CHAPTER 9.0

Corrosion Mechanisms and Protection

9.1 Literature Search Background Summary

Sixty-six papers providing information on corrosion mechanisms and protection in collection systems were located through the literature search. Of these, 26 addressed the mechanism of corrosion, and 41 the protection of pipelines or concrete in general. Some papers compared various corrosion control approaches.

Figure 9-1 shows the distribution of papers by source.

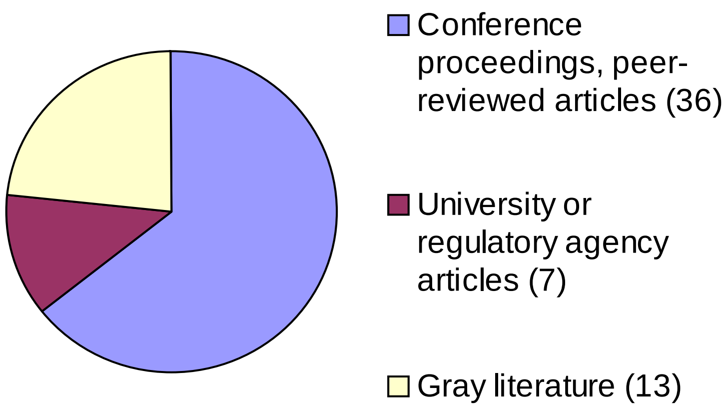

Figure 9-1. Corrosion Mechanisms and Protection Literature by Source

Papers covered experiences as far back as 1990, with many covering both mechanisms and protection. A good, overall, "plain English" description of corrosion mechanisms and of several coating and lining methods was found in an article by Tator (2003). Additional valuable information is available from well-established reference books and texts, such as the following:

- EPA (1985) Design Manual 625: *Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants*
- *Hydrogen Sulphide Control Manual* (Melbourne Water, 1989)
- WEF (1995) Manual of Practice 22: Odor Control in Wastewater Treatment Plants
- *Odor and VOC Control Handbook* (Rafson, 1998)

- WEF (2004) Manual of Practice 25: *Control of Odors and Emissions from Wastewater Treatment Plants*

9.2 Introduction and Background

There has been corrosion of sewer pipelines for as long as sewer pipelines have been in service, and pipeline corrosion was reported as long ago as the end of the 19th century (Olmstead and Hamlin, 1900). But pipeline corrosion has increased noticeably in recent decades because of trends and policies applicable to wastewater collection systems. Two such examples are pretreatment regulations instituted in 1980 and infiltration/inflow (I/I) regulations and policies. Pretreatment has decreased the concentration of metals in collection systems, metals that would otherwise have reacted with and bound up corrosion-causing sulfide compounds, and I/I, which dilutes wastewater and thus decreases odor and corrosion, has been reduced in collection systems.

Corrosion mechanisms have been discovered and studied relatively recently, and measures to control such corrosion have been developed in parallel. Of the many methods currently available to repair, rehabilitate, and replace wastewater collection and conveyance systems are these three: adding coatings, most frequently on the crown of the pipe; lining the pipe wall; and installing pipes made of corrosion-resistant material. The first two measures are generally used for existing pipeline repair or rehabilitation, and the latter for replacement or new pipelines. Because the suitability of a given technology for a specific project is always a function of many varying factors, each method has its appropriate uses and its limitations. Categories of control discussed in other chapters of this report include chemical addition and ventilation.

9.3 Corrosion Mechanisms

Corrosion and odors in a wastewater collection system are mostly a function of the production and release of sulfide compounds, primarily hydrogen sulfide (H_2S). An evaluation of corrosion and odor requires an understanding of the types of compounds likely to cause problems and the mechanisms that form these compounds in a wastewater collection system.

9.3.1 Corrosion and Odor Compounds

Most odor-producing substances found in domestic wastewater are relatively volatile substances with molecular weights between 30 and 150. Most of these compounds form as a result of the anaerobic decomposition of organic material containing sulfur and nitrogen, which produces hydrogen sulfide, ammonia, carbon dioxide, and methane, among other compounds.

Hydrogen sulfide, with its characteristic rotten-egg smell, is the most prevalent and most notable odorous compound in the wastewater collection system. Hydrogen sulfide causes direct corrosion of metals such as iron, zinc, copper, lead, and cadmium. More importantly, hydrogen sulfide is oxidized to sulfuric acid, which can severely damage wastewater facilities.

Wastewater-pipeline corrosion is primarily microbially induced. This is a complex process involving many active organisms that, as is apparent from current research, is not fully understood or modeled. There are two distinct phases of microbially induced corrosion (MIC): (1) the conversion of ubiquitous sulfate in wastewater to sulfide, some of which is released as gaseous hydrogen sulfide, and (2) the conversion of hydrogen sulfide to sulfuric acid, which subsequently attacks susceptible pipeline materials.

