded along the protected water main. It is also recommended that test-monitoring stations be installed at selected intervals along the water main to verify that the

systems are operating as intended, to assess the break reduction efficiency and to monitor the replacement timeframe for anodes.

D. Analysis of Distribution Pipe Materials for Future Use

In order to make recommendations regarding future pipe material usage, it is necessary to understand the differences between each of the potential pipe materials. This investigation is limited to “distribution size” materials (up to approximately 24”) which includes ductile iron (DI), polyvinyl chloride (PVC), and high density polyethylene (HDPE). Pipes larger than 24” are typically evaluated on a case by case basis, and also include steel and concrete pipes which are typically not cost effective in the smaller sizes. Exhibits No. 11a, 11b, and 11c below list the material properties, pipe properties, and operational considerations for each of the three types of pipes.

Exhibit No. 11a
Comparison of Distribution Size Pipe Materials - Material Properties

Material Property	DI	PVC	HDPE
Tensile strength	60,000 psi	7,000 psi	3,200 psi
Compressive strength	48,000 psi	9,000 psi	1,600 psi
Yield strength	42,000 psi	14,500 psi	5,000 psi
Ring bending stress	48,000 psi	none specified	none specified
Impact strength	17.5 ft-lbs/in	0.75 ft-lbs/in	3.5 ft-lbs/in
Density	441 lbs/ft ³	88.6 lbs/ft ³	59.6 lbs/ft ³
Modulus of elasticity	24,000,000 psi	400,000 psi	110,000 psi
Temperature range	< 150° F	< 140° F	-50 to 140° F under press.
Thermal expansion	0.07” per 10° F per 100’	0.33” per 10° F per 100’	1” per 10° F per 100’
Corrosion resistance (int)	Good - w/cement lining	Excellent	Excellent
Corrosion resistance (ext)	Good - w/polywrap	Excellent	Excellent
UV resistance	Excellent	Gradual strength decline	Yes - w/carbon black
Abrasion resistance	Excellent	Good	Good
Cyclic resistance	Excellent	Fair	Good
Permeation resistance	Yes	No - solvents & petroleum	No - solvents & petroleum
Scale & growth resistance	Good	Excellent	Excellent

The primary difference between the three materials is that DI is much stronger than PVC or HDPE. However, DI is susceptible to corrosion which is not an issue with the other two materials. PVC pipe is very similar to DI pipe in terms of installation, repair, and tapping, and thus it was easy for water utilities, which had historically used cast iron pipe, to transition to PVC pipe. HDPE is just starting to gain acceptance in the United States. It is flexible and less brittle than PVC pipe, and has been popular in applications such as directional drilling, slip lining, and pipe bursting. 70% of all new pipe installed in the United Kingdom is HDPE, and it has successfully been utilized in that country for over 50 years. Gas utilities in the United States, which have a much lower leak tolerance than water utilities, use HDPE almost exclusively. However, since gas mains are typically smaller in diameter than water mains, the gas industry also enjoys the advantage of purchasing 500’ coils in the smaller sizes and eliminating the labor associated with 10 joints. One of the main disadvantages of HDPE had been that it required specialized equipment to create the joints. The size and weight of the machine required that the

joints be fused above ground which could be difficult in congested areas. However, the technology for heat fusing HDPE pipe has improved in recent years with the advent of electrofusion couplings which can be utilized in the trench.

Exhibit No. 11b

Comparison of Distribution Size Pipe Materials - Pipe Properties

Pipe Property	DI	PVC	HDPE
Trade organization	DIPRA	Uni-Bell	PPI
AWWA designation	C151	C900 and C905	C906
Diameter range	3" - 64"	4" - 12" (C900) 14" - 48" (C905)	4" - 63"
Pressure range	350 psi	100 psi - 200 psi	50 psi - 255 psi
ID range (8")	8.425"	7.76" - 8.33"	6.918" - 8.136"
Wall thickness range (8")	0.25"	0.362" - 0.646"	0.265" - 1.182"
Weight range (8")	21.1 lbs/ft	6.6 lbs/ft - 11.4 lbs/ft	5.1 lbs/ft - 11.06 lbs/ft
OD nominal (8")	9.05"	9.05"	9.05"
Buoyant (8" 100 psi)	No	Yes	Yes
Surge allowance	100 psi	125 - 200% of press. rating None for 14" - 48" (C905)	50 - 100% of press. rating
Surge potential (8" 100 psi)	53.6 psi per 1 ft/sec <V	17.6 psi per 1 ft/sec <V	9.8 psi per 1 ft/sec <V
Integrity under vacuum	Excellent	Good	Poor
C-factor	140	150	150
Standard pipe lengths (8")	18 ft or 20 ft	20 ft	40 ft or 50 ft
Type of joints	Push-on or mechanical	Push-on or mechanical	Heat fused
Max joint deflection (8")	5°	3°	Radius = 20 - 50 times OD
Compatible w/DI fittings	Yes	Yes	Yes - in DI sizes

