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Hydrogen Sulfide Corrosion In Wastewater Collection And Treatment Systems

Report To Congress

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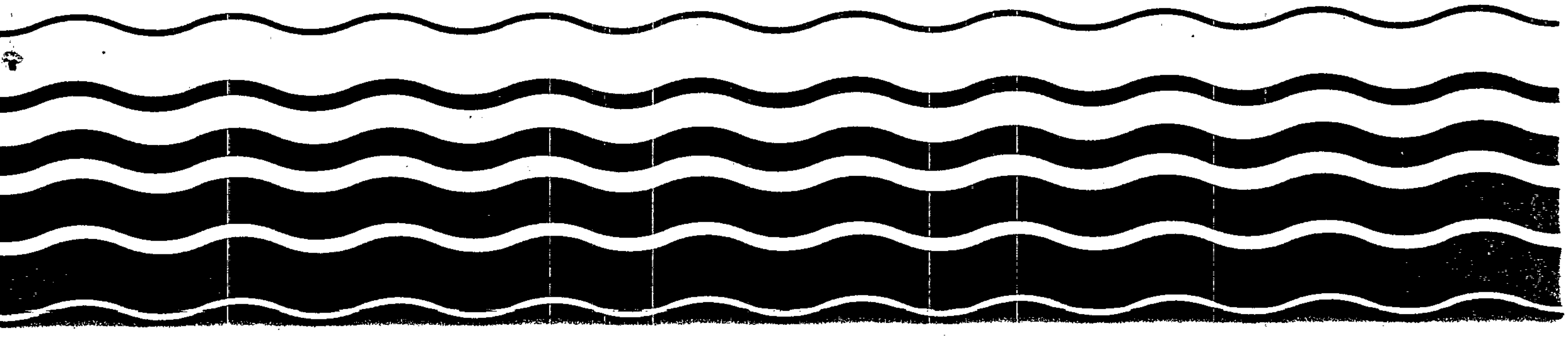

REPORT TO CONGRESS

HYDROGEN SULFIDE CORROSION IN WASTEWATER COLLECTION AND TREATMENT SYSTEMS

U.S. Environmental Protection Agency
Office of Water (WH-595)
Washington, DC 20460

May, 1991

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Previous reports on hydrogen sulfide corrosion were prepared by EPA in 1988 with the assistance of E.C. Jordan Co. under EPA Contract No. 68-03-3412. Under subcontract to E.C. Jordan Co., Brown and Caldwell staff, including Perry Schafer, Robert Witzgall, Roy Fedotoff, and Walt Meyer, prepared five case studies of corrosion.

Many people provided valuable assistance during this study. However, special acknowledgment is appropriate for the staff of the County Sanitation Districts of Los Angeles County, especially the support from John Redner and Calvin Jin.

Ms. Irene M. Suzukida [Horner] was the EPA 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.

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1.0 BACKGROUND AND OVERVIEW

Between the early 1970's and mid 1980's, the County Sanitation Districts of Los Angeles County (CSDLAC) observed that the rate of sewer corrosion in their system had increased dramatically. Subsequent studies showed a high correlation between the reduction in certain wastewater constituents of industrial origin and the increase in hydrogen sulfide responsible for corrosion. This raised the question as to whether implementation of industrial pretreatment standards was related to increased sewer corrosion rates.

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 systems. As defined in the Act, the objectives are to determine the following:

- the corrosive effects of hydrogen sulfide in wastewater collection and treatment systems.
- the extent to which uniform imposition of categorical pretreatment standards exacerbates this corrosion problem.
- the range of available options to deal with such effects.

Corrosion due to the presence of hydrogen sulfide is a well known phenomenon in wastewater systems. Its effects can range from poor reliability and premature replacement of electrical systems to sewer pipe failures and street collapses. Several manuals have been prepared which discuss the mechanisms of hydrogen sulfide corrosion, design procedures to avoid corrosion in new systems, and options to control corrosion in existing systems. Although the rate and severity of corrosion may vary widely depending on wastewater characteristics and environmental conditions, CSDLAC is the first to provide documentation of accelerated corrosion whereby the rate of corrosion has significantly increased. Accelerated corrosion leads to significantly reduced lifetimes or premature failure of pipes, structures, and equipment; and costly repairs and replacement of such components.

Attempts to gain an understanding of 1) the extent of hydrogen sulfide corrosion problems in the U.S., and 2) the impact of industrial pretreatment standards on corrosion rate were thwarted by the lack of available data and information. Most municipalities have little or no documentation of corrosion problems, and some respond to such problems only in the event of a catastrophic failure such as a pipe collapse. No entities other than CSDLAC were found to have sufficient historical data to establish a correlation between implementation of industrial pretreatment standards and an increase in corrosion rate. Research on this relationship appears to be limited to that conducted or sponsored by CSDLAC.

The Report to Congress generally follows the objectives established by the Water Quality Act, and is organized as follows:

- Background and Overview
- Corrosive Effects of Hydrogen Sulfide
- Effects of Industrial Pretreatment
- Detection, Prevention and Repair of Corrosion Damage
- Recommendations to Congress

A significant amount of technical data and information was collected as part of this study. Such information has been included in a separate "Technical Report on Hydrogen Sulfide Corrosion in Wastewater Treatment Systems."

2.0 SUMMARY OF FINDINGS

2.1 Corrosive Effects of Hydrogen Sulfide

Very few municipalities in the U.S. have good documentation of hydrogen sulfide corrosion problems, much less monitor corrosion rate. Many municipalities are unaware of the severity of their corrosion problems, and sulfide control measures are generally instituted for the purpose of controlling odor emissions, not corrosion. An analysis of the information collected as part of this study yielded the following conclusions regarding the corrosive effects of hydrogen sulfide:

- Severe problems are not limited to CSDLAC. Extensive corrosion damage requiring immediate repair or rehabilitation has been observed in sewers and treatment plants in other cities.
- The geographical distribution of severe corrosion problems is widespread, and is not limited to areas having warm climates. Severe corrosion was observed in Wyoming, Idaho, Wisconsin, and Washington, as well as California, New Mexico, Louisiana, Texas, and Florida.
- Hydrogen sulfide corrosion problems in operating systems are often not recognized early enough to take corrective action before considerable

damage has occurred.

- Severe hydrogen sulfide corrosion may reduce the 50- to 100- year life expectancy of infrastructure to less than ten years.

- In a 1984 survey, of 89 cities, 32 cities reported sewer collapses, 26 of which were judged to be due to hydrogen sulfide corrosion.

- In two independent surveys, 60 to 70 percent of the municipalities reported corrosion problems at their wastewater treatment plants. In one of the surveys, 14 percent of the plants reported corrosion as being severe. EPA projects that more than 14 percent of the collection systems experienced severe corrosion.

- Hydrogen sulfide corrosion problems in sewers have been reported by at least 20 foreign countries.

- Due to lack of historical data, average corrosion rate is often 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.

2.2 Effects of Industrial Pretreatment

The national effects of industrial pretreatment on hydrogen sulfide corrosion are very difficult to ascertain since no sanitation districts 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 may have caused an acceleration in corrosion rate, possibly due to decreased 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. (This is consistent with the known toxic effects of metals on other microorganisms.)

- When compared with data from 50 other wastewater treatment plants in the 1970's, total metals and cyanide levels in the CSDLAC wastewater were higher than levels in wastewater entering 47 of the 50 facilities. While 32% of the cities had total metals and cyanide levels higher than CSDLAC levels after pretreatment, it is difficult to project how many cities could potentially have a corrosion problem affected by industrial pretreatment since it is not known at what levels industrial constituents begin to suppress sulfide generation.

- Data comparing corrosion in residential vs. industrial sewers were inconclusive as to whether metals suppressed hydrogen sulfide corrosion.
- Local regulation of certain non-toxic constituents in industrial waste discharges (BOD, sulfide, temperature, pH) has had a beneficial impact in reducing the potential for hydrogen sulfide corrosion.
- Additional research is necessary to establish the constituents and their associated levels at which sulfide generation is suppressed or accelerated.

2.3 Detection, Prevention, and Repair of Hydrogen Sulfide Corrosion Damage

Based on current information, the following findings and conclusions are presented for the detection, prevention and control of hydrogen sulfide corrosion, and for repairing damage by hydrogen sulfide corrosion:

- Some municipalities are not aware of sewer corrosion problems until street collapses or sewer blockages occur.
- No standardized technique exists for measuring corrosion to obtain accurate corrosion rate data.
- Educational programs are necessary to disseminate information on corrosion detection and monitoring to municipalities.
- Although design procedures have been developed to assist in controlling sulfide generation and corrosion, these procedures are not universally practiced. Some observed corrosion could have been foreseen and avoided using existing design principles that minimize sulfide generation and corrosion.
- A large variety of chemicals and techniques are used to control sulfide in sewers and treatment plants, often for odor control. However, their costs and effectiveness for corrosion control vary widely based on site-specific conditions.
- Based on a 1984 survey of 89 cities, 34 percent take measures to reduce

sulfide in sewers, and 63 percent provide corrosion protection of sewers or use one or more techniques to rehabilitate corroded sewers.

- The current national expenditure for controlling sulfide generation in sewers is on the order of tens of millions of dollars per year. CSDLAC alone is spending approximately two million dollars per year on chemicals to control sulfide. Some cities have discontinued chemical sulfide control measures due to the high costs.

- National expenditures for rehabilitation of sewers and structures damaged by hydrogen sulfide corrosion is very difficult to estimate. Although municipalities maintain records of operation and maintenance activities, often the cost of corrosion-related rehabilitation and replacement activities are not readily retrievable.

