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TECHNICAL REPORT

HYDROGEN SULFIDE CORROSION IN WASTEWATER COLLECTION AND TREATMENT SYSTEMS

U.S. Environmental Protection Agency
Office of Water (WH-595)
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Ms. Irene M. Suzukida [Horner] was the Work Assignment Manager for this report.

This report is dedicated to all the individuals who work to preserve the wastewater systems of this country, whose contributions are too numerous to identify.

DISCLAIMER

This report contains discussions of several proprietary products and processes used for the control and prevention of corrosion induced by hydrogen sulfide. Mention of trade names or commercial products does not constitute endorsement by EPA or recommendation for use.

For this report, information was not collected for all products and processes, and omission of products or trade names from this report does not reflect a position of EPA regarding product effectiveness or applicability.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (cont.)

LIST OF TABLES

LIST OF TABLES (cont.)

LIST OF FIGURES

1.0 BACKGROUND AND OVERVIEW

1.1 Legislative Charge

In the mid 1980's, the County Sanitation Districts of Los Angeles County (CSDLAC) observed that the rate of corrosion of concrete sewer pipe in their system had increased dramatically since the early 1970's. Subsequent studies showed a high correlation between the reduction in the levels of metals and other wastewater constituents and the increase in levels of hydrogen sulfide responsible for the corrosion. Metals and other constituents of industrial origin had been reduced through implementation of industrial pretreatment standards in 1975-1977 (ocean discharge requirements) and in 1983 (EPA categorical pretreatment standards). This raised the question of whether implementation of industrial pretreatment standards had resulted in an increase in corrosion rate, which would have significant economic implications.

Section 522 of the Water Quality Act of 1987 requires the U.S. Environmental Protection Agency (EPA) to conduct a study and prepare a report on corrosion in wastewater collection and treatment systems and to coordinate its activities with the City and County of Los Angeles. Section 522 of the Act specified that:

> The Administrator shall conduct a study of the corrosive effects of sulfides [sic] in collection and treatment systems, the extent to which the uniform imposition of categorical pretreatment standards will exacerbate such effects, and the range of available options to deal with such effects (1).

The study concentrated on the three areas mandated by the Act. Many factors influence corrosion besides the implementation of pretreatment requirements, such as solids deposition, turbulence, temperature, and so on. The lack of an accurate corrosion-measuring technique and the limited data base on hydrogen sulfide corrosion would have limited the ability of EPA to ascertain the effects of these factors. In addition, the study did not explore the impacts of transporting sewage further to regional treatment plants, constructing separate sewers for sanitary wastewater and storm water, or implementing water conservation programs. This report does not discuss the problems caused by the toxicity of hydrogen sulfide gas or the odor nuisance associated with its presence, as these issues were not mandated by the Act.

1.2 Los Angeles County System History

The County Sanitation Districts of Los Angeles (CSDLAC) provide wastewater collection, treatment, and disposal services for approximately four million residents of Los Angeles County. The service area covered by CSDLAC, 640 square miles in size, includes most of metropolitan Los Angeles County with the exception of the City of Los Angeles. Wastewaters from residential, commercial, and industrial sources, totalling over 500 million gallons per day (gpd), are conveyed through 9,000 miles of collection sewers to six wastewater treatment facilities. Approximately 1,000 miles of these sewers are owned and maintained by CSDLAC, while the remaining 8,000 miles are owned and maintained by local cities or Los Angeles County (2).

Most of the CSDLAC collection sewers, especially the large-diameter lines in the lower reaches of the tributary system, are constructed of reinforced concrete pipe with no protective coatings or liners. These large sewers generally range in size from 54 inches in diameter up to 144 inches in diameter. The oldest of these sewers have been in service for approximately 65 years.

At the time these sewers were designed, concerns existed about the possibility of corrosion. To guard against this possibility, the earliest of the large sewers had vitrified clay liner plates installed on the interior sides and crowns. However, sulfuric acid easily penetrated the joints between the tiles and destroyed the grouting and cementitious materials underneath. By the late 1930's after approximately 10 years of service, enough of the tiles had fallen off into the bottom of the pipes to create flow obstructions and necessitate cleaning of the debris from these pipes.

Because of the problems experienced with the tile liners, CSDLAC looked for another method to prevent corrosion damage. The Districts chose to design sewers to induce sufficient wastewater velocities so that natural reaeration would minimize the growth of the anaerobic slime layers on the submerged pipe walls where the sulfide-generating bacteria grow. Such natural reaeration forces would also help oxidize any sulfide that did form in the wastewater, preventing its release to the sewer headspace as hydrogen sulfide gas.

In the early 1950's, concrete pipe manufacturers began to market internally lined pipes to protect against hydrogen sulfide corrosion. However, at that time, little information was available to document how well these plastic liners would remain securely bonded to the concrete and provide effective protection. The lined pipe was expensive when compared to regular, unlined pipe, and CSDLAC decided to rely on high design velocities to control corrosion, rather than lined pipe. Consequently, during the 1950's and 1960's, as the size of the collection system increased dramatically, CSDLAC continued to install unprotected, reinforced concrete pipe for much of the sewer system. Current County standards require lined concrete pipe in all new installations to prevent corrosion.

By the mid-1960's, sulfide generation was increasing within CSDLAC major trunk sewers, especially at locations where depletion of available dissolved oxygen (DO) occurred. To protect its substantial capital investment in unprotected concrete pipe sewers, CSDLAC undertook a three-year research program in 1968. The objectives of the research program were to better understand the processes by which sulfide is generated by the Desulfovibrio bacteria and to develop methods to control these bacteria. This research was partially funded by federal agencies that would later be merged to form EPA.

The research was conducted by Dr. Richard D. Pomeroy, who in the 1940's had studied sulfide generation in the CSDLAC system. Through measurements made at a number of monitoring stations throughout the CSDLAC sewerage system, he refined an empirical formula which predicts sulfide generation rates and resulting concrete corrosion rates. A final report of the study, entitled "Sulfide Occurrence and Control In Sewage Collection Systems" was published in 1973 (3). The predictive formula is also included in more recent design manuals and guidance documents (4)(5)(6)(7).

In the early to mid-1970's, CSDLAC conducted an inspection of the wastewater collection system and concluded that actual corrosion matched closely the corrosion predicted by Pomeroy's formula. Based on the estimated rates of corrosion, CSDLAC calculated that the remaining structural lives of most of the sewer pipes ranged from at least several decades for the oldest of the sewers, up to hundreds of years for most of the post-World War II sewers.

In the early 1980's, a second inspection of these same sewers was made, with very different results. In less than 10 years, reinforcing steel had become exposed in many sewers. Based on measurements taken during the inspections, CSDLAC calculated that corrosion rates increased from 0.01 inches per year to 0.25 inches per year in some instances. A decrease in pipe surface pH levels from 3 to 4 in the 1970's to 1 to 2 in 1980's accompanied the increase in rate of corrosion. Total sulfide levels entering the main wastewater treatment plant increased from an average of 0.4 mg/l in 1971 to 3.0 mg/l in 1986.

The inspections suggested that the rate of corrosion had increased markedly and could no longer be predicted with the existing empirical formula. The causes of the apparent increase of the rate of corrosion are not understood. However, CSDLAC has data that show a strong correlation between an increase in wastewater sulfide levels and a decrease in levels of cyanide and certain priority pollutant metals regulated by EPA categorical pretreatment standards. CSDLAC measurements of wastewater constituent concentrations over the period 1971 through 1986, along with the results of their statistical correlation analyses, are included in Appendix A.

CSDLAC believes that cyanide and these heavy metals in their system may have played an important role in inhibiting the biological reduction of wastewater sulfate to sulfide. In addition, the metals form insoluble metal-sulfide precipitates that would reduce the amount of hydrogen sulfide released to the sewer headspace.

In the past few years, CSDLAC has implemented an intensive program to control hydrogen sulfide corrosion by attempting to reduce the growth of the Desulfovibrio bacteria or to chemically bind the sulfide which is generated using established control techniques. Adding hydrogen peroxide to the sewage to oxidize the sulfide was tried, but the required dosage of hydrogen peroxide was found to be too high to be cost-effective. Both ferrous chloride and liquid sodium hydroxide solutions are now being routinely added to selected sewer lines at a cost of almost $2 million per year. The ferrous chloride is added continuously to form an insoluble iron sulfide precipitate that is carried in suspended form to the main treatment plant. The sodium hydroxide is added at a weekly frequency to certain other sewers to provide a 30-minute, high pH shock to the Desulfovibrio bacteria to inhibit their activity. In addition, pure oxygen has been added to wastewater in one of the large gravity sewers on an experimental basis.

CSDLAC monitoring of hydrogen sulfide concentrations in the headspaces of the sewers has in general shown only modest reductions (i.e., 50 to 60 percent) as a result of these treatments, even though significant (i.e., 75 to 95 percent) dissolved sulfide reductions have been obtained in the wastewater. Measurements taken of the surface pH on the crowns of corroding sewers which have received these treatments have risen one half to two pH units compared to untreated conditions. This is expected to slow the rate of corrosion and extend the life of the pipes.

CSDLAC has estimated that at least $130 million will be needed to replace or repair approximately 25 miles of sewers that are severely corroded. An additional 16 miles will likely require repair or replacement within five years.

Approximately 500 miles of sewers show some evidence of sulfide generation but exhibit no corrosion damage according to CSDLAC. The goal of CSDLAC is to understand the causes and control of corrosion to prevent damage to these vulnerable parts of their system.

1.3 Consequences of Corrosion

Corrosion of wastewater and treatment systems induced by the presence of hydrogen sulfide can cause rapid and extensive damage to concrete and metal sewer pipe, equipment used in the transport and treatment of wastewater, and electrical controls and instrumentation systems. Such problems are rarely brought to the attention of the public until a catastrophic failure occurs such as with street collapses resulting from sewer pipe failure. However, sewer systems suffering from hydrogen sulfide corrosion generally require costly, premature replacement or rehabilitation of pipes, manholes, lift stations, and pump stations.

Equipment used in treatment of wastewater is often subject to hydrogen sulfide corrosion, resulting in equipment malfunctions, poor reliability, increased maintenance, and premature replacement. Electrical components (e.g. brushes, switches, relays) process instrumentation, air conditioning and ventilation units, and computer systems are particularly vulnerable to attack by hydrogen sulfide at pumping stations, lift stations, and treatment plants. This can cause poor reliability of control systems, increased maintenance requirements, and often premature replacement of costly electrical components and computer equipment.

Hydrogen sulfide corrosion can also compromise structural integrity by corroding equipment (bar screens, conveyors, etc.), pipe and equipment supports, wastewater and sludge storage tanks, and guard rails, walkways, and grating at the treatment plant.

1.4 Mechanism of Hydrogen Sulfide Corrosion

Hydrogen sulfide corrosion may result from two mechanisms: 1) acid attack resulting from the biological conversion of hydrogen sulfide gas to sulfuric acid in the presence of moisture and 2) the direct attack of metals such as copper, iron, and steel by hydrogen sulfide gas. The first mechanism is responsible for corrosion of sewers and concrete structures used in the conveyance and treatment of sewage. The second mechanism is generally responsible for corrosion of electrical contacts, copper pipe, and metal components in pumping stations and treatment plants.

First, for hydrogen sulfide to be formed, the wastewater must be anaerobic (devoid of oxygen). Oxygen is depleted due to the activity of microorganisms. In properly designed gravity sewers the velocity of the sewage is such that natural reaeration occurs from the atmosphere in the sewer, helping to replenish any losses of oxygen due to microbial activity. Certain structures and flow conditions often create turbulence of the wastewater, increasing the rate of reaeration and helping to maintain aerobic (oxygenated) conditions. Sources of turbulence include manholes with flows dropping in from the side, manholes with flows colliding, metering flumes, drops in the line, sections with steep slopes, and force main discharges.

Under certain conditions oxygen is depleted faster than it is supplied, causing a change from aerobic to anaerobic conditions. Such conditions can occur in gravity sewers with low sewage velocities or long detention times, force mains which convey wastewater through a full pipe under pressure with no opportunity for reaeration, wet wells of pumping stations having detention times sufficiently long as to cause oxygen depletion due to uptake by bacteria, and other structures or processes where wastewater is detained under near-stagnant conditions with insufficient opportunity for reaeration. Under anaerobic conditions, the microbial community shifts to organisms that can flourish without oxygen. These may be strict anaerobes that cannot utilize oxygen and may be sensitive to its presence, or facultative anaerobes which can utilize either free oxygen or other compounds in their metabolic cycle. The process of sulfide generation and sulfuric acid corrosion is as follows (4)(5)(6)(7)(8):

1. Under anaerobic conditions, strict anaerobic bacteria of the genus <u>Desulfovibrio</u> colonize the wastewater and attach to the slime layer that coats the submerged surfaces of pipes. The bacteria reduce sulfate (SO_4^{2-}), one of the most common anions in water and wastewater, to sulfide (S^{2-}).

2. The sulfide ion combines with hydrogen ions to form dissolved hydrogen sulfide gas (H_2S) and hydrosulfide ion (HS^-), depending on pH. At neutral pH of 7, the distribution of species is approximately 50 percent H_2S and 50 percent HS^-. At pH 6, the distribution is approximately 90 percent dissolved H_2S gas, and 10 percent HS^-.

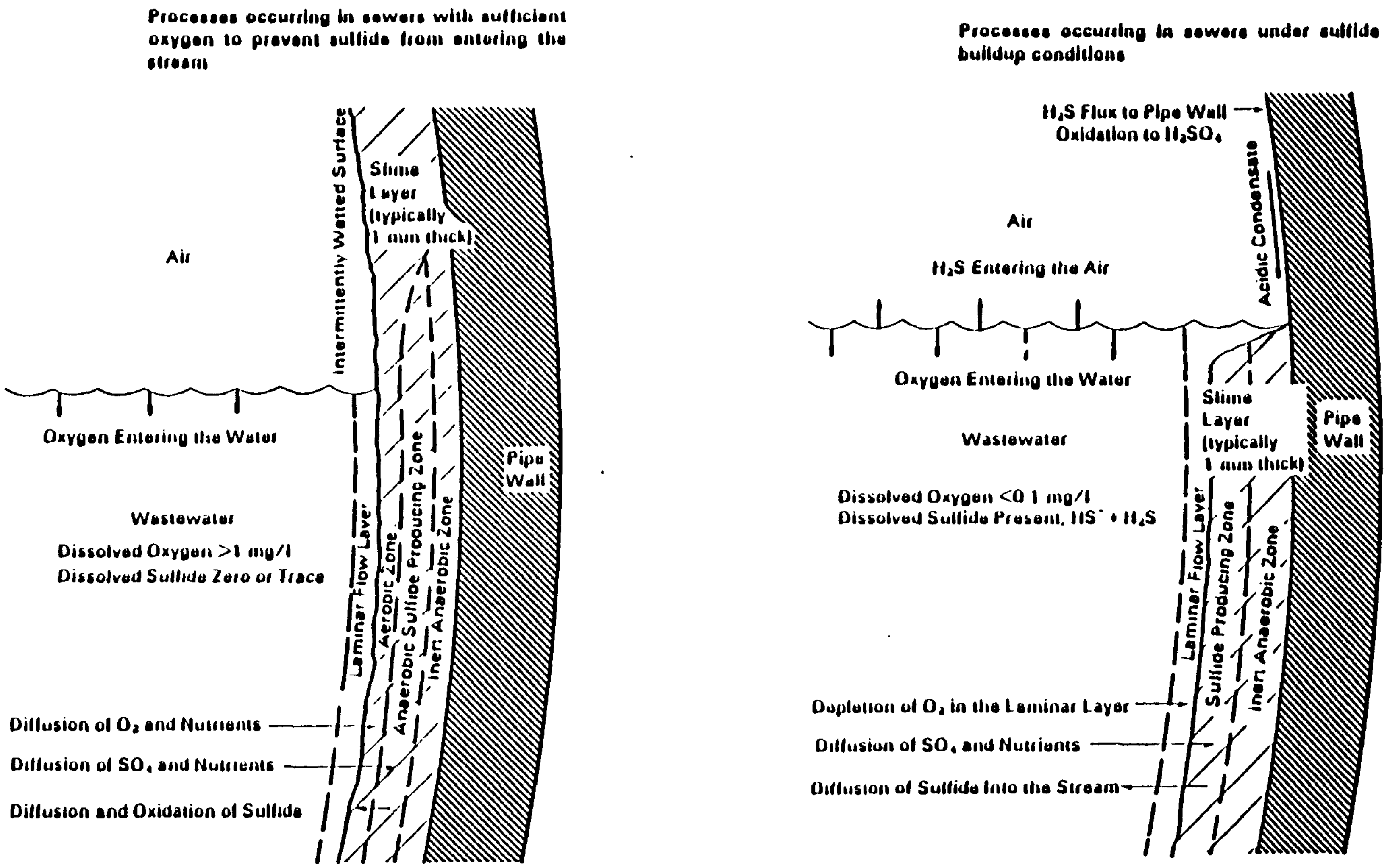
3. Hydrogen sulfide gas is released from the wastewater to the sewer atmosphere. The dissolved gas (H_2S) is the only form of sulfide which can be released. The release of H_2S from solution is accelerated under turbulent conditions and at higher temperatures. Thus, turbulence may be beneficial in maintaining wastewater in an aerobic state, but if the wastewater is anaerobic and dissolved sulfide is present, this same turbulence can cause rapid release of the H_2S to the sewer atmosphere. The H_2S produces the "rotten egg" odor characteristic of stagnating sewage. Since equilibrium conditions are rarely observed, it is virtually impossible to predict atmospheric H_2S concentrations based on Henry's Law.

4. The released H_2S combines with moisture on the non-submerged surfaces of the pipe and is oxidized to sulfuric acid by aerobic bacteria of the genus Thiobacillus, which colonize the pipe surfaces above the water level. There are many species of this bacteria which successively colonize the slime layer as sulfuric acid is produced and the pH drops. More acid-tolerant species then predominate. While new pipe has an alkaline surface pH, weathered pipes have a surface pH of about 6, and pipes which are subject to active sulfuric acid corrosion may have a surface pH of 3 to 1.

5. The hydrogen ions of the acid attack the calcium hydroxide in the hydrated Portland cement of the concrete sewer pipes, while the sulfate combines with the calcium ions to form gypsum ($CaSO_4$), a soft corrosion product. In addition, calcium sulfoaluminate ($3CaO\ Al_2O_3CaSO_4\ 31H_2O$), also known as ettringite, may form. Both gypsum and ettringite occupy considerably greater volume than the compounds they replace. This leads to expansion and disruption of the concrete, and loss of aggregate. Both products are easily washed away by wastewater, thus exposing fresh material to sulfuric acid. In early stages of corrosion, the pipe wall swells, making it difficult to measure concrete loss due to corrosion.

Figure 1-1 summarizes the processes which occur in sewers under aerobic and anaerobic conditions.

H_2S directly attacks metals including iron, copper, and silver. H_2S can cause blistering and embrittlement of ductile iron pipe. Even at low concentrations in the atmosphere (<1 ppm), H_2S can cause extensive damage to electrical contacts and circuits present in controls, switchgear, and computer equipment.


Processes occurring in sewers with sufficient oxygen to prevent sulfide from entering the stream

Processes occurring in sewers under sulfide buildup conditions

Figure 1-1 Processes occurring in sewers under differing conditions

The rate of sulfide-induced corrosion is affected generally by the characteristics of the wastewater and the collection system. Many variables directly or indirectly affect sulfide generation, H_2S release, and sulfuric acid corrosion. These variables are summarized in Table 1-1.

TABLE 1-1

FACTORS AFFECTING SULFIDE GENERATION AND CORROSION IN SEWERS

FACTOR	EFFECT
Wastewater Characteristics	
Dissolved oxygen	Low DO favors proliferation of anaerobic bacteria and subsequent sulfide generation
Biochemical oxygen demand (organic strength)	High soluble BOD encourages microbial growth and DO depletion
Temperature	High temperatures increase microbial growth rate and lowers DO solubility
pH	Low pH favors shift to dissolved H_2S gas
Presence of sulfur compounds	Sulfur compounds required for sulfide generation
Sewer System Characteristics	
Slope and velocity	Affects degree of reaeration, solids deposition, H_2S release, thickness of slime layer
Turbulence	Same effect as slope/velocity
Surcharging	Reduces oxygen transfer and promotes sulfide generation, will not corrode while surcharged
Presence of force mains and inverted siphons	Same effect as surcharging, releases H_2S at the turbulent discharge end
Sewer pipe materials	Corrosion resistance of pipe materials varies widely
Concrete alkalinity	Higher alkalinity reduces corrosion rate
Accumulated grit and debris	Slows wastewater flow, traps organic solids

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2.0 NATIONAL ASSESSMENT OF CORROSION

2.1 Introduction

In the spring and again in the fall of 1987, EPA met with representatives of the County Sanitation Districts of Los Angeles County (CSDLAC) and the City of Los Angeles to learn about the nature and severity of the corrosion problem in the wastewater collection system. CSDLAC presented slides and video recordings that documented the degree of corrosion and its increase over time. In addition, a field inspection of a severely corroded sewer line was conducted. It was concluded from the visits that a national assessment of corrosion was warranted to document the severity of corrosion problems in other cities and to determine if other municipalities had experienced increases in corrosion rate upon implementation of industrial pretreatment standards.

The national assessment of corrosion consisted of the following major elements:

- site visits in early 1988 to six cities with documented corrosion problems to determine if severe hydrogen sulfide corrosion problems were unique to CSDLAC.
- site visits in 1989 and 1990 to three cities with hydrogen sulfide corrosion problems at wastewater treatment plants and lift stations to document the extent of problems and prepare case histories.
- site visits in 1988 to three cities with pretreatment programs to assess the effects of pretreatment.
- compilation of detailed case histories in 1988 for several wastewater collection systems to document the history of corrosion in those systems.
- collection of samples from two wastewater collection systems in 1988 for physical, chemical, and microbiological analyses to gain a better understanding of the mechanisms of corrosion.
- telephone discussions with officials of various cities reported to have corrosion problems.
- contacts with engineers, sewer rehabilitation contractors, and manufacturers of materials used in sewer rehabilitation or replacement.
- evaluation of information collected in surveys conducted by CSDLAC, municipal associations, and pollution control organizations.

2.2 Site Visits to Assess Hydrogen Sulfide Corrosion in Sewers

One of the first efforts of the project was to determine whether severe sulfide-induced corrosion was unique to the CSDLAC sewer system. To answer this question, site visits were made to six cities with reported corrosion problems. To identify potential cities for site visits, information was reviewed from several sources, including surveys conducted by the Association of Metropolitan Sewerage Authorities (AMSA) in 1987, CSDLAC in 1984, and the Water Pollution Control Federation (WPCF) in 1984. In addition, regional EPA offices and literature articles provided supplemental information. Based on this information, a list of 131 candidate cities was compiled. Of these 131 cities, 66 were reported to have problems with sewer corrosion. Further review resulted in preliminary selection of 34 cities expected to yield the most valuable corrosion data during site visits.

Six sewer systems were selected for site visits from the list of 34: Albuquerque, New Mexico; Baton Rouge, Louisiana; Boise, Idaho; Casper, Wyoming; Forth Worth, Texas; and Seattle, Washington. Each city had reported severe corrosion problems.

In addition, two other cities, Charlotte, North Carolina and Milwaukee, Wisconsin, were selected for further study. These two differed from the others in that they did not have known corrosion problems, and they had certain sewer segments that carried a large proportion of industrial flow, including pretreated metal finishing wastes, while other sewer segments carried primarily residential wastewater. It was postulated that this may allow observation of whether the industrial sewers had been "protected" by the presence of metals or other industrial waste constituents compared to those sewer segments conveying strictly residential waste. All eight cities had industrial pretreatment programs in effect.

The primary purpose of the site visit program was to determine if severe and high-rate corrosion is unique to the CSDLAC wastewater collection and treatment system. Each site visit typically included one and one-half to two days in the visited city. On the afternoon of the first day, the field team met with representatives of the city or agency to review the characteristics of the local collection and treatment system and to select six to 10 locations for observation the following day.

Field observations and measurements included monitoring gaseous hydrogen sulfide in manhole and sewer atmospheres (Industrial Scientific Devices, Model HS 267), measuring sewage pH with a portable pH meter (Nester Instruments, Model 34100-403), measuring total sulfide in sewage with a portable test kit (HACH Co., Kit No. HS-6), and using a screwdriver to probe manhole and sewer walls to evaluate depth of corrosion and integrity of concrete. Photographs were taken and pH paper (Color pHast, 0-14) was used to measure surface pH at several locations on sewer and manhole walls. Additional observations were made of smoothness of sewage flow, sewage velocity, and the presence of sewer laterals, bends, and drops. Background information (e.g., pipe age, slope, diameter, approximate sewage age, and the presence of coatings or linings) was also recorded when available.

To distinguish levels of severity and rates of corrosion, the following arbitrary definitions were developed for this study:

> Severe corrosion - loss of one inch or more of concrete, loose or missing aggregate, exposed reinforcing steel.
>
> High-rate corrosion - rate of corrosion which would cause a loss of at least one inch of concrete in twenty years. This rate is significant since reinforcing steel is generally about one inch below the interior concrete surface of large pipes constructed according to industry standards. Exposure of reinforcing steel to corrosion can lead to structural impairment.
>
> Accelerated corrosion - an increase in the rate of corrosion with time.

Corrosion was observed in all eight cities, and was considered severe in at least one location in each city except Charlotte. High-rate corrosion was observed in at least one location in each city except Charlotte and Milwaukee. During EPA's site investigations, the estimated depth of corrosion was divided by the age of the pipe to yield a lifetime average corrosion rate. However, it is impossible to determine from these data whether the corrosion rate has changed with time. Such inspections merely offer a "snapshot" of the corrosion processes and provide no information on the history of corrosion, i.e., whether accelerated corrosion had occurred. A summary of conditions in each city is presented in the following paragraphs. A summary of pertinent information collected during the site visits is shown in Table 2-1.

2.2.1 Albuquerque, New Mexico

The City of Albuquerque maintains approximately 1,400 miles of sewer which serve approximately 450,000 people and transport an average of 49 million gallons per day (mgd) of wastewater to the city's treatment facility. Separate storm sewers are used throughout most of the city, but some combined systems do exist.

Albuquerque experiences 90 to 100 collapses per year that are attributed to hydrogen sulfide corrosion in its approximately 400 miles of 8-inch-diameter concrete pipe. These collapses are mostly in residential areas, and each typically involves two to four pipe sections (20 feet). The problem of pipe collapse is widespread in the city, but seems concentrated in North Valley, an older part of town that has the most concrete pipe, and in pipe 40 to 60 years old. The rest of the collectors are mostly clay pipe.

Corrosion seems to be worst at locations where a force main discharges to a manhole, at lift stations in gravity sewers (the city is beginning to use polyvinyl chloride

TABLE 2-1

SELECTED INFORMATION FROM SITE VISITS

City and State	Sewer Age (years)	Sewer Diameter (inches)	Surface pH						Estimated Concrete Loss (inches)	Estimated Corrosion Rate (inches /year)	Corrosion Status
			Upstream		Downstream		Manhole				
			Crown (s.u.)	Wall (s.u.)	Crown (s.u.)	Wall (s.u.)	Wall (s.u.)	Roof (s.u.)			
Albuquerque, NM											
Arno	--	72	3	3	2.5	2.5	5.0	3.0	1	--	Severe
Marquette Ave. and Edith St.	--	54	--	--	--	--	--	--	--	--	--
Iron Ave. and 14th St.	--	60	4	--	4	--	--	--	2	--	Severe
Coors Blvd. and Churchill Rd.	25	30 in, 36 out	--	--	--	--	2.0	1.0	1	0.04	Severe
Atrisco Dr.	7	54 PVC	5	--	2	--	1.0	--	1 (MH)	0.14	Severe
Rossmoor Rd.	32	78	--	--	--	--	4.0	2.5	0-0.25	<0.01	Negligible
Baton Rouge, LA											
P.S. No. 59	27	NA	NA	NA	NA	NA	6.0	6.0	0.25-0.50	0.01-0.02	Shallow
Front St. and North St.	≥30	30	4.5	6.0	4.0	6.0	4.5	--	0.25-0.50	<0.02	Shallow
Devall St. and Blount St.	≥30	20 in, 42 out	2.5	2.5	5.0	5.5	2.0	--	1.0-1.5	<0.05	Severe
Harding St. and Georgia St.	≥30	30 in, 36 out	6.0	6.0	5.5	6.0	6.0	--	0.25-0.50	<0.02	Shallow
Winbourne Ave. and E. Brookstone Dr.	≥30	36	5.0	5.0	6.0	--	6.0	--	1.0-1.5	<0.05	Severe
E. Contour and S. Contour	≥30	54	3.5	--	2.5	--	--	4.0	0.25-0.50	<0.02	Shallow
Starring Lane	≥30	60	2.5	--	5.0	--	3.0	3.5	0.5-1.0	<0.03	Severe
Boise, ID											
Protest and Federal	14	21	--	--	--	--	--	--	1.0-2.0	0.14-0.28	Severe
Warm Springs and Elm	≥30	10 VC	4.0	--	3.0	--	2.0	--	1.0-2.0 (MH)	<0.06	Severe
Warm Springs and N. Straugham	≥30	10 PVC	4.0	--	3.0	--	5.0	--	0 (MH)	Brick MH	NA
Bruce and Jefferson/Bannock	--	--	6.5	--	6.5	--	--	--	NA	Lined MH	NA
North Gary and Baron	12	--	6.0	--	6.0	--	1.0	--	0.5-1.0	0.04-0.08	Severe
Bluebird and Gary	12	--	3.0	--	3.0	--	1.0	--	0.5-1.0	0.04-0.08	Severe
Glenwood and State	12	--	--	--	--	--	3.0	--	--	--	Severe
Glenwood and Chindon	12	--	--	--	--	--	--	--	1.0-1.5	0.05-0.1	Severe

TABLE 2-1 (continued)

City and State	Sewer Age (years)	Sewer Diameter (inches)	Surface pH						Estimated Concrete Loss (inches)	Estimated Corrosion Rate (inches /year)	Corrosion Status
			Upstream		Downstream		Manhole				
			Crown (s.u.)	Wall (s.u.)	Crown (s.u.)	Wall (s.u.)	Wall (s.u.)	Roof (s.u.)			
Casper, WY											
K Street	29	36	5.0	5.0	4.0	5.0	3.0	--	1.0-1.5	0.04-0.08	Severe
G and Center St.	7	48	--	--	--	--	2.0		--	--	Shallow
801 W. Yellowstone	7	48	4.0	5.0	3.0	--	2.0	--	0-0.25	0.01-0.04	Shallow
Fairgrounds Road	7	36	5.0	5.0	5.0	5.0	6.0	--	0-0.25	0.01-0.04	Shallow
Midway Drive	7	30	6.0	6.0	6.0	6.0	1.0	--	0-0.25	0.01-0.04	Shallow
Mills Cut-Off Road	7	30	5.0	5.0	5.0	5.0	5.0	--	0-0.12	0.01-0.02	Shallow
Aster and Daffodil	7	21 in, 24 out	6.0	--	6.0	--	6.0	--	0-0.12	0.01-0.02	Shallow
Charlotte, NC											
Clanton St. at I. Creek	--	36	6.0	6.0	6.0	6.0	6.0	--	--	--	Absent
Remount St.	--	36	6.0	6.0	6.0	6.0	6.0	--	0-0.12	--	Shallow
Freedom Dr. and Thrift Rd.	--	36	6.0	6.0	6.0	6.0	6.0	--	--	--	Absent
E. 12th St. and Meyers	--	30	6.0	6.0	6.0	6.0	6.0	--	--	--	Absent
Davidson and E. 22nd	--	30	6.0	6.0	6.0	6.0	6.0	--	--	--	Could not observe
Old Providence Rd. near Sharonview	--	42	5.0	5.0	4.5	5.0	6.0	--	0-0.25	--	Shallow
Arborway near Sedley Road	--	24	6.0	6.0	6.0	6.0	6.0	--	--	--	Absent
Park Road and Moncure	--	54	6.0	6.0	6.0	6.0	6.0	--	--	--	Absent
Old Nations Ford near Ervin Lane	--	54	6.0	6.0	6.0	6.0	6.0	--	--	--	Absent
Granite St. near Continental Blvd.	--	21	6.0	6.0	6.0	6.0	6.0	--	0-0.12	--	Shallow
Fort Worth, TX											
Rosedale St.	>30	36	6.0	6.0	6.0	6.0	--	--	2.0-3.0	<0.1	Severe
Kimbo St.	31	12	5.0	--	5.0	--	5.0	--	--	--	--
Kimbo St.	31	8	6.0	--	6.0	--	4.0	6.0	1.0	0.03	Severe (MH)
Pharr St.	31	54	4.0	--	--	--	4.0	--	0.75	0.02	Shallow
Bomar St.	65	54	6.0	--	6.0	--	6.0	--	2.0-4.0	0.03-0.06	Severe

TABLE 2-1 (continued)

City and State	Sewer Age (years)	Sewer Diameter (inches)	Surface pH						Estimated Concrete Loss (inches)	Estimated Corrosion Rate (inches /year)	Corrosion Status
			Upstream		Downstream		Manhole				
			Crown (s.u.)	Wall (s.u.)	Crown (s.u.)	Wall (s.u.)	Wall (s.u.)	Roof (s.u.)			
Milwaukee, WI											
Hampton and 32nd	--	36	--	--	--	--	6.5	--	--	--	Absent
Lydell and Chateau	--	42	6.5	6.5	6.5	6.5	6.5	--	--	--	Absent
Greentree Rd. Pump Station	5	72 in, FM out	6.5	6.5	6.5	6.5	6.5	--	--	--	Absent
Vienna St.	--	60	6.5	6.5	6.5	6.5	6.5	--	--	--	Absent
N. Water St. and Marshall	--	36	--	--	--	--	--	--	--	--	Absent
N. Water St. and Pierson	--	36	6.5	--	6.5	--	6.5	--	--	--	Could not observe
W. Florida St. and Forth St.	--	54	--	--	--	--	--	--	--	--	Could not observe
Barclay and Madison	--	60	--	--	6.0	--	--	--	--	--	Absent
35th and Kinnickinnic	50	36	6.0	--	3.5	--	6.0	--	1	0.02	Severe
116th and Oklahoma	--	48	6.5	6.5	6.5	6.5	6.5	--	--	--	Absent
Seattle, WA											
E. Marginal Way and 112th St.	24	2x12 in, 42 out	1.0	3.0	2.0	2.0	2.0	3.0	1	0.04	Severe
W. 15th Ave. and W. Raye St.	>20	2x30 in, 96 out	--	--	--	--	2.5	1.0	1.5	<0.08	Severe
15 Ave. NW and 188th St. NW	--	15 in, 18 out	1.0	--	--	--	6.0	1.0	0.25-0.50	--	Shallow
NE Union Hill and Avondale	14	54	--	--	--	--	3.0	--	0-0.25	0.01-0.02	Shallow
Hollywood PS Disc. Struc.	15	--	--	--	--	--	--	--	0.25-0.50	0.02-0.04	Shallow (MH)

[PVC] liners at those locations), near interceptors where hydrogen sulfide moves back into laterals, and at locations midway between manholes. Albuquerque does not have much industrial discharge, and pipe failures are not related to the presence of industrial discharges. There are only about three small electroplaters in the area.