This chapter briefly addresses the formation of sulfides in the collection system. For a more detailed exploration and for the formation of other odorous compounds, see Chapter 4.

Most sulfide is formed by bacteria living in a matrix of filamentous microbes and gelatinous material coating the submerged walls of wastewater pipes that is often referred to as the slime layer. The bacteria producing sulfide are strict anaerobes and, consequently, live beneath the water surface in gravity sewers and on the pipe walls in forcemains. The bacteria may also thrive in sludge and grit deposits found along the bottom of pipes. In order to produce sulfide compounds, the bacteria require a source of sulfur and a food supply. Sulfate, generally abundant in wastewater, is usually the common sulfur source, though other forms of sulfur, such as organic sulfur from animal wastes, can also be reduced to sulfide. The dissolved organic material prevalent in the wastewater provides an ample food supply for the bacteria to flourish. The sulfate reaction in a wastewater collection system can be described as follows:

$$SO_4^{2-} + \text{organic matter} + H_2O \xrightarrow{\text{bacteria}} 2HCO_3^{-} + H_2S \qquad (9.3.1\text{-}1)$$

The overall sulfide and sulfuric acid formation mechanism is illustrated in Figure 9-2.

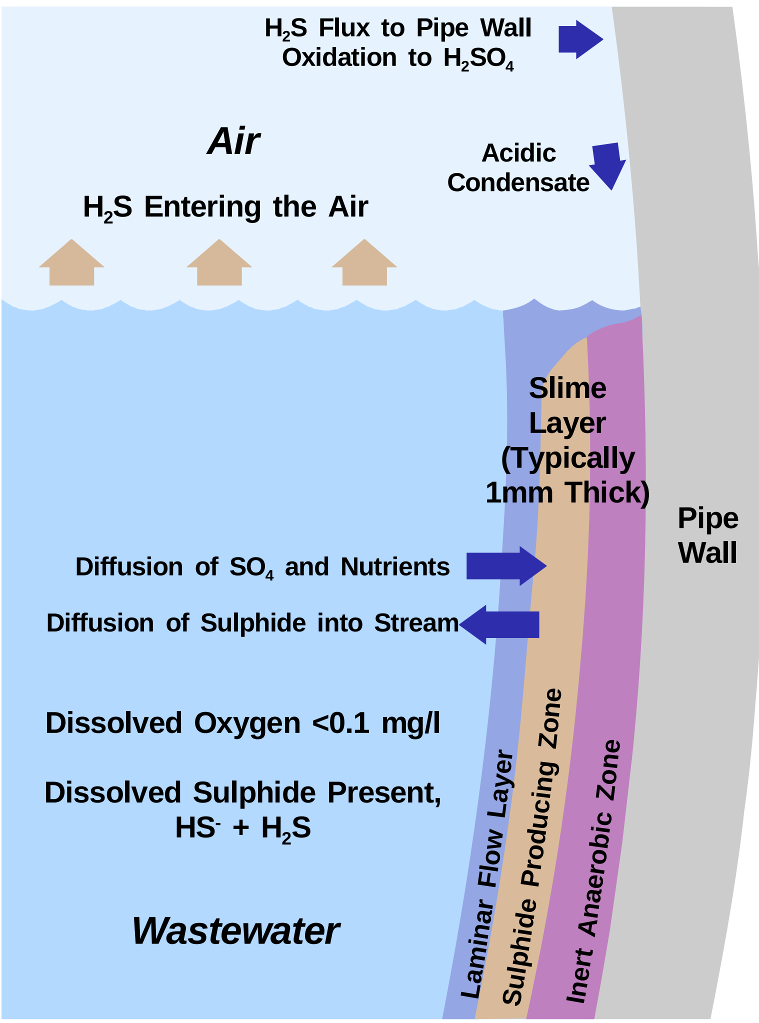

Figure 9-2. Overall Corrosion Mechanism in Wastewater Pipelines (from ASCE, 1989)

If concentrations of sulfate and dissolved organic material in the wastewater are high and if these materials are able to penetrate the solids deposits, then large amounts of sulfides can be produced. Many bacteria can reduce sulfate to sulfide, including the following:

- Assimilatory bacteria—those that assimilate inorganic sulfur and reduce it to sulfide within their protoplasm
- Proteolytic bacteria—those that can hydrolyze proteins and amino acids under anaerobic conditions
- Sulfate-reducing bacteria—specialized bacteria that use inorganic sulfate as the hydrogen acceptor in their energy cycle (*Desulfobacter* and *Desulfovibrio* are two such bacteria.)