- Many options are available to rehabilitate pipe which has been damaged due to corrosion. Some, such as sliplining and cured-in-place inversion lining, have been widely used with satisfactory results. Others, such as application of "corrosion-resistant" coatings, have often experienced early failure.

3.0 RECOMMENDATIONS

Based on the findings of this study, additional emphasis needs to be given to information dissemination and education regarding hydrogen sulfide corrosion. There is a need to inform municipal political officials, design engineers, construction contractors, and operating staff of methods to minimize corrosion in new installations and detect corrosion in existing structures.

- Municipalities should incorporate corrosion detection and monitoring strategies into their collection system operating and maintenance procedures, in order to protect their infrastructure investment and preclude catastrophic failures.

    - In order to assist them in their efforts, EPA is developing a guidance manual and educational material for detecting, monitoring, and correcting hydrogen sulfide corrosion problems.

- Municipalities should maintain records of the extent of corrosion, wastewater characteristics, and corrosion rates in different parts of their systems. These records will assist in identifying factors that contributed to changes in rate over time. As monitoring of corrosion rate becomes more established, the relationship between corrosion rate and other factors such as water conservation, regionalization of wastewater treatment, and combined sewer separation can be studied.

- Programs to educate engineers regarding design procedures to minimize corrosion must continue, and should be incorporated into academic curricula.

- Other agencies should be encouraged to disseminate information on corrosion issues.

    - The Department of Housing and Urban Development and the Department of Agriculture's Farmer's Home Administration should be encouraged to issue corrosion prevention design information to municipalities obtaining funding from them for collection and treatment systems.

In spite of numerous previous and on-going efforts, corrosion is not entirely a controllable phenomenon. Therefore, additional research should be done in order to reduce the high costs of correcting corrosion in existing infrastructure.

- Additional research should be conducted on the effect of metals and cyanide on sulfide generation, and to establish threshold levels at which sulfide generation is inhibited.

- Research should be conducted to find a reliable method of monitoring the rate of corrosion.

- Microbial research should be encouraged to increase the understanding of the specific microbes contributing to the corrosion process as well as to study the relationship between these organisms and other microbial populations in a dynamic system.

- Applied research should be conducted on methods which offer low-cost approaches to controlling sulfide generation and hydrogen sulfide corrosion in sewers.

1.0 BACKGROUND AND OVERVIEW

1.1 Legislative Charge

This report presents the results of the Hydrogen Sulfide Corrosion Study, a study conducted by the U.S. Environmental Protection Agency (EPA) in response to a specific Congressional mandate in the Water Quality Act of 1987 (Public Law 100-4). Section 522 of the Act specified that:

> The Administrator shall conduct a study of the corrosive effects of sulfides 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).

1.2 Los Angeles County System History (2)

The sewer system of Los Angeles County serves over 4 million people in a 640 square mile area containing some 70 cities. Over 500 million gallons per day of wastewater is collected from residential, commercial, and industrial sources and conveyed through 9,000 miles of sewers to six wastewater treatment plants. Approximately 1,000 miles of sewers are owned and maintained by the County Sanitation Districts of Los Angeles County (CSDLAC), and the remaining 8,000 miles are owned and maintained by local cities or Los Angeles County.

The large sewers, typically constructed of reinforced concrete pipe with no protective coatings or linings, range in size from 54 to 144 inches in diameter. The oldest of these sewers have been in service for over 65 years. During design it was recognized that corrosion resulting from the presence of sulfide generated in the wastewater was a potential problem, and in-house research on the subject began in the 1930's. It was believed that proper design could minimize the problem by preventing the conditions which favor sulfide generation. As the size of the collection system increased, it became apparent that sulfide generation was occurring.

In 1968, a three-year research project was initiated to better understand the processes of sulfide generation and hydrogen sulfide corrosion. Through measurements made at monitoring stations throughout the sewer system, an empirical equation was developed to allow prediction of sulfide generation and corrosion. Detailed inspections and monitoring in the early 1970's indicated the equation to be valid and able to predict corrosion rates with reasonable accuracy. Based on observed corrosion rates, the useful structural lifetimes of the sewers were estimated to range from several decades for the oldest sewers, up to hundreds of years for most of the sewers constructed after World War II.

A second series of inspections in the early 1980's revealed that the rate of corrosion had increased dramatically since the previous inspections in the 1970's, and was no longer predictable using the empirical formulas. In some sewers corrosion rates had increased from 0.01 inches per year to 0.25 inches per year. This would reduce the life expectancy of those sewers from 100 years to four years.

Subsequent studies showed a high statistical correlation between the reduction in the levels of certain metals and other specific wastewater constituents and the increase in levels of hydrogen sulfide responsible for the corrosion. These constituents 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.

Two of the theories being researched by CSDLAC are that the high levels of metals and toxic constituents present in the early 1970's 1) inhibited the biological generation of sulfide, or 2) reduced release of hydrogen sulfide to the sewer atmosphere where it can be converted into sulfuric acid to cause corrosion. When concentrations of these compounds were reduced upon implementation of industrial pretreatment standards, CSDLAC reported that the rates of sulfide generation and corrosion increased. Indeed, CSDLAC found a high correlation between the drop in such constituents and the increase in sulfide generation. Between 1971 and 1986, average total sulfide levels entering the main wastewater treatment plant increased from 0.4 to 3.0 mg/l.

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. Almost $2 million per year is currently being spent for chemicals to control corrosion in the CSDLAC sewer system. CSDLAC is conducting corrosion-related research as well as supporting research at the University of California - Los Angeles, University of Southern California, California Institute of Technology, and University of Arizona.

1.3 Scope of Study

Hydrogen sulfide corrosion is a well-known phenomena that occurs in many wastewater collection and treatment systems throughout the world. Several design manuals have been published on the subject (3)(4)(5)(6)(7).

The objectives of this study were to 1) document the extent and severity of hydrogen sulfide corrosion problems in wastewater collection and treatment systems in the United States, 2) investigate the effects of implementing industrial pretreatment standards on sulfide generation and corrosion, and 3) study options available to prevent corrosion and rehabilitate corroded structures.

Achieving the first two objectives was limited by the lack of existing data and information. Specifically, many cities are unaware of the existence of severe corrosion problems, and have little or no documentation of corrosion. Corrosion problems often are addressed only in the event of a catastrophic failure, as with a cave-in or pipe collapse. No standardized technique is available to accurately measure the extent of corrosion, resulting in poor reproducibility and questionable accuracy. Those municipalities that have attempted to quantify corrosion in sewers have done so recently. Thus, the estimated corrosion rate represents an average rate over the lifetime of the pipe, and does not reflect changes in the rate of corrosion which might have occurred in the past. No entities other than CSDLAC were found to have sufficient historical data on sulfide levels or corrosion rates to establish a correlation between implementation of industrial pretreatment standards and increased rate of corrosion. Research on the relationship between wastewater characteristics and potential corrosion rates appears to be limited to that conducted or sponsored by CSDLAC.

The study concentrated on the three areas mandated by the Act (see Section 1.1). 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.

This report addresses the following topics:

1. <u>The Corrosive Effects of Hydrogen Sulfide</u>

    - consequences of corrosion
    - mechanisms of corrosion
    - factors affecting corrosion
    - extent of corrosion problems in wastewater systems in the U.S.

2. <u>Effects of Industrial Pretreatment</u>

    - theories of potential effects of industrial wastewater constituents on corrosion rate
    - results of CSDLAC research
    - comparison of metals and other industrial constituent levels in wastewater in the U.S.
    - results of EPA site visits to industrial cities
    - beneficial effects of industrial pretreatment on corrosion rate

3. Detection, Prevention and Repair of Corrosion Damage

- options for corrosion control in existing systems
- techniques for corrosion prevention during design
- rehabilitation techniques

4. Recommendations

- guidance to municipalities
- continuing education to design engineers
- additional research

A separate document entitled, "Technical Report on Hydrogen Sulfide Corrosion in Wastewater Collection and Treatment Systems" has been prepared as a companion document to the Report to Congress. The Technical Report contains additional data and technical detail to support the findings and conclusions presented in the Report to Congress.

2.0 CORROSIVE EFFECTS OF HYDROGEN SULFIDE

2.1 Consequences of Corrosion

Corrosion of wastewater conveyance 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 street collapses or sewer blockages 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. Figure 1 shows the mechanism of sewer failure due to hydrogen sulfide corrosion.

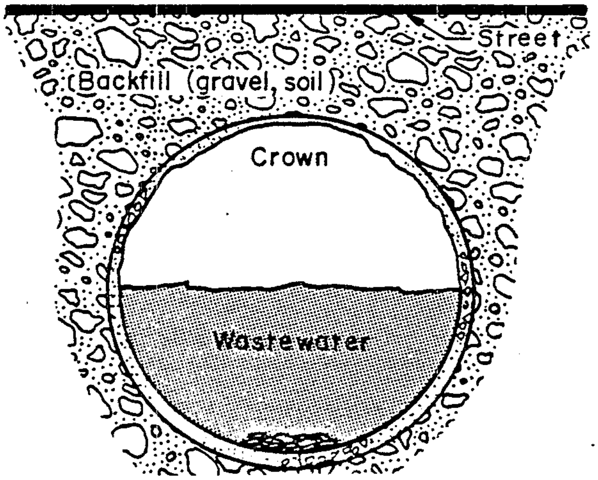
Equipment used in the treatment of wastewater is often subject to hydrogen sulfide corrosion, resulting in equipment malfunctions, poor reliability, increased maintenance, and premature replacement. Electrical components (e.g. brushes, switches, relays) process instrumentation, air conditioning and ventilation 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 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.