In the past, Albuquerque has not had a formal program to identify corrosion. The city now has a television inspection program for small-diameter sewers (8 inches). The city replaces about 18,000 feet per year of 8- to 10-inch pipe. The goal is to replace 30,000 feet per year. The city has replaced up to 12-inch concrete lines with clay or PVC to prevent further corrosion. A total of about 40 miles of mostly 8-inch-diameter pipe has been sliplined since 1978.

Albuquerque experiences a summertime odor problem, and injects chlorine gas and hydrogen peroxide at several locations for odor control during the summer. Untreated wastewater has had total sulfide concentration of up to 4.3 mg/l. The city will be switching some of the chlorine units to hydrogen peroxide in the future, because of longer lasting effects and safety concerns.

Sewers 24 inches or less in diameter are cleaned at intervals ranging from three months to two years. Larger sewers are not cleaned.

Corrosion at the wastewater treatment facility is limited primarily to metal components. Ventilation is used to help control corrosion inside the treatment buildings.

The city identified six sites scattered throughout the area to exemplify the corrosion problem in Albuquerque: Arno and Wesmeco streets; Marquette Avenue and Edith Street; Iron and 14th streets; Coors Boulevard and Churchill Road; Atrisco Street; and Rossmoor Street.

An example of high-rate corrosion exists at the Atrisco Street site. The site is seven years old and near the upstream end of the system. The slope in this reach of pipe is very flat, and sewage velocity was estimated to be 0.5 feet per second (fps). The manhole at this site was installed with a bituminous coating that has separated almost entirely from the concrete. In seven years, the concrete on the walls and soffit of the manhole has corroded up to an estimated depth of 1.0 inch. The inlet and outlet pipes at this manhole are PVC-lined and in good condition. Measurements of pH on the manhole and pipe walls ranged from 1 to 5.

Three other sites (i.e., Arno and Wesmeco streets, Iron and 14th streets, and Coors and Churchill streets) have experienced severe corrosion. Measurements of pH on the walls of manholes and pipe ranged from 2 to 5 at Arno Street, and from 1 to 2 at Coors Street, and were 4 at Iron Street. Depth of friable concrete or corrosion product ranged from 0.50 to 2 inches. However, the pipe and manholes at these sites are considerably older than the Atrisco Street site, reflecting a lower rate of corrosion over the life of the installation. The current rate of corrosion at these sites cannot be determined from available information.

The manhole at Marquette Avenue and Edith Street has experienced some corrosion; however, manhole access problems prevented quantification. The flow in this manhole is turbulent. The Rossmoor Street site is not corroded badly, although pH ranged from 2.5 to 4 at this site.

Except for the Marquette Avenue and Edith Street site, release of hydrogen sulfide gas is not believed to be accelerated by turbulence or drops at the Albuquerque sites. Long detention times, flat slopes, and warm sewage temperatures are thought to promote hydrogen sulfide corrosion of concrete system-wide in Albuquerque, as reflected by low pH readings at all sites.

2.2.2 Baton Rouge, Louisiana

The City of Baton Rouge maintains approximately 250 miles of sewer which transport an average of 36 mgd of wastewater to the city's three treatment facilities. The sewer system serves the entire East Baton Rouge Parish except for two small communities. The system serves 375,000 people. Baton Rouge officials estimate that they have approximately 75 miles of unlined reinforced concrete pipe larger than 24 inches in diameter.

Industry contributes less than 5 percent of the total sewered flow. The major industries, including a large oil refinery, treat their own waste and do not discharge industrial effluent to the sewers. Those industries that do discharge to the Baton Rouge system are generally in compliance with the established pretreatment program. Industry is not concentrated in any one area of the system, and city engineers do not correlate corrosion in their system with industrial discharge.

The Baton Rouge sewer system is completely separate. Corrosion of concrete pipe is system-wide. Baton Rouge experienced its first sulfide-related pipe collapse about five years ago. This collapse was the first indication to the city of the severity of its corrosion problem. A consultant's report to the city on preventative maintenance of the system made reference to odor control, but did not focus on corrosion. The city did try chlorine addition in the mid-1970s, but abandoned the program in less than one year because of high costs. The city does some television inspection of the system, but does not have a system-wide hydrogen sulfide corrosion prevention program.

The city has experienced multiple problems in some pipe reaches. Repairs made with fiberglass or plastic pipe appear to be holding up well; however, one repair done with concrete pipe experienced corrosion and needed subsequent replacement. Baton Rouge acknowledges that turbulent flow conditions due to changes in grade or direction, pump station discharges, or drop connections are usually prevalent at problem areas.

Baton Rouge selected eight sites for EPA to observe: a pump station, the Central Treatment Plant, and six manholes located throughout the sewer system (two in the north subsystem, one in the central subsystem, and three in the south subsystem). The sites ranged in location from one within approximately 1 mile of a treatment plant and 10 miles from the upstream end of a reach, to one located near the upstream end of a reach. Corrosion was observed at each site, with varying degrees of severity. All sites visited were constructed in the early 1960s. Pipe slopes ranged from 0.003 ft/ft to 0.00015 ft/ft.

Pump Station No. 59, a 27-year-old structure, which is located 1 mile upstream from the Central Treatment Plant and collects wastewater from about 10 miles upstream, was the first site visited. A pH of 6 was measured on the wet well walls; shallow corrosion, 0.25 to 0.5 inches deep, was observed. The wet well often surcharges, washing the walls.

The Central Treatment Plant had shallow corrosion of some concrete structures. The force main discharge structure at the plant headworks was corroded, and aggregate was exposed in both the primary clarifier influent and effluent channels. Some corrosion of metal had also occurred at the plant headworks. A 0.6 parts per million (ppm) total sulfide content was measured in wastewater at the plant headworks. Plant influent pH was 6.

The first manhole visited is located at Front and North streets in the Central District, about 0.75 miles downstream of a pump station and within 1 mile of the Central Treatment Plant. Measurements of pH in the manhole and the 30-inch-diameter pipe ranged from 4 to 6. Large aggregate, indicating up to 0.5 inches of pipe loss, was visible in the pipes above normal water line. Flow at this location was turbulent due to the pump station upstream, a change in slope about 100 feet downstream, and a 12-inch-diameter inlet with to 2- to 3-foot drop. The wastewater had a trace of sulfide and pH of 6.

The next two sites are in the North District: Devall Lane off Blount Road, and Georgia Street at Harding Boulevard. The Devall Lane site is directly downstream of a pump station, and flow is made more turbulent by a 1.5-foot drop across the manhole. The site is located at the midpoint of a 12-mile-long drainage area. A total sulfide concentration of 0.05 mg/l and a pH of 6 were measured in the wastewater. Pipe surface pH measurements ranged from 2 to 5.5. The pipe at this location was severely corroded above the normal water surface (during pump discharge). Some mortar is missing between the bricks in the manhole and some bricks were observed on the floor of the downstream pipe. Observations revealed that as much as 1.5 inches of concrete may be corroded.

The Georgia Street site is in the upstream third of the same drainage area. The wastewater had a sulfide concentration of 0.08 mg/l and pH of 6.5. Pipe pH measurements ranged from 5.5 to 6. Although this site is also less than 0.25 miles downstream of a pump station, pipe corrosion was estimated to be minor. Only small aggregate was exposed, indicating 0.25 to 0.50 inches of concrete loss. Two drop pipes enter this manhole, and the pipe changes direction about 100 feet downstream.

The final three sites visited are in the South District: Winbourne Street at East Brookstown Drive, East Contour Drive, and Staring Lane. The Winbourne Street site had a wastewater pH of 7 and sulfide of 0.17 ppm. Pipe surface pH measurements ranged from 5 to 6. The 36-inch pipe at this location is corroded severely and corrugations were visible at reinforcing steel locations. There is a 2-foot drop across the manhole. Winbourne Street is located near the upstream end of a 15-mile-long drainage reach.

The Contour Drive and Staring Lane sites are on the same 54-inch pipe in the middle and near the downstream end of the reach, respectively. Wastewater sulfide content was 1.1 ppm at the Contour Drive site; wastewater pH averaged 6 at the two sites. Pipe surface pH measurements were between 2.5 and 4 at the Contour site, and 2.5 and 5 at Staring Lane. Corrosion at these sites was limited to about 0.50 to 1 inch of concrete loss, exposing only the first layer of aggregate.

Hydrogen sulfide gas levels of 3 to 4 ppm were measured at the Contour Drive site. The Staring Lane site is just downstream from a 36-inch-diameter force main terminus. In addition, the downstream pipe at the Staring Lane site had a broken invert near the manhole, which has created a backwater condition and turbulence at the manhole.

2.2.3 Boise, Idaho

The City of Boise maintains approximately 325 miles of sewer which transport an average of 24 mgd of wastewater to the city's three treatment facilities. Boise provides sewer service to three sewer districts and to Garden City. Boise has recognized a hydrogen sulfide corrosion problem in its system since 1983. Concrete sewers and manholes in at least four areas have experienced severe corrosion. Some of their most seriously damaged manholes have been coated recently with materials to resist further sulfide attack.

Hydrogen sulfide corrosion in Boise is system-wide. Boise officials feel their corrosion problem can be correlated to low flows in hydraulically oversized sewers and to turbulent flows created by force main discharges and drops in manholes. There is very little industry in the area, and Boise operates a completely separate sewer system.

Boise, in consultation with CSDLAC, has tried Polymorphic resin and Zebron coatings and Chrystallok and fiberglass liners in several of their manholes. Insituform and sliplining have been and are presently being used in Boise to rehabilitate corroded sewers.

After Boise discovered its problem in 1983, it realized that the 1977 television monitoring tapes indicated previously overlooked signs of corrosion such as concrete swelling and spalling. During the visit, Boise displayed over 15 samples of 4-inch-diameter cores, recovered from a 1984 coring program, which showed the extent of corrosion in different pipe sizes, ages, and areas of the system.

Based on measurements of core thickness and the known age of the pipe, Boise has calculated that lifetime corrosion rates are as high as 0.12 inches per year in the sewer pipe at Glenwood and Chinden streets, and 0.15 inches per year in the sewer pipe at Canal and Columbus streets. Corrosion rates calculated similarly for pipe in the warm springs area was 0.03 inches per year over a 37-year period, and 0.06 inches per year at Protest and Federal streets.

About 30 homes in the Warm Springs area use a geothermal water source for home heating. The water is extracted from the ground at about 175°F and discharged from homes to the sewer at about 130°F. The sewage in this area of town averages between 90 and 100°F. The sulfate concentration of this water source is about 23 mg/l. Corroded manholes were observed in this area.

The maintenance supervisor from the neighboring West Boise Sewer District (West Boise) described a serious problem in his system. West Boise replaced six manholes after a 5-year-old sewer collapsed due to hydrogen sulfide corrosion in 1983. There were 10-foot-drop laterals at some of these spun concrete, Type 2 concrete manholes. West Boise feels that hydrogen sulfide conditions are worse at turbulent flow areas (e.g., drop manholes). In addition, the supervisor cited uneven slope during installation of the system as contributing towards solids deposition in the lines.

West Boise previously used chlorine and hydrogen peroxide dosing and experimented unsuccessfully with bacterial seeding to control sulfide generation. The chemical treatment program was successful once the proper dosing was defined, but very expensive. The West Boise maintenance supervisor also feels that hydrogen sulfide conditions are worse at turbulent flow areas resulting from drop manholes. He noted that Garden City, a nearby area with high infiltration and inflow, has little corrosion.

The West Boise Sewage Treatment Plant, owned and operated by Boise City, has had air scrubbing equipment installed to reduce odor emissions.

A tour of Boise's treatment plant revealed some concrete corrosion. Influent channels covered for three years at the plant's headworks have experienced corrosion, particularly the channel that formerly carried sludge. The covered wet wells had no corrosion, but the air has been scrubbed since the 1970s to reduce odor complaints. The remainder of the process tanks at the plant are not covered (except for the anaerobic digesters), and are not experiencing any concrete corrosion.

The field team members made observations at 12 sites in Boise. Of these, five sites (i.e., one at Protest Avenue and Federal Way, and four along a segment of another sewer between North Gary Street at West Baron Street and Glenwood Street at Chinden Boulevard) showed a high rate of corrosion. The remaining sites, although they often have acidic pH levels on walls, do not yet show evidence of corrosion.

The Protest Avenue site is located only 2 miles from the upstream end of the collection area and has a 10-foot-drop inlet. The long drop creates turbulence that is believed to accelerate release of hydrogen sulfide and corrosion. A screwdriver could be pushed up to 2 inches into the remaining concrete of the manhole wall. Measurements of pH were 2 on the manhole wall. This site is 14 years old.

Four sites along a single 12-year-old line between North Gary Street at West Baron Street and Glenwood Street at Chinden Boulevard also have high-rate corrosion. Pipe at the downstream end (Glenwood Street at Chinden Boulevard) showed deep corrugations at reinforcing steel, indicating that corrosion had penetrated deeper than the reinforcement. Surface pH levels were 6 in the pipe and 1 in the manhole at North Gray Street, 3 in the pipe and 1 in the manhole at Bluebird, and 3 in the manhole at State Street. The wastewater sulfide concentration was 2.25 mg/l near the upstream end.

A brick manhole and a previously corroded concrete manhole coated with Polymorphic resin were inspected in the Warm Springs area of Boise. The surface of the brick manhole had a pH of 5, and the coated concrete manhole had a pH of 2.0 - 3.0. Both the brick manhole and the resin coating appeared to be in good condition.

Additional observations at one unlined and two lined manholes did not reveal corrosion. Shallow corrosion, zero to 0.50 inches deep, was observed at a pump station wet well.

2.2.4 Casper, Wyoming

Casper officials feel that a severe hydrogen sulfide corrosion problem exists in that city. The problem first came to light in 1975 during reconstruction of the wastewater treatment facility when a severely corroded influent line to the primary clarifier needed replacement. Since that time, the city has begun looking for corrosion in manholes as part of its manhole inspection program. In addition, the city tried sodium hydroxide dosing once in 1986 and once in 1987 to control the slime layer inside sewer pipes and has added clean water to upstream portions of the system to increase flow rates and decrease detention times. The sodium hydroxide treatments were effective for approximately three-week periods. Generation of hydrogen sulfide is only a problem during summer months. Casper also has a problem with hydrogen sulfide corrosion of the engines being fueled with digester gas in its cogeneration plant. A $16,000 rebuild was recently completed. City staff reported that this digester gas cogeneration problem is shared with Billings, Montana, and Boulder, Colorado.

Casper officials identified seven manholes for the visit. The first observation was in a manhole on a 29-year-old 36-inch sewer line about 0.75 miles from the wastewater treatment facility. The remaining observations were along a 10-mile segment of a 6- to 7-year-old sewer that transports wastewater from the western side of Casper to the wastewater treatment facility.

Corrosion is clearly evident in the 29-year-old manhole. Aggregate is exposed and loose in some instances. Up to 1.5 inches of pipe wall may have washed away. Corrosion product was not observed at this location; however, a pH of 3 was measured on the manhole wall and a pH of 4 to 5 was measured in the crown of the downstream pipe. Corrosion is evident at all the manholes observed on the 6- to 7-year-old sewer. Furthermore, corrosive conditions appear to worsen the farther downstream that observations were made. The farthest upstream observation was at a manhole located about 200 feet below a force main river crossing. The sewer pipe appeared in very good condition, except for 0.125 inch of erosion evident along the side of the outlet. Pipe and manhole surface pH was 6 at this location; there was no corrosion product.

As the observers progressed to downstream locations, the presence of corrosion product increased and pH levels on pipe and manhole surfaces decreased. Measurements at three downstream locations showed pH levels of 2 or less. At the farthest downstream location, Center and G St., approximately 1.5 inches of soft, mushy corrosion product was evident on the walls of the manhole. Because of the short length of time that this sewer segment had been installed, it was difficult to estimate the amount of concrete that had corroded. However, corrosion was clearly occurring.

The effluent channel of the primary clarifiers at the wastewater treatment facility at Casper had severe corrosion. Up to 2 inches of concrete may be missing from parts of the channel. The facility superintendent believes that a major contributing factor to sulfide generation in that city is excessive sewage detention time. This results from hydraulically oversized sewers constructed in anticipation of growth that did not occur because of a regional economic downturn. In addition, high sulfate concentrations in the local drinking water, 180 to 200 mg/l, may aggravate the problem.

2.2.5 Fort Worth, Texas

The City of Fort Worth maintains approximately 2,000 miles of sewer which transport wastewater to a single treatment facility located adjacent to Village Creek, a tributary of the Trinity River. A second facility, the Riverside facility, used to treat wastewater for the city; however, flow to that facility was diverted to the Village Creek facility several years ago.

Fort Worth experiences hydrogen sulfide odor problems during warm weather and has had a pipe collapse that is attributed to hydrogen sulfide corrosion. In particular, one of the Village Creek collectors collapsed. The city now injects chlorine into the two main interceptors (90 and 96 inches) to control sulfide and odor. The closing of the Riverside Treatment Facility and concomitant shifting of flow to Village Creek have decreased detention time and hydrogen sulfide levels in these two interceptors.

The industrial contribution of wastewater is a fairly uniform 10 to 20 percent throughout the collection system. The major sources are from electroplating, brewing, food processing, and aircraft manufacturing.

The levels of metals in the wastewater have declined dramatically during the past five years. However, levels of aluminum and iron are high because of the discharge of drinking water treatment sludge to the wastewater collection system at several locations.

A pipe collapse was reported to have occurred at the end of a force main in the neighboring City of Grand Prairie. The City of Pantego, also a neighbor, was said to have a major problem.

Field team members entered five manholes in Fort Worth to assess the presence and effects of corrosion in the city sewer system. The manholes are spread out across the city and represent several sewer main subsystems. Two manholes manifested severe corrosion. At Rosedale Street, a section from the crown of a 36-inch pipe is clearly visible lying on the pipe floor. The pipe walls have corrugations 1.5 to 2 inches deep; an estimated 2 to 3 inches of pipe is missing. The city is aware of problems in this 30-plus-year-old line and has rerouted wastewater to allow replacement of this sewer. This sewer has a steep, easily observable slope that increases sewage velocity and could accelerate the release of hydrogen sulfide gas. The pH of the pipe surface at this manhole was approximately 6, indicating that conditions were not as corrosive at the time of the visit as in the past, probably because of the rerouting of the wastewater.

The second location with severe corrosion was a 65-year-old, 54-inch pipe on Bomar Street. At this location, the pipe upstream and downstream of the manhole had corrugations 1 to 2 inches deep. In addition, a section of pipe wall approximately 1 foot high by 6 feet long is missing from the right side of the pipe approximately 15 feet downstream. An estimated 2 inches of concrete has eroded from the lower portion of the manhole, and the joint between the manhole and outlet pipe has deteriorated. Two 15-inch laterals enter this manhole, but do not appear to be very active. The upstream manhole has an active drop lateral, and flow in the downstream manhole is very turbulent. In both instances, these factors could have contributed to release of hydrogen sulfide gas and an increased corrosion rate. The pH of the pipe surface at this manhole was approximately 6. There is no apparent indication of current or ongoing corrosion.

The other three manholes observed in Fort Worth are approximately 30 years old. Even though these locations had lower pH levels of 4 to 5, corrosion is not as severe as at the other two locations. Drop laterals were not observed at or near these three locations.

2.2.6 Seattle, Washington

The Municipality of Metropolitan Seattle (Metro) maintains approximately 247 miles of sewer which transport 186 mgd of wastewater to Metro's treatment facilities. Metro has had a hydrogen sulfide odor problem for many years. A large number of its concrete sewers and sewage structures have experienced extensive corrosion damage. The most serious identified cases of hydrogen sulfide corrosion have been replaced or repaired by coatings or liners.

Construction of Metro's interceptor facilities began in 1963; corrosion is widespread in this relatively new system. Local municipalities provide smaller-diameter sewage collection systems which were not investigated during this study. The Seattle area is heavily industrialized, and industrial flow represents about 25 percent of the total flow; however, industrial discharges have not been correlated with sulfide generation or concrete corrosion. Areas served by Metro to the east and north of Lake Washington have separate sewer systems for stormwater transport. Areas to the west of Lake Washington are served predominantly by a combined sanitary-stormwater sewer system.

Metro has an extensive sulfide monitoring program, and has had full-time staff working on the problem since early 1987. Metro personnel look for hydrogen sulfide damage as part of sewer inspections during which headspace hydrogen sulfide concentrations and pipe surface pH levels are also measured. Hydrogen sulfide concentrations from 0.1 to over 50 ppm have been found along with pH readings as low as 2. Metro's records indicate lower pH readings occur at sites with higher hydrogen sulfide gas concentrations.

Metro has tried various concrete liners and coatings in pipes and on structures to control corrosion as well as chemical addition to control sulfide. Sliplining, epoxy, polyethylene (PE), PVC, UPC (a polyurethane polyethylene copolymer), Ameron lining, polyurethane (Sancon), C.T.E. coating, and Aquatapoxy all are being or have been tested by Metro since 1974. Both satisfactory and unsatisfactory performances have been observed. For example, the PE liner on the East Bay Interceptor - Section 8 is in good shape and is protecting the concrete behind it, but the UPC coating on the Lake Sammanish Interceptor failed and is peeling off. Hydrogen peroxide addition to control sulfide was tried but abandoned for monetary reasons. However, Metro did find that once a large shock dose of peroxide was added, subsequent dosages could be reduced to control sulfide.

Metro has been involved in other activities related to hydrogen sulfide corrosion control. Power cleaning of sewers, use of sacrificial concrete in its sewers, and sonar, radar and ultrasonic measurement of pipe wall thickness have been tried. Metro has also tried to monitor corrosion rate with concrete coupons and copper shavings hanging in pipes; but found reactions too slow to provide useful data. In addition, the Renton Treatment Plant has a $5,000,000 odor-control system employing scrubbers, activated carbon, impregnated carbon, and chlorine addition. A facilities plan study by a consultant included sulfide-control recommendations. Concrete corrosion at Metro's treatment plants is not a problem.

Seattle Metro personnel recommended five sites for observation. The sites are widely distributed throughout the system and in parts of different subsystems. Three sites are directly downstream of force main discharges: a manhole at East Marginal Way and South 112th Street, downstream of the Renton sludge force main; a manhole near 15th Avenue W and W Raye streets, downstream of the Interbay Pump Station force main; and the Hollywood Pump Station discharge structure. One of the remaining sites, a manhole at 15th Avenue NW and 188th Street NW, is a few blocks downstream from a force main. The fifth site, a manhole on the Lake Sammanish Interceptor at NE Union Hill and Avondale roads, is not downstream of a force main.

Concrete pipe downstream of both the Renton and the Interbay force main discharges has experienced severe corrosion. Corrosion appears to have penetrated the second layer of aggregate (1-inch loss) leaving only a short distance to reinforcing steel in the pipe downstream of the Renton force main. The surface pH averaged 1.8. The sewer downstream of the Interbay force main carries combined flow and occasionally surcharges. The 21-year-old sewer pipe was PVC-lined in 1978 for about 200 feet downstream of the Interbay force main; however, severe corrosion begins where the liner ends. Assuming that the corrosion all occurred in the seven years following the lining, the corrosion rate at the Interbay site is over 0.2 inches per year. Rust spots are visible on the unlined concrete pipe wall, indicating that reinforcing steel will likely be exposed soon. One and one-half inch is estimated to be missing. Measurements of surface pH average 1.3 at Interbay.

Exposed aggregate and corrosion were observed around the flap gates at the Hollywood Pump Station discharge and on concrete not protected by a PVC lining. However, most of this structure is PVC-lined. The exposed portions are probably exposed to erosional forces when the pumps discharge.

The manhole at Union Hill and Avondale roads showed shallow corrosion, zero to 0.50 inches deep, and had a surface pH of 3. The inlet and outlet pipes to this manhole were in good condition, even though the UPC lining was in poor condition. The site at 15th Avenue and 188th Street NW also showed only shallow corrosion, which was limited to the outlet pipe. This sewer carries combined sanitary-stormwater flows. The surface pH level averaged 1.2 at this site. A wastewater total sulfide concentration of 0.6 mg/l was measured at the Union Hill Road site.

The frequent presence of force mains, required to overcome topographic barriers, appears to increase the hydrogen sulfide corrosion problem in Seattle. Seattle feels industrial metal bearing discharges have no correlation with corrosion, since that industry has always had pretreatment standards.

2.2.7 Charlotte, North Carolina

In the Charlotte-Mecklenburg Utility District (CMUD) system, EPA compared corrosion conditions in purely domestic sewers with conditions in sewers that carry industrial flow. Approximately 15 metal finishers and a large foundry are permitted for discharge into the CMUD sewer system. The field team entered six sewers with a large flow contribution from industry and four sewers with only domestic flow.

CMUD personnel were not aware of system-wide hydrogen sulfide corrosion problems, although a failure occurred in the Briar Creek sewer sometime prior to 1973. Since that time, CMUD has been specifying tricalcium phosphorus as an additive to its concrete pipe. CMUD also currently specifies a 1-inch sacrificial layer of concrete in its pipe. In the late 1960s, CMUD had an odor study done on the Briar Creek Sewer; it implemented a program of hydrogen peroxide addition for odor control in 1974. The hydrogen peroxide was added to a point about 3 miles upstream of the Sugar Creek Treatment Plant to which the Briar Creek sewer is tributary. This action was unrelated to the prior Briar Creek failure. Strong odors at the Sugar Creek treatment facility prompted another odor study in the late 1970s. The second study lead to the injection of hydrogen peroxide at a location 0.50 miles upstream in both 54-inch influent lines to the plant.

The Charlotte water supply is categorized as "soft" by CMUD and has a 8.0- to 9.0-ppm total sulfate concentration.

Two of the domestic sites (Davidson Street at East 22nd Street, and Myers Street at East 12th Street) are in the Sugar Creek drainage area and two (Arborway near Sedley Road, and Old Providence Road near Sharonview Road) are in the McAlpine Creek drainage area. The Sugar Creek sites are 7 and 6 miles from the treatment plant, and 5 and 6 miles from the upstream end of the same drainage area, respectively. The McAlpine Creek sites are 7 and 8 miles from the treatment plant, and 3 and 10 miles from the upstream end of their respective drainage areas. All pipe observed in the CMUD system is 20 to 25 years old. Wastewater sulfide concentrations at the four sites ranged from 0.2 to 0.6 mg/l. Wastewater pH measurements were 6 at three sites, and 5.5 at the Old Providence Road site. It was the only site in Charlotte with pipe and manhole surface pH measurements below 6. Pipe surface pH measurements were 4.5 to

5. Corrosion product extended about 0.25 inches deep, exposing "peastone" aggregate at this site.

Two of the four domestic sites experience turbulent flows due to a bend and an obstruction. Although the wastewater contained measurable concentrations of sulfide at each site (0.6 mg/l and 0.4 mg/l), there was no measurable headspace hydrogen sulfide. The Old Providence Road site has a 42-inch pipe and was flowing half full at about 2 fps when observed. The three clean pipes ranged in size from 24 to 54 inches in diameter.

Three of the industrial sewers (Clanton Road at the Irwin Creek Bridge, Remount Road at the municipal park, and Freedom Drive at Thrift Road) are in the Irwin Creek drainage area, 1 to 6 miles from the treatment plant, and 5 to 10 miles from the upstream end of the same drainage area. Two of the industrial sewers (Old Nations Ford Road near Ervin Lane, and Granite Street near Continental Boulevard) are located in the McAlpine Creek drainage area. The remaining industrial site is located next to Park Road near Moncure Drive in the Sugar Creek drainage area. The McAlpine Creek sites are located approximately 10 and 7 miles, respectively, from the farthest upstream points in their drainage areas. The Granite Street site is about 1 mile downstream of a 12,000-foot, 24-inch-diameter force main; the wastewater pH was 5.5 at this site. The Park Road site is located about 7 miles from the farthest upstream point in its drainage area.

Two of the six industrial sites showed signs of very shallow hydrogen sulfide corrosion. The Remount Road site had lost just enough concrete to expose aggregate and also had turbulent flow. The Granite site had turbulent flow and an observed velocity of approximately 10 fps. This site also had four consecutive drop manholes upstream. Pipe wall and manhole surface pH measurements were pH 6, and some corrosion product was observed. Wastewater pH measurements were 6 at four of the industrial sites, 5.5 at one site, and 10 at the remaining site. Wastewater sulfide ranged from 0.0 to 0.3 mg/l. The wastewater sulfide level was 0.05 mg/l at the site where wastewater pH was 5.5, and 0.0 mg/l at the site where wastewater pH was 10. There was no measurable headspace hydrogen sulfide gas at any of the six industrial sites.