The most troublesome problems occur when large amounts of sulfides are produced. Turbulence associated with normal flows in sewers encourages the release of hydrogen sulfide gas from the wastewater. Slugs of sulfides are often carried by wastewater down the interceptor, thereby providing a mechanism for significant hydrogen sulfide gas to be released. This slug effect complicates efforts to control hydrogen sulfide releases.

9.3.2 Hydrogen Sulfide Corrosion

Once sulfides are produced in the wastewater as the result of sulfate reduction, hydrogen sulfide gas will be released into the atmosphere. The hydrogen sulfide gas is oxidized on the pipe surface above the water line as described by the following equation:

$$H_2S + O_2 \xrightarrow{\text{bacteria}} H_2SO_4 \qquad (9.3.2\text{-}1)$$

Oxidizing bacteria, such as *Thiobacillus concretivorous, Thiobacillus neapolitanus, Thiobacillus ferro-oxidans,* or *Thiobacillus thioxidans,* as shown in Figure 9-3, create this second phase of corrosion. They are aerobic and thrive in low-pH environments. To grow, they require a source of sulfur (H_2S), a moist surface (the pipe walls above the water surface), and a carbon source (CO_2). The surface pH of new concrete pipe is generally between 11 and 13. Cement contains calcium hydroxide, which neutralizes the acids and inhibits formation of oxidizing bacteria when the concrete is new. However, as the pipe ages, the neutralizing capacity is consumed, the surface pH drops, and the sulfuric acid–producing bacteria become dominant. In active corrosion areas, the surface pH can drop below 2.0. As sulfides are formed and sulfuric acid is produced, calcium hydroxide is converted to calcium sulfate (gypsum). Calcium carbonate is easily eroded by wastewater. As the gypsum material is eroded, the concrete loses its binder and begins to spall, exposing new surfaces. This process will continue until the pipeline fails or corrective actions are taken. Sufficient moisture must be present for the sulfuric acid–producing bacteria to survive, however; if it is too dry, the bacteria will become desiccated, and corrosion will be less likely to occur.

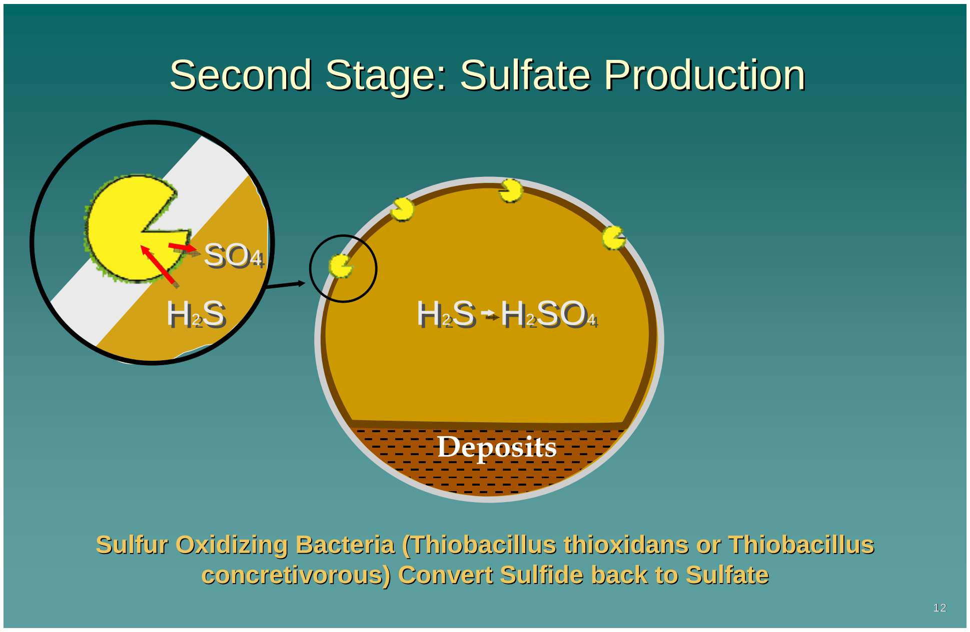

Figure 9-3. Second Phase of Corrosion: Sulfate Production

Several factors are critical in determining how much hydrogen sulfide off-gassing will occur from the wastewater. Among the most important of these are the following:

- ***Dissolved sulfide concentration.*** Sum of liquid phase sulfide constituents in the wastewater [$H_2S + HS^-$]
- ***Wastewater pH.*** A lower pH results in a larger percentage of sulfide in the form of H_2S, which is then available for off-gassing. This is illustrated in Figure 9-4.