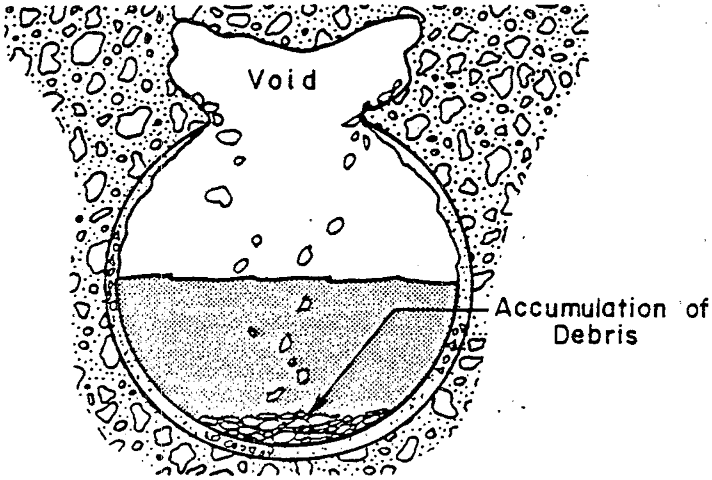
2.2 Basic Mechanism of Hydrogen Sulfide Corrosion

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 structures used in the conveyance and treatment of sewage. The second mechanism is generally responsible for corrosion of electrical contacts, copper pipe, and other metallic components in pumping stations, lift stations, and treatment plants.

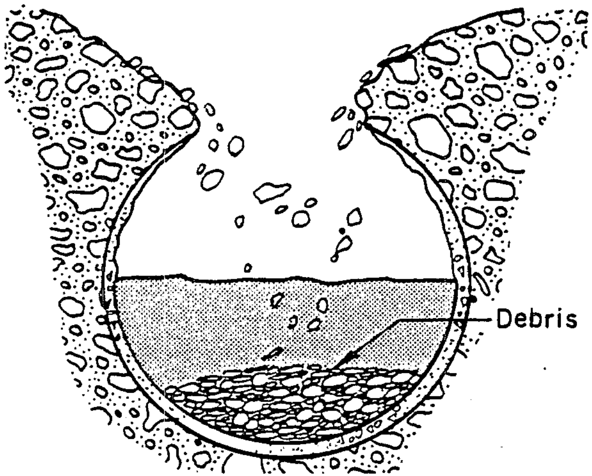
In properly designed gravity sewers the velocity of the sewage promotes surface aeration helping to replenish any losses of oxygen due to microbial activity. Under certain conditions oxygen is consumed by microorganisms faster than it is supplied, causing a change from aerobic to anaerobic (devoid of oxygen) conditions. Such conditions can occur in gravity sewers with low sewage velocities or long detention times, in pressurized or surcharged mains which convey wastewater through a full pipe with no opportunity for aeration, and in pumping stations or retention basins having



(A) Corrosion reduces structural integrity of pipe crown.



(B) Crown collapses and void forms from backfill washing into sewer.



(C) Backfill continues to wash into sewer eventually leading to sewer blockage and/or street collapse.

Figure 1

Process of Sewer Failure due to Hydrogen Sulfide Corrosion

long detention times. In such cases, high velocities and turbulence actually promotes release of dissolved hydrogen sulfide gas.

The process of sulfide generation and sulfuric acid corrosion is as follows (4)(5)(6):

1. Under anaerobic conditions, anaerobic bacteria reduce sulfate, one of the most common constituents in water and wastewater, to sulfide. Warmer wastewater favors increased bacterial growth and metabolic activity. In large sewers this occurs primarily in slimes (0.25-3 mm, but typically 1 mm thick) attached to the submerged portion of the interior pipe surface (Figure 2a).

2. The sulfide ions combine with hydrogen ions to form hydrogen sulfide, which exists as a gas dissolved in the water (Figure 2b).

3. Hydrogen sulfide gas is released from the wastewater to the sewer atmosphere. The escape of hydrogen sulfide gas from solution increases with temperature due to decreased solubility in the wastewater, and is greatly accelerated under turbulent conditions (Figure 2b).

4. The released H_2S is oxidized to sulfuric acid by aerobic bacteria of the genus <u>Thiobacillus</u> on moist, non-submerged surfaces of the pipe (Figure 2c).

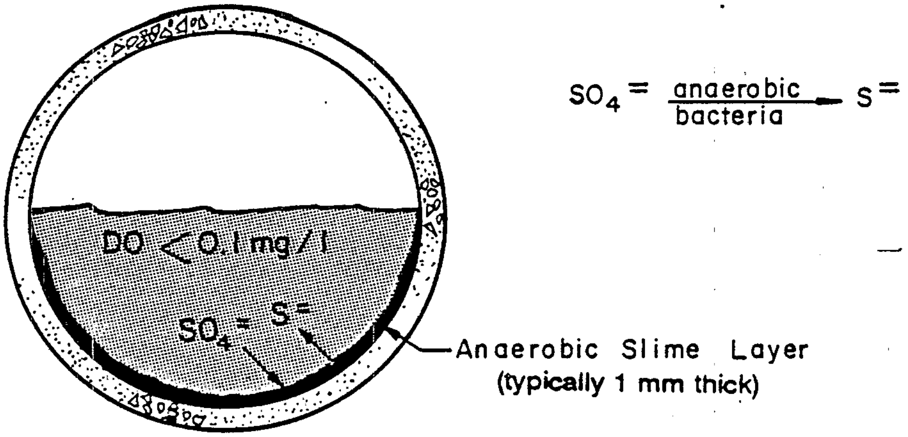
5. The acid attacks the Portland cement and calcareous aggregate (limestone) of the concrete sewer pipes to form soft corrosion products such as gypsum. These products are washed away or fall out of the concrete matrix, exposing fresh concrete and aggregate to corrosion processes (Figure 2c).

Concrete has been one of the most widely used pipe materials for large diameter pipe, traditionally used for interceptor sewers that carry large amounts of wastewater contributed from smaller collector sewers. Results of one survey indicated that over 90 percent of the cities used unlined, reinforced concrete sewer pipe in portions of their collection systems. Certain pipe materials such as polyvinyl chloride (PVC) and vitrified clay, which are immune to hydrogen sulfide corrosion, have been used frequently for pipes less than approximately 36 to 42 inches in diameter (see Section 3 for further discussions of corrosion protection).

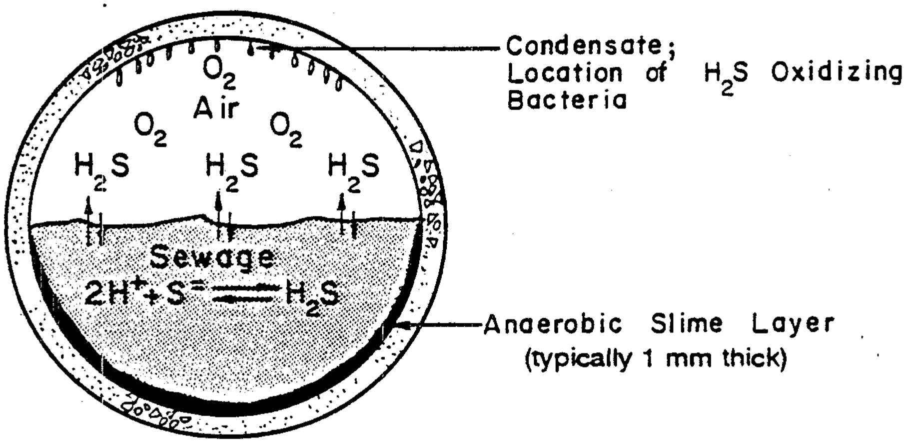
2.3 Factors Affecting Corrosion

Many factors affect the presence and rate of sulfide generation in wastewater systems and the corrosion which may occur as a result of the presence of hydrogen sulfide gas.

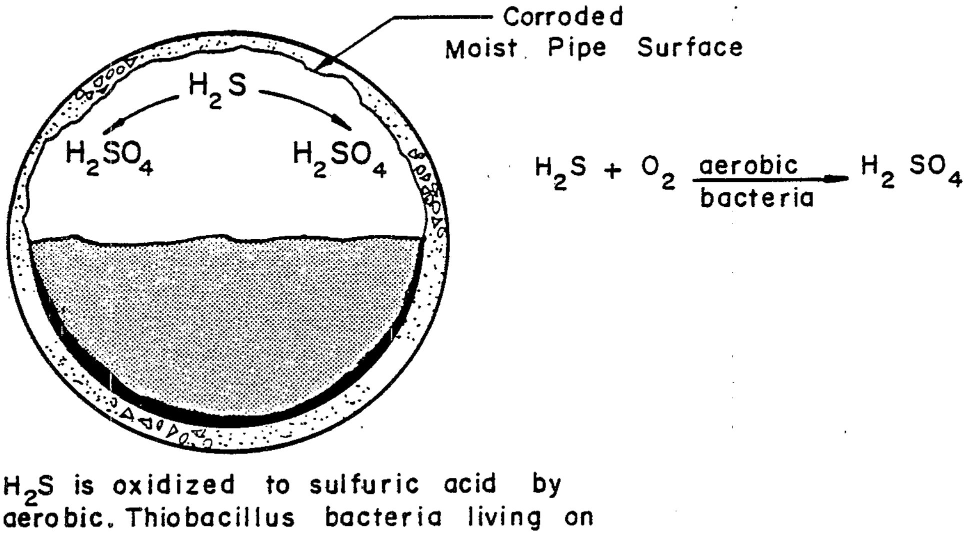
Sulfide generation occurs in a sewer when dissolved oxygen (DO) levels in



(A) Sulfate is biologically reduced to sulfide in the anaerobic slime layer on the submerged pipe wall.



(B) H_2S formed in the wastewater is released from solution as a gas and enters the sewer atmosphere.