Exhibit No. 11c

Comparison of Distribution Size Pipe Materials - Operational Considerations

Operational Consideration	DI	PVC	HDPE
Ease of installation	Subjective	Subjective	Subjective
Can be direct tapped	Yes	Yes	No
Need for special installation equipment	No	No	Yes
Need for special bedding for typical installations	No	Yes	No
Need for joint restraint	Yes	Yes	No
Ability to locate underground	Excellent	Poor - needs tracer wire	Poor - needs tracer wire
Applicable for above ground installations	Yes	With opaque material for UV resistance	Yes - w/proper support
Applicable for aqueous installations	Yes	Yes	Yes - but potential for flattening is high
Anticipated service life	100 years	50 - 100 years	50 years

Although PVC and HDPE pipe have their place in the market and in specific areas of the country, some concerns need to be considered. PVC in sizes 14" and greater is not designed with a surge allowance. Another consideration is the design life of HDPE, which, per the

manufacturers, is 50 years. Although PVC manufacturers state that their pipe has an estimated 100-year life (similar to DI), there are concerns similar to that of HDPE of strength reduction over time due to cyclic loading. Relative life cycle costs should be considered when selecting the best pipe material for both new and replacement mains.

IV. Value Added Management Strategies for Buried Infrastructure

This section presents and evaluates various management strategies for addressing the challenges discussed in the previous sections. This includes broad based assessment methods and a proposed performance based management approach.

A. Broad Based Infrastructure Assessment Methods

Broad-based assessment methods refer to those methods that provide an overview of the replacement needs of a distribution system. In other words, they present the big picture as to the condition of the system. Broad-based assessments typically include:

1. Accumulating basic historical information on the system's infrastructure (miles of pipe in system, age of the pipe, and material of pipe).
2. Categorizing and analyzing this information.
3. Estimating life expectancies of the different types of mains.
4. Summarizing results.

Broad-based assessment methods help determine whether a utility is currently spending enough capital on its infrastructure maintenance. These methods are forecasting tools that predict future infrastructure replacement needs and can provide insight as to the appropriate level of investment for the system. They help answer questions such as "how much pipe should be replaced each year in the distribution system?" and "is the current expenditure level adequate, or is the utility facing a major financial burden in the next few years?" Consequently, they can provide guidance in helping to determine a utility's long-term capital investment plan to address infrastructure renewal.

Two of the most prominent broad-based infrastructure models are KANEW and NESSIE. Both models provide a forecast of the amount of infrastructure that will need to be replaced each year over a future time period. KANEW provides results in terms of miles of main, whereas NESSIE provides it in dollars. With just a limited amount of data that should be readily available for most utilities, broad-based infrastructure assessment methods can provide a reasonable estimate of the amount of pipe that should be replaced each year in the system, thus providing a benchmark with which to compare current levels of spending. However, life expectancies of mains are simply estimates provided by utility personnel. There is no engineering or economic determination that supports these estimates; consequently, results are very subjective. Such models do not identify or prioritize individual mains to be replaced. Consequently, broad-based assessment models are useful, but alone are insufficient to manage buried infrastructure.

B. Performance Based Buried Infrastructure Management Approach

A performance based buried infrastructure management approach involves a detailed inventory by pipeline segment and monitoring how well individual pipelines are meeting the level of service that is required of them. This type of approach is more commonly used for above ground infrastructure, and in particular, mechanical equipment which requires routine preventative maintenance. Since buried infrastructure primarily consists of pipe which has no moving parts and is not readily accessible, performance based management of these buried assets has historically not been performed in the water industry. However, the following are reasons for implementing such a plan:

- a. Current infrastructure planning for water utilities primarily addresses pipe replacement needs from a reliability and hydraulic standpoint. Another tool is needed to complement this which will address pipe replacement needs from a maintenance and customer service perspective.
- b. Currently, pipe replacement decisions are made, for the most part, reactively. Once a pipe stops providing the level of service expected of it, it is targeted for replacement. A performance based management approach would allow for proactive planning. For example, if specific vintages of pipe are reactively being replaced at a high rate, proactive decisions can be made for similar vintages of pipe exposed to similar operating conditions before they stop providing an acceptable level of service to the customer.
- c. It is the preferred approach of GASB 34, and is also recommended by the H₂O Coalition for private utilities that would potentially apply for federal assistance.