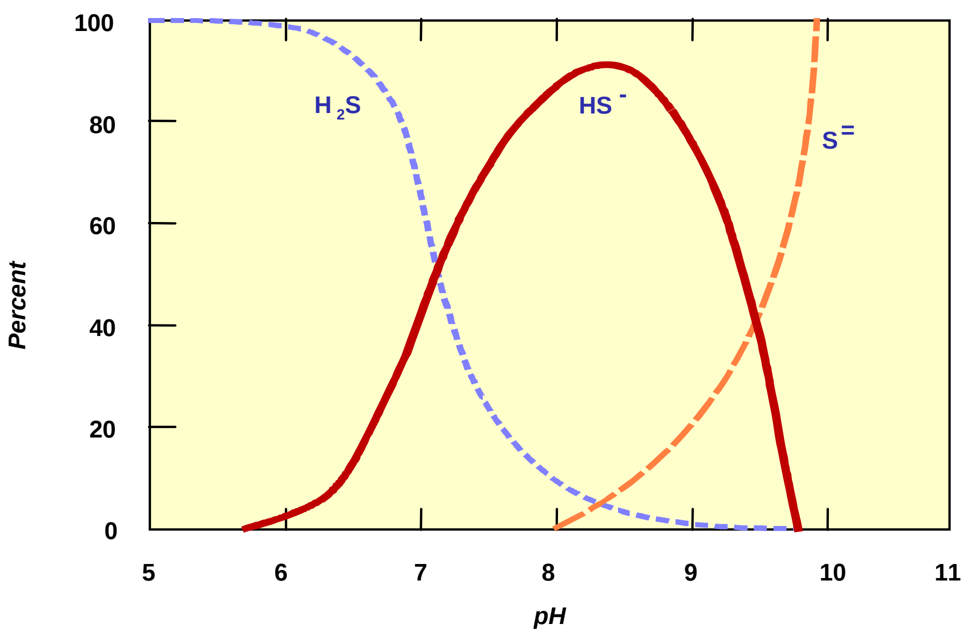

Figure 9-4. Sulfide Species as a Function of pH

- ***Turbulence.*** Increased turbulence promotes off-gassing by providing a greater surface area for hydrogen sulfide to escape into the atmosphere and by bringing gases into more frequent contact with boundary layers.

Factors that play a less significant role include wastewater temperature, ambient hydrogen sulfide concentration in the sewer atmosphere, and barometric pressure of sewer atmosphere.

A relatively large number of articles was found on corrosion mechanisms. Most covered the two corrosion phases, sulfide formation and sulfuric acid formation. Among these are the following, grouped by their major themes. Papers dealing primarily with the corrosion mechanism were the following:

- Little et al. (2000) provided a detailed description of the various corrosion mechanisms and the biological sulfur cycle.
- Nica et al. (2000) performed laboratory work to isolate and characterize microorganisms that were involved in the corrosion mechanism. Many different heterotrophic, autotrophic, and fungi organisms were identified, but their roles were not fully known.
- Cho et al. (1994) isolated a new fungus, sporormia concretivora, that participates in corrosion. It was found to be acid resistant, thus accelerating the *Thiobacillus thiooxidans* corrosion mechanism.
- Hvitved-Jacobsen et al. (2000) developed a generation model that focused on sulfides. The model was used for design development of a gravity sewer in the River Emscher catchment area, in Germany.
- Vincke et al. (2001) analyzed the microbial communities on corroded sewer pipes using electrophoresis and found *Thiobacillus thiooxidans*, *Acidithiobacillus sp.*, and *Mycobacterium sp.* in the greatest numbers.
- Witzgall et al. (1990) performed a full-scale study of five collection systems and reported that whereas the sulfide formation correlated with the models, the corrosion did not.
- Weiss (1996) reported that sulfide generation rates in sewers in the County Sanitation District of Los Angeles ranged from 8 to 1,165 mg/m_2-hr in one system and from 137 to 257 mg/m_2-hr in another system. This resulted in the corrosion rates in concrete pipelines shown in Table 9-1.

Table 9-1. Concrete Pipeline Corrosion Rates

H_2S Concentration, ppm	Corrosion Rate, in./yr	
	In Cast Pipe	In Spun Pipe
<1	<0.03	<0.02
1–3	0.03–0.05	0.02–0.03
3–8	0.05–0.08	0.03–0.05
>8	>0.08	>0.05

- Mori et al. reported corrosion rates in sewer pipelines in Japan of 5 mm per year (1991) and 4.3 to 4.7 mm per year (1992).
- In an unreferenced Belgian report, 2.3 to 3.1 cm of corrosion occurred after 6 years.

Eighteen other reviewed articles addressed corrosion mechanisms to a lesser extent.