Pipe diameter at the industrial sites ranges from 21 to 54 inches, and all pipes are approximately 20 years old. The observed flows range from one-third to two-thirds full, from smooth to extremely turbulent, with velocities typically 2 to 4 fps.

2.2.8 Milwaukee, Wisconsin

The Milwaukee Metropolitan Sewerage District (MMSD) maintains approximately 305 miles of sewer and two treatment facilities which serve approximately one million people in the Milwaukee area. The average daily wastewater flow is 190 mgd, of which industrial flows represent over 25 percent. MMSD estimates that 15 percent of the area served by its system contributes storm flow. Wet weather flows at both treatment plants double dry weather flows. The average biochemical oxygen demand (BOD) is 200 mg/l, and total suspended solids (TSS) is 250 mg/l at the two plants.

In the MMSD system, EPA compared corrosion conditions in purely domestic sewers to conditions in sewers that carry industrial flow. Approximately 90 electroplaters and metal finishers and about 15 tanneries are permitted for discharge into the MMSD sewer under its pretreatment program. Some of the permitted tanneries have waivers to discharge wastewater without pretreatment for sulfide, making data obtained from the MMSD system particularly pertinent to this study. Observations covered five sewers with only residential flow and five sewers with a heavy industrial contribution to the flow.

MMSD personnel were not aware of any hydrogen sulfide corrosion problems. The District recently inspected (by television) 20 percent of its large-diameter pipe. Annually, it inspects an additional 40,000 feet. MMSD also manually inspects manholes and sewers during a standard manhole step replacement program and a seasonal manhole cleaning program. MMSD has some odor problems; however, these are located in parts of the system where the odors do not generate public complaints.

Three of the residential sites are in the northern part of the service area, 4 to 6 miles from the Jones Island Treatment Plant, and 3 to 5 miles from the upstream end of the system. Pipe ages at these sites range from 50 to 70 years old. None of the three sites revealed any wastewater sulfide. Wastewater pHs were all 6.5, and pipe and manhole surface pHs were all 6.5. (According to carbonate chemistry, one would expect weathered concrete to be about pH 6.3.) No corrosion or signs of corrosion of pipe or manhole concrete were observed at these sites, even though one site is a junction structure and another site is located just downstream of a pump station. In both cases, these locations often experience turbulent flow and potential release of hydrogen sulfide gas.

The other two residential sites, located in the South Shore Treatment Plant basins, are 8 to 10 miles from the treatment plant, and 3 to 5 miles from the upstream end of the basin. The first site is less than 20 years old, and the second site, Kinnickinnic, is 50 years old. Observations at the 20-year-old site were similar to those at the first three residential sites. However, a wastewater sulfide content of 0.5 mg/l was found at the Kinnickinnic site and pH of 3.5 was measured on the crown of the downstream pipe. Kinnickinnic had severe corrosion from the water line up the pipe about 1 foot. Up to 1 inch of concrete appeared lost as estimated by aggregate exposure in this 36-inch-diameter pipe. A black slime growth was observed from 1 inch above the normal water line to 2 inches below.

Five sites had large amounts of industrial flow. Three sites are about 2 to 3 miles north of the Jones Island Treatment Plant and two are immediately upstream of the plant. All five sites are at least six miles from the upstream end of the system and are at least 40 years old. Corrosion was not observed at any of these sites.

Two of the industrial sites had measurable sulfide in the wastewater: 0.18 and 0.40 mg/l. Wastewater pH ranged between 6.5 and 7.5. Pipe and manhole surface pH measurements ranged between 6.0 and 7.0. One of the industrial sites was located less than 0.5 miles downstream from a tannery. Two sites had initial hydrogen sulfide gas concentrations of between 0.5 and 0.6 ppm in the pipe headspace. One site located in the downtown industrial area could not be entered because of a photoionization meter reading of greater than 1,000 ppm. Two sites had abrupt changes in direction 20 to 30 feet upstream from the manhole and 6 to 8 inches of bottom debris. Typical at these sites was a grease buildup on pipe and manhole walls, calcium buildup, and slime, but solid concrete pipe underneath.

2.3 Site Visits to Assess Hydrogen Sulfide Corrosion at Wastewater Treatment Plants and Pump Stations

Site investigations were conducted at five wastewater treatment plants in three cities. The purpose of these investigations was to document the location, nature and severity of hydrogen sulfide corrosion problems at these facilities. The wastewater treatment plants included the Hookers Point facility in Tampa, FL, the East Bank and West Bank plants in New Orleans, LA, and the Hyperion and Terminal Island plants in Los Angeles, CA. Pump station corrosion was also investigated as part of these site visits.

The type and extent of information available from the various cities varied widely. Some cities closely monitored hydrogen sulfide levels in the wastewater and in the atmosphere, and maintained detailed records of corrosion repair and rehabilitation efforts. Others had done little to monitor or control corrosion.

The following provides a summary of the information collected from the site visits to cities where corrosion was believed to be a problem in the wastewater treatment plant and pump stations.

2.3.1 Tampa, Florida

2.3.1.1 Wastewater Treatment Plant

The Hooker's Point Advanced Wastewater Treatment Plant was expanded in 1978 to handle a design flow of 60 mgd. The plant is averaging approximately 57 mgd, and employs advanced waste treatment (AWT) for biological nitrogen removal. Unit processes at the plant include influent screens and grit chambers, primary clarification, two stage activated sludge treatment, secondary clarification, denitrifying filtration, chlorination and dechlorination. The plant achieves nitrification/denitrification before it discharges to Tampa Bay. Sludge handling processes are varied, and consist of gravity, dissolved air flotation, or belt filter thickening of waste activated sludge, anaerobic or aerobic digestion, and belt press or drying bed dewatering. A new sludge dryer and pelletizer will come on-line in the fall of 1990.

Hydrogen sulfide corrosion at the wastewater treatment plant is very severe. The walls of the influent junction box were constructed with a corrosion-resistant plastic liner. H_2S corrosion is also severe in the screen and grit building and in the effluent chamber in the grit building. Dissolved sulfide is approximately 10 mg/l in the influent wastewater. Concrete on the roof of the junction box had also corroded to an extent that the aggregate was exposed. All mechanical equipment showed mild to severe corrosion. Hand rails, platform, and other structures at the primary clarifiers were corroded.

The plant expends significant resources to combat hydrogen sulfide corrosion. All carbon steel parts have been replaced by stainless steel parts wherever possible. Electrical components have been covered and electrical sockets replaced using plastic materials. A very rigorous painting schedule is maintained on all equipment and parts at the junction chamber. H_2S levels in the atmosphere of the screen and grit building are as high as 20 ppm. A fine-mist scrubber was installed to treat the H_2S-laden air emissions from the junction box. Although designed to handle 50 ppm of H_2S, levels entering the scrubber range from 400 to over 1000 ppm. The capital cost of the scrubber system was approximately $1,000,000. Annual operating cost is estimated to be $400,000/yr.

The primary clarifiers at the wastewater treatment plant are also at an advanced stage of corrosion. Some clarifiers are 40 years old and the others were built during the expansion. There is little corrosion at the influent end of the clarifiers but severe corrosion at the effluent end. The wastewater has a fall of four feet in the effluent channel thereby creating turbulence and releasing H_2S to the atmosphere with the result that the concrete structure at the effluent channel is severely corroded.

Most of the moving parts on the clarifiers have been replaced by plastic, including the scraper mechanism. Gear motors and electrical/mechanical components are covered with corrosive-resistant materials. Approximately 2 to 4 inches of the side walls at the effluent channel in the primary clarifiers have been lost due to corrosion. At some locations, reinforcing steel was visible. The rehabilitation of the clarifiers is now under contract and includes the installation of a plastic liner on the walls. Hydrogen sulfide corrosion downstream of the clarifiers is very limited. There is very little hydrogen sulfide corrosion found at other treatment processes and sludge handling facilities.

Hydrogen sulfide corrosion of instrumentation and controls at the wastewater treatment plant was severe at the transformer cabinets. All copper tubing and wiring corrodes rapidly. Corrosion of electrical contacts was widely observed. Switchgear at the influent junction chamber also corrodes rapidly. Corrosion prevention measures for instrumentation and control equipment includes covering the instruments, purging with clean air, and air conditioning control rooms. All electrical equipment at the plant is on a preventative maintenance and painting schedule. Contacts and relays are cleaned regularly. Transformer housings must be replaced periodically.

Although corrosion of sludge handling components and structures has been a problem in the past, such problems have largely been eliminated through gradual replacement with corrosion resistant materials such as galvanized and stainless steel. Spare parts are stored in an air-conditioned warehouse to prevent corrosion. Minor corrosion problems are still evident where components such as conduit fittings are not available in corrosion resistant materials.

2.3.1.2 Lift Stations

There are 160 lift stations in the sewer system that collect and transport wastewater to the treatment plant. The more recent pump lift stations are built of concrete.

Medium to very high rate corrosion was found at many of the lift stations. Most of the manholes, wet wells and interior control room walls in lift stations have sulfur (yellow) deposits. There was severe corrosion near turbulent areas of the lift stations. The concrete was corroded and reinforcing steel was visible. Most of the lift stations have mild to severe corrosion present. Steel sound enclosures over wet wells had to be replaced by fiberglass buildings. Most of the larger pump stations have fine-mist scrubber systems. The City tried a hydrogen peroxide dosing system, but it was judged to be too expensive to operate. A few lift stations have used a ferrous sulfate dosing system to control H_2S. The City also tried packed tower air scrubbers. They were very high in maintenance. Carbon adsorption systems were also installed on some lift stations.

Corrosion of instrumentation and control systems at the lift stations was not quite as severe as at the plant. This was primarily due to the active preventative maintenance program imposed by the City. Copper tubing and exposed wiring were seen to be corroded. All motor control centers and electrical equipment were covered.

2.3.2 New Orleans, Louisiana

2.3.2.1 Wastewater Treatment Plants

The East Bank and West Bank wastewater treatment plants of the City of New Orleans were visited to document the extent of hydrogen sulfide corrosion at the facilities. The East Bank plant treats the sanitary flows from downtown and the northeast part of the City. The plant was originally built in 1963 for primary treatment and was later expanded for secondary treatment in 1980. The original design flow at the plant was 30 mgd but the facility has been expanded to handle 122 mgd. A total of 1500 miles of collection system comprised of gravity and force mains collect and convey sewage to the plant. The treatment plant consist of screens and grit removal, pure oxygen activated sludge system and secondary settling. Effluent is discharged to the Mississippi River. Secondary sludge is dewatered and then incinerated. The ash, along with screenings and grit, are disposed of in a sanitary landfill.

Plant headworks at the East Bank plant had severe corrosion in the screen and grit basins. Some parts of the grit basins were built in 1963 and were then expanded to meet the new design flows. Three force mains feed wastewater to these grit basins. One force main conveying flows from the City has long detention times, and hence the wastewater is very septic when it reaches the plant. The color of the wastewater was very dark (black) and was deficient in D.O.

The side walls of the grit chamber were severely corroded. Approximately 1 to 1½ inches of concrete was corroded away at some locations. Severe corrosion was also observed at the effluent end of the grit box where the wastewater spills into a channel which led it to the pure oxygen activated sludge tanks. The grit chambers were installed with screens on each pass. These screens were in a deteriorated condition. Many of the components of the screens had rusted and the metal frames on which they were attached were corroded along with the concrete below the frames.

Corrosion of instrumentation and controls was found to be severe at the East Bank plant. Contacts on electrical equipment were oxidized. The plant personnel replace small items and clean contacts and equipment on an annual basis. They sometimes must take equipment off-line for service and maintenance. As preventative maintenance, they use a light coating of oil, and cabinets purged with cleaned air. The plant has entered into an annual preventative maintenance contract. They allocate two men 1 to 1-1/2 days/wk for electrical equipment maintenance. The electrical contacts on indicator lights, pump relays, and contacts operate intermittently because of oxidation problems at the contacts. The instrument control room is fully air conditioned. Air cleaning is done through permanganate beads which are replaced every month. The plant expends significant effort for replacement and maintenance of the electrical and instrumentation components.

The plant does not have any control measures to prevent future corrosion. No efforts have been made to rehabilitate the corroded structures. The plant has a limited budget and does not plan to employ rehabilitation of structures as a corrective action until there is a failure.

The West Bank plant serves the population of the western side of the City of

New Orleans. The plant was originally built in 1971 for a design maximum flow of 15 mgd. The average dry weather flow (ADF) to the plant is approximately 7 to 8 mgd. The plant is now under design for expansion to 40 mgd. The treatment plant consists of influent bar screens, grit removal, primary sedimentation, high rate trickling filters, secondary sedimentation, chlorine contact and final discharge to the river. The sludge from the clarifiers goes to a thickener and a vacuum filter and is then incinerated. The ash from the incinerator is disposed of in a local landfill.

The West Bank plant also has severe corrosion at the influent head box where the screens and grit chamber are located. Corrosion has degraded the sidewalls on the grit chamber to a depth of 1 to 1½ inches. Again, corrosion was found to be severe at areas of high turbulence i.e. at the influent and effluent end of the grit basins. The metal grating and handrails on the grit basins were also corroded. The wastewater entering the plant was septic and the dissolved oxygen was always found to be 0 mg/l except during heavy rainfalls when the D.O. would increase to 0.2 mg/l. As the plant is located adjacent to a golf course, there are plans to cover the plant headworks, the sludge thickener and some other tanks to control odor emissions.

There are no efforts being taken to rehabilitate the degraded structures. No rehabilitative techniques have been employed to correct the odor and corrosion problems.

The vacuum filters at the West Bank Plant are located in a building that is equipped with a passive air ventilation system. The mechanical and support parts of the vacuum filters are in a severely corroded state. The plant had to replace grating over the filter supports. When the filters are operating, high H_2S levels are reported in the building. There is no corrosion reported at other parts of the plant. Corrosion at instrumentation and controls is minimal. Corrective action at this plant is based primarily on minimizing odors which are affecting the neighboring golf course.

2.3.2.2 Lift Stations and Collection Systems

There are a total of 87 lift stations and 1500 miles of sewers that serve both the East and West Bank Treatment Plants in the City of New Orleans. The lift station wet wells are made of brick and concrete. Force mains range in size from 42 to 52 inches and are constructed of cast iron, steel or concrete. Ninety to 95 percent of the collection system is 8 to 10 inch diameter pipes. Concrete pipes were laid in late 1930's. There are a few older pipes made of clay. Since the 1970's, plastic pipe has been used where possible.

All of the 87 lift stations employed in the collection systems for the East Bank and West Bank plants are in some stage of corrosion. The older lift station wet wells were built of brick and are severely deteriorated. The pump base and supports have corroded and at some places are on the verge of falling down into the wet well.

Rehabilitation of brick wet wells consists of coating by gunite. The New Orleans Sewage Board experimented with pump cycle times to minimize detention times and decrease H_2S levels. Continuous ventilation is provided in the lift stations at six air changes per hour. At some places the Board has tried adding ferric chloride but found that it forms clinkers in the incinerator at the plant. H_2S levels in the atmosphere of the wet wells average approximately 100 ppm. The Board spends around $5.2 million per year for lift station maintenance. About 30 percent of total man hours is utilized for lift station maintenance. Electrical and instrumentation equipment have minor corrosion problems. New electrical equipment has been installed with clean air supplied by treatment through potassium permanganate. There is reported to be more corrosion in lift station wet wells at the east side of town.

2.3.3 City of Los Angeles

2.3.3.1 Hyperion Wastewater Treatment Plant

The plant is designed for 400 mgd through primary treatment and 150 mgd through secondary treatment. Present day flows are 370 mgd and 200 mgd, respectively. The ability of the secondary process to handle the additional flow is attributed to the addition of fine bubble diffusers. The headworks, primaries, secondaries and anaerobic digesters are approximately 40 years old. Regulations eliminating ocean sludge disposal and requiring full secondary treatment, along with population growth, have resulted in 10 years of construction at the plant. The City foresees at least another 5 to 10 years at the same pace. The latter includes replacement of the existing secondary process with a pure oxygen process.

With the exception of the gravity degritter in the east headworks, all trash and grit removal tankage are under cover, making direct observation of corrosion on these processes difficult without considerable expenditure of staff manpower. The covers on the west aerated grit chamber effluent channel were small enough to be managed by one person and were lifted for observation. Corrosion of the concrete sewer at those points was observed to be severe, with penetration to at least 12 inches at the water line diminishing to 1 to 2 inches in the closed channel and 0 to 1 inch at ground level of the open tank. The plant carpentry superintendent in charge of all in-house concrete repair indicated the observed areas were typical of all headworks tankage of the same age. The cost of these repairs are not segregated from general plant maintenance costs.

The extent of corrosion below the water line in both tanks and channels was described as minor (less than 1 inch) even in the oldest tankage. All covers (tank and channel) and deck plates are made of aluminum, as were handrails, conduit and other hardware (some stainless steel). No corrosion of these materials was apparent.

The headworks processes are all contained in buildings. The ambient atmosphere of the buildings is swept by fans and discharged to a collection point at the suction of the secondary process blowers. Thus a slight negative pressure is maintained in each building. This prevents noxious odors from escaping the plant and with normal infiltration plus some outside air intakes, avoids the build up of corrosive gases in the atmosphere of the process buildings. All windows in the aerated grit chamber building were sealed in order to reduce escape of hydrogen sulfide, even though the tanks are covered. The few pieces of carbon and galvanized steel found in the buildings were severely corroded. This was especially true of steel doors. No maintenance program is in force for the doors other than repainting when scratched or chipped. The ambient air removal system piping is fiberglass and most other piping is PVC. Conduit is aluminum or PVC.

A short section of the force main entering the plant collapsed and was replaced in 1987. The collapse was attributed to corrosion-weakened concrete pipe combined with the ground vibration caused by heavy construction equipment.

The decision to rehabilitate or replace all or part of the headworks has yet to be made. There is obvious structural damage in some places and some doubt in the mind of staff as to the structural integrity of a rehabilitation effort given the frequency of earthquakes in the area. In either case, PVC liners with concrete slabs will be used in all channels and the inside of all tankage will be at least coated with coal tar or an alternative coating material.

The primary clarifiers are covered with concrete slabs so casual inspection was not possible. The influent and effluent channels are covered by aluminum plates which can be easily removed for inspection. Like the headworks, concrete exhibited deep corrosion penetration from the water line to the surface, with some of the deepest penetration (6 to 8 inches) at the surface adjacent to the channel covers. Most of the corrosion at the top has been repaired by cutting back to good concrete, reforming to the original geometry and grouting. These repairs are recent, and are not covered by any protective coating. An epoxy-type coating had been applied to the early patches and began peeling almost immediately, so coating was discontinued. The channels will be covered with PVC liners. The type of coating for the inside of tank walls and covers is as yet undetermined. They are in the process of converting from steel to plastic chain and from wood to fiber glass boards for the sludge rakes. The existing primaries will be rehabilitated once new primary construction is complete.

With the exception of anaerobic digestion, the sludge handling processes came on-line in 1985-1986. Ocean disposal of sludge ceased in 1987, and digested sludge is now either dried and applied to power generation (Carver-Greenfield process) or dewatered by centrifuges and transported to a Yuma, AZ land application site. Due to safety regulations for construction at the site, the sludge handling facility was off-limits to visitors. The addition of ferrous chloride (280 mg/l) for hydrogen sulfide reduction after sludge digestion is to control sulfur emissions as opposed to corrosion control.

All instrumentation and control electronic equipment is conformably coated (a thin lacquer-like coating applied to circuit boards and components to seal them from the atmosphere) in the manufacturing process. This is standard practice in the industry for wastewater treatment equipment suppliers. In addition, all field mounted instrumentation (sensors, transmitters, etc.) are nitrogen purged. The case of each instrument is connected to a low pressure nitrogen supply which maintains a slight positive pressure in the instrument housing to prevent exposure of the components to ambient air. Inspection of the equipment disclosed no sign of corrosion. All circuit boards, contacts, wire terminations and other exposed metal was bright and shiny. The annual cost of nitrogen is estimated at less than $3,000. The only sensing elements immersed in liquid process streams are DO probes. These are newly installed and as yet have no track record. The control room is isolated from ambient atmosphere by scrubbing, filtering, and air conditioning. No problems were reported or apparent with these systems.

Although not as severe, there is ample evidence of concrete corrosion in secondary treatment. The worst is at the aeration basin influent mixing channel where corrosion has penetrated to the reinforcing steel (2 inches). Other areas of the reactors have exposed aggregate. Steel hand rails and steel plate on the side of the reactors are pitted and rusted where chipped or peeled paint allowed exposure to atmosphere.

Since a new oxygen activated sludge system is planned, only those repairs necessary for the existing system to remain operational will be made.

The scavenged air recovered from buildings and below tank covers is ducted to the aeration basin blowers for scrubbing in the activated sludge mixed liquor. This air is not cleaned by other than conventional blower inlet air filters, nor are the blowers constructed of special corrosion resistant materials. This has not caused any additional blower maintenance or reduced the useful life of the blowers. The only impact is on the carbon steel linkage that moves the internal guide vanes and this impact is considered minor by the maintenance staff.

2.3.3.2 Terminal Island Wastewater Treatment Plant

The original plant was constructed in 1935 and completely rehabilitated in 1977. The plant is designed for full secondary treatment of 30 mgd. Present day dry weather diurnal flow ranges were modified from 5 to 35 mgd, a 7:1 ratio, to 10 to 30 mgd, a 3:1 ratio, by requiring (as part of pretreatment enforcement) local industries to shift discharges to off-peak hours. Over 50 percent of the flow and 70 percent of the load is of industrial origin.

With the exception of the bar screen, all trash and grit removal tankage is under cover, making direct observation of corrosion on these processes difficult without considerable expenditure of staff manpower. Corrosion of the concrete at the bar screens was negligible at those points observed, with penetration barely to the aggregate at the water line. The extent of corrosion below the water line in both tanks and channels was described as minor (less than 1 inch) in the oldest tankage. All covers (tank and channel) and deck plates are made of aluminum, as were handrails, conduit and other hardware (some stainless steel). No corrosion of this material was apparent. The bar screen frame and sheet metal is of coated (coal tar) carbon steel, which was severely corroded. Most of the sheet metal has been replaced with sheet PVC. The frame (¼ inch angle iron) will probably be replaced with stainless steel.

The headworks processes are all contained in buildings. The ambient atmosphere of the buildings is collected by the suction of the secondary process blowers (no fans). Thus a slight negative pressure is maintained in each building. This prevents noxious odors from escaping the plant and with normal infiltration plus some outside air intakes, avoids the build up of corrosive gasses in the atmosphere of the process buildings. The few pieces of carbon steel found in the buildings were severely corroded including galvanized steel hardware. This was especially true of steel doors. No maintenance program is in force for the doors other than repainting when scratched or chipped.

The ambient air removal system piping is fiberglass and most other piping is PVC. Conduit is aluminum or PVC.

The primary clarifiers are fitted with aluminum covers. The influent and effluent channels are also covered by aluminum plates which can be easily removed for inspection. Plant staff had previously converted from steel to plastic chain and from wood to fiberglass boards for the sludge rakes. Because of problems with the plastic chain jumping the sprockets, they are converting back to steel chain.

The egg shaped anaerobic digesters appear to be in good condition externally. An external pipe that collects gas for mixing has been replaced with a welded stainless steel pipe. The sacrificial anodes are replaced routinely as part of the maintenance program. The motorized valves located on top of the digesters are also being replaced, but this is because they do not have weather proof housings, although the problem may have been exacerbated by hydrogen sulfide. The earth ground bonding wire (bare copper) in this location has almost turned to dust and is being replaced with an insulated wire. This location is also exposed to winds from the sea, and the corrosion observed may be the result of salt air. The elevator at this location is a high maintenance item, since it is exposed to both sea air and ambient hydrogen sulfide.

The addition of ferrous chloride (450 mg/l) for hydrogen sulfide reduction (10 fold) after sludge digestion is to control sulfur emissions as opposed to corrosion control.

All instrumentation and control electronic equipment is conformably coated. In addition, all field mounted instrumentation (sensors, transmitters, etc.) are nitrogen purged. The case of each instrument is connected to a low pressure in the instrument housing to prevent exposure of the components to ambient air. Inspection of the equipment disclosed no sign of corrosion. All circuit boards, contacts, wire terminations and other exposed metal was bright and shiny. The annual cost of nitrogen is estimated at less than $2,000. The only sensing elements immersed in liquid process streams are DO probes. These are relatively new yet have performed well to date. The control room is isolated from ambient atmosphere by scrubbing, filtering, and air conditioning. No problems were reported or apparent with this system.

The scavenged air recovered from buildings and below tank covers is ducted to the aeration basin blowers for scrubbing in the activated sludge mixed liquor. This air is not cleaned by other than conventional blower inlet air filters, nor are the blowers constructed of special corrosion resistant materials. This has not caused any additional blower maintenance or reduced the useful life of the blowers. The only impact is on the carbon steel linkage that moves the internal vanes and this impact is considered minor by the maintenance staff.

2.4 Site Visits to Investigate Corrosion Mechanism

Although many authors have discussed the role of the sulfate-reducing bacteria and sulfur-oxidizing bacteria in hydrogen sulfide corrosion, little is known about these organisms or the factors that may promote or inhibit their growth. To confirm existing theories concerning hydrogen sulfide corrosion, gain additional insight into the mechanisms of corrosion, and lay a foundation for future work, a multidisciplinary field team was assembled to make observations and collect samples for microbiological, physical, and chemical analysis from locations in the CSDLAC system and the Metropolitan Seattle system. The field team included microbiologists who had studied sulfate-reducing bacteria, sulfur-oxidizing bacteria, and microbiologically-induced corrosion, and a structural consultant who had studied corrosion of concrete.

The field program for this work segment involved collecting samples from three locations in each of the two sewer systems. Two of the sites in each system were locations where corrosion was well established and ongoing. A third site in each system where corrosion had not been observed was selected as a control site. Samples of surface deposits were collected from the crown, sidewall, and waterline areas of the pipe at each location, as well as samples of the wastewater itself for microbial and chemical analysis. Samples of concrete were chipped from the crown and sidewall areas for chemical and physical analysis.

2.4.1 Results of Microbial Analysis

The microbial analyses showed that a large and complex microbiological community is present in the wastewater and on the structure walls and crown at the locations sampled. Very high levels of aerobes, anaerobes, acid-producing bacteria, and sulfate-reducing bacteria were found in most wastewater, sidewall, and submerged sidewall samples. Relatively large populations of sulfate-reducing bacteria were found in the bulk wastewater samples. However, CSDLAC slug dosing of caustic has been shown to suppress sulfide generation for 7 to 10 days after treatment, indicating that the slime layer is the predominant site for reduction of sulfate to sulfide (1).

The microbial community of the pipe crown region appears, particularly at corroded sites, to be significantly different. A much lower level of viable organisms, including aerobes, organic acid-producing bacteria, and sulfate-reducing bacteria was found in this region. It is possible that the low pH of corroding crown regions reduces the total level of viable organisms and selects for the organisms that do live there.

The microbial analyses showed, nonetheless, that samples from areas of crown corrosion in both the CSDLAC and Seattle systems contain large numbers of acidophilic, sulfur-oxidizing bacteria of the genus Thiobacillus, and probably the species thiooxidans. Samples from crown areas in the CSDLAC system where reinforcing steel was exposed also showed the presence of T. ferrooxidans, an iron- and sulfur-oxidizing bacterium. Samples from the location in the CSDLAC system where wastewater was being treated with ferrous chloride to control hydrogen sulfide showed fewer T. ferrooxidans and acidophilic sulfur oxidizers in the crown area than in the corroded location being slug dosed with NaOH.

Large numbers of sulfur-oxidizing organisms that grow at neutral pH were also found in all samples, including the wastewater. The wastewater could continuously inoculate these organisms on the concrete surface. These organisms can oxidize sulfur and produce sulfuric acid, which would lower the pH of the concrete surface. Lowering the pH would allow more acidophilic organisms, (e.g., T. thiooxidans, which has a pH preference of 4.5 to 1.0) to grow. Additionally, large numbers of acid-tolerant fungi and yeasts were present in most samples. The role of these organisms in contributing to corrosion is not understood.

All the sites in Seattle appeared to have similar microbial communities which included high levels of sulfate-reducing bacteria in the wastewater and in the surface-associated populations. More variety of species were observed in the Seattle sites, however. The sites which had high corrosion rates had very turbulent wastewater flows which could increase the out-gassing of hydrogen sulfide to the sewer headspace. This is supported by the fact that these sites had high levels of hydrogen sulfide in the sewer headspace.

At CSDLAC, there were major differences between the control site with low corrosion rate and those sites with high corrosion rates.

- The amount of moisture on the crown at the control site was low compared to the other sites.

- The levels of metals in the springline sample were higher at the control site than at the other sites.

- The average sewage age (the length of time the sewage is in the sewer system) was less at the control site than at the other sites.

- The levels of sulfate-reducing bacteria at the control site were 10,000 times lower than at the other sites.

The low level of moisture on the crown at the control site certainly would inhibit both growth of bacteria on the crown and the corrosion reaction. However, even if moisture was present, the corrosion rate would be low due to the low levels of sulfate-reducing bacteria and hydrogen sulfide. The temperature differences are not considered sufficient to affect the growth of sulfate-reducing bacteria and Thiobacilli. This leads to the conclusion that the low levels of sulfate-reducing bacteria and hydrogen sulfide production are responsible for the low rate of corrosion at the control site, and by implication that the high levels of sulfate-reducing bacteria at the other sites are responsible for the high rates of corrosion.

The results of microbial analysis support the accepted theory of hydrogen sulfide corrosion: production of hydrogen sulfide by bacteria in the wastewater and on the sewer wall, followed by oxidation of the hydrogen sulfide to sulfuric acid by bacteria on the sewer crown. However, unanswered questions remain concerning:

- The role of acidophilic heterotrophic organisms in the corrosion process.

- The minimum sulfide levels needed to sustain the growth of sulfur-oxidizing bacteria.

- Whether techniques could be developed to interrupt the microbial pathways of sulfide generation and sulfuric acid production.

2.4.2 Results of Physical Analyses

The samples of concrete collected in the CSDLAC and Seattle Metro sewer systems were evaluated using standard petrographic examination techniques and X-ray diffraction techniques. In addition, chloride ion content was determined on selected samples.

Petrographic examination revealed the presence of corrosion at all six of the sampled sites, including the "control" sites. Corrosion at the control site in the CSDLAC system was shallow (0.04 to 0.08 inches) and the high surface pH values measured at this site, as well as observations, indicate that this corrosion may have occurred in the past. At the remaining five sites, petrographic examination and X-ray diffraction analysis of samples collected above the waterline showed gypsum deposits covering a zone of deterioration extending up to 0.5 inches beneath the concrete surface. Within this zone, the normally crystalline concrete paste showed reduced levels of crystallinity and an increasingly amorphous nature depending on the extent of deterioration. This concrete was soft in comparison to non-deteriorated concrete. Microcracks in the concrete (typical of most concrete) were usually lined with gypsum and, in some instances, ettringite also. Below the waterline, the concrete samples were sound. These conditions are considered typical of classical hydrogen sulfide corrosion of concrete.

Determination of chloride ion levels in the concrete samples indicated that, with the exception of one location in Seattle, chloride levels in the concrete of the original pipe were below the threshold needed to initiate chloride-induced electrochemical corrosion of reinforcing steel.

The observations at the two control sites point out the difficulty involved in field assessment of the presence and extent of corrosion. The concrete surface at both control sites looked smooth and in good condition, and the pipe wall at both sites produced a sharp ringing sound indicative of sound concrete when struck with a rock hammer. However, the surface pH at the CSDLAC site was 4.0, and laboratory examination of samples revealed that shallow corrosion had occurred, perhaps in the past. At the Seattle Metro control site, surface pH levels were between 1.0 and 2.0, and laboratory examination indicated that corrosion had penetrated up to 0.25 inches into the concrete.