It is important to selectively identify the data that would be required in a performance based management plan. If the data requirements are too high, it could hinder the implementation of the plan and also put an unnecessary and costly workload requirement on the utility. However, if the data requirements are too low, the information needed to make appropriate and justifiable management decisions will not be available. Exhibit No. 15 outlines the recommended data requirements for both existing infrastructure and new infrastructure. This data is broken down into physical, performance, and commercial/service information. The requirements for existing and new infrastructure are different since certain historical data may simply not be available, or the effort to acquire the historical information could not be justified when considering the additional value it would provide in making informed management decisions.

Exhibit No. 15
Data Requirements for a Detailed Management Plan

Physical	Exist	New	Performance	Exist	New	Commercial/Service	Exist	New
Year of Installation	Y	Y	Complaint Frequency	A	Y	Critical Customer	Y	Y
Diameter	Y	Y	Type of Complaint	A	Y	Affect on Community	Y	Y
Material	Y	Y	Break Frequency	A	Y	No. of People Served	A	A
Length	Y	Y	Type of Break	A	Y	Length of Shutdown	A	A
Location	Y	Y	Reason for Break	A	Y	Coordination w/Others	A	A
Interior Lining	A	Y	Service (hydraulic) Adequacy	Y	Y			
Exterior Protection	A	Y	Fire Flow Adequacy	Y	Y			
Joint	A	Y						
Wall Thickness	A	Y						
Soil conditions	A	A						
Internal Condition	A							
External Condition	A							

Y = yes, in all cases
A = as needed, or as available

It is necessary to know specific physical information for all existing and new buried assets as identified in the first set of columns in Exhibit No. 15. It is not possible to manage the assets without knowing the basic “what, where, and when”. Tracking additional information, which is available for new installations but might not be readily available for existing assets, is useful in understanding service characteristics and potential deficiencies associated with the pipe and what remedial actions could potentially be considered. Although this information may not have been recorded at the time of installation, much of it can be obtained when performing maintenance on the pipe. One important physical parameter that warrants additional discussion is the “length” of the main. Length is defined as a section of main which has similar physical, operational, and commercial/service characteristics that can be isolated in the field. It does not necessarily correlate exactly with the work order under which the main was installed since the diameter or other property might not be the same for the entire length. To simplify the data requirements, the specified length of main should be as long as possible, and relate to the street on which it is installed, if possible.

Regardless of what is physically located in the ground, the performance information, as defined in the middle set of columns in Exhibit No. 15, is the most important to know. Decisions on the need for maintenance or replacement of a pipe should be based solely on how the pipe performs. Similar types of pipes in different operating conditions will perform differently. For example, a thin walled spun cast pipe operating under low pressure and installed in non-corrosive soil may provide considerably longer service than one operating at a higher pressure in corrosive soils. Pipes should remain in service, regardless of their physical attributes, until they stop providing the level of service that is expected of them, or until it can be proactively predicted that they will soon stop providing this level of service.

Commercial/Service aspects of the pipe performance, as defined in the last set of columns in Exhibit No. 15, provide a further distinction on the importance of the performance parameters. Factoring this aspect into a performance based management plan results in more intelligent

decision making. Defining the “level of service” that is expected from a pipe is dependant on the specific customers that it is serving. For example, a relatively low main break frequency may be acceptable in most instances; however, if the main is serving a critical customer, such as a hospital, or would have a great impact on the community (such as closing down a major road), even a low break frequency may not be tolerable. Other information, such as coordination with municipal work (e.g. street paving) is also important to factor into any decisions regarding pipe maintenance vs. replacement.

In order to prioritize the mains which should be targeted for replacement, rehabilitation, or preventative measures, a rating system is needed. In developing such as system, it is important to only rate the variables which pertain to the basic question - “is the main providing the level of service that is expected of it?”. Referring back to Exhibit No. 9, this would include the following four performance variables:

- Complaint Frequency
- Break Frequency
- Service (hydraulic) Adequacy
- Fire Flow Adequacy

The other three performance variables - Type of Complaint, Type of Break, and Reason for Break - are useful in determining how to address the potential lack of adequate service being provided by the main, and would factor into decisions such as whether to replace or to rehabilitate the main.