Papers that discussed corrosion inhibitors included these:

- Bell et al. (2000) discussed the biochemistry and chemistry of the corrosion mechanism and found that ammonium salt in the concrete inhibited the bacterial growth of corrosion-causing microorganisms.
- Yamanaka (2002) speciated corrosive bacteria and also showed their neutralization by calcium formate; the laboratory tests showed that *Thioparus* is a precursor to *Thiobacillus thiooxidans*.
- Sima (1992) conducted inhibition experiments and showed that metabolic modifiers could eliminate acidophilic *thiobacilli*. Weak organic acids inhibited the *thiobacillus* mechanism. In particular, pyruvate and oxaloacetate acids were effective, but the reasons for this were not clear. This finding made unclear what the toxicity mechanism might be. It had been suggested that the modification of intracellular pH interfered with *thiobacillus* metabolism, and performing direct measurement of intracellular pH was suggested.

A general consensus of the reviewed literature was that measurable corrosion due to the hydrogen sulfide–sulfuric acid mechanism starts at hydrogen sulfide concentrations of 2 to 5 ppm.

9.4 Coatings

Coatings that are applied to the entire pipe circumference are distinguished from liners in that they are brushed or sprayed on rather than inserted as preformed material. Some coatings are applied during pipe manufacture, and others are applied in situ after installation, typically on pipelines that have started to exhibit corrosion. When perfectly applied, these coatings can be very effective, but each has potential shortcomings.

9.4.1 Factory-Applied

Factory-applied coatings include the following:

- Epoxy, typically applied to ductile iron, cast iron, and concrete pipes. Shortcomings include welding and cutting difficulties, potential for cracking during installation, and difficulty being repaired in the field.
- Concrete, typically applied to ductile or cast iron pipes. Shortcomings include the difficulty of welding or cutting, potential for cracking during installation, and the reduction in pipeline diameter.
- Galvanized coating, typically applied to steel pipes. Shortcomings include difficulty of welding and potential for accelerating corrosion.

Very few references to the above factory-applied coatings were found in the reviewed literature.

9.4.2 In Situ

Several papers reported on different in situ coatings, including coal tar epoxy, caustic soda, magnesium hydroxide, and organic acids. These coatings can be expected to need reapplication regularly, typically every few months to over a year. The issues with applying coatings include the logistics of accessing the sewers, traffic disruption, and the hazardous nature of chemical coatings, in particular, caustic soda, typically available at 25 and 50 percent solution.

In one instance, a magnesia slurry successfully reduced corrosion (Gebler et al., 2002) after a coal tar epoxy had failed. It was reported that the coal tar epoxy failed due both to hydrogen sulfide corrosion and to leaching by carbon disulfide.

Badia et al. (1992) reported that caustic crown spray, while raising pH from 2 to 11, provided 60 days of protection. Above pH 4, the corrosion rate was reduced from 0.3 inch per year to 0.03 inch per year. The life-cycle cost was substantially lower than that of PVC lining. In 1992 the costs were $11 per inch-diameter per linear foot for lining. The caustic crown spray costs in the same units were $0.03 per application. A typical application lasted 60 days, indicating an annual cost of $0.18 per inch-diameter per foot. For a 1-mile, 63-inch-diameter sewer, the cost comparison over 50 years was $3,700,000 in capital cost for sliplining versus $6,900,000 ($138,000 annually) for caustic crown spray.

Guan (2001) described many of the alternative coating materials for both the inside and the outside of pipes, including bituminous enamels, zinc/enamel, tape, liquid epoxy, cement mortar, heat-shrink sleeves, chlorinated rubber, and polyurethane.

Eight other reviewed articles addressed coatings.

9.5 Linings

Several types of plastic can be used as liners for sewer rehabilitation. Established limitations on the use of these materials are discussed below.

“Plastics” is a broad group of construction materials that can be divided into two major categories: thermoplastics and thermosetting plastics.

Thermoplastics soften and flow when heated. They are formed by joining individual carbon atoms into linear chains that create very large molecules. The most common thermoplastic sewer pipe materials are PVC and polyethylene. Others are polystyrene, polypropylene, acrylonitrile butadiene styrene, acrylics, nylons, polycarbonates, and thermoplastic polyesters.

Thermosetting plastics are formed as networked, rather than linear, structures. The network is formed by heating the base materials together. Unlike thermoplastics, once formed, thermosetting plastics do not melt. Thermosetting plastics are used for rehabilitating cured-in-place pipe (CIPP) and are typically composed of thermosetting polyesters and epoxies. Other thermosetting materials are phenolics, amino resins, and silicones.

Thermoplastics are more easily formed (and deformed) than thermosetting plastics, which are more rigid and have a much higher modulus of elasticity.

Table 9-2 summarizes the alternative liner types.