(C) H_2S is oxidized to sulfuric acid by aerobic. Thiobacillus bacteria living on moist, non-submerged surfaces. Acid attacks concrete, causing corrosion.

Figure 2

Mechanism of Sulfide Generation and Corrosion in Sewers

the wastewater are nearly depleted. Dissolved oxygen is reduced when the uptake of oxygen by bacteria present in the wastewater exceeds the replenishment of oxygen by natural aeration. Factors that affect the depletion of dissolved oxygen include:

1. Velocity of sewage (low velocities reduce turbulence which decreases surface aeration).
2. Detention time (long detention times allow for oxygen depletion and subsequent sulfide generation).
3. Temperature (higher temperatures reduce the solubility of oxygen and increase growth rates of oxygen-consuming microorganisms).

Once dissolved oxygen levels have been depleted, factors that affect the rate of sulfide generation are:

1. Concentration of organic materials and nutrients (higher concentrations increase bacterial growth and metabolism).
2. Temperature of the wastewater (higher temperatures increase bacterial growth rates).
3. Presence of toxic materials, including metals (reduces bacterial activity).

The subsequent release of hydrogen sulfide gas to the atmosphere of a sewer, retention basin, or other structure is affected by:

1. Relative acidity (pH) of the sewage (pH values below 7 favor the formation of dissolved hydrogen sulfide gas, which can be released to the atmosphere).
2. Level of turbulence (turbulence promotes release of H_2S gas).
3. Temperature of the sewage (higher temperatures reduce solubility of H_2S in the wastewater).
4. Presence of metals (metal ions react with sulfide to form insoluble metallic sulfide precipitates which reduce the amount of H_2S released). (see Section 3.2).

Finally, the corrosion of the concrete or metal pipe or structure is affected by:

1. Presence of moisture (needed for bacterial activity).
2. Temperature of the pipe (higher temperatures increase bacterial activity).
3. Alkalinity of the concrete and its aggregate (higher alkalinity increases resistance to acid attack).

Thus, it is clear that many interacting factors affect the conditions in which hydrogen sulfide corrosion occurs, and the rate of corrosion. In summary, the major conditions which must be satisfied in order for hydrogen sulfide corrosion to occur are:

1. Absence of, or very low levels of dissolved oxygen in the wastewater.
2. Release of hydrogen sulfide gas from solution.
3. Presence of moisture on a material that is subject to attack by sulfuric acid.

2.4 Findings of Study

2.4.1 Sites with Severe Corrosion

Hydrogen sulfide corrosion may be found in many wastewater collection and treatment systems throughout the world. Such corrosion varies widely with respect to severity and rate. To distinguish levels of severity and rate, 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 (see glossary). Exposure of reinforcing steel to corrosion can lead to structural impairment.

Accelerated corrosion - an increase in the rate of corrosion with time.

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.

Site visits conducted by EPA revealed that the most severe cases of corrosion generally occurred at areas of high turbulence, where hydrogen sulfide gas was released from the wastewater in large quantities. Examples of sites where severe corrosion was observed are:

1. Discharges of pressurized pipes (force mains) into manholes or other structures.

2. Junction boxes, metering stations and transition structures.

3. "Wet wells" of pumping stations from which the pumps draw the sewage.

4. "Drop" manholes, where wastewater cascades through a drop of several feet, creating high turbulence.

5. Treatment processes at wastewater treatment plants, where anaerobic sewage is subjected to screening, aeration, discharge over weirs, and other processes which impart turbulence.

6. Shallow slope collector sewers, large diameter or low-flow interceptors conveying wastewater containing relatively high levels of sulfide.

7. Structures, equipment, and instrumentation near areas where hydrogen sulfide is released to the atmosphere due to turbulence.

2.4.2 Biological Mechanism of Corrosion

EPA field studies included sampling and analysis of sewer slimes from corroded and non-corroded sites in CSDLAC and Seattle for microbiological analysis. The Thiobacillus microbial community, responsible for production of corrosive sulfuric acid at the pipe crown, was significantly different at corroded sites in CSDLAC. Much lower numbers of viable, aerobic organisms were found on pipe crowns with low pH in both systems. However, all the crowns contained high numbers of the Thiobacillus bacteria responsible for the production of sulfuric acid. As would be expected, higher numbers of sulfate-reducing (sulfide-producing) bacteria were found in the submerged sewer slimes at corroded sites. Although relatively large numbers were also found in the bulk wastewater, the sewer slimes are still considered to be the predominant site for sulfide generation.

A review of the literature and discussions with microbiologists active in the field of hydrogen sulfide corrosion revealed that the body of knowledge on the role of other microorganisms in sulfide generation and corrosion is limited. Because of the genetic diversity and adaptability of the bacteria responsible for hydrogen sulfide corrosion, results of laboratory studies are not directly applicable to the field.

2.4.3 Extent of Corrosion

Site visits conducted by EPA revealed that severe corrosion problems are not limited to areas having warm or semi-tropical climates. Severe corrosion was observed in Seattle, WA; Milwaukee, WI; Boise, ID; and Casper, WY; in addition to Albuquerque, NM; Baton Rouge, LA; Fort Worth, TX; Los Angeles County, CA; New Orleans, LA; and Tampa, FL. Figure 3 is a photograph of a severely corroded sewer in Casper, Wyoming. Figure 4 depicts a severely corroded, 108-inch diameter sewer in Seattle. Corrosion processes had removed at least one inch of concrete and had exposed the reinforcing steel. For comparison, Figure 5 shows a 50 year old uncorroded sewer in Milwaukee, WI. Figure 6 shows a brick manhole in Baton Rouge, LA, in