Simply rating each of these four operational variables; however, does not fully address the issue of “level of service” since the necessary level of service can vary for each main as previously discussed. For this reason, all of the commercial/service variables defined in Exhibit No. 15 also need to be included in the rating system. These variables are as follows:

- Critical Customer
- Affect on Community
- Number of People Served
- Length of Shutdown
- Coordination with Others

Although the physical information is not included directly in the rating system, it is still extremely useful in making ultimate decisions regarding the need to replace mains. However, attempting to include it in the rating system could skew the results. For example, if a rating were provided for the type of joint, all leadite joints would receive the worst rating since they have historically performed poorly in the industry. However, if these joints are performing well at a specific location under specific operating conditions, why “penalize” that main by giving it a poor rating simply based on the physical properties of the joint and not its performance? Another example would be year of installation (i.e. the age of the pipe). Many mains in this country that were installed in the 1800’s continue to provided adequate and reliable service, and again, there is no need to skew the rating of a pipe by arbitrarily including this information in the rating system. However, this information can and should ultimately factor into the final

decisions regarding pipe replacement once the rating system, which is based on performance and commercial/service variables, identifies those critical mains which need attention. For example, if two mains score equally poor in the rating system (based on performance), and one has leadite joints and is older than the other main, then that information should be brought into the final decision making process and considered at that time.

C. Data Management

There are three options to consider for maintaining the data that is recommended for a detailed management plan. The first option would be to utilize a simple personal computer spreadsheet or database. Although this would be the least costly solution, it would also be the most labor intensive. An important factor when implementing a computerized program is to assure, where possible, that the required data is entered in the course of doing daily business (a self populating database) thus minimizing duplication of data entry. A personal computer spreadsheet or database would likely not meet this criteria.

The other two software options would utilize either an infrastructure management software package or a computerized maintenance management system (CMMS). The two are similar, and vary mainly in that infrastructure management software is typically less flexible and more specifically geared to the municipal market, whereas CMMS software is more powerful and more customizable (and ultimately more costly). Again, the key with either is that they integrate with other software currently utilized by the utility and that they meet the needs of other operations, customer service, and maintenance tasks in addition to buried infrastructure management. For example, if a new main is being installed, and information is being entered into a utility's asset management system, this information needs to populate the database selected for use in managing buried infrastructure. A customer complaint that is recorded in a Customer Information System would be another example of information that needs to link with the buried infrastructure software. The other advantage that these types of software packages have over simple spreadsheets or databases is that they allow integration with Geographical Information System (GIS) software. The value of GIS is that it provides the necessary geographical information which should factor into decisions regarding pipe replacement. For example, if main replacement is warranted in a particular geographical area, it might be appropriate to replace other mains in the area to avoid future disruption to the customers and the community. Without GIS, it would be difficult to perform the same type of evaluation except possibly in very small systems.

V. Implementation

- a. Data Collection & Buried Asset Inventory: The data necessary for a performance based management plan (see Exhibit No. 15) can be found in a variety of places that would include:
 - Distribution drawings
 - Work orders
 - Asset records
 - Customer Information Systems

- Maintenance records
- Tapping records

As a last resort, information such as material type could be estimated based on information provided in Exhibit No. 2 of this report.

- b. *Integrated Buried Asset Inventory and Performance Monitoring and Reporting System*: Formulate the systematic process for tracking performance variables for individual pipeline segments included in the Buried Asset Inventory. Develop a system that allows the review of pipeline segment performance in conjunction with the commercial/service importance of the main. The need for geographical interface (GIS) should also be considered. The ability to query, select, sort, and prioritize buried asset information, based on multiple selection criteria, is needed to facilitate decision making.
- c. *Training and Education*: Formal training is important to address relevant technical issues such as hydraulic transients, pipe failure mechanisms, operational strategies for reducing or eliminating pipe failures, and pipe rehabilitation techniques. The data collection needs and the importance of maintenance activity feedback should be covered.

VI. Conclusions

- a. The industry's assessment of buried infrastructure needs appears to be reasonable although health risks have not factored into the analysis to date.
- b. Utilities have begun addressing the issue, although primarily with a reactive approach. A pro-active, uniform, and systematic approach would be more efficient. The current level of investment may be inadequate.
- c. Direct costs (repair vs. replace) will not drive the decision making process. Health risks, commercial and service impacts must be considered. The appropriate time to replace or rehabilitate a main is when it stops providing the level of service that is expected of it. This requirement will vary, even within the same physical system.
- d. Operational strategies, rehabilitation technologies, and preventative technologies have merit and should be considered in the decision making process.
- e. Broad based assessment methods are useful planning tools but are not adequate to use as a management tool.
- f. A performance based management plan is valuable, and integration with operations and information management strategies is essential.
- g. A prudent and systematic management process will better serve a utility in the

support of capital investment needed to properly replace or rehabilitate distribution systems.

- h. “Knowing your system” and organizing the data is the first and most critical step in any buried infrastructure management approach.
- i. Training and education of personnel regarding technical issues associated with buried infrastructure is critical. Specifically, the technical content would include hydraulic transients, pipe failure mechanisms, operational strategies for reducing or eliminating pipe failures, pipe rehabilitation techniques, and corrosion control.

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