Table 9-2. Pipeline Lining Rehabilitation Alternatives

Rehabilitation Option	Products	Pipe and Liner Materials	Available Diameters (in.)	Structural Issues	Approximate Hydraulic Capacity Reduction
Sliplining with continuous pipe	Chevron/Plexco, Phillips/ Driscopipe	HDPE fusion-welded	4–54	Structural repair, wall thickness based on condition of host pipe. Annular space grouting results in a composite pipe	40 percent reduction for 32-in. outside diameter, 28.2-in. inside diameter, SDR 17 inside a 36-in. pipe
Sliplining with segmented pipe	Chevron/ Spirolite	HDPE	18–120	Structural repair, wall thickness based on condition of host pipe. Annular space grouting results in a composite pipe	46 percent reduction for 27-in. inside diameter, 31-in. outside diameter, Class 160 inside a 36-in. pipe
	Lamson Vylon	PVC	21–54	Structural repair. Annular space grouting results in a composite pipe.	29 percent reduction for 30-in. inside diameter, 32.2-in. outside diameter inside a 36-in. pipe.
	Hobas	Reinforced thermosetting resin pipe	4–144	Structural repair, wall thickness based on condition of host pipe. Annular space grouting results in a composite pipe	24 percent reduction for 31-in. inside diameter, 33-in. outside diameter (bell) inside a 36-in. pipe, (smaller annulus okay due to high allowable jacking force). Prone to failures if stressed by bending
CIPP	Insituform, FirstLinerUSA, CIPP Corp., National Liner, InLiner, Impreline Tech, Permaliner, Cure-line	Nonwoven, multi-layered felt liner with thermosetting resin (isophthalic polyester, vinyl ester, or epoxy)	4–108; noncircular sections okay	Structural repair, wall thickness, and resin selection based on condition of host pipe	4 percent increase for 0.67-in.-thick liner inside 36-in. pipe. Based on 10 foot depth, H-20 live load, 5 percent ovality, and computed with formulas from ASTM F-1216
Fold and form, deformed and reformed, die-draw liners	AM-Liner, NuPipe, EX Method, Ultraliner, U-Liner, Sure-Line, Rolldown, Swagelining	PVC, or PVC alloy, PE	4–24 maximum for selected products	Structural repair, wall thickness based on condition of host pipe	Reduction not applicable for greater than 24-in. pipes since product is not made in those sizes
Site-folding PE pipe	PIM Corp Subline	PE	3–60	Nonstructural repair	1 percent reduction for 36-in. outside diameter, 34-in. inside diameter
HDPE liner with grout	Trolining	Studded HDPE sheeting with grouted annulus	8–95	Structural repair, wall thickness and optional use of reinforcing based on condition of host pipe. Annular space grouting results in a composite pipe	5 percent increase for maximum 0.63-in. wall thickness inside 36-in. pipe

Rehabilitation Option	Products	Pipe and Liner Materials	Available Diameters (in.)	Structural Issues	Approximate Hydraulic Capacity Reduction
Spiral-wound PVC liner with grout	Danby, Ameron	PVC strip with grouted annulus	24–120	Structural repair, wall thickness and grout characteristics based on condition of host pipe. Annular space grouting results in a composite pipe	8 percent reduction for 33-in. inside diameter inside 36-in
PVC sheet liner with grout	Linabond, Riblock	PVC sheeting with thermosetting polymer in annulus	48 and larger	Structural repair, thickness of polymer based on condition of host pipe	1 percent reduction for 1-in. thickness applied to 36-in. pipe (thickness of 1/4 in. minimum to 6 in. or more available)

Table 9-3 matches criteria with recommended lining rehabilitation suggestions.

Table 9-3. Pipeline Lining Criteria

Criterion	Suggestion
Corrosion and abrasion resistance	Advanced hydrogen sulfide corrosion is the principal reason that rehabilitation of these pipelines is necessary. Materials used for rehabilitation must have superior resistance to sulfuric acid. Resistance to other chemicals must be considered for pipelines near significant industrial discharges. Abrasion or erosion of the pipeline invert by sand, grit, and other solids in sewage is also a concern; thus the selected materials must have high resistance to abrasion.
Temperature sensitivity	Due to extreme daytime temperatures in certain hot climates, some sewer and street construction projects are scheduled for nighttime construction. Depending on the time of year these projects are bid and constructed, construction methods and procedures that are able to withstand high temperatures throughout installation, as well as warm ground conditions, may become an issue. In addition, materials with high coefficients of thermal expansion can create problems, such as blocking or shearing off of lateral connections, if exposed to a wide temperature range. High density polyethylene pipe is a rehabilitation material that is susceptible to this problem.
Lateral reinstatement	The reinstatement of sewer laterals is normally completed either internally, using a robotic cutter guided by a television camera, or externally, by excavation and replacement. External reinstatement is preferable in those instances where existing connections are in poor condition. However, internal connection, if appropriate, results in less disruption to the project area.
Bypass pumping requirements	Many rehabilitation methods require full or partial bypass pumping of sewage flows throughout the installation process. Bypass pumping can be a significant portion of the total rehabilitation project cost (upward of 35 percent; City of Phoenix, 2005). Bypass pumping requires round-the-clock pumping equipment, maintenance personnel, standby pumps and generators, and long runs of surface piping that allows traffic to cross at driveways and intersections.
Disruption	The more excavation required for rehabilitation, the greater the disruption to traffic, businesses, and neighborhoods. For projects located under major streets or other critical surface improvements, minimizing excavation can be an important factor in selection of methods. Noise and odor can create additional impacts from the project.