2.5 Other Cities Reporting Hydrogen Sulfide Corrosion

Information was analyzed from surveys conducted by the County Sanitation Districts of Los Angeles County (CSDLAC), Association of Metropolitan Sewerage Agencies (AMSA), and the Water Pollution Control Federation (WPCF). Results of the CSDLAC survey are summarized in Table 2-2. Of the 89 cities responding to this survey, 32 cities (36%) reported sewer collapses. Twenty-six cities experienced collapses that were believed to be due to hydrogen sulfide corrosion. Thirty cities (34%) reported taking measures to control sulfide generation in sewers. Fifty-six cities (63%) had taken steps to protect pipe from corrosion, or had rehabilitated pipe damaged by corrosion.

The AMSA survey asked if the municipalities experienced hydrogen sulfide corrosion at the treatment plant. Almost 70 percent of the 61 respondents responded positively. In addition, 34 percent of the respondents indicated that they were currently employing techniques to control sulfide generation. Results of the AMSA survey are summarized in Table 2-3.

TABLE 2-2

SUMMARY OF CSDLAC SURVEY DATA

City	State	Sewer Collapse	Sulfide Control	Corrosion Protection/ Rehab.
Birmingham	AL	X	X	
Phoenix	AZ		X	X
Tucson	AZ		X	
Little Rock	AR			X
Pine Bluff	AR	X		X
Carlsbad	CA		X	X
Cucamonga	CA			X
Orange County	CA	X	X	X
Whittier	CA	X	X	X
Colorado Springs	CO			
Denver	CO		X	
Hartford	CT			
Washington	DC			
Fort Lauderdale	FL		X	
Jacksonville	FL	X		X
Miami	FL			X
Orlando	FL	X	X	X
Tampa	FL	X		X
Atlanta	GA	X		X
Honolulu	HI	X	X	X
Boise	ID			X
Chicago	IL			
Downers Grove	IL			
Elgin	IL			
Kankakee	IL			

TABLE 2-2 (cont.)

SUMMARY OF CSDLAC SURVEY DATA

City	State	Sewer Collapse	Sulfide Control	Corrosion Protection/ Rehab.
Rockford	IL			X
Springfield	IL	X		
Urbana	IL	X		
Wichita	KS			X
Louisville	KY		X	X
Jefferson Parish	LA		X	X
New Orleans	LA	X		X
Baltimore	MD			X
Glen Burnie	MD			
Hyattsville	MD	X		X
Boston	MA	X		X
Salem	MA			X
Detroit	MI			X
Kalamazoo	MI			
Duluth	MN			X
St. Paul	MN	X		X
Kansas City	MO			X
St. Louis	MO	X	X	X
Omaha	NE	X	X	X
Bayville	NJ		X	X
Elizabeth	NJ			
Little Ferry	NJ		X	X
Newark	NJ			X
Sayreville	NJ			X

TABLE 2-2 (cont.)

SUMMARY OF CSDLAC SURVEY DATA

City	State	Sewer Collapse	Sulfide Control	Corrosion Protection/ Rehab.
Albuquerque	NM	X	X	X
Las Cruces	NM			X
Albany	NY			
Buffalo	NY			
New York City	NY			
Mineola	NY	X	X	X
North Syracuse	NY	X		
Rochester	NY		X	
Greensboro	NC		X	X
Akron	OH			X
Cincinnati	OH			X
Cleveland	OH			
Columbus	OH	X		
Dayton	OH			
Toledo	OH			
Tulsa	OK			
Hillsboro	OR			X
Portland	OR			
Oregon City	OR			
Philadelphia	PA		X	X
Pittsburgh	PA			X
Providence	RI			
Chattanooga	TN	X		X
Knoxville	TN		X	X
Memphis	TN			X
Nashville	TN	X	X	X

TABLE 2-2 (cont.)

SUMMARY OF CSDLAC SURVEY DATA

City	State	Sewer Collapse	Sulfide Control	Corrosion Protection/ Rehab.
Arlington	TX	X		
Dallas	TX	X		X
El Paso	TX	X	X	X
Fort Worth	TX	X	X	X
Houston	TX	X		X
San Antonio	TX		X	X
Salt Lake City	UT			
Fairfax	VA		X	X
Virginia Beach	VA	X	X	
Seattle	WA	X	X	X
Tacoma	WA	X		X
Green Bay	WI			X
Madison	WI	X	X	X
Milwaukee	WI			

TABLE 2-3

AMSA SURVEY SUMMARY

Question		Percent Responding Yes	Percent Responding No	Number of Responses
1.	Are any or your sewers unlined reinforced concrete pipe (RCP)?.	89	11	62
2.	Has the rate of corrosion of the RCP increased since implementation of national pretreatment standards?	5	95	37
3.	Have core borings of the RCP been taken to determine how much the pipes have corroded?	19	81	59
4.	Does the industrial wastewater conveyed by the RCP contain heavy metals?	82	18	61
5.	Have you taken measures (e.g., addition of metal salts to the sewers) to reduce the sulfide in your sewers?	34	66	61
6.	Has your method of sulfide reduction reduced the rate of corrosion of the RCP's?	78	22	18
7.	Have you experienced sulfide corrosion of structures at your treatment plant(s)?	69	31	61

In 1989, the Water Pollution Control Federation received survey responses from 1003 wastewater treatment plants in the United States. The survey of "Problem Technologies and Design Deficiencies at POTW's" was intended to identify information needed to improve wastewater treatment plant design and operation. The WPCF Plant Survey database was utilized by this study as a means to determine the source of corrosion problems at wastewater treatment plants. The survey asked the 1003 participants to rate the level of problems in various areas of the plant and also asked questions about plant age, daily flow, and methods of operation.

Several questions dealt with the level of corrosion experienced in major portions of the plant, as well as the incidence of influent H_2S and odors. A summary of the responses related to corrosion problems is shown in Table 2-4. The approach taken to determine the source of corrosion was to develop a matrix of responses in an attempt to correlate the incidence of corrosion to such factors as influent H_2S, odors, age and recycle streams.

Overall, it was found that 68 percent of the plants surveyed experienced some level of corrosion within the plant. The same level of corrosion is generally experienced in all portions of the plant. For example, if the respondent classified corrosion problems at preliminary treatment as major but periodic, then the corrosion problems experienced at the secondary clarifier tended to be rated the same.

The age of the plant does not explain the consistent level of corrosion problems in all sections of the plant. When compared to the level of corrosion at preliminary treatment, the same age distribution was seen for all levels of corrosion. The plants reporting no corrosion at preliminary treatment are generally over 20 years old and have had major liquid and sludge train expansions in the last 5 years. The plants showing some degree of corrosion are between 1-15 years old but have also had train expansions in the last 5 years.

As for plant size, the majority of wastewater treatment plants without corrosion problems in preliminary treatment handle 0.1 to 1.0 mgd (42%) or 1 to 5 mgd (31%) average flow. The plants exhibiting corrosion are rather large - 34 percent treat between 1 and 5 mgd. One interesting finding is that of the largest wastewater treatment plants (>10 mgd), those reporting corrosion outnumber those without corrosion by almost 7 to 1. The distribution of corrosion severity for each size category is generally the same, but with a tendency for larger plants to show slightly more severe corrosion problems.

The recycle of filtrate or supernatant streams from digesters, thickeners and dewatering equipment does not appear to increase the incidence of corrosion at preliminary treatment. The distribution of responses was similar for those plants which recycled and those which did not. There was also no tendency for an increase in corrosion with a particular recycle stream. For all recycle streams, the level of corrosion

TABLE 2-4

SUMMARY OF RESPONSES TO WPCF SURVEY - CORROSION OF WASTEWATER TREATMENT SYSTEMS

Corrosion Problem Severity and Frequency,
Percent of Responses

	Minor Problem		Major Problem		Total
	Periodic	Continuous	Periodic	Continuous	
Preliminary Treatment	30	23	6	9	68
Aeration Basins	27	15	3	4	49
Fixed Film Systems	23	13	3	5	44
Susp. Growth Clarifiers	27	13	2	3	45
Fixed Film Clarifiers	23	7	1	3	34
Disinfection	23	12	2	2	39
Sludge Thickening	30	15	5	5	55
Sludge Digestion	26	15	6	4	51
Sludge Treatment	24	11	4	2	41

is rated as minor periodic.

The primary relationship of concern to this study is that of influent H_2S to corrosion. For preliminary treatment the survey participants were asked to rate the severity of problems with corrosion and hydrogen sulfide. The matrix of responses indicates that for any level of corrosion problem most wastewater treatment plants generally have minor periodic or no troubles with sulfide. It is also noted, however, that the majority of plants reporting major continuous problems with H_2S also report the same level of severity for corrosion.

The severity of odor releases was also compared to the level of corrosion problems in preliminary treatment. Of those plants reporting major continuous corrosion problems, the majority of responses were evenly divided among minor and major odor problems. Only a few of these plants reported no odor problems.

The matrix of responses for corrosion and odor was similar to that for corrosion and sulfide. It was found that wastewater treatment plants seem to recognize a relationship between odor releases and the presence of hydrogen sulfide. In general, the same response to the severity of H_2S was also given to the problems with odor releases. Approximately 30% of the wastewater treatment plants surveyed reported no problems with either.

As part of the selection process for site visits, information was analyzed from 34 cities reported to have hydrogen sulfide corrosion problems. This information is summarized in Table 2-5.

Other organizations, manufacturers, and contractors were contacted to gain additional perspective on the national extent of hydrogen sulfide corrosion. These entities included the Clay Pipe Institute, National Association of Sewer Service Contractors, Insituform of North America, Spirolite Corporation, Ameron Corporation, Sauereisen Cement Co., LaFarge Cement Co., and Specialty Sewer Services, Inc., and others. Highlights of information collected from these sources are briefly summarized in Table 2-6.

Figure 2-1 is a map pinpointing locations where severe corrosion problems are judged to exist in the sewer system or treatment plant. This is based on EPA site investigations, surveys conducted by other organizations and the experiences of professionals active in the field of hydrogen sulfide corrosion control. This does not represent all the cities experiencing severe corrosion problems.

Figure 2-2 is a map which shows the frequency of use of a proprietary, corrosion-resistant liner for concrete pipe. This type of liner is specified during design for concrete pipes which may be subjected to hydrogen sulfide corrosion. The map does not represent actual corrosion problems.

TABLE 2-5

SELECTED INFORMATION FROM THIRTY-FOUR CITIES

CITY	POPULATION (MIL)	TOTAL SEWER LENGTH (MI)	RCP LENGTH >24" (MI)	NO. OF WWTP	AVG. FLOW (MGD)	PERCENT COMBINED FLOW	PERCENT INDUSTRIAL FLOW	INDUSTRIAL FLOW UNIFORM THROUGHOUT	INDUSTRIAL FLOW PRETREATED	WWTP DISCHARGE SLUDGE TO DOWNSTREAM	CORROSION[1] PROBLEM EXISTS	EXPOSED AGGREGATE OR STEEL
Jefferson City, MO			0	1							N	
Milwaukee, MI	1.0	305	0	2	190	15	25	Y	Y	N	N	Y
Topeka, KA	0.2	650		1							N	
Duluth, MN	0.1	40		1							M	
Indianapolis, IN				1							M	
Charlotte, NC	0.4	2000		5	50	0	33	Y	Y	N	M	Y
Orlando, FL	0.3	650		3	40	0	10	N	Y	N	M	Y
Urbana, IL				1							M	
El Paso, TX				1							P	
Sacramento, CA	0.8	3000	200	1	130	20	9	N	Y	N	P	Y
Albuquerque, NM		1400		1	49	0		Y	Y	N	Y	Y
Baltimore, MD	1.7	1869		1	220	15		Y	Y		Y	Y
Baton Rouge, LA	0.4	250	75	3	36	0	4	Y	Y		Y	Y
Battle Creek, MI	0.1	350		1	13	1	60	N	Y	N	Y	Y
Boise, ID	0.1	300	10	1	24	0	18	Y	Y	N	Y	Y
Casper, WY	0.1	200		1	7	0	2	N	Y	N	Y	Y
Dallas, TX	1.1	5000	100	2	45	0	10	N	Y	N	Y	Y
Denver, CO	1.3	240		1	156	0	9	Y	Y	N	Y	Y
Fort Worth, TX	0.8	2000	300	1	100	0	14	Y	Y	N	Y	Y
Honolulu, HI	0.6	1750	50	16	120	0	2	N	N	Y	Y	Y
Houston, TX	1.7	4900		30		0		N	Y		Y	Y
Jacksonville, FL	0.3	1400	3	5	45	0	10	N	Y	N	Y	Y
Nashville, TN	0.5	1600	320	3	95	34	9	N	Y		Y	Y
Omaha, NE	0.4	3500	9	2	78	50	18	Y	Y	N	Y	Y
Phoenix, AR	0.9	3400	100	2	140	0	18	Y	Y	Y	Y	Y
Pine Bluff, AK	0.1	375	15	1	10	0	20	N	Y	Y	Y	Y
Raleigh, NC	0.3	800	240	1	26	0	5	N	Y	N	Y	Y
St. Louis, MO	1.5	6500	975	6	320	30	30	N	Y	N	Y	Y
San Antonio, TX	1.0	3600		3		0		Y	Y		Y	Y
San Diego, CA	1.5	3300	0	1	180	0	9	Y	Y	N	Y	Y
Seattle, WA	1.0	184	92	5	70		25	N	Y	Y	Y	Y
Tampa, FL	0.4	1500	30	1	58	0	13	N	Y	N	Y	Y
Tuscon, AR	0.6	2300		2	65	0	12	N	Y	N	Y	Y
Virginia Beach, VA	1.2	360	360	9	23	0	10	Y	Y	N	Y	Y

TABLE 2-5 (cont.)

CITY	PIPE AGE WHEN AG/SIL FIRST EXPOSED (YR)	CORROSION[2] LOCATION	HIGH RATE CORROSION	RATE INCREASED SINCE 1970	IMPLEMENTED[3] CORROSION CONTROLS	CORROSION CONTROLS EFFECTIVE	ANNUAL RAIN PRECIP (IN)	ANNUAL SNOW PRECIP (IN)	AVG SUMMER TEMP (FAR)	AVG WINTER TEMP (FAR)	AVG WW TEMP (FAR)
Jefferson City, MO							36.0	18.0	78.6	31.3	
Milwaukee, WI		G			G		29.0	45.0	69.9	19.4	55
Topeka, KA	20	C			KM		37.0	20.0	78.8	27.8	
Duluth, MN					M		30.0	78.0	65.6	8.5	
Indianapolis, IN		GI					39.0	21.0	75.0	27.9	
Charlotte, NC		B	N	N	B	Y	43.0	6.0	78.5	42.1	70
Orlando, FL		BCE	N		B		51.0	0.0	81.8	60.3	
Urbana, IL							35.0	22.0	76.1	26.7	
El Paso, TX					CEM	Y	8.0	5.0	82.3	43.6	
Sacramento, CA			N	N	ABD	Y	17.0	0.1	75.2	45.1	
Albuquerque, NM	15	J	Y	N	ABC	Y	7.7	11.0	78.7	35.2	70
Baltimore, MD	36	C	N	N			40.0	22.0	76.6	33.4	
Baton Rouge, LA	15	ACDEGHI	Y	Y	A		57.0	0.2	81.9	52.9	
Battle Creek, MI	10	BG	Y		DE	Y	32.0	39.0	72.3	24.6	
Boise, ID	10	ACDE	Y	N			12.0	21.0	74.5	29.0	67
Casper, WY	5	CDEGHI	Y	N	F	N	11.0	77.0	71.0	23.2	60
Dallas, TX	10	BCDEGHI	N	N	LM	Y	32.0	3.0	84.9	44.8	
Denver, CO	10	ACDEFGHI	Y		B	Y	16.0	60.0	73.0	29.9	
Forth Worth, TX	10	EI	Y	N	B	Y	32.0	3.0	84.9	44.8	73
Honolulu, HI	10	CDEGI	Y	N	M	Y	23.0	0.0	80.7	72.3	
Houston, TX	20	CDEGH	Y				48.0	0.0	83.4	52.1	
Jacksonville, FL	10	ACDE	Y	N			54.0	0.0	81.0	54.6	
Nashville, TN		BCDEGHI	Y		M	Y	46.0	10.7	79.6	38.3	
Omaha, NE		BCDEGI	Y	N	I	Y	30.0	32.0	77.2	22.6	
Phoenix, AR	10	D	N	N	ABDM	Y	7.0	0.0	91.2	51.2	
Pine Bluff AK	10	CD	Y	Y	J	Y	49.0	5.0	81.4	39.5	
Raleigh, NC	15	G	N	Y	AM	Y	43.0	7.0	77.5	40.5	
St. Louis, MO	10	BDGHI	N	N	D	Y	36.0	18.0	78.6	31.3	
San Antonio, TX	15	ACDEH	N				28.0	0.5	84.7	50.7	
San Diego, CA	8	ACDEGHI	Y	N	M		9.0	0.0	71.4	55.2	
Seattle, WA	15	ACDEFGHI	N	N	B		39.0	15.0	64.5	38.2	55
Tampa, FL	20	ACDEGI	N	N	J	N	49.0	0.0	82.2	60.4	
Tuscon, AR	20	BCDEHI	N	N	N		11.0	2.0	86.3	50.9	
Virginia Beach, VA	4	ACDEGHI	Y	N	ABM		45.0	7.0	78.3	40.5	

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[1] N=no, M=minor, P=past, Y=current major problem

[2] A=throughout system, B=only specific locations, C=after force mains, D=at manholes, E=at flow transition structures, F=associated with industrial discharges, G=in large diameter pipe, H=in small diameter pipe, I=long detention times, J=other.

[3] A=Cl_2 injection, B=H_2O_2 injection, C=O_2 injection, D=air injection, E=$KMnO_4$ injection, F=NaOH injection, G=NaOCl injection, H=$FeSO_4$ injection, I=$FeCl_3$ injection, J=unspecified chemical injection, K=GAC filter, L=maintain minimum pipe slope, M=use corrosion resistant material (vitrified clay, or PVC)

TABLE 2-6

SUMMARY OF INFORMATION FROM SELECTED ASSOCIATIONS, MANUFACTURERS, AND CONTRACTORS

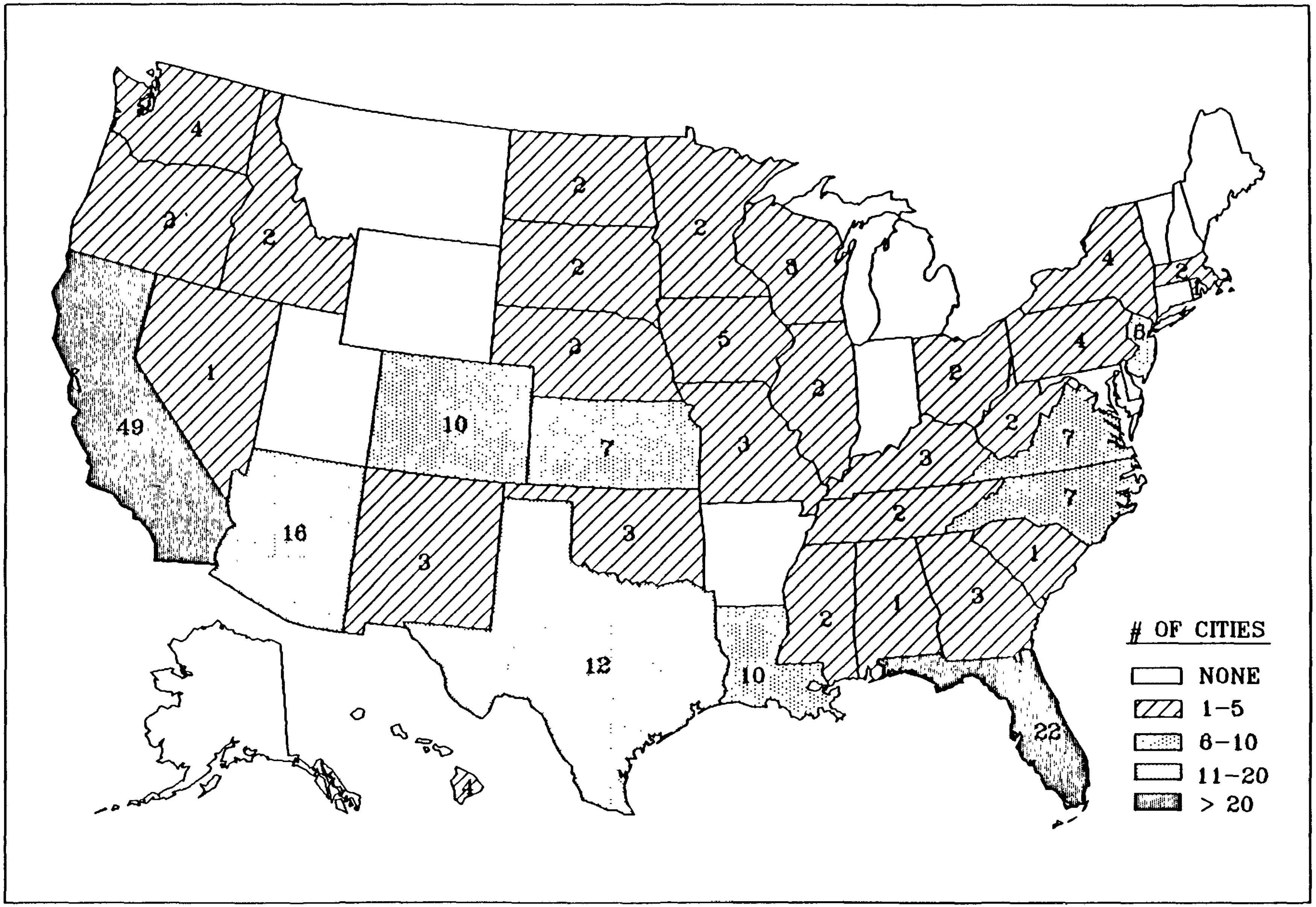
Source	Comments
Clay Pipe Institute	From 1950 to 1969, over 154 miles of severely corroded concrete pipe in 57 cities was replaced with clay pipe, with over 5% of production tonnage used for this purpose
Spirolite Corporation	From 1986 to 1989, approx. 20 miles of sewer was sliplined using Spirolite polyethylene pipe
Insituform of North America	Over 100 miles of large diameter sewer was lined using cured-in-place inversion lining in more than 36 U.S. cities between 1977 and 1988
Ameron Corporation	From 1947 to 1988, over 900 miles of sewer pipe in 500 U.S. projects was specified with T-lock liners to prevent crown corrosion

FIGURE 2-1

STATES HAVING SEVERE CORROSION PROBLEMS IN WASTEWATER SYSTEMS OF FOUR OR MORE MUNICIPALITIES

FIGURE 2-2

USE OF PROPRIETARY PVC LINING TO PREVENT CORROSION OF CONCRETE PIPE



2.6 Case Studies

To gain further insight into the causes and prediction of hydrogen sulfide generation and subsequent hydrogen sulfide corrosion, case histories were prepared from previous evaluations of five wastewater collection systems located in three cities. The following systems were investigated:

- Sacramento County, California, Central Trunk Sewer
- Sacramento, California, Regional Interceptor System
- City of Lakeland, Florida, Western Trunk Sewer
- City of Omaha, Nebraska, Papillion Creek Wastewater System
- City of Omaha, Nebraska, South Interceptor Sewer

A brief summary of each of the five case studies is provided below (2)(3):

2.6.1 Sacramento County, California, Central Truck Sewer

2.6.1.1 Description and History

The Central Trunk Sewer conveys both domestic and industrial wastewater and, for several years, conveyed sludge from two upstream wastewater treatment plants. The trunk is approximately 16 miles long. About 2 miles of the upper reach is vitrified clay pipe ranging from 18 to 24 inches in diameter. The remaining 14 miles is granitic-aggregate reinforced concrete pipe 27 to 60 inches in diameter. The slope varies from 0.18 percent in the upper reaches to 0.05 percent in the lower end of the trunk.

The Central Trunk Sewer was constructed in 1962. The following is a brief history of the system:

- 1964--The entire line was visually inspected by County personnel by floating on rafts through each reach. A powder deposit on the inside of the pipe was the only evidence of corrosion.

- 1968--Anaerobically digested sludge discharge to the Central Truck Sewer was initiated.

- 1968--The entire pipeline was again visually inspected and samples of concrete were taken. The pH of the concrete walls was greater than 3.0. Maximum corrosion at that time was estimated to be 1/4 inch, and no coarse aggregate was exposed.

- 1969--Dr. Richard Pomeroy completed an analysis of portions of the trunk. Existing corrosion was estimated to be 1/8 or 1/4 inch. The useful life of the trunk was estimated to be 100 years.

- 1972--The County studied the effects of chlorine on sulfide generation in the Central Trunk system.

- 1972-1973--Vitrified clay plugs were installed at the manholes in the trunk. Three sulfide control facilities were designed and one was bid. Due to the high price of the bid, the sulfide control facilities were not constructed.

- 1976--The clay plug locations were inspected. Significant corrosion was evident, and a hydrogen sulfide corrosion study was initiated in September 1976.

- 1979--Three chlorine injection stations were placed in service along the Central Trunk to reduce sulfide levels and to minimize further corrosion.

- 1982-83--Sludge discharge to the Central Trunk was stopped.

- 1984--The County completed another field investigation which showed continued corrosion, but at a reduced rate.

- 1984--A 1,800-foot reach of 60-inch-diameter pipe from the Central Trunk Sewer was abandoned primarily due to a new alignment, and partially due to concern about the structural integrity of the pipe.

- 1987--County inspection of the Central Trunk showed reduced sulfide concentrations and indications of reduced corrosion rates.

2.6.1.2 Summary of Results

Average annual total sulfide concentrations ranged from approximately 0.5 to 1.5 mg/l from 1965 to 1976, based on weekly or monthly sampling at 12 noon at one location. Average 24-hour sulfide concentrations were approximately 40 percent higher.

Corrosion penetration was as much as 1.5 inches at some locations in the sewer. Cores taken from the crowns of the pipes showed that the worst corrosion conditions usually existed in the first 30 ft downstream of the manholes.

Predicted sulfide concentrations from the Pomeroy-Parkhurst equation were compared with measured values. When the effect of sewer junctions was considered, the predictive equation estimated sulfide concentrations with reasonable accuracy. Predicted corrosion penetration was also compared with measured values, and showed an excellent correlation. It was also found that peaking factors of 2 were justified to account for minor turbulence at manholes. Higher peaking factors would be required where high turbulence levels were encountered to account for the increase in off-gassing of H_2S.

Dead load testing was conducted on a 12 ft section of 60 inch diameter pipe in 1984. The pipe was highly corroded, but reinforcing steel was not exposed. Tests showed that, although concrete loss had occurred, the pipe strength was still significantly greater than the original specification for dead load.

Based on inspections in 1987, the rate of corrosion was reduced from that observed in the 1970's due to elimination of sludge discharges and installation of chlorination stations.

2.6.1.3 *Findings and Conclusions*

1. The observed corrosion information from 1976 is in general agreement with Pomeroy's corrosion predictive equation, if conservative assumptions are made and input data are based on field measurements and monitoring data.

2. Valid, positive measurements of the depth of actual corrosion of in-place pipe for the Central Trunk were difficult. Accuracy of all methods used was less than desirable.

3. The discharge of anaerobically digested sludge to the Central Trunk for 14 years was partly responsible for the higher corrosion rates over those years. Sludge discharges increased the BOD and the temperature of the wastewater in the Central Trunk.

4. With removal of the sludge discharges and installation of chlorination stations along the Central Trunk Sewer, the sulfide concentration has been reduced in the 1980's, and the rate of corrosion appears to have dropped significantly.

5. The Central Trunk is believed to be made from spun RCP. It seemed to take several years before corrosion penetrated the surface layer of this granitic aggregate pipe. Once the high-alkalinity surface layer had been corroded, the corrosion rate increased, since the alkalinity of the rest of the pipe concrete was only 16 percent.

6. The corrosion information on manholes and structures with turbulent flow characteristics is particularly interesting. This information points out the need to use conservative corrosion rate peaking factors in predicting hydrogen sulfide corrosion rates within close proximity to these locations (within several pipe diameters).

2.6.2 Sacramento, California Regional Interceptor System

2.6.2.1 Description and History

The Sacramento terrain is quite flat, and the climate features hot summers and mild winters. The collection system extends 20 miles east of the Sacramento River, and for more than 20 miles north to south. The longest interceptor, nearly 30 miles long, drops less than 200 feet from end to end. Several pumping stations are included in the system.

The Regional Interceptor System is extensive in scope, with a total capital cost of about $143 million. It was constructed during the period 1975 to 1982, and encompasses about 62 miles of gravity sewer, over 25 miles being pipe in the 60- to 120-inch diameter range.

In designing the regional interceptors, a number of passive measures were implemented:

1. County Source Control Ordinance. Sacramento County passed an ordinance in 1977 controlling the quality of industrial waste discharges into the Regional System.

2. Calcareous Aggregate. Use of sacrificial calcareous (rather than granitic) aggregate was specified for all concrete pipe construction.

3. Turbulence Control. Junction structures were designed for smooth transitions to minimize wastewater turbulence.

4. Lining of Hydraulic Structures. Junction structures, and other hydraulic elements especially vulnerable to corrosion, were lined with plastic (locking PVC liners).

5. Slope/Velocity. Pipe slope and velocity were carefully evaluated to limit solids accumulations within the system.

An extensive study to determine needed sulfide controls commenced in 1974 and was completed in 1976. Several sulfide control measures appeared feasible from this study for use in the Regional Interceptor System. Except for chlorination, no reliable performance data existed prior to the mid-1970's for the control measures being considered. To develop this information, a field testing program of several sulfide control measures was undertaken in the summer of 1974. Information was obtained for the following:

1. Air injection in a force main (injected at pumping station)
2. Hydrogen peroxide injection in a force main

3. Oxygen injection in a force main
4. Chlorination in a force main and gravity sewer
5. U-tube aeration (air) at the end of a force main
6. U-tube aeration (oxygen) at the end of a force main

For upstream pumping stations, chlorine was selected to provide control of hydrogen sulfide generation. However, for a 60-inch diameter and a 72-inch diameter force main, injection of high purity oxygen into a fall structure was selected as the most cost-effective alternative. The injection of high purity oxygen enriches the atmosphere of the fall structure with oxygen to allow entrainment of oxygen through turbulence induced by the fall, and elevation of dissolved oxygen levels in the wastewater, thus allowing oxidation of existing sulfide and prevention of further sulfide generation.

Attention was also focused on the potential problems of solids deposits, especially during the early years of system operation. Since solids deposits can generate sulfide, the objective of the design was to eliminate the possibility of solids accumulation, or otherwise plan for removal of any such deposition.

The predicted lack of adequate velocities during early years of operation in several interceptors led the designers to a decision to construct flushing facilities at two locations. In this manner, flows could be greatly increased for a few hours at a time during the long periods of low dry weather flows, flushing solids down the system of interceptors.

The Pomeroy-Parkhurst sulfide prediction equations and the Pomeroy corrosion prediction equation were used extensively during design of all regional interceptors. Many different assumptions were used to determine the best mix of passive and active sulfide controls to provide assurance of long pipe life (100-year minimum) and lack of odor problems.

2.6.2.2 Summary of Results

Chlorine gas is used at upstream pumping stations and at three locations along the Central Trunk. The chlorination stations have been successful in maintaining low dissolved sulfide levels (generally less than 0.3 mg/l) at the force main discharge points.

Solids deposition in the interceptor system has not been a problem. Peak wet weather flows have provided adequate flushing of the lines, and use of the flushing stations has not been required in the northern portion of the system.

Two oxygen injection stations were constructed and operated at fall structures (4). In one system, DO concentrations of 13 mg/l have been achieved in the wastewater at a point nearly 4000 ft downstream of the fall structure. Similar results have been reported for the other oxygen injection system. Dissolved sulfide concentrations downstream of the fall structures are consistently less than 0.5 mg/l.