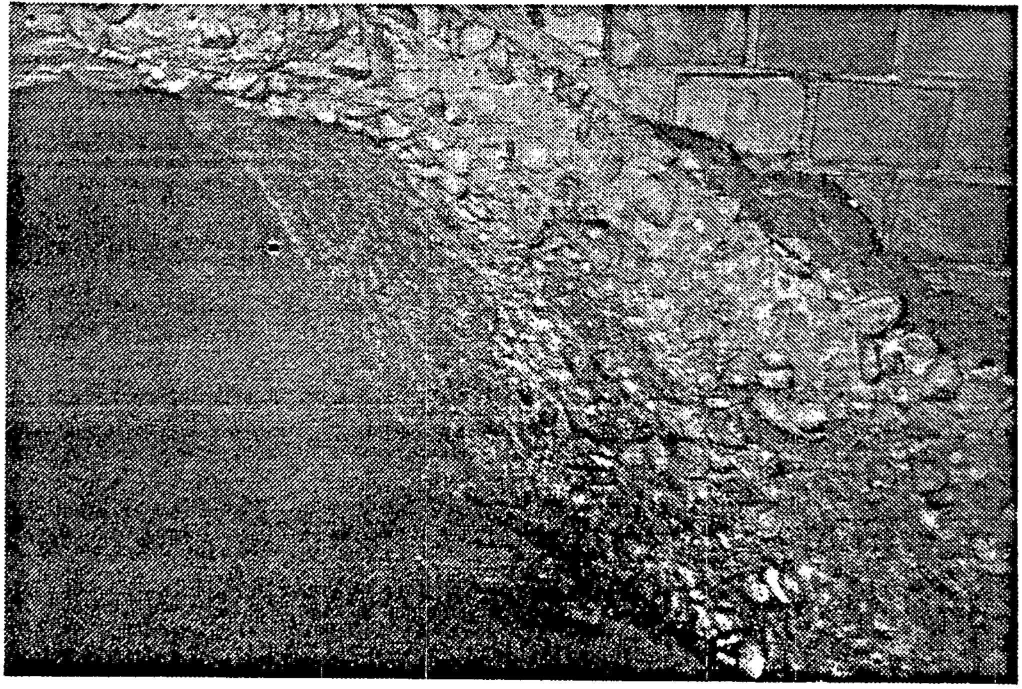


FIGURE 3. SEVERELY CORRODED SEWER IN CASPER, WY

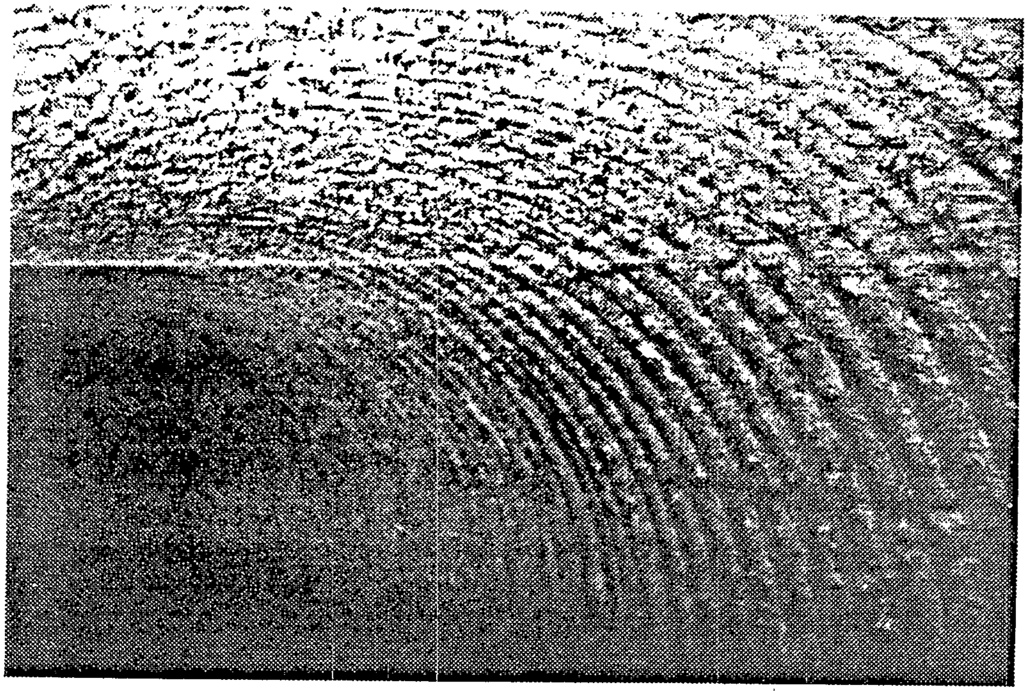


FIGURE 4. SEVERELY CORRODED SEWER IN SEATTLE, WA

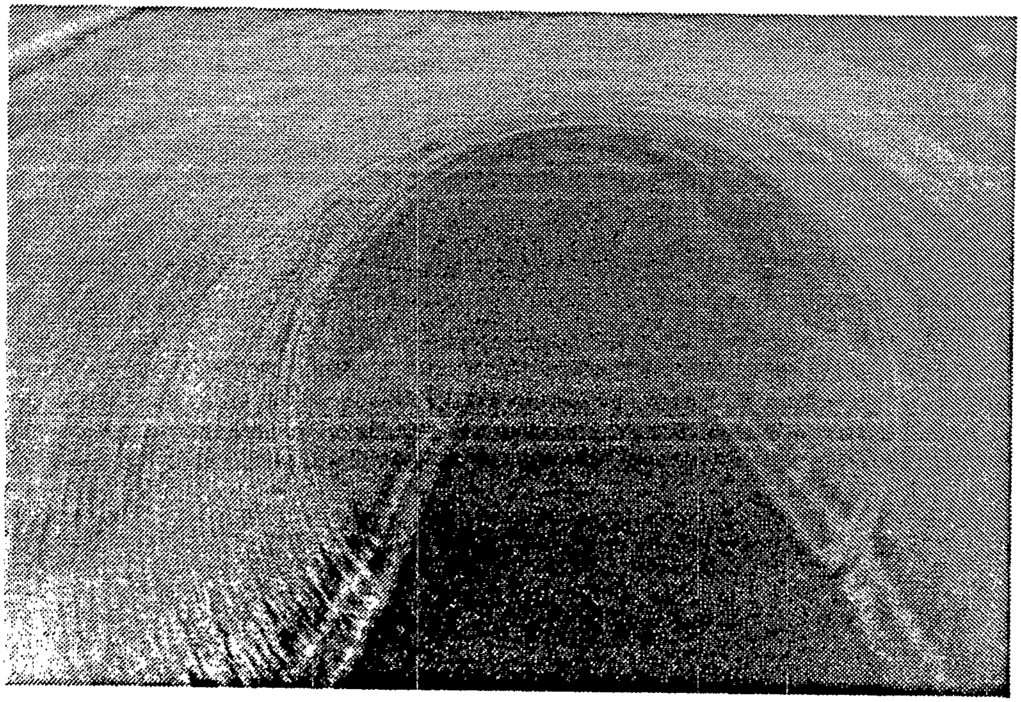


FIGURE 5. NON-CORRODED, 50 YEAR OLD SEWER IN MILWAUKEE, WI

FIGURE 6. BRICK MANHOLE WITH LOOSE AND MISSING BRICKS

which bricks were loose or missing due to corrosion of the mortar.

In the 1984 survey, 32 of 89 cities reported sewer collapses. Based on review of the responses, it is estimated that 26 of the 32 cities had experienced collapses due to hydrogen sulfide corrosion. Overall, almost 30 percent of the cities surveyed had experienced one or more pipe collapses that were judged to be due to hydrogen sulfide corrosion.

Corrosion of sewers due to the presence of hydrogen sulfide is an international problem. At least twenty countries have reported hydrogen sulfide corrosion problems in their sewer systems.

Corrosion problems are also prevalent in wastewater treatment plants. In two independent surveys, approximately 60 to 70 percent of the respondents indicated the existence of corrosion problems at their wastewater treatment plants. In one of the surveys, 14 percent of the 1,003 cities reported severe corrosion problems at their wastewater treatment plants. (see Figure 7). Corrosion at the wastewater treatment plant may be an indication of corrosion in the collection system (6), and is more easily detected. On the other hand, half of the jurisdictions EPA visited with severe corrosion problems in the collection systems had minor or no corrosion problems at the wastewater treatment plants. Therefore, it is likely that more than 14 percent of the surveyed systems may have some serious corrosion problems in their collection systems.

Site visits were made to two plants in the city of Los Angeles, two in New Orleans, and one in Tampa where severe corrosion problems were observed. Problems ranged from severe deterioration of concrete structures to corrosion of equipment, electrical contacts and instrumentation systems. Severe corrosion of wastewater treatment plant components was also observed. Figure 8 shows a corroded metal slide gate and concrete channel at Tampa, FL. Figure 9 depicts a severely corroded concrete channel at the Hyperion wastewater treatment plant in Los Angeles. Figure 10 shows the badly corroded exterior of an electrical control panel at the Hookers Point plant in Tampa. Figure 11 depicts a severely corroded steel I-beam in an influent screen chamber that was previously covered (St. Petersburg, Florida).

Figure 12 shows relative frequency of severe corrosion problems in sewer systems or treatment plants throughout the United States. 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 13 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, but rather indicates where corrosion prevention

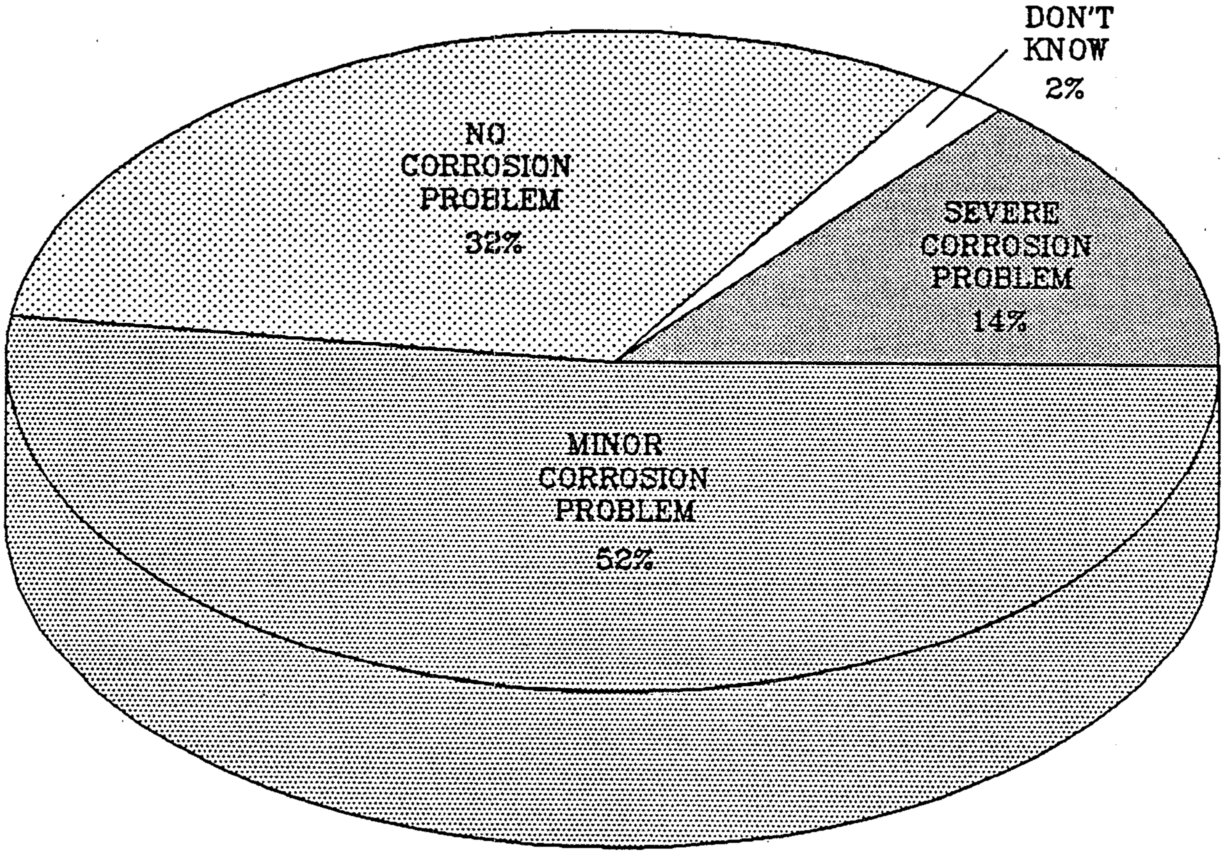


FIGURE 7. FREQUENCY OF CORROSION PROBLEMS AT WASTEWATER TREATMENT PLANTS (FROM WPCF SURVEY, 1989)