Criterion	Suggestion
Quality control	For a rehabilitation method to be successful, it must be properly installed and inspected. Some methods are more installation sensitive than others, and have a higher risk of potential problems. These problems may be apparent in the short term or may not show up until later. Inspection by a knowledgeable Resident Engineer, including sample testing of the installed product, is critical to project success.
Track record/estimated service life	The sewer rehabilitation industry has evolved rapidly in recent years, with many new entrants into the market. Some of these ventures have been short lived for a variety of reasons. A proven history of successful installation and performance is an important predictor of a product's likelihood for success on future projects. The estimated service life for each rehabilitation method is a key factor in assessing the value of the various alternatives.
Relative cost	Cost is always a primary consideration in selecting pipeline rehabilitation methods. The most expensive technologies often serve specific market niches that make them the only appropriate method for certain circumstances. However, a simple comparison of relative costs is usually sufficient for screening purposes, without the need for detailed cost estimates, in those situations where a less expensive method will result in an equivalent final product.
Other construction issues	This criterion is included to identify any other important factors not previously covered and typically unique to a given rehabilitation technique. Each of the pipelines to be rehabilitated has a sanitary flow that must be considered during the design and construction phases of the project. Traffic control plans will be required from the Contractor. Insertion pits or trenches should be within rights-of-way and located to avoid street intersections and access driveways. Sites are frequently located in residential and commercial/light industrial areas; access to some residences and/or businesses may be blocked for a brief period of time. During sewer rehabilitation there will be odor generation and the potential for release of these odors to the atmosphere.

The reviewed literature described several full-scale lining installations, and several provided cost information. Uhren and Gilbert (2001) evaluated various pipe materials, concrete additives, and liners for a new sewer tunnel in Columbus, Ohio, and found that lined concrete pipe was the best option for that specific case. The exact lining method was to be determined during detailed design.

Saricimen et al. (2003) reported on 24-month laboratory tests of two proprietary, high-alumina, cementitious linings and found that one, "SC," performed significantly better. Both linings performed better than Type 1 cement with 20 percent fly ash cement and better than Type 1 cement with 10 percent silica fume. Accelerated laboratory tests and a 2-year field study were performed for a collection system in Jubail, Saudi Arabia. It was recommend that the field study be continued.

Los Angeles County in 1995 conducted pilot tests of polyester mortar coatings and PVC liners and determined that 19 of 71 methods analyzed were successful. They have tested seven coatings at full scale since 1983. Comparative cost information is provided, showing generally that coatings have been significantly less expensive than PVC liners.

Eight other reviewed articles addressed linings.

9.6 Corrosion-Resistant Materials

Among many possible wastewater pipeline materials, some of the most common are the following:

- ***Vitrified clay.*** Completely resistant to H_2SO_4 corrosion, but joining materials such as mortars can corrode it
- ***Concrete pipe.*** High corrosion potential. Can be constructed of mixtures that improve resistance
- ***Steel pipe.*** High corrosion potential
- ***Cast iron pipe.*** High corrosion potential but lower than that of steel
- ***Ductile iron pipe.*** Better resistance than steel or cast iron. Carbon and silicon content increases resistance.
- ***Plastic pipe.*** Many plastic pipe materials available, including PVC, polyethylene, high-density polyethylene, and fiber-reinforced plastic. Highly resistant to corrosion, but varying structural properties.

Of the 16 reviewed articles on corrosion-resistant materials, 10 addressed additives to concrete.

Bell et al. (2000) reported on the use of an ammonium salt as a concrete additive and its subsequent corrosion reduction.

Vroom et al. (2000) compared sulfur concrete and hydraulic cement concrete, concluding that sulfur concrete was better structurally and in terms of corrosion resistance. Shortly thereafter, Wahshat (2001) performed pilot tests of sulfur mortar and polymer-modified sulfur mortar and found that the latter provided good corrosion resistance.

A laboratory test reported by Yamanaka et al. (2002) showed that the addition of calcium formate to the concrete mixture completely inhibited the growth of sulfur-oxidizing and iron-oxidizing bacteria.

Research into polymer concretes performed at the Catholic University of Leuven, in Belgium (Beeldens et al., 2001), showed that most polymer additives improved corrosion resistance and increased flexural strength but decreased compressive strength. However, two polymers, polyacrylic and styrene-acrylic, exhibited weaker structural properties.