The primary problem with these stations has been that hydrocarbon compounds are stripped from the wastewater under the turbulent conditions found in these structures. Explosion meters that monitor the Lower Explosive Limit (LEL) are used in each station. When 25 percent LEL is reached, pure oxygen addition is shut down. This shutdown event occurs often. In the summer months, 25 percent LEL is reached on almost a continuous basis. Investigation by the District into the source of the hydrocarbons has shown that it may be methane gas generated under the anaerobic conditions in the upstream force mains and gravity sewers, and within the combined sewer system of the City of Sacramento.

Vitrified clay plugs were installed at many locations in the pipe of the Regional Interceptor System to allow future measurement of the corrosion of the pipe surrounding the plug. The District has had difficulty obtaining measurements from these plugs due to a variety of problems including: problems in finding the plugs in the dark, uncomfortable environment of the sewers, and, if found, difficulty achieving highly accurate measurements due to the conditions. Collected data have been analyzed and, in general, indicate that corrosion to date is very low.

2.6.2.3 Findings and Conclusions

1. Although only a few years of monitoring data are available, the information suggests that the Regional Interceptor System design, and its sulfide control systems, are providing the level of protection anticipated.

2. District monitoring work has confirmed the need for PVC, or other type of non-corrodible lining material, for all junctions and structures where even limited turbulence occurs and where wastewater contains minor amounts of dissolved sulfide.

3. The lack of accurate measurements on the amount of corrosion in the early years of operation of the Regional Interceptor System has been frustrating. The level of accuracy needed is in the range of hundredths of an inch. The level of accuracy for corrosion measurements needs to be improved.

4. The stripping of hydrocarbon compounds in the fall structures has caused additional safety considerations that were not initially anticipated during design. In the summer, one of the fall structures is now bypassed, and oxygen is injected in the bypass. This results in satisfactory oxidation of sulfide at the ends of the two long, large-diameter force mains.

5. Solids deposits have not been a problem, and do not appear to produce any significant sulfide.

6. Chlorination in upstream force mains has performed satisfactorily to minimize sulfide at the discharge points of these force mains.

7. Data on wastewater sulfide concentrations and sewer atmospheric H_2S levels have been difficult to correlate at specific locations in the Regional Interceptor System. This is probably due to analytical inaccuracy at low dissolved sulfide concentrations (typically less than 0.3 mg/l), slight wastewater pH variations, and the degree of wastewater turbulence, all of which are critical to H_2S off-gassing rates.

8. The operating data from the Regional Interceptor System show that careful and conservative use of the sulfide and corrosion predictive equations can be of major assistance in designing long interceptor systems in warm climates to meet stringent corrosion standards.

2.6.3 City of Lakeland, Florida, Western Trunk Sewer

2.6.3.1 Description and History

The City of Lakeland is a growing community of approximately 66,000 population. Lakeland has experienced corrosion problems in portions of its sewer system due to sulfide generation. An engineering study was undertaken in early 1988 to assess the existing conditions and to develop a plan to renovate portions of the Western Trunk Sewer.

The Western Trunk Sewer receives wastewater discharges from food processing, other industrial, commercial, and residential areas. The collection system consists of both force mains and gravity sewers.

The gravity portion of the Western Trunk consists of about 27,300 lineal feet (LF) of primarily reinforced concrete pipe (RCP) and vitrified clay pipe (VCP) ranging in size from 24- to 48-inch diameter. There are variable slopes on most reaches which cause changes in velocity. Most dry weather velocities are greater than 2 fps, and some reaches have velocities of 7 fps.

The Western Trunk Sewer was constructed in 1960 and 1961. Lakeland has rehabilitated or replaced portions of this sewer in recent years because of pipe collapses. An odor control study conducted by the City of Lakeland in 1987 confirmed high levels of H_2S gas and high wastewater sulfide concentrations. The City undertook a sewer system evaluation study to determine the extent of hydrogen sulfide corrosion and appropriate solutions to correct the deficiencies.

2.6.3.2 Sewer System Corrosion Evaluation

The corrosion evaluation consisted of detailed inspection and analysis of the conditions of both manholes and truck sewer. A total of 79 manholes were inspected. Internal television inspections were conducted on nearly all the gravity portions of the trunk sewer. Core borings of concrete pipe were taken at eight representative locations along the trunk.

In general, the manholes were found to be corroded and in need of rehabilitation. Seventy-seven manholes had corroded barrels, and 66 had deteriorated frames.

In the trunk sewer system, all reaches of reinforced concrete pipe (RCP) had lost from one to four inches of concrete due to corrosion. Reinforcing steel was found exposed or missing in numerous locations, and aggregate was exposed in all reaches of RCP. A section of 30-inch diameter ductile iron pipe, installed in 1966, was severely blistered and brittle enough to break by hand. While the vitrified clay pipes did not suffer from corrosion damage, there were numerous cracks and leaking joints in the lower portion of that segment; and manhole corrosion was worse in the VCP reach.

Predictive models were utilized to estimate sulfide generation, corrosion rates, and remaining useful lifetimes of pipes. The model predicted sulfide build-up of 1.5 to 2.0 mg/l. Recent field data show levels of 1.0 to 1.5 mg/l. Approximate correlation was shown by the model. Similarly, predicted corrosion rates approximated estimated corrosion rates based on field measurements. Predicted average corrosion rates were 0.03 to 0.15 inches/year, with peak rates approximately double these values. It was estimated that, at turbulent structures, corrosion rates could be five times predicted average rates. This underscores the importance of turbulence on hydrogen sulfide corrosion, and the difficulty in estimating corrosion rate based on sulfide levels.

Based on existing depth of corrosion and estimated corrosion rates, forty-six percent of the RCP was determined to have no remaining useful life, and 54 percent was determined to have a useful life of 1 to 8 years.

Alternatives were analyzed for rehabilitation of the corroded pipe. The following five methods of rehabilitation were considered feasible for the Western Trunk sewer:

1. Slip lining with high density polyethylene pipe (with fusion joints, or bell and spigot joints) or with fiberglass pipe (filament wound, or centrifugally cast).

2. Inversion lining with polyester, resin-impregnated fabric.

3. Removal of existing pipe and replacement with one of the following: 1) reinforced concrete pipe with PVC liner, 2) fiberglass pipe (centrifugally cast)

designed for direct burial.

4. Parallel replacement of pipe using the same two options listed above.

5. Chemical grouting for specific locations (limited on this project to grouting structurally sound vitrified clay pipe for infiltration control).

2.6.3.3 Findings and Conclusions

1. Conditions which contribute to the high corrosion rates in the Western Trunk Sewer include at least the following: high wastewater BOD, high soluble BOD fractions, high wastewater temperature, low wastewater pH, variable slopes, formation of deposits, use of drop structures, and existence of upstream force mains.

2. The Pomeroy-Parkhurst sulfide predictive equation and the Pomeroy corrosion prediction equations were used with a series of conservative assumptions for the Western Trunk evaluation. In doing so, and by assuming that historical system flows, characteristics and operation were similar to current situations, the "modeled" corrosion approximated the actual corrosion. This tends to indicate the quantity of sulfide and corrosion expected in similar situations. However, it also points out that the equations should be used cautiously and with substantial conservative assumptions and safety factors.

3. The velocities in the Western Trunk system are insufficient, in some reaches, to transport the grit and heavier solids. Additional sulfide production can be expected in these reaches due to the ability of high soluble organic and sulfate concentrations to penetrate into these deposits.

4. The high likelihood of substantial sulfide generation in the Western Trunk in the future was judged to preclude the use of corrodible materials, or at least minimize use of these materials, in the rehabilitation/replacement of the Western Trunk Sewer.

2.6.4 Omaha Nebraska, Papillion Creek Wastewater System

2.6.4.1 Description and History

Corrosion and odor problems have occurred in Omaha's Papillion Creek Wastewater System over the past decade. The start-up of the expanded Papillion Creek Interceptor System in the mid-1970's brought new dischargers into the system, and substantially increased the transit time of wastewater to reach treatment facilities. The new Papillion Creek Wastewater Treatment Plant has experienced corrosion and odor problems which are partly related to interceptor sulfide problems. Safety has been an additional problem due to high concentrations of hydrogen sulfide in the confined spaces of interceptors and treatment facilities.

Omaha's Papillion Creek Wastewater System has evolved over several decades of growth and urban expansion. It now includes a service area bringing wastewater flows over 25 miles to the Papillion Creek Wastewater Treatment Plant (Papio Plant).

Only the largest Papillion Creek interceptors were evaluated in the 1984/85 corrosion and sulfide study because these were the interceptors suspected of corrosion damage. The interceptor downstream from the old Papio Plant was a primary target of the study. These interceptors were put into service in the mid-1970's to transport raw wastewater to the new Papio Plant. This system of interceptors allowed several treatment plants in the Papillion Creek drainage area to be abandoned.

In 1971, a limited study was completed on potential sulfide and corrosion problems in this interceptor system, which was then being designed. This report made predictions of sulfide levels in the interceptors and confirmed the need for lining the sewer with either sacrificial concrete or plastic.

Between 1973 and the start-up of the new Papio Plant in August, 1977, communities and industries were allowed to discharge treated effluent and, in some cases, raw wastewater to the new Papio Interceptor System. Many odor complaints from residents living near manholes and structures were received during this period. The worst odor conditions occurred in the last five miles of the system, where high BOD wastes and flows of only a few mgd probably caused very high sulfide production in at least 1974 and 1975.

Significant corrosion of the unlined outfall portion (last 3,200 feet to the Missouri River) was noted in 1977. This corrosion was evidently a result of these raw and partially treated flows. The unlined outfall portion of the interceptor was estimated to have 1/2-inch of corrosion in August 1977. Extensive corrosion of unlined manhole risers in the lower interceptor reaches also occurred prior to 1977, to the extent that some risers were replaced during the mid-1970's.

Odor problems became a major issue in Sarpy County, and the City of Omaha decided to seal all manhole covers from the old Papio Plant south to the new Papio Plant in 1975. Little ventilation of the system can occur, and only one siphon has ventilation stacks. The West Branch has little ventilation since manhole covers are solid.

Data collected at the Papio Plant show influent total sulfide levels of 4 to 5 mg/l from July through February, dropping to between 1 and 3 mg/l during spring months.

2.6.4.2 Summary of Results

Inspection of the interceptor was conducted in 1984. Manhole risers were badly corroded, in some cases, to over 1 inch. The risers were constructed of concrete with non-calcareous aggregate. Measured pipe corrosion in calcareous aggregate reaches ranged from zero to 0.5 inches. At points of high turbulence such as discharge structures, up to 0.75 inches of calcareous/granitic aggregate concrete had been lost over a 10 year period.

Use of predictive models was unsuccessful in that actual sulfide concentrations at the Papio plant were double those predicted by the model. The reasons are judged to be 1) high fraction of soluble BOD, 2) low oxygen content in the sewer atmosphere due to sealing of manhole lids, 3) need for more conservative coefficients in the predictive equation.

The Papio plant, commissioned in 1977, was also inspected for corrosion in 1984. Corrosion at the headworks was significant, with up to 0.75 inches of concrete lost over a 6-1/2 year period. Several locations within the plant had little or no concrete cover remaining. Reinforcing steel was exposed in the sludge storage tank, decant tank, drain manholes, and trickling filter walls. Hydrogen sulfide corrosion problems were caused by three basic factors:

1. High sulfide concentrations and low pH of influent wastewater

2. Long storage times for sludge and recycle streams

3. Recycle of streams from anaerobic digestion process

2.6.4.3 Findings and Conclusions

1. The large Papillion Creek interceptors were designed with attention to sulfide and corrosion issues, and based on 1984 inspection work, most of the interceptor system was in good condition. Use of sacrificial concrete, coatings, PVC linings, and calcareous aggregate prevented serious corrosion problems in the interceptor system.

2. There have been a few specific corrosion problems in the interceptor system. These include metal gates and aluminum grating which was subject to destructive acid attack. H_2S off-gassing from highly turbulent wastewater in certain structures has caused corrosion rates that are largely unpredictable. Unprotected manholes have been subject to extensive corrosion.

3. If structural rehabilitation work is required on any of the primary interceptor structures, costs could be extensive for diversion and rerouting of raw wastewater

flows.

4. Assessment of concrete corrosion rates over time is difficult without historical sulfide data and/or historical inspection information identifying the depth of corrosion from the original surface.

5. Actual sulfide buildup in the interceptor system seems to be at least twice that predicted by the Pomeroy-Parkhurst equation.

6. Actual concrete corrosion rates are greater than predicted in the design for portions of the interceptor system due to: 1) greater sulfide production than planned, and 2) reduction in pH of wastewater as it travels down the long anaerobic interceptor system.

7. Concrete, metal, and instrumentation corrosion in the Papio Plant occurred at many locations over the period of 1977 to the mid-1980's. The corrosion was caused by high wastewater sulfide levels, and high H_2S off-gassing rates. High dissolved sulfide levels in the wastewater were partially caused by high influent sulfide concentrations, and partially by sulfide produced within the plant.

8. Solutions to plant hydrogen sulfide corrosion problems are now mostly in-place. These solutions encompassed rehabilitation, process changes, chemical addition, and ventilation improvements. The solutions implemented thus far appear to be working satisfactorily.

9. There remains an odor problem at the Papio Plant caused in large part by the high influent sulfide levels. High sulfide production in the interceptor system and high plant influent sulfide concentrations constitute the most significant unresolved sulfide issues in the Papillion Creek Wastewater System.

2.6.5 *Omaha, Nebraska, South Interceptor Sewer*

2.6.5.1 Description and History

In the late 1950's, planning was initiated for collection, diversion, and treatment of raw waste discharges to the Missouri River. By 1965, the system of diversion structures, interceptors, pumping stations, and primary treatment facilities had been constructed and placed in operation. The system involves a series of structures along the west bank of the Missouri River to intercept flows and pump them to the Missouri River Wastewater Treatment Plant (MRWTP). The area served by the MRWTP is the older and more highly developed portion of Omaha. It contains Omaha's central business district and industrial centers which are located adjacent to, or near, the Missouri River.

The South Interceptor Sewer (SIS) is a 4-1/2 mile long force main that brings the majority of the plant flows to the MRWTP. Flow from the SIS is discharged at the North Inlet. Dry weather flow in the winter is about 20 million gallons per day (mgd) from the SIS. This flow increases in the warmer months due to infiltration, runoff from lawn watering, and discharges to the sewer system from drawdown of Carter Lake.

Velocities in the 66-inch diameter South Interceptor Sewer are about 0.7 foot per second (fps) or less at night and typically average 1.2 to 1.6 fps in dry weather. Deposition of solids is no doubt occurring under these conditions. Dissolved sulfide levels in the plant influent are typically 3 to 6 mg/l during warm months.

Additions to the MRWTP completed in 1980 included covering open tankage at the North Inlet, as well as other locations throughout the plant. Fans were installed to exhaust foul air from under most of these covered areas and scrub it in chemical mist units prior to discharge to the atmosphere. The City has not found the chemical scrubber at the North Inlet to be effective, and does not use it. Hypochlorites and permanganate solutions were attempted in the scrubber with little success. The covers have remained in place, but the ventilation system is not used, since very high H_2S concentrations would be discharged to the atmosphere. Corrosion of the concrete is occurring faster since installation of the covers, due to high levels of hydrogen sulfide in the atmosphere of the tanks and channels of the North Inlet. Gaseous hydrogen sulfide levels under the North Inlet covers have reached the 50 to 300 ppm range during summer and fall months.

In 1984, a study was initiated to evaluate odor and corrosion problems in the South Interceptor Sewer and at the Missouri River Wastewater Treatment Plant. The results are summarized below.

2.6.5.2 Summary of Results

Hydrogen sulfide corrosion has occurred at a number of locations in the MRWTP, but the North Inlet is the location where the problem is most apparent at this time. Besides the North Inlet, concrete corrosion has occurred at the South Inlet and in various wastewater channels and boxes prior to, and following, primary clarification. Corrosion in foul air ducts from the biological filters has also occurred, as well as corrosion in the anaerobic digestion portion of the plant.

Inspection work in 1984 showed that concrete spalling was occurring above the water line in the Parshall flume area and in other channels. The worst corrosion was at the drop structure where at least 1/2- to 3/4-inch of concrete was estimated to have become corroded from walls and structural support members. Most of this corrosion probably occurred in the 1980 to 1984 period after the tanks were covered. No reinforcing bars were exposed. Metal corrosion at gates was also significant. In the bar screen building, continued corrosive environmental conditions had deteriorated many metal components, and the exposed electrical and instrumentation equipment had suffered irreparable damage.

The recommended approach to sulfide control at North Inlet was as follows:

1. Reduce the high sulfide and H_2S concentrations through sulfide control methods in the South Interceptor Sewer.
2. Leave the covers in place at the North Inlet and implement improved ventilation and odor scrubbing to reduce corrosive atmospheres and treat residual H_2S and other odorants more reliably.
3. Once improved ventilation and H_2S control is in place, conduct structural rehabilitation and replace equipment as necessary.

Alternatives evaluated for the SIS included chlorination, iron chloride addition upstream from the plant, and caustic slugging. Costs favored caustic slugging, although the performance was not expected to be as consistent as other alternatives. Full-scale testing of caustic slugging was undertaken in late 1984 to confirm its effectiveness and define costs more accurately.

The objectives of a caustic injection program is to inactivate sulfide-producing bacteria which grow in the slime layer on the walls of the pipe. High pH (12 to 12.5 and above) is toxic to these bacteria, and interim application of a strong alkaline solution has proven effective in depressing sulfide production within sewers. The test program was successful, and the technique has been used on the SIS each summer since that time. Caustic slugging is effective for reducing dissolved sulfide levels in the plant influent from over 3 mg/l to an average of 0.4 mg/l. In 1985 the City spent $44,000 on 17 truckloads of caustic, estimated to eliminate 47,000 pounds of sulfide. In the summer of 1988, the effectiveness of caustic slugging was reduced. This was believed to be due to the dry weather conditions which led to higher wastewater strengths, and lower velocities and greater solids deposition in the SIS. Evidently, the caustic slug is unable to penetrate sludge deposits and inactivate the bacteria.

The City is currently evaluating alternatives to caustic slugging for control of sulfide generation in the South Interceptor Sewer.

2.6.5.3 Findings and Conclusions

1. Significant corrosion and odor problems have occurred at the North Inlet, due to sulfide production within the SIS. Attempts to control the odor problem in 1980 by covering tankage and scrubbing the foul air resulted in worsening of the corrosion problem due to failure of the odor scrubbing system, and subsequent shutdown of the ventilation system.

2. Rapid rates of corrosion can be expected for concrete and metal exposed to the high H_2S concentrations (50-300 ppm) and moist environment which exist beneath the covers at the North Inlet. The life of some of these facilities appears to be 10 years or less under the severe conditions which have existed in the 1980's. The high H_2S concentrations constitute a safety hazard.

3. Caustic slugging has provided a cost-effective reduction in high sulfide concentrations from the SIS since late 1984 when it was initiated. Its performance is variable, primarily because of the solids deposition problem in the SIS, caused by low wastewater velocities. Atmospheric H_2S levels beneath the primary clarifier domes have dropped from over 50 ppm to below 10 ppm.

4. Other sulfide control methods are likely to be more reliable and have better overall performance than caustic slugging; however, the costs for other control methods appear to be substantially higher than caustic slugging.

5. The low velocity and resulting deposition problem in the SIS is likely to continue to plague attempts at reliable sulfide control in this pipeline. Velocities of about 4 to 5 fps are needed on a regular basis to scour grit deposits from a force main of this size. The periodic scouring of the SIS causes considerable solids loading fluctuations to the MRWTP which may affect treatment performance.

6. The City, with the use of caustic slugging, has implemented the first phase of a program to solve the sulfide problems at the North Inlet. Substantially more work is needed to restore the North Inlet to a sound, safe, and acceptable condition.

2.7 Hydrogen Sulfide Corrosion in Other Countries

Hydrogen sulfide corrosion has been reported in the literature of many countries including France, Germany, Italy, United Kingdom, the Netherlands, Denmark, Czechoslovakia, Iraq, India, China, the Soviet Union, Japan, Saudi Arabia, Kuwait, Egypt, South Africa, Venezuela, Brazil and Australia. This observation is based on a series of literature searches conducted for EPA in 1982 and 1988 on the subjects of odor and corrosion in wastewater systems.

Several severe cases of hydrogen sulfide corrosion are briefly summarized below (5)(6):

1. Venezuela: Reinforced concrete pipe was corroded to a depth of 2.8 inches within eighteen months of construction in an area downstream from the discharge of a force main. Vitrified clay pipes used in the same system were not affected.

2. Cairo, Egypt: As early as 1920, hydrogen sulfide corrosion of sewer pipes was recognized as a problem in the Cairo system. By 1922, in spite of aeration and regular flushing, the crown of the original main outfall sewer, 60 inches in diameter and made of local cement concrete, was corroded to a depth of 3.9 inches over a length of 8 miles. By 1930, the depth of corrosion had increased to 5.9 inches, nearly half the thickness of the pipe.

3. Baghdad, Iraq: A system of reinforced concrete interceptors was put in operation in 1963, and by 1977 the maximum depth of corrosion in extended sections of the interceptors varied from three to four inches at the crown where reinforcing steel, which was designed to be protected by a two-inch concrete cover, was exposed and had corroded away in places. The walls were also damaged to a depth of two inches and the access manholes showed severe corrosion. The rate of internal corrosion was estimated at 0.3 inches per year, which would have led to a critical situation in approximately 15 years. Rehabilitation had begun in certain sections of the system, and new extensions have been made with PVC or fiberglass-reinforced plastic lining.

4. Singapore: The sewer of concern was 71 inch diameter concrete pipe internally lined with 0.5 inches of high alumina cement mortar. The line was over 1600 ft long with a design capacity of 81 mgd. The sewer was commissioned in 1961. This portion of the line received almost entirely pumped sewage, much of which was pumped more than once.

   Inspections since 1970 revealed extensive and continuing hydrogen sulfide corrosion. The high alumina lining was completely corroded away or reduced to a soft past above the waterline. Corrosion in some areas had proceeded to a depth of over 1.5 inches, and had gone beyond the reinforcing steel, in less than 15 years.

   Several rehabilitation options were under consideration including sliplining with glass-reinforced polyester or high-density polyethylene, installation of corrosion-resistant panel liners, and cured-in-place inversion liners.

2.8 Conclusions

Attempts to gain a thorough understanding of the severity and extent of hydrogen sulfide corrosion problems in U.S. were thwarted by the lack of historical data on sewer corrosion, the lack of a standardized technique to measure corrosion, and the poor documentation by municipalities of sewer corrosion and the expenditures for sewer rehabilitation or replacement. Upon review of information gathered, the following findings and conclusions are presented:

- Severe hydrogen sulfide corrosion problems are not limited to CSDLAC.

Extensive corrosion damage requiring immediate repair or rehabilitation has been observed in sewers in other cities. In some cases, corrosion damage is so extensive as to compromise the structural integrity of the pipe, which could lead to collapse.

- Hydrogen sulfide corrosion problems in operating systems are often not recognized early enough to take corrective action before considerable damage has occurred.
- In a 1984 survey, approximately 30 percent of the 89 cities reported sewer collapses that were judged to be due to hydrogen sulfide corrosion.
- In two independent surveys, 60 to 70 percent of the municipalities reported hydrogen sulfide corrosion at their wastewater treatment plants. Of those plants experiencing corrosion, about 20 percent are considered to have severe problems.
- Hydrogen sulfide corrosion problems have been documented in the literature of at least 20 foreign countries.
- Due to lack of historical data, corrosion rate is estimated based on depth of corrosion and age of pipe. This may not reflect the true corrosion rate, which may be substantially higher at a given time and condition.
- No entities other than CSDLAC had sufficient data on corrosion rate to establish whether the rate of corrosion had changed over time.
- Due to changing alkalinity in spun vs. cast concrete pipes, corrosion rate can change over time.

Evidence of severe corrosion may be found in cities throughout the United States and other countries. Cases of "high rate" corrosion are also common. However, at this time EPA has been unable to document other cases of "accelerated" corrosion of the type that has been experienced in the sewers of CSDLAC.

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3.0 EFFECTS OF INDUSTRIAL PRETREATMENT

3.1 Overview

Section 522 of the Water Quality Act of 1987 requires EPA to study the extent to which implementation of the categorical pretreatment standards will affect hydrogen sulfide corrosion in wastewater collection and treatment systems in the United States (U.S.). EPA's industrial pretreatment program regulates the discharge of certain constituents such as metals and toxic materials into municipal sewer systems. The County Sanitation Districts of Los Angeles County (CSDLAC) implemented industrial pretreatment standards in 1975-1977 to meet ocean discharge requirements, and additional controls starting in 1983 to comply with the EPA-mandated industrial pretreatment program.

Metals and other constituent levels in CSDLAC wastewater dropped substantially between the early 1970's and the mid 1980's as a result of implementation of these industrial pretreatment programs. A concomitant rise in both total and dissolved sulfide levels in the wastewater occurred over this same time period. Further, CSDLAC observed an increase in the rate of corrosion in their concrete sewers.

Two hypotheses have been set forth to explain increased corrosion rates in CSDLAC sewers due to the reduction in levels of metals. The first is that at the higher levels of metals, a significant amount of sulfide was rendered insoluble in metal-sulfide compounds, reducing the amount of dissolved H_2S available for release to the sewer atmosphere. The second is that the higher levels of various metals and other compounds in the wastewater had a toxic effect on the sulfate-reducing bacteria responsible for the generation of sulfide. When the metal concentrations were significantly reduced, the sulfate-reducing bacteria flourished, increasing sulfide levels in the wastewater, which generated more dissolved H_2S. Both phenomenon would increase the amount of H_2S available for release to the sewer atmosphere, and subsequent corrosion of the sewer crown due to increased sulfuric acid production.

A thorough search of the literature and contacts with municipalities throughout the U.S. revealed that no data existed from other cities to show a correlation between implementation of industrial pretreatment standards and increased sulfide generation and corrosion. Municipalities simply do not have historical data on corrosion rates or sulfide levels that would allow establishing a correlation such as was found in CSDLAC.

Given the unavailability of full-scale data to support the theory proposed by CSDLAC, the study objectives were determined to be as follows:

1. Investigate the theoretical impacts of metals on sulfide levels.
2. Review and analyze research conducted or supported by CSDLAC.

3. Compare metals levels of CSDLAC with other cities to assess whether other municipal sewerage systems could potentially experience a similar phenomenon (decrease in industrial wastewater constituents and increase in corrosion).

4. Review data from site visits to industrial cities to determine if corrosion rates differed in sewers with high industrial contributions vs. those with predominately residential contributions.

5. Review other potential impacts of implementing pretreatment standards.

3.2 Theoretical Impacts of Sulfide Reaction with Metals

It is well known that many metals "bind" with sulfide to produce a precipitate which is insoluble, effectively preventing release of hydrogen sulfide gas to the sewer atmosphere and preventing formation of corrosive sulfuric acid. As discussed in Section 4, salts of metals such as iron and zinc are routinely added to wastewater to prevent odors and corrosion associated with hydrogen sulfide.

The weight of metal required to precipitate a given weight of sulfide can be predicted theoretically using chemical reaction equations. Table 3-1 shows the probable precipitation reactions of metals with sulfide in wastewater devoid of oxygen. Based on the stoichiometry of the reactions, the necessary concentration of each metal required to precipitate 1 mg/l of sulfide has been calculated. The last column shows the inverse of this value, or the theoretical concentration of sulfide that would be precipitated by 1 mg/l of metal. However, in wastewater containing a complex mix of organic and inorganic compounds which interfere with such reactions, the amount of metal required to precipitate a given weight of sulfide may be much greater than what would be predicted from the equations.

Table 3-2 shows the theoretical stoichiometric increase in dissolved sulfide concentration based on the reduction in metals concentration experienced in CSDLAC between the periods 1971-1974 and 1983-1986. The total theoretical increase in dissolved sulfide due to reduced availability of metals to precipitate the sulfide is approximately 4 mg/l. The measured increase in dissolved sulfide during that same period was approximately 1 mg/l.

Reduction in iron alone accounts for 69 percent of the theoretical increase in sulfide. Zinc accounts for 16 percent, and chromium 10 percent. The reduction in these three metals accounts for 95% percent of the theoretical increase in dissolved sulfide levels.

Because of its toxicity, chromium is not used for sulfide control. However, data are available on dosage requirements for iron and zinc to precipitate sulfide that are

TABLE 3-1

PROBABLE METAL - SULFIDE PRECIPITATION REACTIONS IN WASTEWATER DEVOID OF OXYGEN

Reactions			Theoretical mg/l of Metal to Precipitate 1 mg/l of Sulfide	Theoretical mg/l of Sulfide Precipitated by 1 mg/l of Metal
$Fe^{+2} + S^{-2}$	—>	FeS	1.74	0.57
$Zn^{+2} + S^{-2}$	—>	ZnS	2.04	0.49
$Ni^{+2} + S^{-2}$	—>	NiS	1.83	0.55
$Cd^{+2} + S^{-2}$	—>	CdS	3.51	0.28
$Pb^{+2} + S^{-2}$	—>	PbS	6.48	0.15
$Cu^{+1} + S^{-2}$	—>	Cu_2S	3.97	0.25
$Cr^{+2} + S^{-2}$	—>	CrS	1.63	0.61

TABLE 3-2

THEORETICAL INCREASE IN DISSOLVED SULFIDE BASED ON METAL PRECIPITATION; LA COUNTY

Metal	Reduction in Metals[1] mg/l	Theoretical Increase in Dissolved Sulfide Concentration[2] mg/l	Expected Increase Based on Field Studies[3] mg/l
Chromium	0.68	0.42	--
Copper	0.38	0.10	--
Lead	0.17	0.03	--
Zinc	1.34	0.66	0.06 - 0.1
Nickel	0.14	0.08	--
Iron	4.92	2.83	0.1 - 0.7
Cadmium	0.01	0.00	--
TOTAL		4.12	

[1] Difference in average values for the periods 1971 - 1974 and 1983 - 1986.

[2] Based on stoichiometry of chemical precipation reactions

[3] Based on field dosages required to precipitate dissolved sulfide; LA County research data.

useful to estimate the actual increase in sulfide levels that might be expected by reduction in metals.

Studies by CSDLAC in 1985-1988 on the use of iron addition to control sulfide showed that when the dissolved sulfide levels were between 1 and 4 mg/l, a dosage ratio of six to seven parts iron to 1 part dissolved sulfide was required to achieve 90 percent removal. When the dissolved sulfide was less than 1 mg/l, a dosage ratio of 44 to 1 was required (1). The theoretical dosage ratio is 1.7 to 1. Thus, four to 25 times the theoretical dosage was required for iron. Other studies conducted in 1971-1972 in CSDLAC have showed that five to seven times the theoretical dosage is required to remove sulfide using zinc.

Based on this analysis, it is possible that the reduction in metals experienced by CSDLAC could account for some portion of the observed increase in dissolved sulfide, considering that iron and zinc can account for between 0.2 to 0.8 mg/l of the increase in dissolved sulfide. However, it is unlikely that precipitation could account for all of the measured increase in dissolved sulfide (over 1 mg/l) in CSDLAC wastewater.

During the period 1971 to 1986, total sulfide increased from 0.4 mg/l to 3.0 mg/l, and dissolved sulfide from 0.1 mg/l to 1.4 mg/l. If sulfide precipitation with metals was the only mechanism, the fraction of dissolved sulfide would increase, but the total sulfide level would remain essentially constant as metals were reduced. This is because the insoluble metal-sulfide precipitates are still detected in the total sulfide test. However, research by Pomeroy found that when iron was added to wastewater containing sulfide, a reduction in total sulfide was observed. Two explanations were suggested. The first is that one of the products of the reaction is iron disulfide, which when treated with acid in the sulfide test, forms H_2S and elemental sulfur. Elemental sulfur is not measured in the test. The second is that the iron may act as a catalyst to oxidize sulfide to a product which is not detected in the sulfide test (3). Thus, it is unlikely that chemical precipitation or the presence or absence of iron could account for the increase in total sulfide between 1971 and 1986.