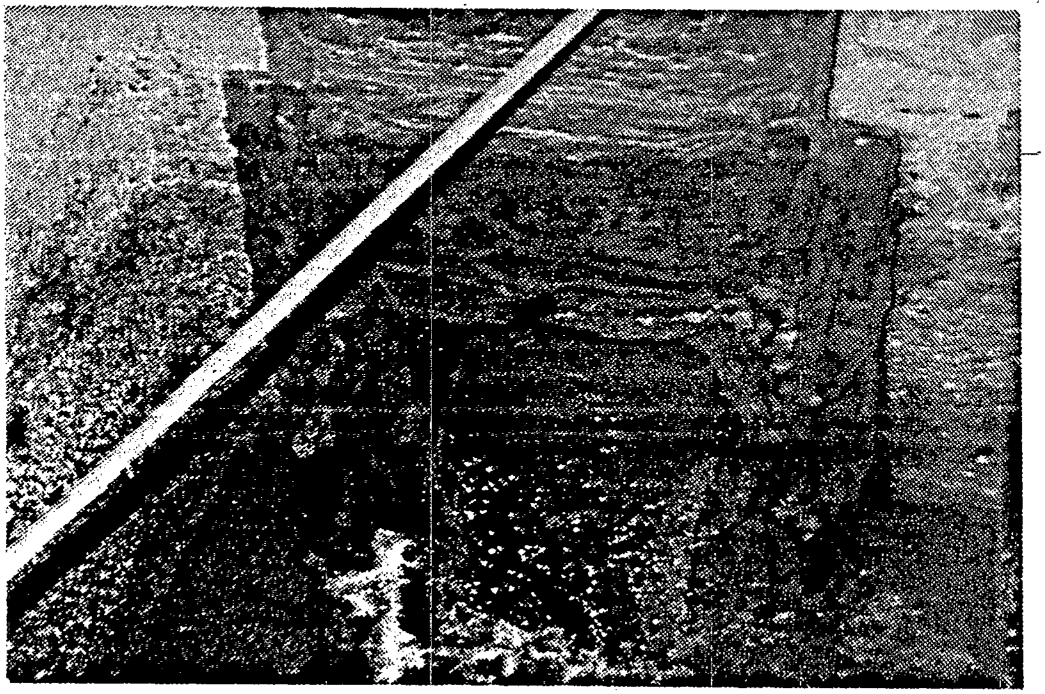


FIGURE 8. SEVERELY CORRODED METAL GATE AND CONCRETE CHANNEL IN TAMPA, FL

FIGURE 9. SEVERELY CORRODED CONCRETE CHANNEL IN LOS ANGELES, CA

FIGURE 10. CORRODED ELECTRICAL CONTROL PANEL IN TAMPA, FL

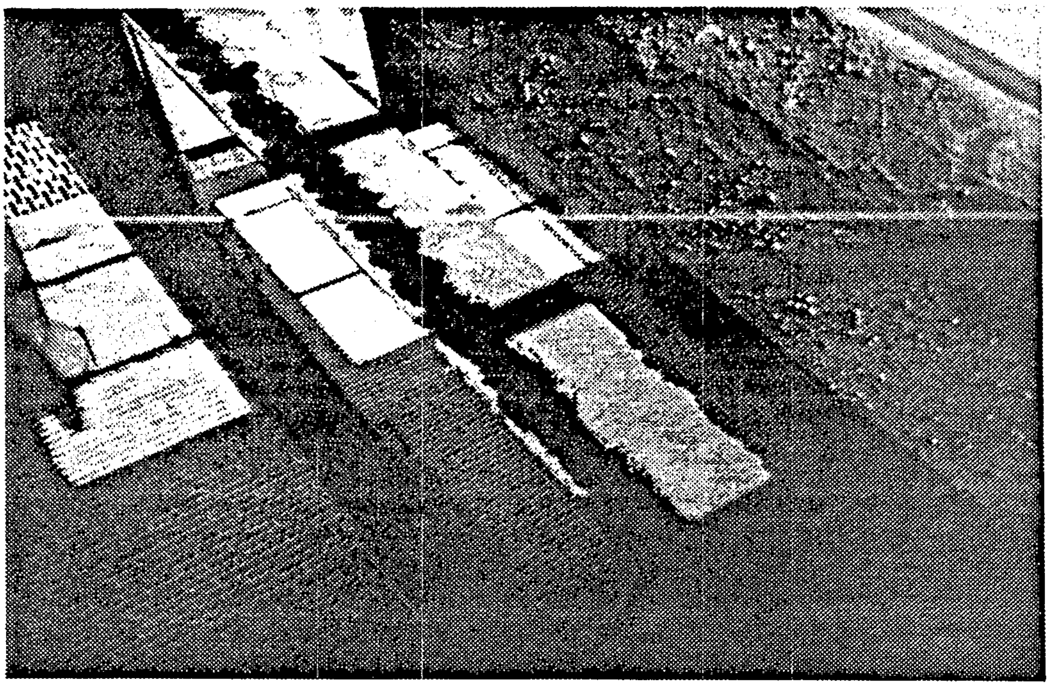


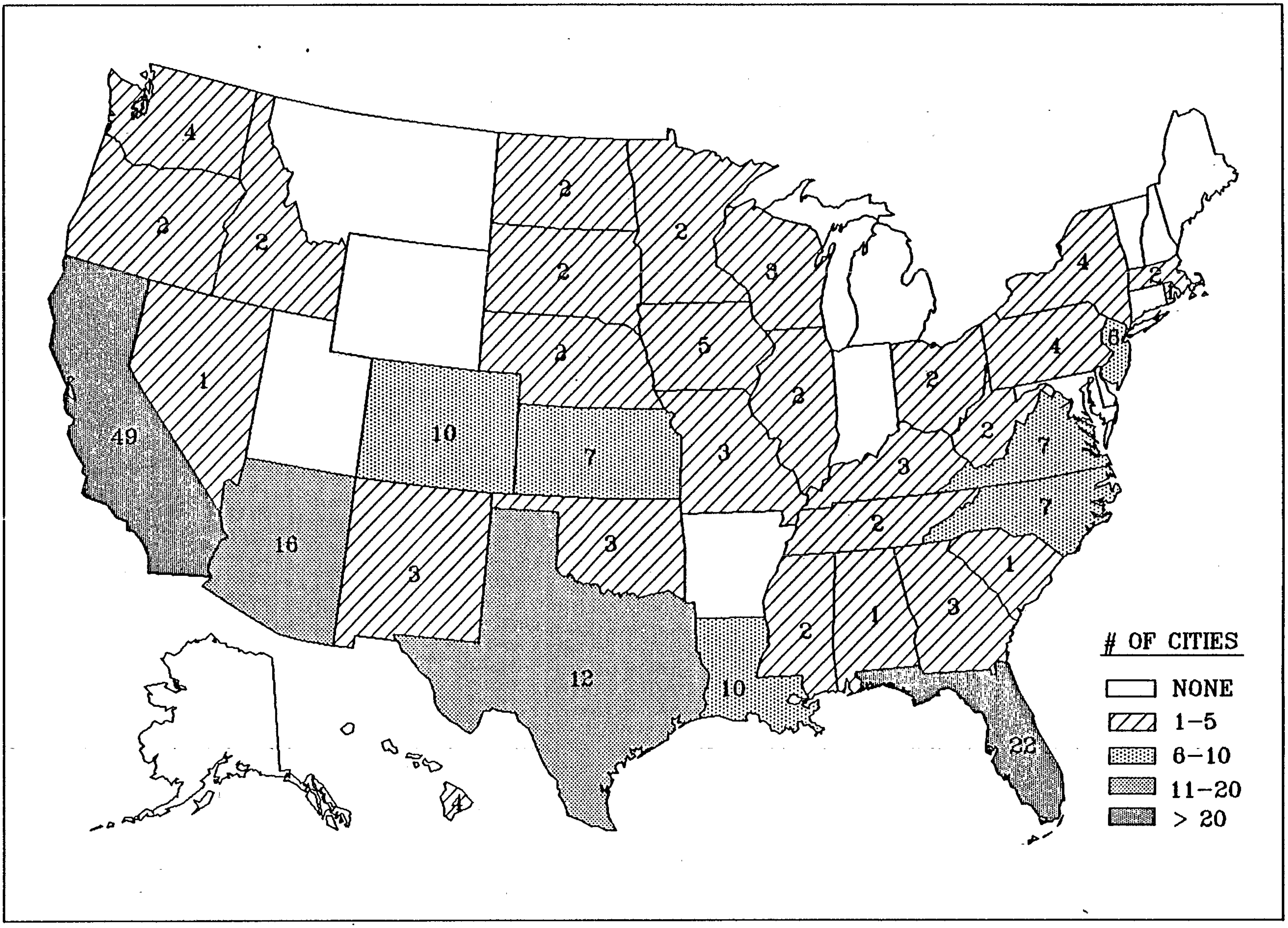
FIGURE 11. CORRODED STEEL I-BEAM IN ST. PETERSBURG, FL

FIGURE 12

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

FIGURE 13

USE OF PROPRIETARY PVC LINING TO PREVENT CORROSION OF CONCRETE PIPE



was considered appropriate for one or more projects in these localities.

High-rate corrosion (> 1 inch in 20 years) was found in many of the cities visited by EPA, including Los Angeles, Albuquerque, Baton Rouge, Boise, Casper, Fort Worth, and Seattle. In one Albuquerque sewer the corrosion rate was estimated to be one inch in seven years. In Boise, corrosion rate in one manhole was approximately one inch in 3½ years (see the Technical Report). The literature reveals corrosion rates of up to one inch in two years being reported in Venezuela, Egypt, and Iraq (8)(9).

2.4.4 Accelerated Corrosion

The term "accelerated" corrosion refers to an increase in the <u>rate</u> of corrosion. This phenomenon was experienced by CSDLAC, where corrosion rate increased from approximately 0.01 inches per year (1 inch in 100 years) prior to 1975 to 0.17 inches per year (1 inch in 6 years) during 1983-1987. Total sulfide levels in the wastewater during this same period increased from about 0.5 mg/l to between 2 and 4 mg/l (2). Clearly, the increase in observed sulfide levels and corrosion rate over the past 20 to 25 years is dramatic.

EPA was unable to document other cases of accelerated corrosion during the site investigations and during discussions with other municipalities, consulting engineers, and vendors of equipment and materials used for sulfide and corrosion control. One of the major problems is lack of data, as CSDLAC is perhaps the only entity with extensive historical data that quantify the sulfide levels and the extent of corrosion over a long time period. Thus, CSDLAC has been able to document the change in rate at which corrosion is occurring, as well as the levels of sulfide in the wastewater. None of the municipalities contacted had such historical data.