As part of research to determine best test methods for corrosion measurement, De Belie et al. (2004) performed an immersion-drying-brushing test cycle and found that limestone aggregate provided good corrosion resistance and that lower water-to-concrete-ratio cements had better resistance; they suggested that water absorption properties be included in the Pomeroy corrosion model.

Hewayde et al. (2003) performed experimental work on selected admixtures, concluding that Metakaolin improved resistance and strength and that corrosion inhibitors in general improved resistance but decreased strength. Contrary to De Belie et al.'s (2004) results, reported above, Hewayde et al. reported that *higher* water-to-concrete ratios provided better resistance but decreased strength.

Monteny et al. (2001) reported that styrene–acrylic ester polymer had the best resistance of five tested additives, whereas acrylic and styrene-butadiene polymers decreased corrosion resistance.

Similar polymer concrete research by Vincke et al. (2002) at the University of Ghent, in Belgium, showed that styrene acrylic ester polymer exhibited increased resistance but that acrylic polymer or silica fume provided less resistance. Their work showed that neither vinyl copolymer nor styrene-butadiene polymer affected corrosion resistance.

Seven other reviewed articles addressed corrosion resistant materials.

9.7 Hydraulic Design

Most rehabilitation methods reduce the interior cross-sectional area of the pipeline and typically change the pipeline wall surface roughness. These factors impact the hydraulic capacity of the sewer. Where capacity is limited, a loss of cross-sectional area may render some rehabilitation methods unacceptable. Alternatives for pipeline rehabilitation must maintain sufficient hydraulic capacity for the existing and projected future flow conditions, including stormwater inflows. In evaluating rehabilitation techniques, the associated reduction in hydraulic capacity of a particular method must be compared to the estimated future flow rates for each specific project.

A major factor in selecting a rehabilitation technique is the available hydraulic capacity of the sewer following rehabilitation. The rehabilitated sewer must be capable of conveying the maximum daily flows with a reasonable factor of safety to allow for uncertainties concerning actual future population growth, winter flow increases, and stormwater inflows. After rehabilitation, a reserve capacity is recommended to account for these uncertainties. Minimum velocities at full flow ($d/D = 1.0$) will not control the design because rehabilitation of the sewers will not decrease the velocities from their current values.

9.8 Cost Comparison of Alternative Measures

The review of documents describing pipe corrosion protection methods produced over 100 coating and lining techniques. Conspicuous by its absence, however, was cost data on these techniques. Only a handful of papers included cost data.

While it is recognized that costs are site specific and that labor can be a high proportion of the cost component, comparative cost data should be obtainable for typical gravity pipe systems. Needed too is a comparison of the costs of coating and lining techniques with costs of the other common protection technique, chemical addition.

9.9 Rehabilitation Scheduling and Funding

It is common practice to plan for repairing and replacing corroded sewer pipelines and to do so, ideally, on the basis of condition assessments. A sewer replacement project investment period can be from 50 to 100 years. The ranking of replacement projects is increasingly performed using a risk-based approach in which the consequences of failure are weighed against the cost of replacement. Those consequences might include property damage, neighborhood and traffic disruption, and odor and health impacts.

The funding source for replacement projects is inevitably the agencies' customers, who must be convinced of the need to replace sewers by having the consequences of failure explained to them. Under normal circumstances, grants are rarely available for sewer replacement.

9.10 Research Gaps

Guidance is needed for agencies having to provide pipeline corrosion protection for both new and existing installations. Though many vendors may claim that their corrosion protection techniques are the most effective, objective data are needed.

For new pipes, the alternatives available include corrosion resistant pipe, linings, and coatings. For existing pipes, the alternatives include linings or coatings.

In addition, the above pipe material corrosion resistance techniques should be compared to other techniques, such as chemical addition.

9.10.1 Objective

To provide agencies with guidelines and a decision path to enable them to determine most effective corrosion protection for new and existing gravity sewer pipelines. Produce a guidance document for cost-effective corrosion protection of gravity pipelines whose diameters range from 24 to 84 inches.

9.10.2 Program

This study would consist of several phases:

9.10.2.1 Phase 1—Conduct Expanded Literature Search

In addition to using the papers discovered in the current project, search for other papers online and by contacting public agencies, consultants, vendors, and contractors.

9.10.2.2 Phase 2—Determine Costs of Pipe Corrosion Protection Techniques

Using information from Phase 1 and by contacting vendors, develop cost ranges for alternative pipe-coating techniques.

9.10.2.3 Phase 3—Compare Pipe Lining to Chemical Addition

Compare the costs developed in Phase 2 with the costs developed in another research gap topic, “Life Cycle Analysis of Chemical Addition on Downstream Processes.”

9.10.2.4 Phase 4—Report Findings

Produce a report summarizing findings and including guidelines as to which corrosion protection techniques are cost effective under what conditions.