3.3 Biological Inhibition by Metals and Toxic Compounds

CSDLAC has conducted in-house experiments to investigate inhibition of microbial sulfide generation by constituents present in wastewater. In addition, CSDLAC is partially funding research at the University of Arizona to investigate the toxic effects of metals on the sulfide-oxidizing bacteria Thiobacilli, which are responsible for the production of sulfuric acid on the sewer crown. Other research at the University of California at Los Angeles funded by CSDLAC has considered the effects of metals concentrations on both sulfate-reducing bacteria and sulfide-oxidizing bacteria.

The first in-house experiments conducted by CSDLAC were bench-scale laboratory studies designed to determine the acute toxicity levels of selected metals and cyanide on sulfate-reducing bacteria. Growth medium for sulfate reducers was dosed with varying concentrations of metals and cyanide. Tubes were inoculated with primary effluent containing the sulfate-reducing bacteria and incubated for three weeks. The tests involved dosing with individual metals and cyanide as well as with a stock solution containing nickel, chromium, zinc, copper, lead, cadmium, and cyanide in ratios approximating that in sewage to determine if a synergistic effect existed.

Table 3-3 shows the results of the experiment with the individual metals and cyanide. Copper was the most toxic at 6 mg/l, while cyanide was the least toxic at 50-55 mg/l(4).

The stock solutions containing the mixtures of metals and cyanide were added to the tubes at various dilutions to simulate total constituent concentrations of 1, 5, 10, 15, 20, and 25 mg/l. The distribution of constituents was as follows: nickel - 6.2%, chromium - 20.4%, zinc - 44.3%, copper - 13.3%, lead - 6.6%, cadmium - 0.7%, and cyanide - 8.5%. The results of this experiment showed that growth was completely inhibited at a total constituent concentration of 10 mg/l, but was not visibly affected at a concentration of 1 mg/l. At 5 mg/l, growth was notably retarded. A synergistic effect apparently existed when the combination of metals and cyanide were added to the growth medium.

CSDLAC performed a second experiment using column tests to determine on a larger scale how changes in wastewater metal concentrations affect the generation of sulfide. The testing was carried out at the Joint Water Pollution Control Plant (JWPCP) in Carson, California.

The test apparatus consisted of three 8-inch diameter, 6-feet high, polyvinyl chloride (PVC) pipes that functioned as test columns. The characteristics of the columns are shown in Figure 3-1. Each column was filled with 4 feet of hand-cut polystyrene cubes measuring 1.5 inches on each side. This provided a substrate for the attached growth of sulfide-generating bacteria. Primary effluent from the JWPCP was pumped through each column at a rate of 0.75 liters per minute at a temperature of 80°F. One column was used as a control while solutions with known metal concentrations were added to the influent of the other two columns. Dissolved sulfide and total sulfide levels were measured at the influent and effluent ends of each column. After each solution was tested, all the columns were cleaned, the polystyrene was replaced, and the system was flushed. As of April 1, 1989, seven different metal solutions had been tested.

The first of the seven trials was performed with a cocktail of chromium, copper, zinc, and cyanide. The feed rate of the cocktail was controlled so that the concentrations of metals in the wastewater approximated those of the early 1970's. The second trial was performed with five times the concentration of metals and cyanide in the wastewater. In the remaining trials, chromium, copper, nickel, and cyanide were

TABLE 3-3

TOXICITY OF WASTEWATER CONSTITUENTS ON SULFATE-REDUCING BACTERIA[1]

Compound	Toxic Conc. mg/l
Copper	6
Nickel	13
Chromium	23
Lead	25
Zinc	25
Cyanide	50-55

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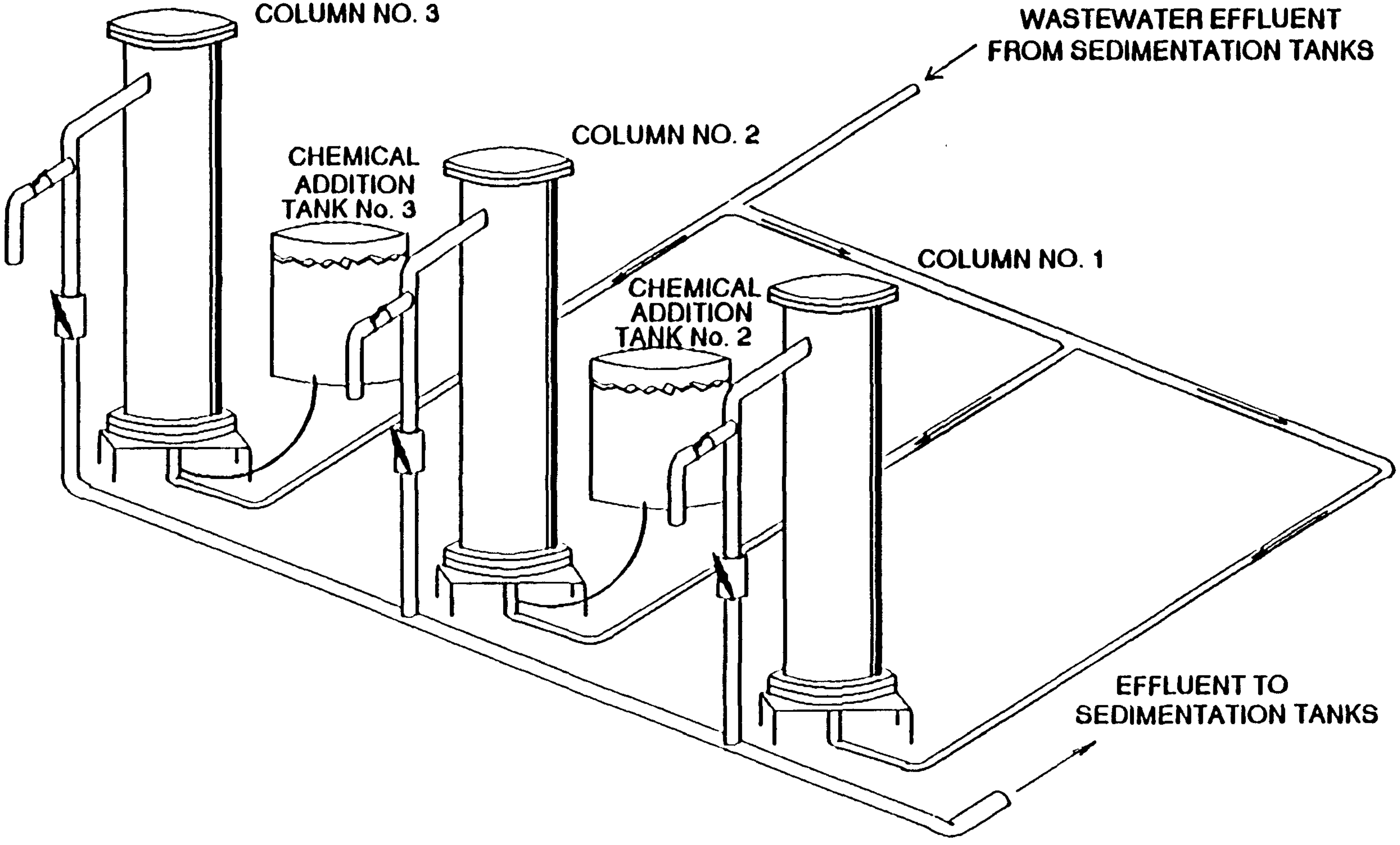
[1] In-house experiment conducted by CSDLAC

Figure 3-1

Sulfide Generation Pilot Plant
Upflow Packed Columns



each tested separately at wastewater concentrations approximating those of the early 1970's. The target concentrations for the trials are listed in Table 3-4.

Results of the column experiments are summarized in Table 3-5 and 3-6. Examination of the data yields several pertinent conclusions. Clearly, when the "cocktail" of metals and cyanide were added at five times the 1971-1974 concentration, sulfide generation was significantly inhibited. These results are supported by bench scale studies at the CSDLAC laboratory which showed that inhibition of sulfide-reducing bacteria requires metals concentrations much higher than that observed in wastewater. However, the concentration of metals causing sulfide generation inhibition in these pilot scale studies cannot be used to predict the increased levels of total and dissolved sulfide observed by CSDLAC in their sewers.

Of greater significance is the comparison of performance when the "cocktail" containing metals and cyanide was fed to the columns at the 1971-1974 levels. Total sulfide concentrations in the effluent from the control column and test column were 16.6 mg/l and 12.4 mg/l, respectively. Dissolved sulfide levels were 13.5 mg/l and 9.7 mg/l for the control and test columns, respectively. A statistical analysis was conducted of the data from the experiment in which metals and cyanide were added at the 1971-1974 levels, assuming identical influent metals concentrations in both control and test columns. The analysis indicated that at a 0.01 level of significance (highly significant), the total and dissolved sulfide concentrations in the effluent from the control columns were higher than the levels in the effluent from the test column. Further, it was determined that, at the 90% confidence level, the actual difference in effluent total sulfide concentrations was between 2.8 and 5.6 mg/l. For effluent dissolved sulfide, the actual difference was between 2.7 and 5.1 mg/l.

Based on the difference in sulfide levels in the effluent and influent for both the control column and the test column, CSDLAC staff prepared Figure 3-2 showing the percent change in sulfide generation upon addition of metals and cyanide. At the 1x levels (corresponding to the early 1970's), generation of total and dissolved sulfide was reduced by 34 percent. At the 5x levels, generation of total and dissolved sulfide was reduced by 114 and 106 percent, respectively. Interestingly, addition of zinc alone at the 1970's levels resulted in reduction of sulfide generation by approximately one third.

Another pilot study conducted by CSDLAC involved the construction of two 3/4-inch diameter, PVC "force mains," each 150 feet in length. One served as a control pipeline, receiving primary effluent, and the other served as a test pipeline receiving a "cocktail" of metals and cyanide similar to that used in the column experiment. One difference in the feed material to the pipeline pilot system was that iron was also included in the metals cocktail at a level approximately that of the early 1970's (10.7 mg/l). Only the 1x levels of metals and cyanide were used during the pipeline experiments. Figure 3-3 is a diagram of the pipeline pilot plant system.

TABLE 3-4

CONCENTRATION OF AGENTS ADDED TO UPFLOW PACKED COLUMNS (5)

Agent	1971-74 Concentration mg/l	1987 Concentration mg/l	1x Concentration mg/l	5x Concentration mg/l
Chromium	0.92	0.178	1.00	5.00
Copper	0.60	0.18	0.50	2.50
Cyanide	0.32	0.02	0.40	2.00
Nickel	0.285	0.087	0.25	2.25
Zinc	2.17	0.60	2.00	10.00

TABLE 3-5

AVERAGE INFLUENT SULFIDE, TOTAL COD, SUSPENDED SOLIDS AND EFFLUENT SULFIDE; UPFLOW PACKED COLUMNS (5)

	CONTROL COLUMN						TEST COLUMNS					
	------------Influent---------				--Effluent--		-----------Influent-----------				--Effluent--	
Additive	DS mg/l	TS mg/l	COD mg/l	SS mg/l	DS mg/l	TS mg/l	DS mg/l	TS mg/l	COD mg/l	SS mg/l	DS mg/l	TS mg/l
1x Mixture	7.3	9.5	413	84	13.5	16.6	5.6	7.6	399	112	9.7	12.3
5x Mixture	6.2	8.2	420	71	11.3	14.6	0.8	3.0	426	70	0.5	2.1
Cyanide	8.9	11.0	381	80	15.0	17.8	5.7	7.6	360	61	13.9	17.4
Chromium (VI)	7.5	10.0	289	58	12.7	15.8	4.9	6.9	407	88	9.9	12.5
Nickel	6.5	8.4	509	77	15.1	17.4	6.1	8.8	608	211	13.8	16.1
Copper	6.5	8.4	509	77	15.1	17.4	4.6	6.9	513	149	13.4	16.3
Zinc	4.2	7.0	440	86	13.1	15.9	2.8	5.8	407	135	9.0	11.7
Chromium (III)	6.2	6.8	681	342	12.0	14.1	3.8	5.0	537	238	11.6	13.5

TABLE 3-6

COMPARISON OF CONTROL AND TEST COLUMNS' SULFIDE GENERATION; UPFLOW PACKED COLUMNS (5)

	EFFLUENT MINUS INFLUENT SULFIDE				PERCENT CHANGE	
	Control		Test		Control vs. Test	
Additive	DS mg/l	TS mg/l	DS mg/l	TS mg/l	DS %	TS %
1x Mixture	6.2	7.1	4.1	4.7	-34.0	-34.0
5x Mixture	5.1	6.4	-0.3	-0.9	-106.0	-114.0
Cyanide	6.1	6.8	8.2	9.8	34.0	44.0
Chromium (VI)	5.2	5.8	5.0	5.6	-4.0	-3.0
Nickel	8.6	9.0	7.7	7.3	-10.0	-19.0
Copper	9.6	9.0	8.8	9.4	2.0	4.0
Zinc	8.9	8.8	6.1	5.9	-32.0	-33.0
Chromium (III)	5.8	7.3	7.9	8.5	36.0	16.0

Figure 3-2

Percent Change in Sulfide Generated Due to Metals and Cyanide

Upflow Packed Column Pilot Plant

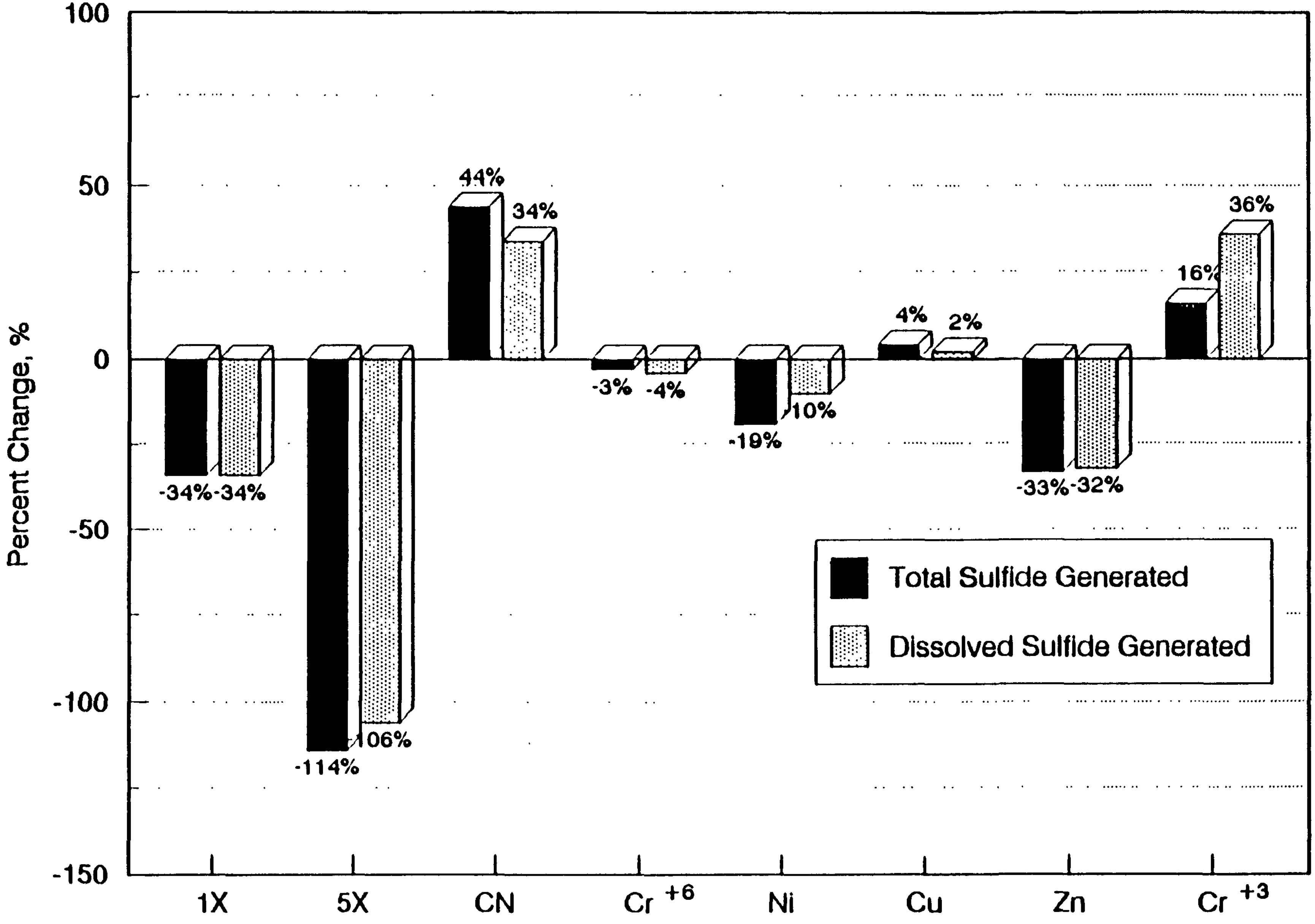
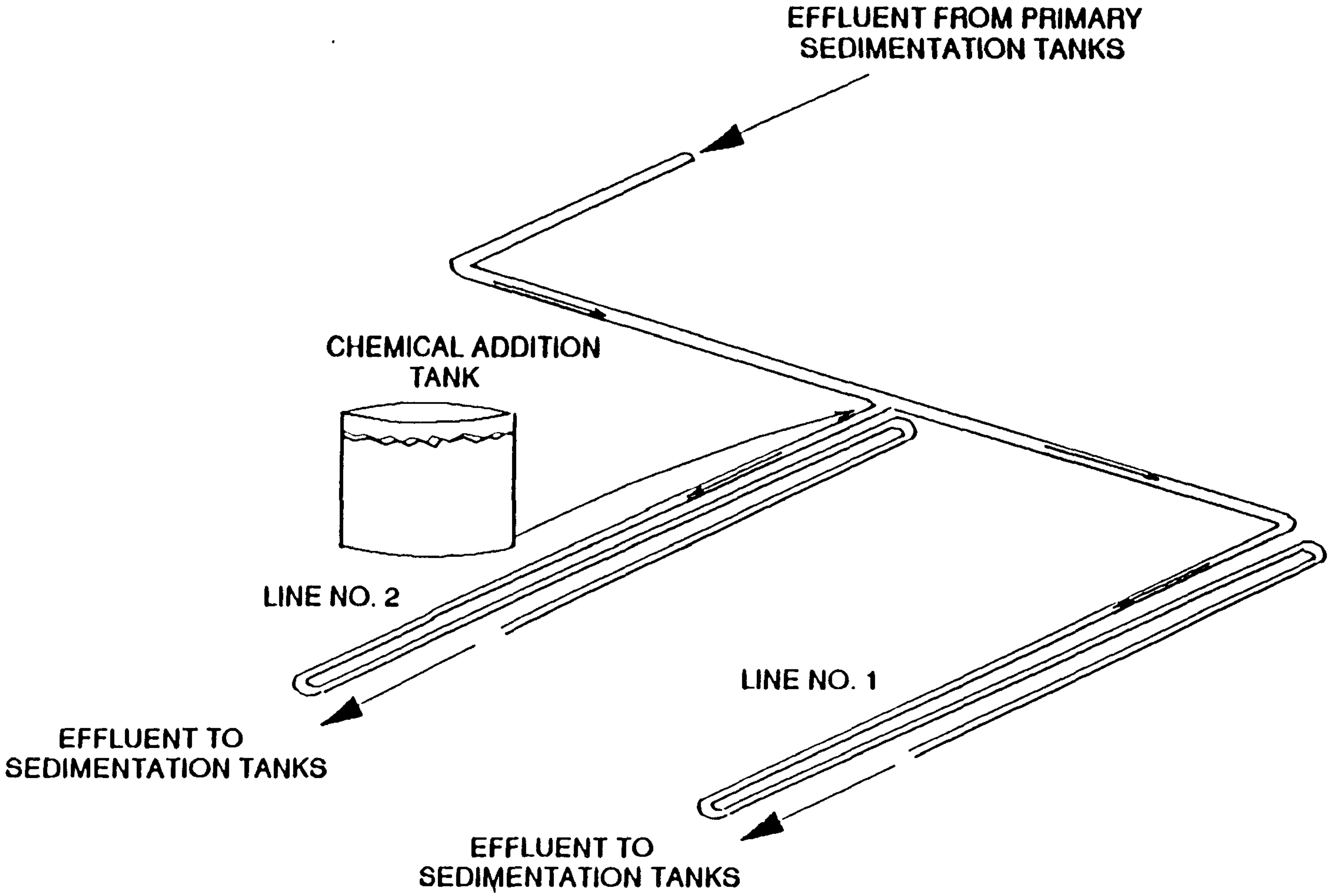


Figure 3-3

Sulfide Generation Pilot Plant

Pipeline System



Tables 3-7 and 3-8 provide the results of the experiment. At the 1x metals and cyanide dosage without supplemental iron, the generation of total and dissolved sulfide was reduced by 36 to 25 percent, respectively. When iron was added to simulate concentrations in the early 1970's, total dissolved sulfide generation was reduced by 51 and 77 percent, respectively. These results are depicted graphically in Figure 3-4.

The results of these experiments strongly suggest that the generation of hydrogen sulfide in the wastewater of CSDLAC was suppressed due to the presence of constituents associated with industrial discharges of the early 1970's. Higher levels of sulfide in the wastewater would be expected to result in higher concentrations of hydrogen sulfide gas in the sewer atmosphere and higher sewer corrosion rates. However, the relationship between wastewater sulfide levels and corrosion rate is not well established.

3.4 Comparison of Metals at CSDLAC with Other Cities Before Pretreatment

Using available data, pre-1975 levels of metals and cyanide entering the main CSDLAC wastewater treatment plant were compared with levels in the wastewater of other municipalities across the U.S.. Data were analyzed for 50 cities from the EPA report, "Fate of Priority Pollutants in Publicly Owned Treatment Works"(6)(7). These data were collected in 1978-1979 prior to any significant implementation of industrial pretreatment standards. The fifty cities typically had estimated industrial flow contributions ranging from ten to fifty percent of the total flow. Analysis of these data allowed determination of the number of cities with metals and cyanide levels similar to those of CSDLAC prior to pretreatment, and assessment of whether other cities may have had the potential to experience suppression of sulfide generation and corrosion due to the presence of these constituents.

Table 3-9 shows a ranking of the 50 cities plus CSDLAC based on the concentrations of selected metals and cyanide in the wastewater. This was developed from the sum of the equivalent weight concentrations of each of the constituents, and does not account for the relative toxicity of the constituents on sulfide-producing bacteria. Of the 50 other municipalities, only three (six percent) are ranked higher than CSDLAC, while 47 (94 percent) are ranked lower. The total concentration of metals and cyanide in CSDLAC wastewater was approximately three times the median concentration for the 51 cities. Table 3-10 shows the actual constituent concentrations, in ug/l, for the 51 cities.

The total metals levels in CSDLAC wastewater in 1986 are also shown in Table 3-9. On an equivalent weight basis, 1986 levels were 42 percent of 1971 - 1974 levels. Comparing 1986 CSDLAC levels with 1978 - 1979 levels of 50 other cities, 16 cities (32 percent) were higher than CSDLAC, and 34 cities (68 percent) were lower.

Clearly, sulfide generation and corrosion in CSDLAC sewers increased

TABLE 3-7

AVERAGE INFLUENT AND EFFLUENT SULFIDE; PIPELINE PILOT PLANT (5)

	CONTROL PIPELINE				TEST PIPELINE			
	--Influent--		--Effluent--		--Influent--		--Effluent--	
Additive	DS mg/l	TS mg/l	DS mg/l	TS mg/l	DS mg/l	TS mg/l	DS mg/l	TS mg/l
1x Mixture	2.5	3.8	7.9	9.7	2.7	3.7	6.4	7.5
1x Mixture+Fe	2.5	3.9	7.8	9.8	2.5	3.6	3.9	6.4

TABLE 3-8

COMPARISON OF CONTROL AND TEST PIPELINE SULFIDE GENERATION: PIPELINE PILOT PLANT (5)

	EFFLUENT MINUS INFLUENT SULFIDE				PERCENT CHANGE	
	Control		Test		Control vs. Test	
Additive	DS mg/l	TS mg/l	DS mg/l	TS mg/l	DS %	TS %
1x Mixture	5.2	5.9	3.8	3.8	-25	-36
1x Mixture+Fe	5.3	5.9	1.4	2.8	-77	-51

Figure 3-4

Percent Change in Sulfide Generated Due to Metals and Cyanide

Pipeline Pilot Plant

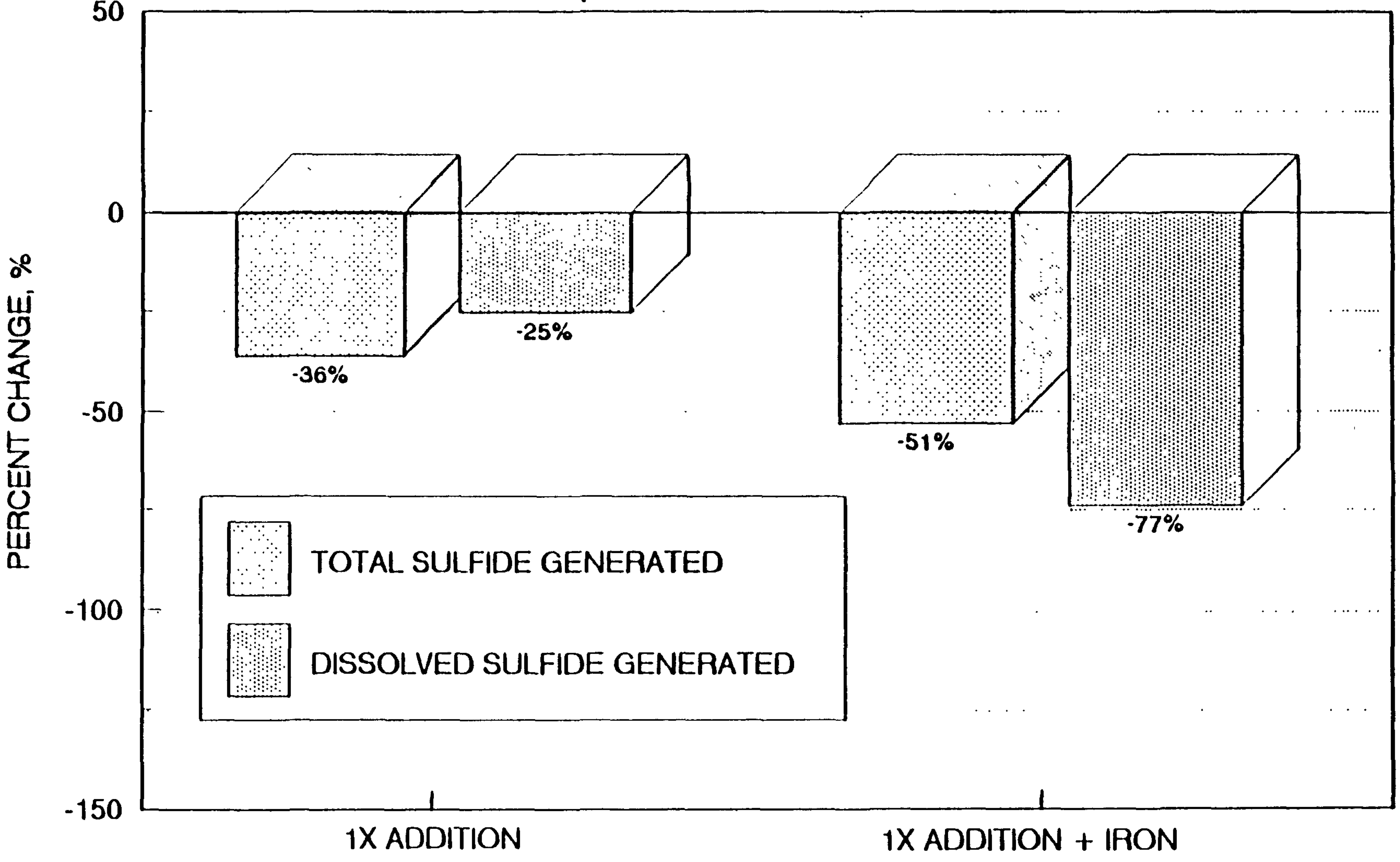


TABLE 3-9

COMPARISON OF CSDLAC METALS LEVELS BEFORE AND AFTER PRETREATMENT WITH METALS LEVELS OF 50 CITIES IN 1978-1979

	Equivalent wt.									
	CADMIUM	CHROMIUM	COPPER	CYANIDE	LEAD	MERCURY	NICKEL	ZINC	IRON	TOTAL
PLANT	ueq/l	ueq/l	ueq/l	ueq/l	ueq/l	ueq/l	ueq/l	ueq/l	ueq/l	ueq/l
1	0.30	33.00	8.40	2.35	5.63	0.00	6.44	205.44	5440.47	5702.04
2	17.19	82.04	25.27	4.73	1.58	0.05	14.99	119.19	313.00	578.05
3	19.14	80.20	23.92	3.81	1.92	0.03	23.89	150.94	263.68	567.54
LA County(A)	0.57	52.79	18.76	12.38	3.01	0.01	9.75	66.19	383.40	546.87
4	1.78	72.24	4.34	3.23	2.09	0.00	7.43	28.38	423.55	543.05
5	0.07	1.62	8.47	3.85	0.95	0.01	2.08	9.70	468.21	494.94
6	0.91	9.81	53.63	15.92	11.81	0.01	3.10	219.30	110.01	424.50
7	0.02	9.17	10.39	0.19	1.87	0.02	1.57	24.65	364.28	412.16
8	0.04	240.88	3.27	2.08	2.51	0.02	4.77	46.49	91.18	391.24
9	0.18	13.04	3.87	182.58	1.31	0.00	3.34	14.86	152.81	372.00
10	0.02	14.77	10.61	0.42	3.18	0.00	14.55	52.67	195.53	291.75
11	0.04	4.62	1.48	1.42	1.23	0.01	0.68	15.11	263.51	288.09
12	0.07	24.64	4.78	50.88	1.27	0.01	37.38	8.66	134.30	261.99
13	0.07	26.54	11.90	5.42	2.71	0.00	10.22	28.35	170.29	255.51
14	0.04	8.94	9.16	12.96	0.07	0.00	13.43	24.44	180.60	249.63
15	3.10	23.89	29.02	34.27	0.56	0.01	5.59	49.40	103.43	249.24
16	0.21	24.17	5.76	0.65	0.46	0.00	3.17	7.95	190.88	233.27
LA County(B)	0.25	10.90	5.63	0.85	1.50	0.00	3.37	22.98	183.99	229.47
17	0.02	13.79	1.86	3.19	0.48	0.01	0.85	5.78	199.40	225.38
18	0.04	23.66	0.63	60.31	0.48	0.00	1.70	84.69	45.27	216.78
19	0.09	16.67	7.02	1.62	0.69	0.01	11.76	18.93	124.02	180.81
20	0.04	3.17	3.68	81.62	0.56	0.00	0.34	7.13	79.22	175.75
21	0.02	9.40	2.58	67.42	0.43	0.01	0.34	7.98	84.98	173.18
22	0.04	2.94	3.68	6.50	1.31	0.01	0.82	10.09	146.94	172.33
23	0.05	2.83	3.21	2.73	0.34	0.00	0.72	11.65	135.73	157.26
24	1.78	26.43	5.35	1.46	1.93	0.00	5.79	24.25	73.88	140.88
25	0.07	0.87	0.66	0.08	1.19	0.01	0.37	3.49	132.50	139.24
26	0.04	2.25	5.82	9.35	0.25	0.01	2.15	11.32	104.75	135.93
27	0.04	7.21	7.59	1.08	0.48	0.01	1.87	12.08	96.16	126.51
28	0.27	9.92	5.19	9.81	1.01	0.01	2.35	18.08	79.57	126.22
29	0.07	4.62	3.37	46.73	0.53	0.01	0.20	5.47	63.32	124.32
30	0.18	6.17	3.08	27.46	0.45	0.01	1.84	6.85	72.88	118.93
31	0.04	0.06	0.63	6.73	0.48	0.00	0.34	2.84	103.50	114.62
32	0.09	6.29	3.30	17.38	0.49	0.00	2.93	7.10	71.52	109.11
33	0.04	0.06	1.23	77.04	0.48	0.00	0.34	3.15	25.18	107.51
34	0.14	5.54	7.93	6.31	1.93	0.00	9.03	5.54	65.50	101.92
35	1.19	7.62	11.27	10.27	0.88	0.01	3.68	10.77	46.16	91.84
36	0.04	2.65	10.58	8.23	0.37	0.01	2.11	6.91	60.63	91.52
37	0.16	8.77	7.71	27.42	1.53	0.01	2.18	5.99	34.42	88.19
38	0.44	4.73	1.95	7.85	0.09	0.00	0.75	8.38	60.09	84.28
39	0.16	5.77	4.47	11.12	1.30	0.01	2.73	7.40	49.06	82.02
40	0.04	5.83	6.96	19.23	0.15	0.01	0.17	3.67	45.34	81.39
41	0.04	1.90	3.46	14.23	0.48	0.01	0.44	3.58	53.79	77.93
42	0.07	4.10	1.70	2.96	0.15	0.00	1.02	8.50	58.73	77.24
43	0.05	0.69	3.75	3.92	0.28	0.01	3.99	8.99	52.36	74.04
44	0.48	6.23	5.82	10.65	0.78	0.00	1.16	8.32	39.50	72.95
45	0.05	3.17	2.20	3.15	0.88	0.01	1.29	4.89	53.90	69.56
46	0.04	0.92	2.27	31.62	0.33	0.01	0.14	6.36	25.50	67.17
47	0.11	5.89	2.20	0.46	0.65	0.00	0.00	7.59	42.69	59.58
48	0.04	0.06	0.72	0.77	0.39	0.01	0.27	2.72	50.14	55.12
49	0.02	0.52	1.83	4.81	0.09	0.00	3.27	4.43	26.21	41.18
50	0.02	0.75	6.23	4.65	0.23	0.00	0.14	3.67	24.32	40.01