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 was impossible to determine from these data whether the corrosion rate had changed with time. Such inspections merely offer a "snapshot" of the corrosion process and provide no information on the history of corrosion.

2.5 Results and 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 can be 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.

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.

3.0 EFFECTS OF INDUSTRIAL PRETREATMENT

3.1 Overview

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 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. A concomitant rise in sulfide levels in the wastewater occurred over this same time period, and CSDLAC observed an increase in the rate of corrosion in their concrete sewers. One theory proposed is that the high levels of metals and other toxic constituents present in the early 1970's inhibited the biological generation of sulfide. A second theory is that these materials prevented release of hydrogen sulfide to the sewer atmosphere where it could be converted into corrosive sulfuric acid.

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. (See Section 2.4.4).

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 sewer 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 Reduction of Sulfide by Precipitation 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 4.2, 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. 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 1 shows the theoretical increase in sulfide levels which could be accounted for by the reduction in metals available to precipitate the sulfide. Based on the measured decrease in metals in CSDLAC wastewater between the periods 1971-1974 and 1983-1986, the theoretical increase in dissolved sulfide is in excess of 4 mg/l. However, the actual increase measured in dissolved sulfide in CSDLAC wastewater during that same period was approximately 1 mg/l.

Actual dosages needed to precipitate sulfide are considerably higher than the theoretical dosage ratio of 1.7 to 1. Field studies by CSDLAC on the addition of iron 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 dissolved sulfide was less than 1 mg/l, a dosage ratio of 44 to 1 was required (10). Thus, four to 25 times the theoretical dosage was required in the CSDLAC system. Other studies have shown that five to seven times the theoretical dosage is required to remove sulfide using zinc. The last column in Table 1 indicates the predicted increases in sulfide based on the decreased zinc and iron. Based on these field studies, the expected increase in dissolved sulfide expected from decreased zinc and iron concentrations is 0.1 to 0.8 mg/l, vs. the 1 mg/l observed.

It is unlikely that decreased precipitation alone could account for the changes in sulfide levels. Decreasing metals concentrations would be expected to increase the amount of dissolved sulfides without affecting the total sulfide concentration. This is because the total sulfide test measures dissolved sulfides and metal-sulfide precipitates. However, between 1971 and 1986, average total sulfide levels entering the main CSDLAC wastewater treatment plant increased dramatically from 0.3 to 3.0 mg/l. Therefore, metal precipitation principles do not explain the rise in total sulfides experienced in CSDLAC.

TABLE 1

THEORETICAL INCREASE IN DISSOLVED SULFIDE BASED ON METAL PRECIPITATION; CSDLAC

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	NFD[4]
Copper	0.38	0.10	NFD
Lead	0.17	0.03	NFD
Zinc	1.34	0.66	0.06 - 0.1
Nickel	0.14	0.08	NFD
Iron	4.92	2.83	0.1 - 0.7
Cadmium	0.01	0.00	NFD
TOTAL		4.12	0.16 - 0.8

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

[2] Based on stoichiometry of chemical precipitation reactions

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

[4] No field data on dosage performance are available

3.3 Biological Inhibition by Metals and Toxic Compounds

Another potential mechanism to explain the increased sulfide generation in the CSDLAC sewer system is that the high levels of metals present in the 1970's inhibited the bacteria responsible for the biochemical generation of sulfide. CSDLAC set up several laboratory and pilot-scale experiments to investigate this theory.

The first experiments involved laboratory-scale investigations to determine the acute toxicity of selected metals and cyanide on cultures of sulfate-reducing bacteria. While the results were inconclusive at the levels of metals present in CSDLAC wastewater in the 1970's, the experiments showed some bacterial inhibitions at various levels of constituents. In general, field conditions are difficult to reproduce in laboratory "bench scale" experiments.

The next experiment used a series of columns designed to provide conditions appropriate for the generation of sulfide. Wastewater "spiked" with individual metals and cyanide as well as a "cocktail" of multiple metals and cyanide was added to the columns. The cocktail containing multiple metals and cyanide was added to the wastewater at levels approximating those in the early 1970's, as well as at five times those levels. At the 1970's levels, total and dissolved sulfide generation was reduced by 34 percent. At five times the 1970's levels, sulfide generation virtually ceased (11).

The most recent experiment involved the construction of small diameter piping systems to more closely simulate conditions in a sewer. At metals and cyanide levels approximating those in the early 1970's, results similar to the column experiments were obtained: Total sulfide levels were reduced by 34 percent and dissolved sulfide levels by 25 percent (11).

The results of these experiments strongly suggest that the generation of hydrogen sulfide in the wastewater of CDSLAC 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 Levels at CDSLAC with Other Cities Before Pretreatment

Using available data, levels of metals and cyanide for CDSLAC wastewater entering the main treatment plant during the periods 1971 - 1974 and 1986 were compared with levels in the wastewater of 50 municipal treatment plants across the U.S. in 1978 - 1979. Data were analyzed for these 50 cities from the EPA report, "Fate of Priority Pollutants in Publicly Owned Treatment Works" (12)(13). These data were collected in 1978-1979 prior to any significant implementation of industrial pretreatment standards. The fifty cities had estimated industrial flow contributions ranging from ten to fifty percent of the total flow. Thirty-two (64%) of the 50 cities listed industries with metal wastes. Analysis of these data allowed determination of the number of cities with metals and cyanide levels similar to those of CDSLAC 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 2 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 consider the toxicity of the constituents (alone or in combination) on sulfate-reducing bacteria. Of the 50 other municipalities, only three (six percent) are ranked higher than CDSLAC, while 47 (94 percent) are ranked lower. The total concentration of metals and cyanide in CDSLAC wastewater was approximately three times the median concentration for the 51 cities.

The total metals levels in CSDLAC wastewater in 1986 are also shown in Table 2. 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. Current concentrations of metals in these cities, with pretreatment standards, is not available.

Clearly, sulfide generation and corrosion in CSDLAC sewers increased 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. Results of the inspections were inconclusive, as corrosion was observed in both residential and industrial sewers. Further efforts to inspect residential and industrial sewers were abandoned due to the multitude of factors and conditions which affect sulfide generation and corrosion, which could easily mask any effects associated with the presence of industrial constituents.

TABLE 2

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

	Equivalent wt.									
PLANT	CADMIUM ueq/l	CHROMIUM ueq/l	COPPER ueq/l	CYANIDE ueq/l	LEAD ueq/l	MERCURY ueq/l	NICKEL ueq/l	ZINC ueq/l	IRON ueq/l	TOTAL 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

3.6 Beneficial Effects of Local Industrial Pretreatment Programs

It is important to recognize that several aspects of local industrial pretreatment regulations can lower the potential for hydrogen sulfide corrosion in sewer systems. Among the more important of these are reduction in: 1) sulfide-bearing wastes, 2) high strength organic waste discharges, 3) high temperature discharges, 4) fats, oils, and grease, and 5) acidic wastes. Because of the complex interaction of all the factors that affect hydrogen sulfide corrosion 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. 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 analyses, 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. (This is consistent with the known toxic effects of metals on other microorganisms.)

- 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 have a corrosion problem affected by industrial pretreatment since it is not known at what levels industrial constituents begin to suppress sulfide generation.

- 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.

TABLE 3

BENEFICIAL IMPACTS OF CONTROLLING INDUSTRIAL DISCHARGES ON HYDROGEN SULFIDE CORROSION

Type of Discharge Controlled	Benefit
Sulfide-bearing wastes	Lowers sulfide levels, corrosion potential
High organic strength wastes	Sulfide generation rate proportional to organic strength; reduction in organic strength reduces oxygen uptake and depression of dissolved oxygen in wastewater
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
Acidic wastes	Maintaining pH at or above neutral decreases amount of H_2S available for release to the sewer atmosphere

- 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.

4.0 DETECTION, PREVENTION, AND REPAIR OF HYDROGEN SULFIDE CORROSION DAMAGE

Significant advances have occurred during the past twenty years in the area of sewer rehabilitation. More economical techniques are now available to rehabilitate sewers damaged by corrosion, eliminating the need to excavate and replace the damaged pipe. Several design manuals have been prepared on the subject of preventing and controlling sulfide generation in sewers, both for the design of new systems and for the operation of existing systems. These include manuals by the Environmental Protection Agency, the American Society of Civil Engineers, the American Concrete Pipe Association, and others (3)(4)(5)(6)(7). Methods for the detection of corrosion are resource intensive and not routinely used by cities. Public education programs are needed to make municipalities aware of the problem before considerable damage has been done so that funding can be provided to correct the problems.

4.1 Detection of Hydrogen Sulfide Corrosion

Many municipalities are unaware of a corrosion problem until it manifests itself in the form of a pipe collapse or other catastrophic failure. With improved resolution of remote television cameras used in sewer inspections, corrosion can be detected by the trained observer. In most cases, however, considerable damage may already have been done. Sonic devices have also been successfully applied for sewer corrosion detection and measurement, but damage must already have occurred for detection by this method. Physical measurements of corrosion have also been attempted, but the accuracy using such techniques is poor. No standardized technique is available for measuring and quantifying the extent of corrosion.

Detection of acid on the pipe crown and walls is probably the best "early warning" that a potential or existing corrosion problem exists. However, most municipalities are not aware of the pH test or its application (4). An education program is necessary to train municipal officials on proper techniques for the detection and monitoring of corrosion.