LA County (A) - Average levels during 1971 - 1974

LA County (B) - Average levels during 1986

TABLE 3-10

METALS AND CYANIDE CONCENTRATIONS IN WASTEWATER FROM 51 CITIES[1]

	Concentration								
PLANT	CADMIUM ug/l	CHROMIUM ug/l	COPPER ug/l	CYANIDE ug/l	LEAD ug/l	MERCURY ng/l	NICKEL ug/l	ZINC ug/l	IRON ug/l
1	17	572	267	61	583	133	189	6717	151917
2	10	226	123	4747	136	333	98	486	4267
LACounty[2]	32	915	596	322	312	1400	286	2164	10706
4	966	1422	803	123	164	5000	440	3897	8740
5	1076	1390	760	99	199	3233	701	4935	7363
6	100	1252	138	84	217	300	218	928	11827
7	4	28	269	100	98	1000	61	317	13074
8	51	170	1704	414	1223	617	91	7170	3072
9	2	55	117	2122	58	67	10	233	2212
10	1	159	330	5	194	1667	46	806	10172
11	4	427	152	1323	132	983	1097	283	3750
12	2	410	20	1568	50	295	50	2769	1264
13	1	163	82	1753	45	1050	10	261	2373
14	174	414	922	891	58	517	164	1615	2888
15	2	1	39	2003	50	200	10	103	703
16	2	80	47	37	127	1250	20	494	7358
17	1	256	337	11	329	350	427	1722	5460
18	2	155	291	337	7	333	394	799	5043
19	2	4175	104	54	260	2000	140	1520	2546
20	4	80	107	1215	55	600	6	179	1768
21	4	460	378	141	281	117	300	927	4755
22	1	239	59	83	50	900	25	189	5568
23	12	419	183	17	48	305	93	260	5330
24	10	107	98	714	47	600	54	224	2035
25	2	51	117	169	136	517	24	330	4103
26	5	289	223	42	72	1000	345	619	3463
27	9	152	245	713	158	667	64	196	961
28	3	49	102	71	35	283	21	381	3790
29	2	39	185	243	26	767	63	370	2925
30	2	16	72	822	34	633	4	208	712
31	5	109	105	452	51	300	86	232	1997
32	15	172	165	255	105	933	69	591	2222
33	4	15	21	2	123	833	11	114	3700
34	2	101	221	500	16	833	5	120	1266
35	2	1	20	175	50	67	10	93	2890
36	100	458	170	38	200	400	170	793	2063
37	2	125	241	28	50	617	55	395	2685
38	2	33	110	370	50	533	13	117	1502
39	67	132	358	267	91	550	108	352	1289
40	8	96	252	164	200	333	265	181	1829
41	2	46	336	214	38	683	62	226	1693
42	9	100	142	289	135	817	80	242	1370
43	25	82	62	204	9	50	22	274	1678
44	27	108	185	277	81	350	34	272	1103
45	3	12	119	102	29	833	117	294	1462
46	4	71	54	77	16	214	30	278	1640
47	3	55	70	82	91	999	38	160	1505
48	6	102	70	12	67	12		248	1192
49	2	1	23	20	40	1167	8	89	1400
50	1	9	58	125	9	483	96	145	732
51	1	13	198	121	24	500	4	120	679
	CADMIUM	CHROMIUM	COPPER	CYANIDE	LEAD	MERCURY	NICKEL	ZINC	IRON
AVG:	55	314	232	472	131	757	135	911	6393
STD:	198	638	284	799	187	812	198	1539	20791
Without PLANT #1									
AVG:	56	299	226	477	120	770	133	771	3416
STD:	200	644	287	805	177	816	199	1315	2948

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[1] Compiled from data contained in Refs. 5,6,7

[2] LA County - average levels during 1971-74. All other data for 1978-79.

dramatically between 1971 and 1986, and metals and cyanide levels dropped significantly. Unfortunately, it is not known what levels of specific metals, cyanide, and combinations cause suppression of hydrogen sulfide corrosion. Although CSDLAC appears to have passed a threshold level of metals and cyanide which resulted in increased sulfide levels and corrosion, it is difficult to predict whether other cities could experience a similar increase in sulfide generation and corrosion upon reduction in metals levels resulting from industrial pretreatment.

3.5 Site Visits to Industrialized Cities

EPA conducted site visits to three cities having portions of the sewer system with high industrial contributions. Initially, it was believed that comparison of corrosion in residential vs. industrial sewers might show differences attributable to the metals and other constituents present in the wastewater. The cities were Charlotte, NC; Milwaukee, WI; and Tempe, AZ.

3.5.1 Charlotte, North Carolina (see also Section 2.2.7)

In the Charlotte sewer system, four sewers conveying primarily residential wastewater and six sewers with a large industrial flow contribution were inspected. All of the sewers were 20 to 25 years old.

Total sulfide levels in the residential sewers ranged from 0.2 to 0.6 mg/l. Pipe surface pH measurements were generally 6.0, with the exception of one site where surface pH levels ranged from 4.5 to 6.0. At that site, corrosion penetration was approximately 0.25 inches, exposing aggregate. No measurable H_2S was detected in the sewer head space at any of the four sites.

Two of the six industrial sites showed signs of shallow hydrogen sulfide corrosion, with penetration estimated to be up to 0.12 inches. Wastewater sulfide levels at the six sites ranged from 0.0 to 0.3 mg/l. At sites where corrosion was observed, high turbulence levels were noted. Wastewater pH measurements were 6.0 at four of the industrial sites, 5.5 at one site, and 10.0 at the remaining site. No H_2S was detected in the headspace at any of the six industrial sites.

3.5.2 Milwaukee, Wisconsin (see also Section 2.2.8)

In Milwaukee, observations included five sewers conveying primarily residential wastewater and five sewers with a heavy industrial flow contribution. Three of the residential sites were located in the Jones Island WWTP service area, and were concrete pipes ranging in age from 50 to 70 years. No corrosion was observed, and the surface pH of the concrete was measured to be 6.5. Two other residential sites were sewers in the South Shore WWTP service area. One site was a sewer less than 20 years old; the other was 50 years old. The 20 year old sewer was similar to the first three - no corrosion and high surface pH. However, at the other site wastewater sulfide content was 0.5 mg/l and the crown pH was 3.5. Severe corrosion was observed, with up to one inch of concrete lost.

All five industrial sites are at least 6 miles downstream from the beginning of the collection system and at least 40 years old. No corrosion was observed at any of these sites. However, two sites had measurable wastewater sulfide levels of 0.18 and 0.40 mg/l. Crown pH levels were between 6.0 and 7.0 at all of the industrial sites. One site was less than 0.5 miles downstream of a tannery.

3.5.3 Tempe, Arizona

A site visit was made to Tempe because one area of the City generated wastewater primarily of industrial origin. These industries included four circuit board manufacturers, two electroplaters, two metal finishers, one coating operation, and two dry cleaners. It was believed that results of detailed monitoring data from industrial vs. residential areas could provide some insight as to the impact of industrial discharges on the extent of hydrogen sulfide corrosion.

Data from previous monitoring by City of Tempe staff were reviewed, and inspections were made of industrial and residential sewers. The City had measured sulfide, pH, temperature, ORP, and D.O. of the wastewater, and had contracted with a local laboratory for metals analysis. At the industrial site, dissolved sulfide levels ranged from 0.05 to 1.9 mg/l on five separate days (grab samples). Dissolved sulfide levels averaged 0.6 mg/l. Atmospheric H_2S levels were 1 to 2 ppm. Wastewater pH ranged from 8.0 to 8.9. Inspection of a manhole in the 27 inch sewer conveying the majority of wastewater from the industrialized area showed no evidence of corrosion. The sewer system in this area was approximately 20 years old, and appeared to be in excellent condition with no sign of deterioration. On the day of inspection, no atmospheric H_2S was detected in the manhole near the liquid surface.

A large trunk sewer conveying residential wastewater from the adjoining City of Mesa was inspected at several locations. Previous monitoring by the City of Tempe had indicated dissolved sulfide levels of up to 9 mg/l, and atmospheric H_2S levels of up to 68 ppm. The concrete manholes which were unprotected exhibited severe corrosion above the waterline, with abundant quantities of corrosion product. Several manhole chambers had been lined with plastic, and those manholes that were sources of odor complaints were equipped with carbon canisters to control odor emissions.

No conclusions could be drawn from existing data regarding the impact of industrial discharges on hydrogen sulfide corrosion. A further, detailed monitoring program was abandoned because of the high pH (8.0 to 8.9) of the wastewater emanating from the industrial zone. This high pH prevents significant amounts of H_2S from being released from solution, since over 90 percent of the dissolved sulfide is present as the hydrosulfide ion, not as the dissolved gas. In general, it is believed that attempts to assess the impacts of metals and other industrial constituents on hydrogen sulfide corrosion by monitoring industrial vs. residential sewers are futile due to the many factors which affect sulfide generation and corrosion.

3.6 Beneficial Effects of Local Industrial Pretreatment Programs

It is important to recognize that several aspects of the industrial pretreatment standards may actually lower the potential for sulfide generation and corrosion in sewer systems. Among the more important of these are 1) reduction of sulfide-bearing wastes, 2) reduction of high strength organic waste discharges, 3) reduction of high temperature discharges, 4) reduction in fats, oils, and grease, and 5) reduction in acidic wastes. Because of the complex interaction of all the factors that affect sulfide generation, it is very difficult to quantify these effects for a broad base of sewer systems. Beneficial impacts of local regulation of industrial waste discharges on sulfide generation in municipal sewers are summarized in Table 3-11. In this table, sulfide is the only parameter specifically regulated by the EPA Categorical Pretreatment Standards.

3.7 Conclusions

The national effects of industrial pretreatment on hydrogen sulfide corrosion are impossible to ascertain since no municipalities other than CSDLAC were found to have sufficient data to establish a correlation. Based on theoretical analysis, review of full scale and pilot scale research data from CSDLAC, and a series of site investigations, the following conclusions are presented.

- The reduction in metals and other industrial constituents in CSDLAC wastewater apparently caused an acceleration in corrosion rate, possibly due to biological inhibition and/or chemical precipitation.

- Two pilot studies conducted by CSDLAC demonstrated that sulfide generation was reduced when metals were added to the wastewater at levels approximating those in the early 1970's.

- When comparing 1970's data from 50 other cities having 10 to 50 percent industrial flow input, total metals and cyanide levels in CSDLAC wastewater were higher than levels in 94 percent of 50 U.S. cities.

- If current (1986) CSDLAC data are compared with 1970's data from 50 cities, CSDLAC levels would be lower than 32 percent of the cities.

- It is difficult to project how many cities could potentially be adversely affected by industrial pretreatment since it is not known at what levels industrial constituents begin to suppress sulfide generation.

TABLE 3-11

BENEFICIAL IMPACTS OF CONTROLLING INDUSTRIAL DISCHARGES ON SULFIDE CORROSION

Type of Discharge Controlled	Benefit
Sulfide-bearing wastes	Lowers sulfide levels, corrosion potential
High organic strength (BOD) wastes	Sulfide generation rate proportional to BOD; reduction in organic strength reduces oxygen uptake and depression of dissolved oxygen
High temperature wastes	Lower temperature reduces sulfide generation rate; increases solubility of H_2S, reducing release of H_2S; increases solubility of oxygen
Wastes containing fats, oils, and grease	Reduces potential for sewer clogging, reduced velocities, solids deposition, and sulfide generation
Low pH wastes	Maintaining pH at or above neutral reduces release of H_2S to the sewer atmosphere

- Site visits to inspect corrosion in residential vs. industrial sewers were inconclusive regarding the impacts of metals and other industrial constituents on hydrogen sulfide corrosion.
- Local regulation of certain non-toxic constituents in industrial waste discharges has likely had a beneficial impact in reducing the potential for sulfide generation and corrosion.
- Additional research is necessary to establish the constituents and their associated levels at which sulfide generation is suppressed or accelerated.

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4.0 DETECTION, PREVENTION AND REPAIR OF HYDROGEN SULFIDE CORROSION DAMAGE

Alternatives for the detection and prevention of hydrogen sulfide corrosion in both existing and new wastewater systems, and techniques for repairing hydrogen sulfide corrosion damage, are summarized in this section. Additional detailed information may be found in publications prepared by the Environmental Protection Agency, The American Society of Civil Engineers, the American Concrete Pipe Association, and the U.S. Department of Housing and Urban Development (1)(2)(10)(7).

4.1 Detection and Monitoring of Hydrogen Sulfide Corrosion

One of the most useful "early warning" indicators of potential hydrogen sulfide corrosion problems is pH of the pipe crown or structure wall. This is a simple test using color-sensitive pH paper which is applied to the moist crown of the pipe. New pipe has a high pH of 10 to 11. After aging the pH of the crown under non-corrosive conditions may drop to near neutral. Pipe experiencing severe hydrogen sulfide corrosion may have a pH of 2 or lower.

Dissolved sulfide levels in the wastewater and hydrogen sulfide levels in sewer headspaces can be checked to determine if sulfide is being generated in the sewers and where and to what extent it is being released from solution. Routine monitoring may be justified at the lift stations, junction structures, discharges of force mains, treatment plant headworks, or other locations in the collection and treatment system. Such tests indicate whether conditions are present for hydrogen sulfide corrosion to occur.

Routine visual inspections are essential. Where accessible by a worker, this can be done by entering manholes or sewers and checking the soundness of the pipe material. A screwdriver or other sharp tool can be used to determine the depth of penetration into soft corrosion product. Since corrosion products occupy greater volume than the original concrete, depth of penetration is not an accurate measurement of concrete lost to corrosion (section 1.4). Concrete loss can be approximated by measuring the depth of aggregate protrusion from the surface. Sewer pipe may also be inspected remotely through the use of television cameras. With improvements in the resolution of camera equipment, TV inspections can often identify corrosion problems, although considerable damage may already have been done.

A relatively recent development in remote sewer inspections is the use of "sonic caliper" technology to measure the inside dimensions of the pipe. Sonic signals are transmitted from a floating raft to the pipe walls, and the signal is detected after reflecting off the wall. Software developed by a proprietor is used to process the signals and determine the variation in pipe diameter along its length. Areas where loss of pipe material has occurred can thus be detected. The technique was successfully used to inspect over 40,000 feet of 36 in. to 54 in. diameter pipe in Tampa, Florida (9).

Core borings of the pipe crown and submerged pipe may be taken to calculate the extent of the corrosion loss. Some municipalities only take cores of corroded portions of pipes to determine how much pipe remains. Expandable rods have also been used to measure the inside pipe diameter, rather than taking core borings, as a means of estimating the extent of corrosion, although errors are introduced due to variation in wall thickness and pipe "roundness."

To determine the rate of corrosion, the thickness of corroded pipe must be compared at two different points in time, since no instantaneous technique has been proposed for monitoring corrosion rates. CSDLAC is the only entity known that has determined corrosion rate on a regular basis using core borings. Some sewers may be installed with vitrified clay "plugs" or stainless steel rods in the crown at accessible locations, providing a direct visual comparison of adjacent corroded and non-corroded material.

4.2 Prevention of Hydrogen Sulfide Corrosion in Existing Systems

A number of techniques have been used to control corrosion and odors associated with hydrogen sulfide generation in existing systems. The most common techniques can be divided into the general categories of oxidants, precipitants, or pH elevators. Oxidants control sulfide by chemically or biologically causing the oxidation of sulfide to thiosulfate or sulfate. Such techniques include air or oxygen injection, or addition of chemicals such as hydrogen peroxide, chlorine, or potassium permanganate. Precipitants control sulfide by precipitation with a metal salt such as ferrous chloride, ferrous sulfate, or zinc salts. The dissolved sulfide is converted to an insoluble precipitate, preventing release of gaseous H_2S. Elevation of the pH through shock dosing of caustic controls sulfide generation by inactivation of sulfide-producing slimes present on the wall of the sewer pipe. A summary of sulfide control techniques is provided in Table 4-1.

All of the above control techniques are oriented towards reducing the levels of dissolved sulfide in solution such that less sulfide is released to the sewer atmosphere. Work conducted by CSDLAC indicated that, although significant reductions (75 to 95%) in dissolved sulfide could be obtained with chemical addition, only modest reductions (50 to 60%) in H_2S levels in the sewer atmosphere were realized (4). Thus, a 90% reduction in dissolved sulfide does not necessarily indicate that the rate of corrosion will be reduced by 90%. Although empirical predictive corrosion equations assume that corrosion rate is directly proportional to the rate of H_2S flux from the wastewater to the sewer walls, this relationship is very difficult to verify with field data.

No one sulfide control technique can be generalized as being the most cost-effective. Dosages of chemicals to control sulfide vary widely from one wastewater system to another, and are dependent on wastewater characteristics and other site-specific factors. Sulfide control options must be considered on a case-by-case basis.

TABLE 4-1

SUMMARY OF SULFIDE CONTROL TECHNIQUES (4)

Technique	Frequency Of Use	Relative Cost	Advantages	Disadvantages
I. OXIDATION				
Air Injection	Low; limited by application	Low	Low cost, adds DO to wastewater to prevent further sulfide generation	Applicable only to force mains; potential for air binding
Direct oxygen injection	Low in U.S.; high in U.K., Australia	Low	5 x solubility of air; very economical for force mains; adds DO	Achieving good O_2 transfer may be difficult
Sidestream O_2 injection	Very low	Med.	Applicable to oxygenating gravity sewers and wet wells	Potential for degassing of O_2 from solution
Hydrogen peroxide	High	Med.	Effective for odor/corrosion control in grav. sewers or force mains; simple installation	Costs can be high if dosages much greater than stoichiometric
Chlorine	High	Med.-High	Applicable to grav. sewers or force mains	Safety considerations
Potassium permanganate	Low	High	Effective, powerful oxidant	High cost, difficult to handle

TABLE 4-1 (cont.)

SUMMARY OF SULFIDE CONTROL TECHNIQUES

Technique	Frequency Of Use	Relative Cost	Advantages	Disadvantages
II. PRECIPITATION				
Iron salts	High	Low - Med.	Can be used for sulfide control in gravity sewers or force mains	Does not control non-H_2S odors; sulfide control to low levels may be difficult
Zinc salts	Very low	Med.- High	Lower solubility than iron; may inhibit sulfate-reducing bacteria due to intrinsic toxicity	Not economical compared to iron salts; discharge is regulated
III. pH ELEVATION				
Sodium hydroxide (shock dosing)	Med	Low	Economical intermittent application	Special handling of high pH slug may be required at treatment plant
IV. OTHERS				
Sodium nitrate	Very low	Med.- High	Prevents reduction of sulfate to sulfide	Applicable only for the prevention of sulfide generation

Brief descriptions of sulfide control methods applicable to existing wastewater systems are provided below. More detailed information may be found in references (1) and (2).

4.2.1 Air Injection

Injection of compressed air into the wastewater is most applicable to force mains, siphons, and pipes flowing under pressure. Often, air is injected on the discharge side of sewage pumps to provide dissolved oxygen which promotes oxidation of existing sulfide and prevention of further sulfide build-up. The pressure in the pipe, being greater than atmospheric, allows dissolution of greater quantities of oxygen. Air injection is an economical alternative for sulfide control in pressurized lines. Because of the large quantities of air injected, potential exists for gas accumulation and increased head losses. Although research has been conducted on pressure tank dissolvers and U-tubes for use in aerating gravity sewers, such devices appear to be marginal for this purpose.

4.2.2 Oxygen Injection

Oxygen is five times more soluble in water than air, and thus it is possible to achieve higher DO levels in the wastewater. As with compressed air injection, oxygen is most applicable to sulfide control in force mains and pipes under pressure. However, it is currently being used in Sacramento to oxygenate wastewater in a fall structure, and CSDLAC has conducted demonstrations of pressurized sidestream dissolution for oxygenation of gravity sewers. In the *sidestream dissolution system*, a portion of the flow is directed through a pressurized pipe into which oxygen is injected. The oxygen-saturated sidestream is then introduced back into the gravity main.

Oxygen is generally an economical technique for sulfide control. However, the annual costs for purchased oxygen are highly dependent on how efficiently the oxygen is transferred into solution.

4.2.3 Hydrogen Peroxide

Hydrogen peroxide is widely used for sulfide control in force mains and gravity sewers. At neutral and acidic pH, H_2O_2 oxidizes H_2S to elemental sulfur. Dosage weight ratios of H_2O_2 to H_2S vary from near stoichiometric (1:1) to over 5:1, depending on degree of control desired, wastewater characteristics, initial sulfide level, and wastewater travel time between injection station and control point. Costs for sulfide control using hydrogen peroxide are competitive with other sulfide control chemicals.

4.2.4 Chlorine

Chlorine oxidizes sulfide to sulfate or elemental sulfur. Chlorine can be purchased as a gas or as hypochlorite solution. In practice, Cl_2:H_2S dosage weight ratios are typically in the range of 10:1 to 15:1. Although commonly used for sulfide control, dosage requirements and unit chemical costs often make chlorine uneconomical compared to other chemicals used for sulfide control. The hazardous nature of chlorine gas make it less attractive for use near residential areas.

4.2.5 Potassium Permanganate

Potassium permanganate is a powerful oxidant that is effective for sulfide control. In general, dosage weight of $KMnO_4$ to H_2S are approximately 6:1 to 7:1. Potassium permanganate is purchased as dry crystals. Chemical costs are high, and use of $KMnO_4$ for wastewater applications is generally not cost-effective.

4.2.6 Metal Salts

Iron salts such as ferrous sulfate and ferrous chloride are widely used, economical chemicals for sulfide control. Iron reacts with H_2S to form an insoluble precipitate, preventing release of H_2S from solution. In practice, dosage weight ratios of $FeSO_4$ to H_2S are approximately 5:1, although higher dosage ratios may be required depending on wastewater characteristics, initial sulfide levels, and degree of sulfide control required.

4.2.7 Sodium Hydroxide

Sodium hydroxide is added in "shock doses" to sewers for sulfide control. Caustic soda (NaOH) is added over a period of 20 to 30 minutes at sufficient dosages to elevate the pH to between 12.5 and 13.0. The high pH slug temporarily inactivates sulfate reducing bacteria and greatly reduces hydrogen sulfide generation. Within a period of several days to two weeks, the sulfate reducing bacteria become re-established, and caustic dosing must be repeated. If this approach is employed in the collection system near the treatment plant such that dilution of the high pH slug does not occur, provisions must be made to store the high pH wastewater and gradually release it to the plant to avoid biological upset.

4.2.8 Other Chemicals

Other chemicals have been used for sulfide control with varying degrees of success. Sodium nitrate has been used for H_2S control in lagoons, trickling filters, and carbon columns, but has not been widely used for sulfide control in sewers. Nitrate prevents sulfide generation by acting as a hydrogen acceptor which is used preferentially by bacteria over sulfate.

Several proprietary bacterial cultures and enzyme preparations are claimed to be effective for sulfide and odor control although their effectiveness has yet to be demonstrated.

4.3 Prevention of Hydrogen Sulfide Corrosion in the Design of New Systems

Consideration of sulfide generation and corrosion is critical in the design of wastewater collection systems. While it is possible, and sometimes necessary, to incorporate chemical addition stations for sulfide control as part of the overall system design, the most cost-effective and rational engineering approach is to develop a hydraulic design that minimizes sulfide generation. In general, such an approach strives to maintain aerobic conditions in the wastewater by providing adequate wastewater by providing adequate wastewater velocities, and by minimizing the use of force mains, inverted siphons, and surcharged sewers in which anaerobic conditions can develop, resulting in sulfide generation.

Under certain conditions, sulfide generation may be unavoidable. Empirical equations have been developed to allow prediction of sulfide build-up and rates of corrosion. Where sulfide generation is anticipated, corrosion resistant materials can be selected, or the alkalinity and thickness of concrete pipe can be specified to help reduce the effects of hydrogen sulfide corrosion.

Table 4-2 summarizes various approaches used to minimize sulfide generation and corrosion during the design of wastewater collection and treatment facilities. Several key design elements are summarized below. More detailed discussions of corrosion prevention during design may be found in references (1),(2), and (10).

4.3.1 Wastewater Velocity

Wastewater velocity is critical in designing sewer systems to prevent or minimize sulfide generation. Adequate velocity 1) prevents deposition of solids which can cause flow obstructions and increase sulfide generation and 2) provides surface reaeration which helps to maintain aerobic conditions and prevent sulfide generation. Although a minimum scouring velocity of 2 ft/sec has been historically used by engineers designing gravity sewers, large diameter sewers require much higher scouring velocities, on the order of 3 to 4.5 ft/sec. Minimum scouring velocities for force mains are typically 3 to 5 ft/sec depending on pipe size.

The impact of velocity on reaeration rate is significant. For a 24 inch diameter flowing half full, increasing the velocity from 2 to 3 ft/sec increases the reaeration rate by a factor of 2. The effect is somewhat less dramatic for sewers larger than 36 inches.

Velocity in sewers is controlled by flowrate, slope, and pipe diameter. Figure 4-1 is a generalized guide showing the potential for sulfide generation as a function of flow and slope.

TABLE 4-2

APPROACHES TO PREVENT HYDROGEN SULFIDE CORROSION DURING DESIGN

Techniques to Minimize Sulfide Generation and Corrosion	Techniques to Minimize Corrosion when Sulfide Generation is Anticipated
Choose pipe sizes and slope to provide sufficient velocities to maintain aerobic conditions and prevent solids deposition.	Utilize corrosion resistant pipe materials such as PVC, PE and vitrified clay.
Limit use of force mains, siphons, and surcharged sewers which promote anaerobic conditions.	Specify calcareous aggregate (high alkalinity) concrete with additional sacrificial cover over reinforcing steel.
Impose local control of industrial discharges to reduce wastes with sulfide, high BOD, high temperature, low pH, and high grease content.	Specify corrosion-resistant PVC or PE liners for concrete pipe, junction structures, etc.
Avoid excessive detention times in wet wells, holding tanks, etc.	Design junction structures, manholes, etc. to minimize turbulence and release of H_2S.
	Consider air/oxygen injection or chemical addition stations where appropriate.

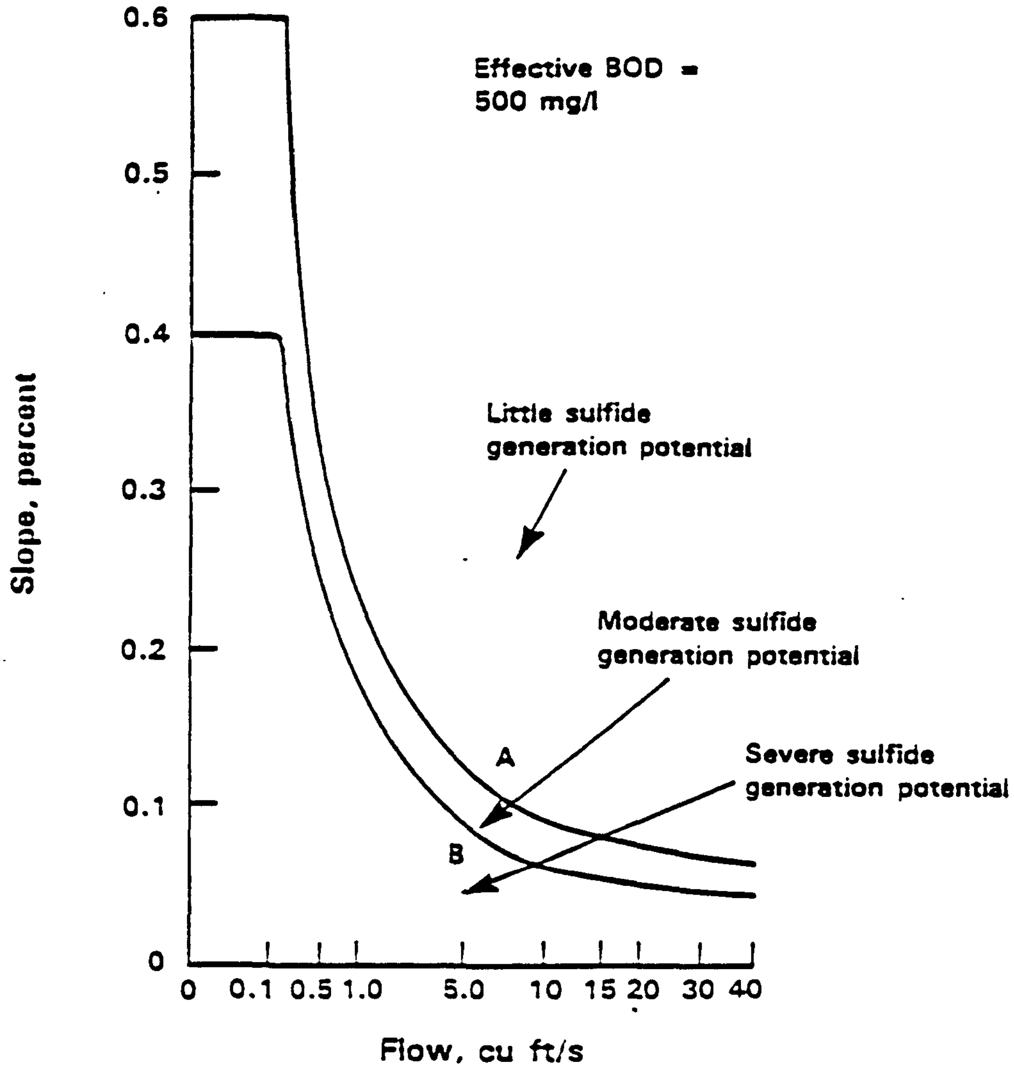

FIGURE 4-1 GUIDE FOR ESTIMATING SULFIDE GENERATION POTENTIAL

4.3.2 Design of Junction and Drop Structures

Turbulence created by junctions and drop structures can have opposite effects on sulfide build-up and corrosion, depending on the characteristics of the wastewater when it reaches the structure. If no sulfide is present, turbulence will increase reaeration rates, thereby adding dissolved oxygen and maintaining aerobic conditions. On the other hand, if dissolved sulfide is present, turbulence will increase the release of hydrogen sulfide to the atmosphere and increase the rate of corrosion. Therefore, if potential for sulfide generation exists, designs of such structures should be such that turbulence is minimized.

4.3.3 Force Mains, Siphons, and Surcharged Sewers

Force mains, siphons, and surcharged sewers have one thing in common: the sewer flows full with no opportunity for reaeration. This results in anaerobic conditions, generation of H_2S, and often severe corrosion at the outlet. In general, use of force mains, siphons, and surcharged sewers should be avoided whenever possible.

Where required, design velocities should be selected to avoid solids deposition, and detention times should be minimized. Where long force mains or siphons are necessary, consideration should be given to positive sulfide control systems (e.g., chemical addition) and/or use of corrosion resistant materials such as PVC liners at discharge points.

4.3.4 Sewer Ventilation

Sewers are naturally ventilated through building vents and manholes, occurring from factors such as changes in barometric pressure, wind, air density differences, and flow conditions. Wet wells at pumping stations have 12-30 changes/hour, and dry wells have 6-30 changes/hr. Ventilation is often practiced at wastewater treatment plants, where air is withdrawn at the headworks and either treated separately or piped to existing biological processes (1).

4.3.5 Local Control of Industrial Discharges

Local control of industrial discharges as a means of minimizing sulfide generation is applicable to both existing and new wastewater systems. Beneficial impacts of controlling industrial discharges on sulfide generation were summarized in Table 3-11. Adequate industrial pretreatment to make such wastes compatible with municipal wastewater can eliminate their contribution to sulfide generation potential.

4.3.6 Design Considerations When Sulfide Generation is Anticipated

4.3.6.1 Prediction of Sulfide Generation and Corrosion

In some cases, it is difficult or not cost-effective to design a wastewater collection system that will be free of sulfide problems. It is then useful to know what levels of sulfide can be expected.

Empirical equations have been developed to allow prediction of sulfide levels. In addition, a model has been developed to allow prediction of corrosion rates where H_2S is present.

The Pomeroy-Parkhurst equations that predict sulfide build-up are given below:

Pipes Flowing Less than Full

$$S_2 = S_{lim} - \frac{S_{lim} - S_1}{\log^{-1} \frac{m(su)^{3/8} t}{2.31\, d_m}}$$

where:

S_2 = predicted sulfide concentration at time t_2

S_1 = sulfide concentration at time t_1

S_{lim} = theoretical upper limit of sulfide concentration

s = slope of the pipe

u = stream velocity

t = $(t_2 - t_1)$ flow time

m = empirical coefficient for sulfide loss

d_m = mean hydraulic depth

Pipes Flowing Full

$$S_2 = S_1 + (M)(t)[EBOD\ (4/d) + 1.57)]$$

where:

M = experimentally determined empirical constant representing the sulfide flux

$$EBOD = BOD[1.07^{(T-20)}]\ (T = \text{temperature, °C})$$

The rate of corrosion of concrete pipe can be predicted using the following equation:

$$C_{avg} = \frac{11.5\ k\ \O_{sw}}{A}$$

where,

C_{avg} = average rate of penetration, mm/yr

k = Coefficient of efficiency for acid reaction considering the estimated fraction of acid remaining on the wall. May be as low as 0.3 and will approach 1.0 for a complete acid reaction.

$\O_{sw}$ = flux of H_2S to the pipe wall, gm/m^2-hr

A = Alkalinity of the cement bonded material, expressed as $CaCO_3$ equivalent. Approximately 0.18 to 0.23 for granitic aggregate concrete, 0.9 for calcareous aggregate, 0.4 for mortar linings, and 0.5 for asbestos cement.

11.5 = constant

$\O_{sw}$ = $0.69(su)^{3/8}j[DS](b/P')$

where,

s = energy gradient of wastewater stream, m/m

u = stream velocity, m/s

j = fraction of dissolved sulfide present as H_2S as a function of pH

[DS] = average annual concentration of dissolved sulfide in the wastewater, mg/l

b/P' = ratio of width of wastewater stream at surface to exposed perimeter of the pipe wall above the water surface.

Peak corrosion rates occur at the sewer crown, and may be higher than the average corrosion rate by a factor of 1.5 to 2.0. This is the crown corrosion factor (CCF). Another factor, the turbulence corrosion factor (TCF) is used to account for greater flux of H_2S to the pipe wall, and may vary from 1 to 2.5 for well-designed junction structures or other areas with nonuniform flow conditions. At drops or turbulent junctions, the turbulence corrosion factor may be 5 to 10.

Thus, the peak crown corrosion rate is given as follows:

$$C_{max} = C_{avg} \times CCF \times TCF$$

4.3.6.2 Selection of Materials

When it is anticipated that sulfide will be present, consideration must be given to use of corrosion-resistant materials. Pipe materials such as PVC, PE, and vitrified clay are virtually unaffected by sulfuric acid produced by the biological oxidation of hydrogen sulfide, and should be specified if hydrogen sulfide corrosion is anticipated. For larger diameter sewers, PVC or vitrified clay pipes are not available, and concrete pipe is often used. However, PE pipe is available in diameters up to 120 inches. Two alternatives are frequently used to protect the concrete pipe from corrosion or to extend its useful design life. These are 1) use of PVC liners which are imbedded into the concrete pipe during manufacture, and 2) use of high alkalinity calcareous aggregate and/or additional sacrificial concrete cover over the reinforcing bars.

The proprietary "T-lock" PVC liner has been successfully used for concrete pipe protection for many years. Although the cost of the pipe is increased, follow-up tests have shown that the PVC liner provides excellent protection of the underlying concrete. The PVC is immune to sulfuric acid attack, and proper installation of the liner prevents migration of acid to the concrete. Surface-applied synthetic coatings have yet to demonstrate the longevity and acid resistance of PVC liners.

Use of calcareous aggregate in concrete pipe increases the alkalinity of the concrete and thus increases the resistance to sulfuric acid attack. An additional sacrificial layer of concrete over the reinforcing steel increases the useful design life of the pipe. An equation has been developed to assist in proper selection of pipe materials (alkalinity) and thickness. This is the "Az" or "life factor" equation, shown below.

$$Az = 0.45k\,\phi_{sw}\,L(CCF)(TCF)$$

where,

Az = life factor, equal to the product of alkalinity and thickness of allowable concrete loss

L = desired design lifetime, years

Thus, assuming a design lifetime of the pipe, it is possible for the engineer to specify the desired combination of pipe wall thickness and concrete alkalinity to achieve the target lifetime.

4.4 Repair of Damage Caused by Hydrogen Sulfide Corrosion

Once corrosion damage has occurred, it may be necessary to repair a structure to reduce the potential for failure or collapse. In the past, excavation and replacement was a common repair solution to corroded pipes and structures. However, due to the expense, the disruption to traffic, the potential for damage to other underground utilities, and the interruption to the service itself, in-line rehabilitation techniques have become more attractive. Rehabilitation techniques are those methods and repairs applied to an existing structure to prolong its useful life. With such techniques, municipalities can repair existing structures at a lower cost than replacement, and without public inconveniences due to traffic disruptions and service interruptions. In many situations, pipelines can be rehabilitated at somewhat less than the cost of replacement. Rehabilitation techniques are not acceptable under the following conditions:

- where significant additional capacity is needed
- where rehabilitation methods that are adequate to restore pipeline structural integrity would produce an unacceptable reduction in service capacity
- for point repair where short lengths of pipeline are too seriously damaged to be effectively rehabilitated by any means
- where entire reaches of pipeline are too seriously damaged to be rehabilitated
- where removal and replacement is less costly in dollars and urban disruption than other rehabilitation methods

Numerous rehabilitation techniques exist, but not all are applicable to corrosion repair. The selection of a particular method of rehabilitation depends on many factors such as economics, extent of damage and structural integrity, disruption of traffic and excavation requirements. High concentrations of sulfuric acid may be detected on the walls of sewers where H_2S is being generated. Sulfuric acid can quickly deteriorate crown and sidewall concrete, thereby exposing aggregate and reinforcing steel, and potentially weakening structural integrity. Therefore, corrosion rehabilitation techniques must focus on internal repairs to ensure structural integrity and provide a protective barrier against subsequent acid attack, rather than on external repairs (e.g., soil stabilization). After surveying consulting engineers, municipal engineers, and manufacturers, the following seven generic rehabilitation measures were identified as appropriate for acid corrosion repair:

- insertion renewal (sliplining)
- deformed pipe insertion
- cured-in-place pipe
- specialty concrete
- coatings
- liners
- spot replacement

Table 4-3 describes various methods of pipeline rehabilitation, indicating their

TABLE 4-3

PRINCIPAL METHODS FOR PIPELINE REHABILITATION

Method	Description	Application	Advantages	Disadvantages
Insertion Renewal (Sliplining)	A liner pipe of slightly smaller outside diameter is inserted into existing pipe, then connected to service laterals. Materials include polyethylene, polybutylene, reinforced thermosetting plastic, reinforced plastic mortar.	Leading method for gas pipe rehabilitation. Also used for cracked or deteriorated sewer pipes and, to lesser extent, water distribution pipes.	Less time, lower cost than excavation and replacement, minimal disruption. May improve hydraulics in some cases. Provides some structural reinforcement when properly grouted. Bypassing not req'd.	If original pipe is deformed, liner pipe may have to be much smaller diameter. Excavation required for access pits, service laterals. Only large radius bends are easily accommodated. May decrease capacity.
Deformed Pipe Insertion	A thermoplastic pipe is deformed by folding or compression and inserted into existing pipe and expanded naturally, hydraulically, or mechanically	Similar applications as for sliplining but for relatively small (<24 inch) circular pipe.	Close fit of liner to pipe; may not require grouting. Requires no mixing of resins, curing. May not require excavation. May improve hydraulics.	Limited track record. Currently applicable only to small diameter, circular pipe. Bypassing required.
Cured-in-Place Inversion Lining	Flexible liner installed through inversion process, thermally or steam hardened. Laterals cut by remote control.	Sewer pipe of any geometry; largest current application is for 96 inch diameter pipe.	For repairs under busy streets, buildings as well as normal locations. Return to service in 12 to 48 hrs. Excavation normally not req'd. May improve hydraulics.	Only used for mainline repairs. Patented system handled by relatively few contractors. Site set-up costs high for small jobs. Bypassing req'd.
Specialty Concrete (Spot repair)	After placement of steel reinforcement, a mixture of fine aggregate cement and water is applied by air pressure.	Large sewers needing structural repairs.	Higher strength than cement mortar linings. Requires no excavation. Variations in cross-section readily accommodated.	Only suitable for large pipes. Difficult to supervise and depends on operator skills. Control of infiltration required. Susceptible to acid corrosion, but at somewhat reduced rates. Bypassing req'd.

TABLE 4-3 (cont.)

PRINCIPAL METHODS FOR PIPELINE REHABILITATION

Method	Description	Application	Advantages	Disadvantages
Coatings	Different materials that can be applied by spray or brush to sewer lines.	Rapidly growing method for pipes with new application methods being marketed continually.	Material cost is low, less disruption to traffic as installation in-line; smooth surface provides good hydraulics.	Many applicable only to man entry size sewers; prolonged by-pass; greater surface preparation; most coatings do not provide long-term resistance to acid attack. Imperfect installations fail completely; bypassing req'd.
Liners	Prefabricated panels or sheets of PE or PVC that are installed manually; or a continuous, interlocking strip that is installed using a special machine or by hand.	Not designed to support earth loads and should be used only in structurally sound sewers. Can easily fit variations in grades, slopes, cross-section for manually applied strip applications.	Less disruption to traffic and urban activity; less costly than replacement.	Possible small reduction in pipe capacity; requires obstruction removal; susceptible to leakage due to numerous joints; bypassing req'd.
Spot Replacement	Replacement in original trench.	Any pipe with major or structural defects.	Only method that can significantly increase flow capacity by replacement with larger diameter pipe; allows substitution with corrosion resistant pipe materials having long service life (e.g. PVC, PE, VCP). Handles tight curves.	Most costly and disruptive method; bypassing required.
Exterior Wrap and Cap	Panels of ribbed PVC are placed on the exterior of corroded pipes and capped with reinforced concrete.	Provides back-up corrosion protection and structurally reinforces existing pipeline. Similar method applicable to monolithic structures.	Service is not interrupted. Bypassing is not required. Less costly than complete replacement.	Pipeline or structure must be in a location where open trenching or excavation is practical.

applications, advantages, and disadvantages. More detailed information may be found in references (5),(6),(7), and (8).

Sliplining or insertion renewal is the most widely used rehabilitation technique. Sliplining involves inserting a new, continuous length of pipe or segments of pipe inside an existing pipe. Pipes are made by joining individual lengths with heat fusion or various types of bell and spigot joints. Materials used for sliplining pipes include polyethylene (PE), polybutylene, fiberglass-reinforced polyesters, reinforced thermosetting resins, and PVC. Material selection is based on application, design needs, economics, and to some extent, space availability at the installation working area. Sliplining is capable of dealing with a variety of serious structural problems if the annular space between the existing pipe and the sliplining pipe has been properly grouted. Exceptions are severely crushed or collapsed pipes. Installation is done by excavating an access pit and pushing or pulling the slipline pipe into the existing pipe. It is widely used for cracked or deteriorated sewer pipes and to a lesser extent, water pipes. It takes less time for installation, has lower cost than excavation and replacement, and requires minimal excavation and disruption. It has the ability to accommodate large radius bends and may improve hydraulics in spite of the reduction in the overall pipe diameter. Most of the sliplining materials available are acid-resistant and provide good hydraulics.

Deformed pipe insertion lining is a new process with a limited experience base. Several variations exist. In general, folded or compressed plastic pipe is inserted into the existing pipe. Pipe material may be polyethylene or plasticized PVC. The pipe may be heated to increase flexibility prior to installation. In one process, the heated pipe is pulled through a die to reduce the diameter prior to insertion. In processes using folded pipe, steam is added after insertion and a ball is propelled through the folded pipe to expand it to conform with the existing pipe, or the pipe is expanded hydraulically using steam pressure. In the process using the mechanical die to reduce the diameter, the pipe naturally reverts to its original diameter within several hours. After insertion and expansion, the ends of the liner are cut off, trimmed, and likely sealed. Proprietors claim that the process results in a tight fit of the liner to the pipe, eliminating the need for grouting of the annular space. Mixing of resins and curing, as required with cured-in-place systems, are unnecessary. The folded liner systems are supplied in rolls, and insertion pit excavation is not required. For the system which reduces pipe diameter using a die, an insertion pit is apparently required as with conventional sliplining. Because of the limited experience with deformed pipe insertion methods for rehabilitating sewers, little information is available on the applicable size ranges, ease of installation, and cost-effectiveness of these systems.

Cured-in-place pipe is formed from a resin-impregnated felt tube which is inverted into an existing pipe and allowed to cure. After curing, the felt tube becomes a smooth, hard pipe of slightly less diameter and of the same shape as the original pipe. Cured-in-place pipe can be installed in pipes of all shapes up to diameters of 96 inches.

It can also adhere to bends present in the original pipe. Inversion lining is successful in dealing with a number of structural problems. Caution must be used in the application of this method to any structural problems involving major loss of pipe wall, reinforcing steel, or exterior pipe and bedding support. Within limits, the liners can be designed to deal with these more serious structural problems. Precautions should be taken in determining the selection of an inversion lining method for sewer rehabilitation. Various resins can be used to provide different degrees of acid resistance. Standard polyester resins are suitable for most sewer applications. Cured-in-place inversion linings have found more acceptance where minimal excavation and traffic disruption is required. This technique is one of the most widely used rehabilitation methods. The long-term acid resistance of the liner is unknown. Observations made within the past 15 years have not indicated corrosion problems.

Specialty concretes are sulfate-resistant cements applied to corroded surfaces primarily for structural reasons and to resist corrosion. Sulfate resistant cements include potassium silicate. Typically, reinforcing steel is added for additional support. Specialty concretes include cement mortar, shotcrete, and cast concrete. Cement mortar is applied with a hand trowel for spot repairs in man-entry size (i.e., greater than 32-inch-diameter) sewers or with a centrifugal lining machine for complete coverage within a stretch of pipe. Shotcrete is applied with a special nozzle using compressed air. Cast concrete is installed using prefabricated or hand-built interior pipe forms. The development of mechanical, in-line application methods (e.g., centrifugal and mandrel) has established mortar lining as a viable rehabilitation technique. Both shotcrete and cast concrete are used in large-diameter sewers where adequate space is available to handle materials and equipment. The specialty concrete applications depend on the degree of corrosion present and the structural integrity of the unit in question. Generally, thin film concrete will perform best on relatively non-corroded concrete whereas an elastic membrane concrete system will work for all cases. Testing performed by CSDLAC revealed that seven out of eight supposedly acid-resistant specialty concretes failed after submersion from 0.1 to 488 days in a 10-percent sulfuric acid solution. Only one concrete has maintained its acid resistance even after 605 days of testing. Specialty concretes are used mostly for spot repairs such as manhole barrels, wet wells, junction chambers, and sections of pipe.

Coatings include a myriad of proprietary epoxies, resins, sealers, silicones, urethanes, and coal tars applied by spray or brush. Coatings are experiencing rapid growth with new products being marketed continually. Unfortunately, field testing has not kept up with the rapid growth. CSDLAC have been testing new products, and cities such as Seattle have been using those products that exhibited good results. Only about 25 percent of coatings tested by CSDLAC exhibited good acid resistance. The majority of failures can be attributed to application difficulties (e.g., pinholes and blowholes). All coating systems require some form of surface preparation. The surface preparation and conditions under which coatings material is applied are extremely critical. The specification of any acid resistant epoxy should require the minimum application of 1.5

mm of material for rehabilitation. Consideration should be given to the use of coatings that will cure underwater for projects that require either short down times, or where it is impractical to completely remove the structure from service, thereby requiring coating application to an intermittently wet area.

Liners used for rehabilitation may be prefabricated panels or flexible sheets that are installed manually with anchor bolts or with concrete-penetrating nails; or continuous, interlocking strips that are installed in a spiral fashion using a special machine or manually. Manual methods are applicable only to man-entry sewers. Common liner materials are fiberglass-reinforced cement, fiberglass-reinforced plastic, PVC, and PE. The liner materials themselves are acid-resistant but problems have occurred due to poor jointing. Liners may be susceptible to acid leakage due to numerous joints. Some panel systems are time consuming to install and thus prolonged bypass is required. Hydrogen sulfide gases have been documented to pass through poor joints and cause failure by attacking the concrete substrate behind the liner. A recent design introduced to the U.S. involves a continuous, helical, interlocking strip with improved joints which may overcome such gas-penetration problems. Also, a new acid-resistant urethylene mastic has shown excellent results in bonding PE and PVC sheets to concrete surfaces, and may eliminate problems with mechanical anchoring and poor jointing. Cracking of polyethylene liners has been observed in areas of high turbulence.

4.5 Conclusions

No material or technique is effective for controlling sulfide generation or sulfide-induced corrosion in every situation. The environmental variables that determine the success of a prevention or repair method (e.g., the characteristics of the wastewater and the collection system and the severity of corrosion) vary with each system and within each reach of sewer. It is only after a system has been analyzed that these variables can be taken into account and an effective measure selected. Often, several different methods must be used in combination or at different points in the same system to combat corrosion under various conditions. The effectiveness of a method is determined by more than just its physical properties and/or theory of operation. Proper design, installation, operation, and maintenance are required to ensure that the material or technique is effective. However, even if studies indicate that a method has the best long-term cost- effectiveness, initial costs may exceed the budgetary constraints of a municipality and force it to use a less expensive and less effective method. Because of the variations in effectiveness, affordability, availability, convenience, and applicability, sulfide control techniques and corrosion rehabilitation methods must be evaluated on a case-by-case basis.

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APPENDIX A

ANNUAL AVERAGE WASTEWATER CHARACTERISTICS FOR LA COUNTY

1971-1986

July 1987

JOINT WATER POLLUTION CONTROL PLANT

RAW SEWAGE PARAMETERS

1971 - 1986 YEARLY AVERAGES

(Based on Water Quality Characteristics Monitoring Program)

ar	Alkalinity Total (mg/l)	Arsenic (mg/l)	Barium (mg/l)	BOD Total (mg/l)	Boron (mg/l)
71	307	0	-	384	1.03
72	302	0	-	319	1.11
73	316	0.0250	0.53	357	1.14
74	298	0.0354	0.55	314	1.35
75	289	0.0155	0.75	302	1.49
76	307	0.0073	1.07	306	1.54
77	330	0.0114	0.91	334	1.51
78	322	0.0135	0.78	324	1.64
79	316	0.0188	0.67	322	1.50
80	314	0.0064	1.02	335	1.52
81	317	0.0067	0.80	322	1.41
82	323	0.0079	0.82	313	1.66
83	340	0.0087	0.91	291	1.68
84	338	0.0257	0.83	317	1.76
85	329	0.0180	1.03	329	1.72
86	339	0.0101	0.97	328	1.58

JWPCP - Raw Sewage Parameters
1971 - 1986 Yearly Averages

Year	Cadmium (mg/l)	Chloride (mg/l)	Chromium Hexavalent (mg/l)	Chromium Total (mg/l)	COD Soluble (mg/l)
1971	0.0250	560	0	0.780	326
1972	0.0320	502	0	1.125	250
1973	0.0320	423	0	0.877	310
1974	0.0400	365	0	0.887	251
1975	0.0390	341	<0.02	1.020	252
1976	0.0310	345	<0.02	0.905	265
1977	0.0343	326	<0.02	0.720	244
1978	0.0385	397	<0.02	0.502	263
1979	0.0358	387	<0.02	0.445	273
1980	0.0343	387	<0.02	0.563	246
1981	0.0244	408	<0.02	0.430	230
1982	0.0206	434	0	0.335	266
1983	0.0337	453	0	0.278	262
1984	0.0199	498	0	0.250	259
1985	0.0180	460	0	0.237	246
1986	0.0140	461	0	0.189	257

PCP - Raw Sewage Parameters
71 - 1986 Yearly Averages

ar	COD Total (mg/l)	Conductance MMHO cm	Copper (mg/l)	Cyanide (mg/l)	DDT Total (mg/l)
71	680	2992	0.450	0.200	0.01527
72	721	2813	0.736	0.293	0.02132
73	925	2785	0.563	0.363	0.01802
74	844	2369	0.635	0.430	0.00278
75	818	2145	0.580	0.280	0.00172
76	1022	2162	0.430	0.290	0.00325
77	863	2353	0.430	0.240	0.00211
78	923	2185	0.360	0.180	0.00273
79	910	2312	0.337	0.178	0.00234
80	813	2273	0.334	0.118	0.00177
81	759	2355	0.268	0.080	0.00172
82	916	2524	0.230	0.063	0.00076
83	904	2582	0.245	0.042	0.00049
84	900	2679	0.240	0.040	0.00096
85	881	2632	0.197	0.020	0.00037
86	879	2620	0.179	0.022	0.00019

JWPCP - Raw Sewage Parameters
1971 - 1986 Yearly Averages

Year	Detergents (MBAS) (mg/l)	Flow (MGD)	Fluoride (mg/l)	Hardness Calcium (mg/l)	Hardness Magnesium (mg/l)
1971	7.23	372	1.05	273	165
1972	7.40	351	1.24	259	162
1973	7.49	359	1.51	215	143
1974	6.60	347	1.40	215	109
1975	6.50	342	1.37	176	81
1976	6.74	353	1.48	165	79
1977	6.31	330	1.45	197	97
1978	8.17	345	1.56	197	105
1979	7.62	367	1.66	191	94
1980	6.97	374	1.56	191	82
1981	5.97	364	1.51	204	97
1982	6.20	360	1.39	194	94
1983	6.67	353	1.99	210	101
1984	6.24	352	2.61	211	104
1985	6.44	361	2.17	192	99
1986	6.10	364	2.01	183	98

ar	Hardness Total (mg/l)	Iron (mg/l)	Lead (mg/l)	Lithium (mg/l)	Manganese (mg/l)
71	438	13.130	0.280	0.070	0.11
72	421	11.340	0.306	0.070	0.12
73	371	8.875	0.292	0.060	0.11
74	350	9.480	0.371	0.050	0.12
75	282	13.950	0.370	0.042	0.15
76	259	6.840	0.272	0.058	0.10
77	294	8.290	0.340	0.100	0.12
78	265	7.562	0.270	0.059	0.13
79	298	7.367	0.225	0.061	0.11
80	294	6.429	0.212	0.053	0.10
81	296	6.106	0.164	0.063	0.09
82	289	5.430	0.160	0.066	0.09
83	307	7.840	0.150	0.063	0.12
84	310	5.290	0.140	0.071	0.11
85	292	4.870	0.129	0.071	0.11
86	287	5.138	0.155	0.065	0.10

JWPCP - Raw Sewage Parameters
1971 - 1986 Yearly Averages

Year	Mercury (mg/l)	Nickel (mg/l)	Nitrogen Ammonia (mg/l)	Nitrogen Organic (mg/l)	Oil and Grease (mg/l)
1971	0.0022	0.230	80.6	26.7	-
1972	0.0010	0.310	41.3	17.4	-
1973	0.0012	0.324	58.5	20.8	-
1974	0.0012	0.280	34.4	16.6	-
1975	0.0014	0.280	33.6	18.8	91
1976	0.0015	0.340	32.9	18.9	219
1977	0.0014	0.310	33.6	17.9	124
1978	0.0014	0.342	34.4	21.0	91
1979	0.0014	0.245	34.2	19.6	90
1980	0.0011	0.245	34.2	20.2	76
1981	0.0009	0.210	34.0	20.3	62
1982	0.0011	0.200	34.6	19.6	73
1983	0.0013	0.220	35.0	23.1	69
1984	0.0011	0.150	31.6	21.1	79
1985	0.0010	0.129	31.9	19.5	72
1986	0.0011	0.099	34.1	21.1	64

PCP - Raw Sewage Parameters
971 - 1986 Yearly Averages

ear	PCB Total (mg/l)	pH	Phenols (mg/l)	Phosphate (mg/l)	Potassium (mg/l)
971	0.02126	7.92	3.83	45.8	20
972	0.01077	7.61	2.51	59.5	20
973	0.01233	7.65	4.64	53.9	19
974	0.01685	7.55	3.27	52.2	19
975	0.00531	7.51	3.74	47.5	19
976	0.00061	-	3.17	38.6	20
977	0.00242	-	3.02	24.5	19
978	0.00180	-	2.69	13.3	19
979	0.00098	-	2.40	11.5	19
980	0.00092	-	2.28	11.5	16
981	0.00070	-	2.51	10.7	18
982	0.00081	-	2.07	10.6	18
983	0.00061	-	2.37	11.6	18
84	0.00064	-	1.93	12.6	18
85	0.00031	-	1.70	12.4	18
86	0	-	2.30	13.2	17

Year	Selenium (mg/l)	Silver (mg/l)	Calculated[4] Sludge Concentration (mg/l)	Calculated[4] Sludge Mass (lbs/d)	Sodium (mg/l)
1971	-	0.0140	-	-	369
1972	-	0.0170	-	-	381
1973	-	0.0126	-	-	357
1974	-	0.0109	58.57	169,656	336
1975	-	0.0140	57.57	164,320	308
1976	0.015	0.0140	74.38	219,122	306
1977	0.016	0.0106	76.47	210,597	336
1978	0.009	0.0191	76.61	220,572	357
1979	0.012	0.0197	72.00	220,524	331
1980	0.010	0.0153	78.52	245,075	333
1981	0.009	0.0150	78.39	238,127	338
1982	0.014	0.0175	92.27	277,223	368
1983	0.016	0.0182	115.44	340,082	369
1984	0.015	0.0170	120.99	355,420	407
1985	0.013	0.0200	108.33	326,353	395
1986	0.017	0.0198	107.54	326,691	378

PCP - Raw Sewage Parameters
71 - 1986 Yearly Averages

ar	Solids Total (mg/l)	Sulfate (mg/l)	Sulfide Total (mg/l)	Sulfide Dissolved (mg/l)	Suspended Solids (mg/l)
71	2112	347	0.4	0.1	397
72	2040	330	0.5	0.2	416
73	1975	349	0.5	0.2	518
74	1828	320	0.5	0.2	459
75	1681	258	0.5	0.2	484
76	-	224	0.6	0.3	424
77	-	260	1.0	0.5	463
78	-	270	1.2	0.6	448
79	-	275	1.3	0.6	435
80	-	275	1.3	0.7	442
81	-	286	1.6	0.7	442
82	-	240	1.6	0.6	442
83	--	282	1.6	0.6	463
84	-	296	2.0	0.8	455
85	-	268	2.6	1.2	445
86	-	285	3.0/2.0	1.4/0.6	454

JWPCP - Raw Sewage Parameters
1971 - 1986 Yearly Averages

Year	TDS (mg/l)	Thiocyanate (mg/l)	TICH (mg/l)	Zinc
1971	1716	-	0.03680	1.930
1972	1624	-	0.01986	2.269
1973	1458	2.76	0.03032	2.470
1974	1368	2.00	0.02157	1.990
1975	1199	1.80	0.00724	1.640
1976	1191	2.00	0.00456	1.420
1977	1300	1.89	0.00459	1.460
1978	1404	2.34	0.00470	1.278
1979	1262	2.11	0.00316	1.000
1980	1259	1.18	0.00302	0.952
1981	1338	1.27	0.00281	1.012
1982	1318	1.53	0.00227	0.960
1983	1474	1.50	0.00166	1.011
1984	1523	1.51	0.00318	0.830
1985	1522	1.09	0.00088	0.720
1986	1426	1.42	0.00040	0.751

:es:

1. The values in the tables are based on the Water Quality Characteristics Monitoring Program and were used for the correlation with dissolved sulfide. The values, in some cases, do not exactly match the graphs and slides previously prepared. Some of the data for the graphs and slides were from sampling conducted for the Industrial Waste Section. However, the industrial waste data is incomplete, so to be consistent, only data from the Water Quality Characteristics Monitoring Program were used for the correlation.

2. Total solids and pH were not correlated with dissolved sulfide because of insufficient data.

3. Sludge mass was not correlated with dissolved sulfide because it doesn't account for any change in flow. Sludge concentration was used instead.

February 1988

CORRELATION OF JWPCP RAW SEWAGE PARAMETERS WITH DISSOLVED SULFIDE FROM 1971-1987

nk	Parameters	Correlation Coefficient
1	Nickel	-0.83
2	Chromium-Total	-0.81
3	Sludge-Concentration (theoretical)	0.78
4	Zinc	-0.78
5	Copper	-0.77
6	Cyanide	-0.77
7	Lead	-0.76
8	Iron	-0.70
9	Potassium	-0.69
.0	Silver	0.69
.1	Fluoride	0.68
.2	Phenols	-0.67
.3	Alkalinity-Total	0.67
.4	Phosphate	-0.66
15	Sodium	0.63
16	TICH	-0.61
17	PCB-Total	-0.60
18	Barium	0.57
19	DDT-Total	-0.53
20	Boron	0.51
21	Oil and Grease	-0.49
22	Mercury	-0.48
23	Nitrogen-Ammonia	-0.43
24	Hardness-Calcium	-0.43
25	COD-Soluble	-0.42
26	Cadmium	-0.40
27	Detergent (MBAS)	-0.39
28	Hardness-Magnesium	-0.38
29	Selenium	0.37
30	Sulfate	-0.33
31	Flow	0.33
32	Maganese	-0.32
33	Thiocyanate	-0.28
34	COD-Total	0.28
35	Hardness-Total	-0.21
36	Chloride	0.20
37	Chromium-Hexavalent	-0.13
38	Lithium	0.12
39	Nitrogen-Organic	0.11
40	Suspended Solids	0.07
41	Conductance	0.05
42	Temperature	-0.05
43	BOD-Total	0.04
44	TDS	0.02
45	Arsenic	-0.02

ote: All parameters correlated with dissolved sulfide without sulfide control except for Iron which was correlated with dissolved sulfide with sulfide control in 1986 and 1987.