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 sulfur, thiosulfate or sulfate. Metals form insoluble metal sulfide precipitates, preventing release of gaseous H_2S. Elevation of the pH through shock dosing of caustic controls sulfide generation by inactivation of sulfate-reducing slimes present on the wall of the sewer pipe. A summary of sulfide control techniques is provided in Table 4.

TABLE 4

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 (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

All of the above control techniques are oriented towards reducing the levels of dissolved sulfide in solution such that less hydrogen sulfide is released to the sewer atmosphere. Work conducted by CSDLAC under field conditions 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. Thus, a 90% reduction in dissolved sulfide does not indicate that the rate of corrosion will be reduced by 90% (2).

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.

Controlling sulfide generation by the addition of chemicals is often a costly proposition. Most municipalities add chemicals to control odors, not corrosion. Some cities have discontinued sulfide control efforts because of the high cost.

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 velocities, preventing deposition of solids, and by minimizing the use of force mains, inverted siphons, and surcharged sewers in which anaerobic conditions can develop.

Under certain conditions, sulfide generation may be unavoidable. Empirical equations have been developed for prediction of the rates of sulfide build-up and corrosion, but these require specific data input and field verification. Where sulfide generation is anticipated, corrosion resistant materials can be selected, or the alkalinity and thickness of concrete pipe can be increased to help minimize the effects of hydrogen sulfide corrosion. Table 5 summarizes various approaches used to minimize sulfide generation and corrosion during the design of wastewater collection and treatment facilities.

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 for 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

TABLE 5

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.

become more prevalent (14). Rehabilitation techniques are methods and repairs applied to an existing structure to prolong its useful life. With such techniques, municipalities can repair existing structures at a somewhat lower cost than replacement, and with less public inconveniences due to traffic disruptions and service interruptions. New techniques are being developed and refined that offer additional solutions to the problems of sewer rehabilitation. However, sewer rehabilitation is still a very costly operation.

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 to structural integrity, disruption of traffic, and excavation requirements. Corrosion rehabilitation techniques generally focus on repairs to protect structural integrity and provide a protective barrier against subsequent acid attack. Table 6 describes various methods of pipeline rehabilitation, indicating their applications, advantages, and disadvantages (15).

4.5 Findings and Conclusions

Based on current information, the following findings and conclusions are presented for the detection, prevention and control of hydrogen sulfide corrosion, and for repairing damage by hydrogen sulfide corrosion:

- Many municipalities are not aware of corrosion problems until catastrophic failure occurs.
- No standardized technique exists for measuring corrosion to allow estimation of corrosion rate.
- Educational programs are necessary to disseminate information on corrosion detection and monitoring to municipalities.
- Although some design guidelines have been developed which should assist in minimizing sulfide generation and corrosion, these guidelines are not universally practiced. Some observed corrosion could have been foreseen and avoided using existing design principles that minimize sulfide generation and corrosion.
- A large variety of chemicals and techniques are used to control sulfide in sewers. However, their costs and effectiveness for corrosion control vary widely based on site-specific conditions.
- Based on a 1984 survey of 89 cities, 34 percent take measures to reduce sulfide in sewers, and 63 percent provide corrosion protection of sewers or use one or more techniques to rehabilitate sewers damaged by hydrogen

TABLE 6

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 6 (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.

sulfide corrosion.

- The current national expenditure for controlling sulfide generation in sewers is on the order of tens of millions of dollars per year. CSDLAC alone is spending approximately two million dollars per year on chemicals to control sulfide.
- National expenditures for rehabilitation of sewers and structures damaged by hydrogen sulfide corrosion is very difficult to estimate. Although municipalities maintain records of operation and maintenance activities, often the cost of corrosion-related rehabilitation and replacement activities are not readily retrievable.
- Alternatives are available to rehabilitate pipe which has been damaged due to corrosion. Some, such as sliplining and cured-in-place inversion lining, have been widely used with satisfactory results. Others, such as application of "corrosion-resistant" coatings, have experienced early failure. Although in-situ sewer rehabilitation has become more prevalent due to its economic advantage over sewer replacement, it remains a very costly operation for municipalities.

Design guidelines for minimizing hydrogen sulfide corrosion in sewers have been developed, although they are not universally practiced and do not ensure absence of corrosion problems. Controlling corrosion is difficult and costly. Procedures for rehabilitating pipe damaged by corrosion are well established, but such options are also very costly. Research on new, economical approaches to controlling existing sewer corrosion appears to be limited.

5.0 RECOMMENDATIONS

Based on the findings of this study, additional emphasis needs to be given to information dissemination and education regarding hydrogen sulfide corrosion. There is a need to inform municipal political officials, design engineers, construction contractors, and operating staff of methods to minimize corrosion in new installations and detect corrosion in existing structures.

- Municipalities should incorporate corrosion detection and monitoring strategies into their collection system operating and maintenance procedures, in order to protect their infrastructure investment and preclude catastrophic failures.
    - In order to assist them in their efforts, EPA is developing a guidance manual and educational material for detecting, monitoring, and correcting hydrogen sulfide corrosion problems.
- Municipalities should maintain records of the extent of corrosion, wastewater characteristics, and corrosion rates in different parts of their systems. These records will assist in identifying factors that contributed to changes in rate over time. As monitoring of corrosion rate becomes more established, the relationship between corrosion rate and other factors such as water conservation, regionalization of wastewater treatment, and combined sewer separation can be studied.
- Programs to educate engineers regarding design procedures to minimize corrosion must continue, and should be incorporated into academic curricula.
- Other agencies should be encouraged to disseminate information on corrosion issues.
    - The Department of Housing and Urban Development and the Department of Agriculture's Farmer's Home Administration should be encouraged to issue corrosion prevention design information to municipalities obtaining funding from them for collection and treatment systems.

In spite of numerous previous and on-going efforts, corrosion is not entirely a controllable phenomenon. Therefore, additional research should be done in order to reduce the high costs of correcting corrosion in existing infrastructure.

- Additional research should be conducted on the effect of metals and cyanide on sulfide generation, and to establish threshold levels at which sulfide generation is inhibited.

- Research should be conducted to find a reliable method of monitoring the rate of corrosion.
- Microbial research should be encouraged to increase the understanding of the specific microbes contributing to the corrosion process as well as to study the relationship between these organisms and other microbial populations in a dynamic system.
- Applied research should be conducted on methods which offer low-cost approaches to controlling sulfide generation and hydrogen sulfide corrosion in sewers.

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GLOSSARY

Aerobic wastewater - Wastewater containing elemental oxygen.

Aerobic bacteria - Bacteria that require free elemental oxygen for their growth. (6)

Anaerobic wastewater - Wastewater devoid of elemental oxygen.

Anaerobic bacteria - Bacteria requiring, or not destroyed by the absence of air or elemental oxygen. (6)

Accelerated Corrosion - An increase in the rate of corrosion over time.

BOD - Abbreviation for biochemical oxygen demand. A standard test used in assessing wastewater strength. modified from (6)

Crown - The top interior surface of a pipe.

CSDLAC - County Sanitation Districts of Los Angeles County.

DO - Abbreviation for dissolved oxygen. The oxygen dissolved in wastewater, expressed in milligrams per liter or parts per million in this report. modified from (6)

Drop Manhole - A manhole in which the wastewater enters at a point higher in elevation than the exit point.

Equivalent weights - Measure of amounts of chemical available for reaction.

Force Main - A sewer flowing full under pressure imparted by a pump.

Gravity Sewer - A sewer sloped to flow partially full under the influence of gravity.

H_2S - Hydrogen sulfide gas in the atmosphere or dissolved in wastewater.

High Rate Corrosion - Corrosion which results in the loss of at least one inch of concrete in 20 years, as defined for this study.

Interceptors - Major sewers transporting large amounts of wastewater contributed from smaller collector sewers.

Lift station - A small wastewater pumping station that lifts wastewater to a higher elevation when the continuation of the sewer at reasonable depths would involve excessive depths of trench, or that raises wastewater from areas too low to drain into available sewers. modified from (6)

PE - Polyethylene

pH - The reciprocal of the logarithm of the hydrogen-ion concentration. Neutral water has a pH of 7, acidic water has a pH value of less than 7, and alkaline water has a pH value greater than 7. modified from (6)

Pilot Studies - Experiments conducted at small scale designed to simulate conditions at full scale.

Precipitation - A chemical process whereby two soluble components combine to form a solid, insoluble product. Metal sulfide precipitates formed during sulfide control are generally carried as suspended solids in wastewater until removed at the wastewater treatment plant.

PVC - Polyvinyl chloride

Reinforced Concrete Pipe - Pipe composed of concrete formed over a framework of steel reinforcing bars. The steel contributes to the strength of the pipe to withstand internal loads and external forces from soil, streets, and traffic.

Septic - Devoid of oxygen.

Severe Corrosion - Corrosion in which at least one inch of concrete is lost, as defined for this study.

Shock dosing - The intermittent application of chemicals.

Sulfide - Commonly refers to a variety of forms of sulfur, usually within the liquid phase, including soluble hydrosulfide (HS), molecular H_2S, organic sulfide complexes, and inorganic metal sulfides (FeS, ZnS, etc.). Technically , sulfide should refer to the sulfide ion (S^{-2}). (6)

Sulfide corrosion - Refers to hydrogen sulfide-induced corrosion, caused either directly by H_2S gas or indirectly from biological conversion of gaseous H_2S to sulfuric acid. Technically, there is no corrosion caused by sulfide ions.

Surcharged Sewer - A gravity sewer in which sewage flow "backs up" and completely fills the pipe.

VCP - Vitrified clay pipe.

Weir - A fixed plate used to regulate the flow of a liquid in an open channel.

Wet Well - A reservoir from which pumps draw liquid.

WWTP - Wastewater treatment plant.